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Preface

The 6th International Conference on Nuclear Physics at Storage Rings, STORI’05, was held May 23–26, 2005, at the Gustav–Stresemann–Institute e.V., a European meeting and education venue in Bonn, Germany. This conference was the most recent in a series, which started in 1991 at Lund (Chair: Bo Jakobsson, University of Lund), and was continued in 1994 in St. Petersburg (Oleg Lozhkin, PNPI), 1996 in Bernkastel–Kues (Fritz Bosch, Peter Egelhof, both GSI), 1999 in Bloomington (Hans–Otto Meyer) and in 2002 in Uppsala (Curt Ekström, TSL). In 2008 it will be held in Lanzhou, China, and it will be organized by Wenlong Zhan from the Institute of Modern Physics (IMP) of the Chinese Academy of Sciences.

The aim of the STORI–meetings is to provide a forum for a diverse international research community for the presentation and discussion of all aspects of nuclear physics at storage rings from the technologies to provide (un–)polarized, cooled internal and extracted beams to the dedicated detection systems for atomic, nuclear and hadronic reaction products, and the measurements to be conducted as well as the physics obtained.

When looking at the enclosed contributions, I hope you will agree that STORI’05 actually provided such an opportunity: we have heard excellent experimental and theoretical overview talks, presentations of recent results and contributions presenting new ideas and developments. Please note that we have included all the contributions as they received from the authors without further editing.

In addition we had an atmosphere, which allowed for critical questions and open discussions but also for mutual support and encouragement, and I guess that the basis for future co–operations as well as the renewal of old and the beginning of new friendships have been laid.

I would like to take this opportunity not only to thank all of you for your efforts to present well prepared talks and written contributions, but also to wish you all good luck in your future scientific and non–scientific endeavours.

Jülich, August 2005

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Overview Talks
Challenges in hadron and nuclear physics

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1 Introductory remarks

Hadron and nuclear physics explore the least understood sector of the Standard Model (SM), namely QuantumChromoDynamics (QCD) at large gauge coupling. In the region of energies below a few GeV, one is faced with two different types of challenges:

- \textit{Precision calculations/measurements}: Many very precise data exist which let one extract fundamental QCD parameters (condensates, quark masses, etc.) or explore bounds for physics beyond the SM. In such cases, precision calculations to accuracies of a few percent or better have to be done, which in certain cases can be achieved utilizing effective field theory (EFT) techniques. However, it should be stressed that contrary to popular opinion, more such precise data are needed, in particular for processes involving strange quarks. I will discuss one particular example that relates symmetry tests and the structure of few-nucleon systems based on EFT.

- \textit{The spectrum}: To really understand the issue of confinement in the light quark sector, we must first bring order into the spectrum. The nature and the spectrum of hadrons can only be understood if we are able to say with certainty which states are genuine quark model states, which are dynamically generated through channel couplings or which ones are exotic. For that, precise measurements of many properties of these states are needed and theoretical tools have to be developed to separate the often overlapping resonances. In this talk, I will address a few topics related to this type of problems, which are a) some properties of the exotic $\Theta^+(1540)$ (the so-called pentaquark) and b) the appearance of molecular states close to certain thresholds.

2 Symmetries of QCD

Symmetries and their realizations pose strong constraints on a given theory. In particular for QCD in the regime of large gauge coupling, symmetry considerations tell us a lot about its structure. To be more specific, consider the sector of the light up, down and strange quarks. Their current quark masses $m_q$ can only be extracted from low-energy processes because at high energies the quark mass term of QCD simply plays no role. One notable exception to this statement is the branching ratio $\text{Br}(\Psi' \rightarrow J/\Psi \pi^0)/\text{Br}(\Psi' \rightarrow J/\Psi \eta)$ because this decay is driven by the light quark...
mass difference \( m_u - m_d [1, 2] \) (for a recent update, see [3]). In general, one obtains complementary information on \( m_q \) from mesonic and baryonic reactions, as discussed in more detail below. Intimately related is the issue of isospin violation, which in most cases is given by an intricate interplay of QCD (quark mass differences) and QED (quark charge differences) effects, as revealed e.g. in the relative size of the strong and the electromagnetic contribution to the neutron-proton mass difference. Also, it is not yet clear whether the strange quark can always be considered light since \( m_s \) is not established how strong the flavor dependence of the quark condensates is? To obtain answers to these questions, one analyzes the chiral, isospin and SU(3)\( _f \) symmetries of QCD as well as its anomalies. The tools to perform such analyses are effective field theories combined with precision measurements, and in the more distant future, lattice QCD will contribute. I will not discuss any lattice results in this talk.

2.1 Isospin symmetry and its violation

For \( m_u = m_d \), QCD is invariant under \( SU(2) \) isospin transformations

\[
q \rightarrow q' = Uq, \quad q = \begin{pmatrix} u \\ d \end{pmatrix}, \quad U = \begin{pmatrix} a^* & b \\ -b^* & a \end{pmatrix}, \quad |a|^2 + |b|^2 = 1. \tag{1}
\]

This symmetry can be made transparent when one rewrites the QCD quark mass term

\[
H_{QBQCD} = m_u uu + m_d dd = \frac{1}{2} \sum_{i=0}^1 (m_u + m_d)(\bar{u}u + \bar{d}d) + \frac{1}{2} (m_u - m_d)(\bar{u}u - \bar{d}d), \tag{2}
\]

in terms of isoscalar (\( I = 0 \)) and isovector (\( I = 1 \)) components. The latter leads to the strong isospin violation (IV). However, there is a competing source for IV - electromagnetism. The standard situation is that one has a small IV on top of a large iso-symmetric background - this requires a precise machinery to perform accurate calculations. The corresponding effective Lagrangian for isospin-violation in systems with pions and nucleons reads (to leading order) \([5]\) (higher order effects are considered in \([6]\))

\[
\mathcal{L}_{\sigma N}^{(2IV)} = N \left\{ c_5 \left( \chi_+ - \frac{f_2}{f} (\chi_-) \right) + f_2 \left( \hat{Q}_+ - \hat{Q}_- \right) \right\} + \mathcal{O}(q^3), \tag{3}
\]

where two low-energy constants (LECs) parameterize the leading strong (\( c_5 \)) and the em (\( f_2 \)) IV effects, due to the different charges of the up and down quarks. These LECs link various observables/processes, such as the proton-neutron mass difference, \( m_n - m_p = 4 c_5 B_0 (m_u - m_d) + 2 e^2 f_2 F_2^2 + \ldots \), or the neutral-pion–nucleon scattering length difference \( a(\pi^0 n) - a(\pi^0 p) = \text{const} \left( -4 c_5 B_0 (m_u - m_d) \right) + \ldots \) \([4, 5]\), which is, however, extremely hard to measure. Another process that vanishes exactly for vanishing quark mass difference is \( dd \rightarrow \alpha \pi^0 \), which I will discuss next.
2.2 Isospin symmetry in few-nucleon systems: $dd \to \alpha\pi^0$

I now consider the reaction $dd \to \alpha\pi^0$. It combines aspects of chiral QCD dynamics with a detailed understanding of non-perturbative few-nucleon dynamics and is thus most challenging for a theoretician. In the absence of isospin violation, its cross section would be zero. However, the pioneering near threshold data from IUCF have firmly established a non-vanishing cross section, $\sigma_{\text{tot}} = 12.7 \pm 2.2$ pb at $E = 228.5$ MeV and $\sigma_{\text{tot}} = 15.1 \pm 3.1$ pb at $E = 231.8$ MeV [9]. To be able to map out the contribution from the quark mass term, polarization is extremely important - only with polarized data a separation of partial waves can be achieved. It is also obvious that one needs a systematic and precise framework for few-nucleon systems to perform such calculations. The corresponding machinery has been developed over the last years. The starting point is the effective chiral Lagrangian

$$\mathcal{L}_{\text{EFF}} = \mathcal{L}_{\pi\pi} + \mathcal{L}_{\pi N} + \mathcal{L}_{NN} + \ldots$$

This EFT encodes the strictures of the spontaneous chiral symmetry breaking of QCD, in particular, pions emerge as Goldstone bosons (or, more precisely, as Pseudo-Goldstone bosons due to the small explicit symmetry breaking). In the purely pionic and in the pion-nucleon sector, one has a systematic expansion in terms of two small parameters, namely $p/\Lambda_\pi$ and $M_s/\Lambda_\chi$, with $\Lambda_\chi \approx 1$ GeV and $p$ denotes an external momentum - chiral perturbation theory (CHPT). In systems with two (or more) nucleons a non-perturbative resummation is required to account for the large S-wave scattering lengths, e.g. $|a_{\pi p}^{(1S_0)}| \approx 24$ fm $\gg 1/M_s \approx 1.5$ fm or the small binding energies (binding momenta), e.g. $\gamma = \sqrt{\beta p m_N} \approx 45$ MeV $\ll M_s = 140$ MeV. The parameters (LECs) in $\mathcal{L}_{\pi\pi}$ and $\mathcal{L}_{\pi N}$ are known from CHPT studies whereas $\mathcal{L}_{NN}$ collects short-distance contact terms that have to be fitted to say NN scattering data. The most successful scheme in this field was originally proposed by Weinberg [8], that is to calculate the two-nucleon potential based on the underlying power counting and use this potential is a regularized Lippmann-Schwinger equation to generate the bound and scattering states. Such a scheme has been carried out to next-to-next-to-next-to-leading order (N$^3$LO) in the chiral expansion [9]. It is as precise as (semi-)phenomenological potentials and it offers a natural explanation for the relative strength of the 2-, 3-, ..., nucleon forces. Furthermore, the forces, external currents and even single nucleon properties are obtained from one chiral effective Lagrangian. Consequently, one can consistently extract neutron properties from nuclear targets, systematically include IV and in the end can put nuclear physics on much more sound basis. A typical result of these calculations for the two-nucleon system is shown in Fig. 1.

Even more interesting, a consistent three-nucleon force emerges in this framework [10]. Its first non-vanishing contributions appear at NNLO. The 3NF is given by three topologies of diagrams at this order: a) two-pion-exchange between the three nucleon lines, b) one-pion-exchange between a four-nucleon contact term and one nucleon and c) a six-fermion contact interaction. While the first type of diagrams is parameter-free (the corresponding LECs are determined from pion-nucleon scattering data), the classes b) and c) are given in terms of one LEC each at this order. Therefore, one needs two low-energy observables to pin these down and make predictions. Note that topology b) also features prominently in the reaction...
NN → NNπ, so that further tests of the 3NF are possible in pion production [11]. In Fig. 2 such predictions for \( nd \) scattering at low and intermediate energies are shown, in particular for \( E_n = 65 \) MeV the 3NF is clearly needed to describe the data. An \( N^3\)LO analysis is needed to further reduce the theoretical uncertainties and to allow for many more tests of the chiral 3NF. Note also that the binding energy of \( ^4\)He is predicted to be in the range \(-29.6 \ldots -27.8\) MeV, quite close to the experimental value of \(-28.3\) MeV. After this digression into systems of 2, 3 and 4 nucleons, I return to the reaction \( dd \rightarrow ^0\). It is clear that the framework exists to analyze this in EFT, but this is a major task. So far, the relevant charge symmetry breaking operators have been surveyed and estimates for the cross sections within a simple model were performed - quite astonishingly, \( \sigma_{tot} \) comes out in the right order of magnitude [12]. More theory works is needed to achieve the required precision (systematic analysis of IV in the 2N system, 3NF at \( N^3\)LO, four-particle scattering) and more data are called for, including polarization. This will be one of the feature experiments with the WASA detector at COSY - a truly great prospect for hadron and nuclear physics. It is also important to stress that this field is largely driven by a very intense interplay of theoretical ideas and precision measurements.

2.3 Further tests of isospin violation in hadronic reactions

Isospin violation induces meson-mixing and triggers certain decays, which allow for other fine tests of this broken symmetry of QCD. Consider first meson mixing. There are three prominent processes in low-energy hadron and nuclear physics: 1) \( \rho - \omega \) \((M_\rho = 770\) MeV, \( M_\omega = 782\) MeV\) mixing is clearly visible in the pion charge form factor and it can be used to obtain a bound on \( m_u/m_d \) [13]. It also plays a role in certain B-meson decays. 2) \( \pi^0 - \eta \) mixing is very important in few-nucleon systems. Note, however, the large mass gap since \( M_{\pi^0} = 135\) MeV and \( M_\eta = 547\) MeV –
a detailed treatment of the energy dependence of this mixing is mandatory. Also, the value of the eta-nucleon coupling $g_{\eta NN}$ is not very well known. 3) $a_0 - f_0^-$ mixing. Here, the masses are almost degenerate, $M_{a_0} \simeq M_{f_0^-} = 980$ MeV, and these states are very close to the $\bar{K}K$ ($\bar{K}^+K^-, \bar{K}^0K^0$) thresholds. This leads to a very large enhancement of the isospin-mixing matrix element [14], which because of kinematical reasons, can best be tested in NN and $dd$ production experiments, i.e. at hadron colliders [15] – another opportunity for COSY in the years to come. Next, I turn to meson decays. The best studied reaction is $\eta \rightarrow 3\pi$, which is driven by $IV$. It can be analyzed in CHPT, the chiral expansion of the amplitude takes the form [16]

$$A(\eta \rightarrow 3\pi) = A^{(2)} + A^{(4)} + \ldots$$

$$A^{(2)} = \frac{B_0(m_u - m_d)}{3\sqrt{3}F_\pi^2} \left\{ 1 + \frac{3(s - s_0)}{M_\eta^2 - M_{\pi^0}^2} \right\}$$  \hspace{1cm} (5)

with $s_0$ the center of the Dalitz plot. The decay width is very sensitive to the light quark mass ratio $Q$, i.e.

$$\Gamma(\eta \rightarrow 3\pi) \sim Q^{-4}, \quad Q^{-1} = \frac{m_u - m_d}{m_s - m_d}$$  \hspace{1cm} (6)

This decay is affected by large unitarity corrections (final-state interactions) which can be handled with a dispersive machinery. One obtains many testable predictions such as the ratio $\Gamma(3\pi^0)/\Gamma(\pi^+\pi^-\pi^0)$ and also for the various Dalitz slopes, see e.g. [17]. Similar effects can also be seen and tested in $\eta'$-decays. In addition, the dynamics of the $\eta'$ is linked to the axial U(1) anomaly of QCD. In Fig. 3 some recent results on $\eta$ and $\eta'$-decays based on one-loop CHPT combined with coupled channel Bethe-Salpeter equations are shown [18]. In that approach, vector mesons like the $\rho$, that play an important role in such decays, are dynamically generated from composite two-pseudoscalar states. In addition, these calculations are consistently
described together with two-photon and hadronic decays of the \( \eta \) and the \( \eta' \). However, to disentangle the anomaly, much more \( \eta' \)-decay data are needed – another ideal playground for WASA at COSY.

These few examples show that in the low-energy sector of QCD many tests of its symmetry and anomaly structure can still be and should be performed. In particular, in the presence of strange quarks there are still very open fundamental issue - namely the flavor dependence of the quark condensate and how to treat the strange quark mass. These question can only be answered when more accurate data will become available that can be analyzed within the effective field theory of QCD. It is very evident that WASA at COSY can contribute significantly to this field.

### 3 Spectrum of QCD

To really understand the confinement property of QCD, we must known exactly the number of states and their nature – the confinement mechanism must be hidden in the spectrum of QCD. Since the quark model is fairly successful in the description of quark-antiquark (mesons) and three-quark (baryons) states, one might focus on crypto-exotic states to get additional information. While exotic states have quantum numbers not accessible for \( \bar{q}q \) or \( qqq \) configurations, crypto-exotic states might have normal quantum numbers but an exotic nature. Typical examples are: 1) the scalar mesons \( a_0(980) \) and \( f_0(980) \), which are presumably kaon molecules. In addition, they mix, leading to some interesting isospin violation as mentioned earlier; 2) the \( \Lambda(1405) \) is believed to be a meson-baryon bound state, more interestingly, it might have a two-pole structure as I will discuss later; 3) extending these considerations to the charm quark sector, I will show that the recently observed \( D_{sJ} \) mesons most probably have a molecular component. A truly exotic state – if it exists – is the pentaquark \( \Theta^+ (1540) \). Because of the recent JLab data [21], its existence is very much under debate, but to my opinion a much cleaner signal (or absence thereof) will be given from the fall 2004 data of associated strangeness production at COSY-TOF.
3.1 Pentaquark properties from hadronic reactions

A very interesting property of the $\Theta^+$ is its width. Most experiments which have seen evidence of this state only quote upper limits for the width given by the resolution of the experiment. In various papers, information on kaon-nucleon scattering [22] was analyzed leading to the conclusion that the width of the $\Theta^+$ has to be less than a few MeV. A strongly interacting particle with such a small width could truly be called “exotic”. In [23] the impact of the pentaquark on differential and integrated cross sections for the reaction $K^+d \rightarrow K^0pp$, where experimental information is available, was investigated. The calculation utilizes an extension of the Jülich kaon-nucleon model that includes the contribution of a $\Theta^+(1540)$ with a variable width. The evaluation of the reaction $K^+d \rightarrow K^0pp$ takes into account effects due to the Fermi motion of the nucleons within the deuteron and three–body kinematics.

As shown in Fig. 4, one concludes from that analysis that the data constrain the width of the $\Theta^+(1540)$ to be less than 1 MeV. In [24], the reaction $K^+Xe \rightarrow K^0pX$ was investigated in a meson-exchange model including rescattering of the secondary protons with the aim to analyze the evidence for the $\Theta^+(1540)$ reported by the DIANA collaboration [25]. It was confirmed that the kinematical cuts introduced by the DIANA collaboration efficiently suppress the background to the $K^+n \rightarrow K^0p$ reaction which may contribute to the $\Theta^+$ production. The effect of a narrow resonance with both positive and negative parity in comparison to the DIANA data was studied in [24]. It is shown that the $K^+Xe \rightarrow K^0pX$ calculations without $\Theta^+$ contribution as well as the results obtained with a $\Theta^+$ width of 1 MeV are in comparably good agreement with the DIANA results.

![Fig. 4. Total $K^+d \rightarrow K^0pp$ cross section as a function of the kaon momentum. The lines in a) show the results of the full calculation for the $K^+d \rightarrow K^0pp$ reaction obtained with different $\Theta^+$ widths: $\Gamma_{\Theta}=1$ MeV - solid, 5 MeV -dashed, 10 MeV -dotted and 20 MeV -dashed-dotted, while the solid (black) line is our calculation without pentaquark. The lines in b) show the calculations for the $K^+n \rightarrow K^0p$ reaction assuming that the neutron target is at rest.](image)

The parity of the exotic state $\Theta^+(1540)$ with positive strangeness (if it exists) is not determined. Its parity is considered a decisive quantity regarding its substructure. The most appealing proposal to determine the parity is based on the application of the Pauli principle in the process $p\bar{p} \rightarrow \Theta^+\Sigma^+$ [26] since it links spin and parity. The ideal observable to determine the parity is the spin-triplet cross section $^3\sigma_{\Sigma}$ in the threshold region [27],

$$^3\sigma_{\Sigma} = \frac{1}{2} (^3\sigma_0 + ^3\sigma_1) = \frac{1}{2} \sigma_0 \left( 2 + A_{xx} + A_{yy} \right), \quad (7)$$
with $A_{xx}, A_{yy}$ spin correlation coefficients. Independently of any naturalness assumption, the spin-triplet cross section is essentially independent of the excess energy $Q$ or rises linearly with $Q$ for negative and positive pentaquark parity, respectively. Therefore, the measurement of the total cross section as well as the (angle integrated) spin-correlation parameter $A_{xx}$ for $pp$ induced pentaquark production at two well separated energies, e.g. at excess energies of $Q = 20$ and $40$ MeV. Such an experiment is under preparation at COSY-TOF. Note also that this method is germane for the parity determination of narrow resonances.

3.2 Nature of the $\Lambda(1405)$

Next, I discuss how baryon resonances can be generated as meson-baryon bound states. For that, consider $K^-p$ scattering. A purely perturbative treatment is not possible due to the strong channel couplings and the appearance of a subthreshold resonance, the $\Lambda(1405)$. A non-perturbative resummation scheme is mandatory to generate a bound state or a resonance. There exist many such approaches, but it is possible and mandatory to link such a scheme tightly to the chiral QCD dynamics. Utilizing such a framework, it was observed in [28] that there are indeed two poles close to the nominal $\Lambda(1405)$ resonance. The physics behind these two poles was recently revealed in [29]. Starting from an SU(3) symmetric Lagrangian to couple the meson octet to the baryon octet, one could in principle generate a variety of resonances according to the SU(3) decomposition, $8 \otimes 8 = 1 \oplus \bar{8} \oplus \bar{8} \oplus 10 \oplus \bar{10} \oplus 27$. As it turns out, the leading order transition potential is attractive only in the singlet and the two octet channels, so that one a priori expects a singlet and two octets of bound states. However, the two octets come out degenerate. This has no particular dynamical origin but rather is a consequence of the actual values of the SU(3) structure constants. In the real world, there is of course SU(3) breaking of various origins. This was parameterized in [29] in terms of a symmetry breaking parameter $x$, where $x = 0$ corresponds to the SU(3) limit and $x = 1$ to the real world. If one analyzes the motion of the various poles in the complex plane, one notes that the two octets split, in particular, one moves to lower energy ($I = 0, 1426$ MeV) close to the position of the singlet ($I = 0, 1390$ MeV). These are the two poles which combine to give the $\Lambda(1405)$ as it appears in various reactions. Recent Crystal Ball data for the reaction $K^-p \rightarrow \pi^0\pi^0\Sigma^0$ [30] seem to give support to this two-pole scenario, see [31] for a detailed discussion.

3.3 Charm-strange mesons

I consider now states including charm quarks, more precisely, $c\bar{s}$ mesons. These are heavy-light systems, i.e. the heavy quark spin is fixed and one has parity doubling for the states with $j_z = l \pm 1/2$, where $l$ denotes the angular momentum of the $s$ quark. Of special interest are the recently observed $D_{sJ}^*(2317)$ and $D^*_{sJ}(2460)$ mesons, the former being close to the $K^+D^0(2358$ MeV) and the $K^0D^+(2367$ MeV) thresholds, the latter close to the $D_{sJ}^*(2516$ MeV) threshold. It is therefore quite natural to ask whether these states are cousins of the $a_0/f_0$ mesons, i.e. possibly $KD$ molecules? To answer this question, we performed an analysis in the framework
of a meson-exchange model [32] which describes well the coupled channel $\pi\pi$-$\bar{K}K$
dynamics and was extended to SU(4). This is of course a crude approximation, but
at least for vector meson decay it works fairly. If one fixes the corresponding SU(4)
coupling constant from $\rho \to \pi\pi$, one can predict $\Gamma(D^{*+} \to D^{0}\pi^+) = 52$ keV and
$D^{*+} \to D^+\pi^0 = 26$ keV, compatible with the empirical numbers of $64 \pm 18$ keV and
$29 \pm 8$ keV, respectively. In this model, the $D_{sJ}^+(2317)$ meson can not be described
as a pure molecule, as shown in Fig. 5 (lower solid line). However, in quark models
this state usual comes out higher in mass, e.g. in the covariant Bonn quark model
at 2460 MeV [33]. If one now allows for a mixing of this state with the molecule,
one obtains a pretty good description of the data, as shown by the upper solid line
in that figure. One can also view these results differently, only with strong isospin
mixing between $I = 0$ and $I = 1$ one can produce enough strength in the final
state. More theoretical investigations and data are needed to determine the true
nature of these interesting states. An another interesting state is the $X(3872)$, which
presumably is a $D^0\bar{D}^0$ molecule, see e.g. [34, 35, 36].

![Diagram](image.png)

**Fig. 5.** Yield of $D_{sJ}^+(2317)$ events in the molecular scenario.
The data are from BaBar (filled circles), Belle (filled diamonds) and CLEO (filled triangles).

### 4 Summary and outlook

I would like to stress again that hadron structure and dynamics and also nuclear
physics are the central issues of strong QCD (of the Standard Model) and require
non-perturbative methods in the few GeV region and below. A (certainly incomplete)
list of challenges reads like:

- **Precision tests of QCD – symmetries, their realization & anomalies:** The analysis
  of isospin and SU(3)$_V$ symmetries and their breaking gives information on
  the quark masses (quark mass ratios) and the quark condensates. Hadronic
  atoms allow one to extract S-wave scattering lengths of hadrons, leading to fine
  tests of chiral symmetry breaking in QCD. Furthermore, accurate determinations
  of QCD contributions to QED tests (I just mention the muon anomalous magnetic
  moment) have the potential of unraveling physics beyond the SM.

- **The spectrum of QCD – confinement mechanism:** To unravel the physics encoded
  in the spectrum, we must find answers to the questions what a the gen-
If we consider the Quark Model states, what are molecules? Are there truly exotic states (pentaquarks)? We need to determine their properties and eventually extend these considerations to systems including heavy quarks, guided by heavy quark symmetry and the corresponding EFT. Also, a detailed study of final-state interactions in heavy meson decays will reveal lots of information on low-energy QCD.

- Lattice QCD – a theoretical tool with great promise: At present, most simulations are (partially) quenched and are performed at too high quark masses. However, chiral extrapolations for finite $m_q$ and finite $a$ become available, these will eventually link the lattice simulations to the physical values of the quark masses. Lattice QCD is already quite reliable for thermodynamics, because bulk properties are cheaper to simulate.

- Modern theory of nuclear forces – direct relation to QCD: As discussed, a systematic and precise approach based on a chiral effective Lagrangian has been developed. It allows for an accurate analysis of few-nucleon systems including consistent three-nucleon forces and external currents, which still have to be worked out to the required order, N$^3$LO. Further, on-going work tries to extend such an approach to medium and heavy nuclei (by considering halos, the No-Core-Shell-Model, and so on).

- Spin dynamics in the few-GeV region – quark-gluon structure of the nucleon: The gluon contribution to the nucleon spin has still not been mapped out in detail (but crude data from pioneering measurements from HERMES and COMPASS exist). Also, the last remaining leading twist operator, the transversity distribution, has not yet been measured. Furthermore, much interest has focused on coordinate space distributions via GPDs.

- Strongly interacting matter – finite densities & temperatures: The QCD phase diagram is very complex and there are regions in temperature and density space where it is only badly known. Recent lattice calculations seem to indicate a tricritical point - and it is one current interest to try to determine it experimentally. Clearly, data on jet quenching and elliptic flow from RHIC have shown that the QGP is not a free gas - what is the nature of the strongly interacting matter above $T_c$? Furthermore, what can we learn from possible medium modifications of hadrons, like e.g the recent work on the omega mass from CB-ELSA/TAPS [37]?
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References


Introduction

Quantum Chromodynamics (QCD) is the widely accepted theory of the strong force. Probing small distance scales (<< 0.1 fm), scattering processes at high energies and momentum transfers have revealed quarks as fundamental building blocks of matter, interacting via the exchange of gluons. Because of the small coupling strength in this regime of asymptotic freedom [1], perturbative methods have provided a quantitative description of strong interaction phenomena. With decreasing momentum transfers, corresponding to larger length scales comparable to the size of hadrons (∼ 1 fm), the magnitude of the strong coupling constant increases to the point that a perturbative treatment no longer applies (see Fig. 1). In this energy regime the interaction between quarks and gluons is highly non-linear. As a consequence, there has been only limited success in a quantitative description of static and low momentum hadronic phenomena, including the strong interaction in nuclei which should also emerge from the fundamental theory. Quantum Chromodynamics at low and moderate energies is thus the least understood sector of the otherwise very successful Standard Model.

This non-perturbative regime of Quantum Chromodynamics is characterized by several new phenomena which pose a series of open questions, providing experimental as well as profound intellectual challenges:

- Why are quarks confined within hadrons? How are hadrons constructed from their constituents?
- What is the origin of hadron masses? These masses are much higher than the sum of the current quark masses.
- Are hadron properties (e.g. their mass) modified in a nuclear medium? What is hereby the role of chiral symmetry restoration?
- What is the role of symmetry breaking in meson production and decay?
- What is the relation between parton degrees of freedom and the low energy structure of hadrons?
- Do hybrids (qq̅g) or glueballs (ggg) exist as a consequence of the selfinteraction among gluons?
These questions have been taken up in experiments with photon-, lepton- and hadron- beams. In this presentation I will discuss the perspectives and the potential of this field opened up by hadronic probes. This discussion will lead us from the future physics program at COSY to the long range plans for hadron physics with antiproton beams at the Facility for Antiproton and Ion Research (FAIR).

5 Perspectives of Hadron Physics at COSY

Finding and studying symmetries and symmetry violations in hadronic reactions will help to get insight into symmetry breaking patterns of QCD. Corresponding experiments are the back bone of the future physics program at COSY. Primary objectives are precision studies of isospin breaking nuclear reactions, e.g. \( dd \rightarrow \alpha \pi^0 \) (extending the pioneering work at IUCF [9]), and decay experiments such as \( \eta, \eta' \rightarrow 3\pi^0 \) which are sensitive to the mass difference between u and d quarks. C, P, and T-invariance and combinations thereof will be tested in meson decay experiments, e.g. \( \eta \rightarrow 4\pi^0, \eta \rightarrow \pi^+\pi^-e^+e^- \), or \( \eta \rightarrow 3\pi^0\gamma \). These measurements with many neutral particles in the final state call for a 4\( \pi \) photon detector which will become available at COSY with the installation of WASA, operated so far at CELSIUS. This detector (see Fig. 4) consists of a central detector around the target, comprising an electromagnetic calorimeter, and a forward detector for detection and identification of scattered projectiles and charged recoil particles. This detector will be installed in 2006 as an internal detector in the COSY storage ring [3]. First experiments are planned for 2007.
Overview Talks

Figure 2: Cross section of the WASA detector as planned for the installation at COSY. The figure is taken from [3].

Figure 3: Current layout of the planned Facility for Antiproton and Ion Research (FAIR) at Darmstadt [4].

6 Perspectives of Hadronic Physics at FAIR

The science goals underlying the FAIR project span a broad range of research activities. These include studies of compressed hadronic matter in nucleus-nucleus collisions, investigations of exotic nuclei, tests of Quantum Electrodynamics in extremely strong electromagnetic fields, and investigations of bulk matter in high density plasma states. Of particular interest for hadron physics are studies of hadronic matter at the sub-nuclear level with beams of antiprotons, one of the pillars of the FAIR project. The current layout of the planned facility is given in Fig. 3, showing the double synchrotron SIS100/300 and several storage rings. Antiprotons are pro-
duced with primary proton beams of \(\approx 30\) GeV. After accumulation and cooling, antiprotons are re-injected into SIS 100, accelerated to the reaction energy and then stored in the High Energy Storage Ring (HESR) (see Fig. 4). A specific feature of the storage ring is the electron cooler which is essential for achieving and maintaining a momentum resolution of \(\Delta p/p \approx 10^{-4} - 10^{-5}\), counteracting the beam heating through atomic beam-target interactions. Antiproton induced hadronic reactions are studied with PANDA, an almost hermetic detector which will allow neutral and charged particle detection and identification at high events rates over the relevant kinematic range.

6.1 The PANDA Physics Program

Gluons, which mediate the the strong force between quarks, carry colour charges themselves. This makes the dynamics of the strong interaction so much different from the other basic forces in nature. The gluon-gluon interaction is the distinct feature of QCD. As a consequence, gluons can form bound gluon rich systems known as glueballs. QCD also predicts the existence of hybrid states consisting of quark-antiquark pairs with excitations of the gluon field. The search for such states and the study of their decay modes constitutes the core of the research program at PANDA.

Fig. 5 shows the type of hadronic configurations which can be studied with antiproton beams of up to 15 GeV/c. In this mass range, lattice QCD predicts the existence of about 15 glueball states (see Fig. 6, some with exotic quantum numbers non-existent for \(q\bar{q}\) states). The latter states cannot mix with usual \(q\bar{q}\) mesons. As a consequence, glueballs with exotic quantum numbers are predicted to be rather narrow and therefore easy to identify experimentally. The lightest glueball with the exotic quantum numbers \(J^{PC} = 2^{++}\) is predicted to have a mass of 4.3 GeV/c\(^2\). The ligthest hybrid configuration with exotic quantum numbers \(J^{PC} = 1^{-+}\) is expected
Figure 5: Mass range of hadrons accessible at the HESR with antiproton beams. The figure indicates the $\bar{p}$ - momenta required for charmonium spectroscopy, the search for glueballs and charmed hybrids, and the production of D meson and $\Xi$ baryon pairs. The energy range covered by the former Low Energy Antiproton Ring (LEAR) at CERN is indicated by the arrow. The figure is taken from [4].

Figure 6: The glueball spectrum predicted in recent lattice QCD calculations [7] in the mass range of 1.5 to 5.0 GeV/$c^2$.

at a mass of 4.1 GeV/$c^2$. Scans up to a mass of 5 GeV/$c^2$ at the HESR will thus reveal the full variety of gluon rich systems. The experimental observation of these exotic particles would confirm one of the hard predictions and characteristic features of QCD. A non-observation of such states would pose a genuine problem for our present understanding of hadronic physics in the framework of Quantum Chromodynamics.

Searches for glueballs and hybrids in this energy regime can be performed in par-
Figure 7: Comparison of the mass resolution of the $\chi_{c1}$ resonance obtained in $e^+e^-$ annihilation [8] and in $p\bar{p}$ annihilation [9].

The production of hadronic states in proton-antiproton annihilation provides several advantages compared to $e^+e^-$ experiments. Hadronic states of all quantum numbers can be directly formed, in contrast to $e^+e^-$ reactions where only states with $J^{PC} = 1^{--}$ can be directly formed. Being a gluon-rich process, antiproton annihilation provides sizable cross sections for states with gluonic degrees of freedom. Antiproton beams can be cooled stochastically and with electron beams allowing a precise measurement of the widths of states, only limited by the beam momentum resolution. This advantage of $p\bar{p}$ compared to $e^+e^-$ experiments is illustrated in Fig. 7.

The research program at PANDA also includes investigations of the properties of mesons with open and hidden charm in the nuclear medium, spectroscopy of double-strange hypernuclei, the search for CP-violation in the neutral $D\bar{D}$ system, and studies of the proton structure in inverted deeply virtual Compton scattering.
6.2 The PAX Physics Program

The proposed PAX (Polarized Antiproton Experiments) physics program extends the measurements of $pp$ reactions to polarisation observables, providing new information on parton distributions within the nucleon. Of particular interest is the transversity distribution $h_1(x)$ which describes the quark transverse polarization inside a transversely polarized proton as illustrated schematically in Fig. 8.

The structure functions $f_1(x)$ and $g_1(x)$, representing the momentum and helicity distributions of quarks, are already quite well measured in deeply inelastic lepton scattering experiments. In contrast, very little is known about the third structure function $h_1(x)$ since it can not directly be accessed in inclusive deep-inelastic scattering of leptons. A direct access is provided by measuring the double transverse spin asymmetry in the annihilation of polarized protons and antiprotons into dilepton pairs (Drell-Yan process) as schematically indicated in Fig. 9.

These measurements require the production of polarized antiprotons [11] and the operation of the HESR in a collider mode. Such a scenario is sketched in Fig. 10 which is at the present stage however not part of the antiproton core program.

Experiments with polarized antiproton beams at the HESR will open unique possibilities to test Quantum Chromodynamics in hitherto unexplored domains. This illustrates the high potential of antiproton physics at FAIR which will also attract physicists presently working with lepton beams.
Figure 10: Proposed asymmetric collider setup for the collision of transversally polarized antiprotons with transversally polarized protons [26].

References


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Nuclear Physics: Throwing our hat in the ring.

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Abstract
The goals of nuclear structure physics and the main questions facing us in this field are briefly reviewed. The question of how to study the structure of atomic nuclei is then addressed. This leads to the conclusion that we need beams of radioactive nuclei to progress. The methods of creating such beams are then discussed. Finally the FAIR project at GSI is reviewed and the contribution it will make to answering the open questions in nuclear structure physics examined. The complex of storage rings that will be a part of FAIR will play a particularly significant role.

1. Introduction

The study of the structure of atomic nuclei has undergone a revolution over the last fifteen years or so. It is a transformation akin to the dramatic changes wrought in Astrophysics by the invention of the telescope, the realisation that one could observe the sky at wavelengths other than the visible and the ability to place telescopes of all types in space. The essence of this change is our new found ability not only to create copious amounts of radioisotopes but to accelerate them to the energies needed to study nuclear reactions. This new found capability is not just important for the study of nuclear structure but has many applications, among them the means of obtaining information on many of the reactions of importance in explosive nuclear processes in stars. To see why this leap forward is important for nuclear physics let us just briefly remind ourselves of how one studies atomic nuclei.

We have access to the properties of nuclei in two ways, namely from the study of radioactive decay and nuclear reactions. The former is extremely valuable and provides,
in some cases, unique information. However, it is, for all intents and purposes, immutable and so we have no control of the process and the information we gain. The situation with the study of reactions is quite different. Figure 1 shows, in cartoon form, what happens in nuclear reactions. In simplistic terms one might characterise such studies as making two nuclei collide and then measuring the masses, velocities etc of all the fragments from the collision and deducing from that the properties of the initial participants. As we can see from the figure there are many possible outcomes of such collisions. Quite apart from the fact that the initial energy plus mass may be shared in different ways many processes may occur. Some, such as Coulomb excitation or single nucleon transfer, are relatively straightforward but others, such as fusion-evaporation or fragmentation(not shown in fig.1), are much more complex in terms of the dynamics. In addition at any given collision energy many different processes are possible energetically. All such processes will occur but with very different cross-sections. These cross-sections will all vary with the energy involved in the collision. Thus one can choose the combination of target and projectile nucleus and the bombarding energy to optimise the production of a particular product nucleus and also control to some extent its excitation energy and angular momentum.

Figure 2 summarises, again in cartoon form, some of the key parameters we seek to vary in reaction studies in order to gain information about nuclear properties and hence lay the foundations for a comprehensive theoretical framework for predicting the properties of nuclei. In brief up to now we have very successfully, but not completely, explored the plane defined by temperature (excitation energy) and angular momentum. At progressively higher energies we see first a variety of collective excitations, followed by particle-hole states followed by a region of quantal chaos where the level density is high. As we increase the rotational frequency we start to see a variety of effects due to the Coriolis force[1]. Until recently our ability to explore the third axis in fig.2 was severely limited. Given only stable target and projectile nuclei one can make a half-hearted attempt at best to make nuclei far from stability. A single example will suffice. In a fusion reaction with two stable nuclear species the compound nucleus must lie on the line of stability at best and, more likely to the neutron-deficient side of stability since, as the nuclear mass A increases, the stable nuclei have a neutron excess. Following fusion the excited nucleus will generally evaporate neutrons since they do not face a Coulomb barrier. Thus neutron-rich nuclei are hard to make in this way.
Different considerations apply to other types of reaction but the upshot is that nuclei far from stability are difficult to make. How can we change this situation? The answer is to use projectiles that are radioactive so that one starts with a combination of nuclei which is inherently off the stability line.

In the next section we will discuss briefly the goal of nuclear structure studies and some of the unanswered questions before us. This is followed by a section on how we can produce beams of radioactive nuclei. This will lead to a section on the new fragmentation facility at GSI, Darmstadt. FAIR, the facility for anti-proton and ion research is based on the fragmentation of stable, relativistic nuclei to create the radioactive species we want. In the final section some of its characteristics will be described as well as the kind of studies it will make possible, with particular emphasis on the complex of storage rings which is a major, unique part of FAIR.

2. The goal of nuclear physics.

In essence the goal is simple. We would like to determine nuclear properties over a wide range of N, Z, T and $\omega$ [where T is the temperature or excitation energy and $\omega$ is the rotational frequency] and, on this basis, try to find a consistent theoretical framework to describe the phenomena observed. We are still a long way from reaching this goal. In terms of experiment there are still many unanswered questions. One of the simplest questions is “What are the limits to nuclear existence?” yet we are a long way from answering it. Figure 3 shows a version of the chart of the nuclides. The so-called magic numbers of neutrons and protons are marked by vertical and horizontal lines respectively. One particular estimate of the positions of the proton- and neutron-drip lines is also shown. These are defined in terms of the locus of points where the appropriate single-nucleon separation energy goes to zero. In a loose sense nuclei beyond these limits are said not to “exist” although it may be possible to study some of them. We now have a reasonable idea of where the proton drip-line lies, partly because it is possible to make the relevant nuclei in fusion-evaporation reactions and partly because ground state proton decay gives a clear signal which can be detected with high
sensitivity[2]. On the neutron-rich side our knowledge is much more limited. Figure 3 indicates the limit of our knowledge of nuclear properties; the boundary lies well short of the drip line. Our best estimates rely on semi-empirical formulae of various types. They all do reasonably well for nuclei with measured masses, the nuclei near stability, but diverge rapidly as we extrapolate and estimates of the neutron drip-line for Sn (Z = 50) can vary by 20-30 mass units.

The nuclear radius also seems an easy quantity to measure. The charge radius, effectively defining the volume occupied by the protons, can be readily measured in electron scattering. All the textbooks come up with the same result, namely \( R = R_0 A^{1/3} \) where \( R_0 \) is a constant. In addition the charge and matter radii are almost indistinguishable.

Although this is an excellent rule of thumb for nuclei near stability it was found to be hopelessly wrong for light neutron-rich nuclei such as \(^{11}\text{Li}\) as soon as we could make beams of them. Measurements [3] of their total interaction cross-sections at relativistic energies showed that their radii were much larger than this formula. Analysis [4] in terms of the adiabatic approximation revealed that \(^{11}\text{Li}\) has a radius of \( 3.53^{10} \text{fm} \), much larger than the \( 2.67 \text{fm} \) we would expect from the formula.

The results are interpreted as being due to an extensive halo of neutrons around a core of \(^9\text{Li}\). We now know of quite a few light nuclei with such haloes and there are examples [5] of nuclei with proton haloes as well.

As nuclei get larger one would anticipate that the halo would become a less prominent feature and become rather a skin of neutrons. Although less prominent a feature we may anticipate that it will have profound consequences for nuclear properties. In essence what is a two fluid system near stability becomes a three fluid system in the nuclear equivalent of the Outback. Now we might expect a whole range of collective motions with these fluids moving against each other. Figure 4 shows some simple examples.

![Shape oscillations of neutron skins](image)

Fig.4.- Some examples of relative motions of neutrons and protons.

Dynamical symmetries also play a major role in nuclear structure; they are best understood in terms of the Interacting Boson Model (IBM) introduced by Arima and Iachello[6]. In this algebraic model based on Group theory we treat even-even nuclei as consisting of bosons, each consisting of pairs of fermions. The model predicts the existence of dynamical symmetries which coincide with the rotation of a deformed, prolate nucleus, a spherical harmonic oscillator and a deformed, axially symmetric \( \gamma \)-soft rotor. Examples of all of these cases have been found in Nature. The model has also
been extended to the prediction and observation [7] of supersymmetry where systems of
even-even, even-odd and odd-odd nuclei are connected by a common structure.
Although eagerly sought in other systems it is only in nuclei that supersymmetry has
been shown to exist. Again all of this is near stability. What happens far from stability?
Will we find new examples of the dynamical symmetries? Will we find new symmetries
in a three fluid system? Will we find examples of co-existing phases? The interested
reader will find a nice summary of the topic in [8].

Every physicist is taught as an undergraduate that nuclei with particular values of  \( N \) and \( Z \), the Magic numbers, are especially stable. For the nuclei near stability it is true.
However it is a labile concept. If one calculates the single particle levels as a function of
nuclear deformation, as in the Nilsson model, then the energy gaps associated with
closed shells change in \( N \) and \( Z \). For example, naively we would expect that 40\( \text{Zr} \) with
both neutrons and protons filling the \( N = Z = 40 \) subshell should be spherical but it turns
out[9] that it is well deformed in its ground state and is close to the centre of a region of
deformed nuclei. Similarly calculations with the cranked shell model reveal that the
energy gaps move with rotational velocity. Accordingly we might not be surprise dif
varying the ration of neutrons to protons also moves the shell or energy gaps. As we
move away from stability the nuclear potential will soften. In the neutron-rich nuclei we
will have a lower density surface associated with the skin of neutrons. As a result, the
spin-orbit interaction which lowers the energy of the higher j spin-orbit partner, will
become weaker and thus we may look forward to a gradual disappearance of the energy
gaps as we move away from stability.

All of these questions and topics are all still open to debate and experiment. They are
also important in terms of the application to nuclear astrophysics. The reader is referred
elsewhere[10] for the detail but it is generally accepted that the heaviest chemical
elements are made either in the slow neutron capture(s-process) process in the gentle
flux of neutrons produced in stellar He burning or in explosive processes such as the
rapid neutron (r-process) or proton (rp-process) processes. This is not our subject here
other than to note that the reaction networks involved in the explosive processes pass
through regions of the chart of the nuclides where our knowledge of nuclear properties
is either limited or non-existent. If we are to pin down the astrophysical sites where
these processes occur and understand their dynamics we need information on nuclear
masses, half lives, structure and level densities.

It will not have escaped the reader’s attention that progress on all these topics demands
better access to nuclei far from stability and that, in turn, means that we need new and
improved facilities producing energetic beams of radioactive ions. We turn now to how
they can be produced.

3. The Production of Radioactive Ion Beams.

In essence we have found two main ways of producing beams of radioactive ions. They
are known generically as the Isotope Separator On-Line (ISOL) and In-Flight or
Fragmentation methods and the basic ideas behind them are summarised in Figure 5. In
the ISOL method two accelerators, or in some cases a reactor and accelerator, are
needed. The primary accelerator is used to produce intense beams that then create the
nuclei of interest in a thick target maintained at a high temperature, either by beam heating or externally or both. The radioactive species diffuse and effuse rapidly out of the target into an ion source. Following ionisation they are extracted with suitable electric fields and separated by mass in a mass separator. The typical extraction energy of 60 keV is useful for many types of experiment, particularly those devoted to solid state studies and other applications. They are also used at this energy if it is radioactive decay to be studied but, if reactions are the main purpose, they are then injected into the second or post-accelerator where they are accelerated up to the energy required in experiment. The great advantages of this method are that one can produce beams of quality comparable or identical to those of similar stable beams. One can also use thick targets to maximise the yields of ions. The main drawbacks are that the process is dependent on the chemistry and the half life of the species concerned. Some elements are difficult to ionise and although rapid progress is being made in terms of laser ionisation it is still difficult to produce beams of refractory elements. The diffusion process is also relatively slow and so a significant fraction of the nuclei produced are lost if the half life is short.

The fragmentation method is conceptually very simple. Here one starts with a high energy beam of heavy ions directed on to a thin target. Peripheral collisions at high energies often involve part of the projectile being sheared off, with the result that a significant fraction of nuclei so produced travel forward with the velocity of the projectile and a wide range of N/Z. Here the great advantage is that the mechanism is entirely independent of chemistry and all chemical species can be produced. The limit in terms of half life is here dictated by the flight time through the spectrometer and is typically of the order of a µs or less.

The disadvantages in this case are that a thin target is used and the beam quality is inevitably poor. The method demands a complex electromagnetic fragment mass.
separating so that the particles in the beam cocktail can be identified on an individual basis. This will be dealt with in a little more detail below.

4. FAIR

A number of major, second-generation facilities of both types, notably FAIR and SPIRAL II, are to be built in Europe over the next 5-6 years. These facilities complement each other and both are needed for different kinds of experiment. Our main subject here is the new FAIR (Facility for Anti-proton and Ion research) facility to be built as an international venture at GSI, Darmstadt. FAIR is aimed at hadronic physics, plasma fusion and atomic physics as well as our subject here, namely nuclear structure. In terms of producing radioactive beams it is firmly based on the fragmentation and fission of stable ions at relativistic energies. Figure 6 shows, in schematic form, the part of FAIR relevant to our subject. As indicated above radioactive ions with energies up to 2 GeV/u are to be used to create the cocktail of radioactive ions in fission or fragmentation on the primary target. The mixed beam produced then passes through a new superconducting fragment recoil separator (Super-FRS). From a combination of measurements of the Bp of the magnets and time-of-flight through the spectrometer and rate of energy loss in detectors one can identify each ion by A and Z.

The beam from the Super-FRS can then be used in one of three experimental branches following the spectrometer. At the low energy branch the beams will be slowed down or even stopped. A variety of techniques will be used to measure their radioactive decays, masses via a Penning trap, laser spectroscopy, reactions induced by ions at the Coulomb barrier or at 100 MeV/u; all aspects of spectroscopy with stopped or slowed down ions.

In the central branch the beams will be used directly, impinging on a fixed target. This will be surrounded by a high-efficiency, gamma-ray detector. A large magnetic dipole behind the target will allow the direction of the heavy ejectiles into either a high-acceptance detector subtending a large solid angle or, in the other direction, into a magnetic spectrometer with a momentum resolution of about 10-4. Lighter fragments such as neutrons or protons will be detected with high efficiency. The overall aim is kinematically complete measurements of reactions with the high energy radioactive
nuclear beams from the Super-FRS. It will allow studies *inter alia* of light ion elastic, inelastic and quasi-free scattering and charge exchange in inverse kinematics as well as break up and knockout reactions.

In essence this particular programme has a sound foundation built on current experiments at GSI. In Figure 7 we see the results of a measurement [5] of the longitudinal momentum distribution of 7Be ejectiles following the knockout of a proton from 8B using the present Fragment Recoil Separator at GSI. From this distribution in momentum one can deduce the corresponding spatial distribution of the protons in 8B. The conclusion of the analysis of the results is that 8B has a proton halo. Measurements in coincidence with the 429 keV gamma ray de-exciting the first excited state at that energy in 7Be also allowed the determination of how much of the time the core of the 8B ground state resembles the ground state or first excited state at 429 keV.

For our purpose here the most exciting and also unique feature of FAIR is the complex of storage rings shown in Fig. 8. Although the present experimental programme at the ESR(experimental storage ring) is highly successful it is limited partly by the intensities of the available secondary beams from the FRS and partly by the poor matching of the emittance of the FRS and acceptance of the ESR. As a result many experiments are ruled out by the low luminosity. The increase in the primary beam intensity and energy at FAIR will lead on average to radioactive beams some 104 times more intense and this huge improvement will make many new experiments feasible and push the boundaries of experiment farther away from stability.
Figure 8 shows the layout of the storage rings.

As stated earlier the largest improvement is the matching of the beam characteristics with the acceptance of the rings. The beam from the Super-FRs will be injected into the Collector ring (CR) at 740 MeV/u efficiently and stochastic pre-cooling will improve the momentum spread to $\Delta p/p \sim 10^{-4}$ in a fraction of a µs. Already experiments can be performed in the CR and it is aimed to measure nuclear masses over broad swathes of the nuclear chart in the same way as has been done in the present ESR. Figure 8 shows an example of the spectra obtained. A large number of fully stripped ions are captured in the ring. In essence their masses are measured by time-of-flight over many revolutions in the ring and so the relevant measurement is one of frequency. Since there are many nuclei of known mass as well as those whose masses are sought one does not need to seek far for calibration. The inset to fig.8 shows how good the resolution is in that one can distinguish ions in the ground state and 754 keV excited state of $^{143}$Sm. The sensitivity is such that we see in this inset the signals from just a single ion in each of the two states. The reader can have no doubt that this is a very powerful tool and it takes little imagination to see that one can make many other types of measurement. Thus if an isomer decays to the ground state then the change in signal strength with time gives the half life.

From the CR the beam can pass through the RESR which will act to reduce its energy within 1 s to 100 MeV/u before injection into the New Experimental Storage Ring (NESR). Here the beam can be cooled by electron cooling. The NESR has several features of importance. Firstly there will be an electron storage ring called ELISE where the electron beam can be collinear with the radioactive ions in the NESR. This will allow studies of electron-ion scattering and hence measurements, for example, of nuclear charge radii. Secondly it will be possible to study collisions with a gas or pellet target in the ring. Here a very similar programme to that pursued at R3B can be pursued but with the great advantage of thin targets. Just as with R3B the intention is to make kinematically complete measurements. The design is not yet complete and is technically demanding but it is envisaged that part of the ring will help act as an element of the spectrometer needed to analyse the spectrum of heavy ejectiles and light particles and gamma rays will be detected with high precision. Taken altogether the aim is that the detector system will handle a wide range of different types of reaction. What can we expect from this first real programme of reaction studies with exotic nuclei in a ring?
The range of possibilities is large and includes elastic scattering to give nuclear matter radii and distributions, which will provide information about haloes, skins and central densities.

Studies of inelastic scattering will provide information on surface collective states, electric giant resonances and bulk properties in asymmetric matter, compressibility and soft collective excitation modes. Charge exchange will allow access to Gamow-Teller and spin-dipole resonances, as well as spin-isospin excitations leading to better understanding of the properties of neutron skins, spin excitations and stellar weak interaction rates. Measurements on transfer reactions will give spectroscopic factors for single particle- and hole-states as well as pair transfer. The idea will be to shed light on single-particle structure, the changing spin-orbit interactions and the pairing interaction. Studies of quasi-free scattering will also allow the measurement of single particle spectral functions and cluster knockout providing detailed information on single particle structure, nucleon-nucleon correlations and in-medium interactions.

5. Summary

The possibility of creating beams of radioactive nuclei has transformed nuclear physics and will allow us to tackle many open questions in nuclear physics and astrophysics. Among the second generation facilities for radioactive ions being built or planned in Europe and elsewhere FAIR stands out as the premier fragmentation facility. Quite apart from its capabilities in other spheres such as hadron physics it will have many unique features for nuclear structure studies such as the planned complex of storage rings. Of necessity this tour d’horizon has been brief. The reader interested in the detail is referred to [hh].

References.

Antiproton physics, past, present and future

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Abstract

It is well known that the study of $p\bar{p}$ annihilation at high energy has originated the important discovery of $W^\pm, Z^0$ and the $t$ quark. Even at low energy, however, the study of $p\bar{p}$ scattering and annihilation has given many contributions to the understanding of strong interactions. Particularly relevant the spectroscopy of $u, d$ and $s$ quark states done in the early 60’s. With the advent of intense and cooled high quality antiproton beams, these results were considerable improved. In particular the annihilation study allowed the determination of the proton form factors in the time like region and gave important results in the charmonium spectroscopy, complementary to the $e^+ e^-$ collider results. To be mentioned also the study of symmetry laws. The new generation of intense antiproton beams coupled with large magnetic spectrometers could give a big step further in the spectroscopy of exotic hadrons, including the charmed states. The possibility to polarize antiproton storage beams can open the way to a complete study of the proton structure.

Introduction

The antimatter dream starts with the positron discovery in cosmic rays, with Wilson cloud chamber and with the interpretation of Dirac equation. The antiproton ($\bar{p}$) was discovered 23 years later in 1955 when the Lawrence Berkley Laboratory built the BEVATRON: a low focusing proton synchrotron where the proton momentum could reach 7,000MeV/c, was sufficient to produce an antiproton-proton ($p\bar{p}$) pair. A very long secondary negative beam with a focusing optics to let the negative pions decays, was constructed and could collect less than 100 antiprotons per day, stopped in emulsion and identified by Chamberlain, Ypsilantis and E. Segrè [1] with the specific ionization and the $p\bar{N}$ annihilation.

Only four years later with the construction of the strong focusing proton synchrotrons of about 30GeV/c at CERN and BNL, beams with some $10^3 \bar{p}$ per second with momentum up to about 5GeV/c, was used in counter, bubble chambers and spark chambers experiments and contributed to the study of spectroscopy and dynamics of hadrons, but the relative low intensity of $\bar{p}$ with respect to the pion beams was a serious limiting factor.

In the early 60’s the hundreds of short living meson and nucleons where classified by M. Gellman, in the octets and decuplets of the SU(3) group symmetry. Studying the generator of the group the particles, needed to build the hundreds of hadrons, were reduced to only a quark with 3 flavors quantum numbers, 3 color charges,
and 1/3 or 2/3 electric charge. The nucleons are made by 3 quarks with different color charge and the mesons by a quark and an antiquark. It was a very big success. But the experimental impossibility to isolate particles with fractional electric charge induced many physicists to consider all the SU(3) construction more a mathematical tool than a real physics reality. The Deep Inelastic Experiments (DIS) performed at SLAC in 1969 with the Bjorken and Feynmann interpretation convinced everybody of the real existence of the quark in the nucleons where they are confined. At that time the Quantum-electro-Dynamics (QeD), a relativistic quantum theory of electromagnetic interaction was accepted and experimentally tested at the level of $10^{-11}$.

In the years 70’s on the basis of the QeD the Standard Model (SM) was developed that unified in a single theory the weak and electromagnetic interactions. The SM was experimentally tested with neutrino and LEP experiments to better than $10^{-3}$, but the most spectacular success was the discovery in 1983, in antiproton-proton annihilation at SPS used as a collider of the bosons mediating the weak interactions: the $W^+$, $W^-$ and $Z^0$ with the expected very high masses. This discovery was rewarded with the Nobel Price to C. Rubbia and S. Van der Meer.

On the same mathematical basis of the electroweak SM, and including the SU(3) symmetry, a dynamics theory of strong interaction was constructed: the Quantum Chromo Dynamics (QCD) based on quarks with three color charges, six flavors and spin $1/2$. The quantum of strong interactions is the gluon, which carries color charge. The QCD theory was successful in particular in understanding the nucleon and meson spectroscopy also for the new heavy quarks, and in the high energy scattering interactions where with the precision of some percent, it was possible to fit many experimental data distributions over a range of many orders of magnitude: in fact at these energies the perturbative method works.

In addition to the well known existence of nucleons ($qqq$) and mesons ($q\bar{q}$) QCD predicts many other quark combination states, called exotics, like Glueballs ($gg$), hybrids ($q\bar{q}g$), baryonium ($qqqqqq$ or $qqqq$), pentaquarks ($qqqqq$) and many others. Only recently some exotics candidates were found, but their unambiguous identification is out of doubt a very difficult experimental task because these states are generally very wide and overlap with other states and it is not easy to determine the corresponding quantum numbers. It is still an open problem. The QCD predictions for low energy dynamical process or with the implication of polarized states are not very precise. The attempt to understand this discrepancies by simply increasing the number of free parameters does not provide any real physical insight.

In fact, the origin of this difficulties is deep: At low energy the perturbative method does not work because the binding energy of hadrons is much larger than the mass of the light quarks and any perturbation produces some quark-antiquark pairs from the strong vacuum, and we transform any interaction in a many body problem. This phenomenology needs probably a different theoretical approach. In these interactions the strong vacuum plays an import role and this could be used to study the vacuum itself. This could be an important “new physics” field of investigation.
The cooled antiproton program

The most important step in antiproton physics happened in 1975 with the Novosibirsk announcement [2] of the spectacular cooling of a proton beam with electrons. Immediately came the proposal of C. Rubbia, P. Mc Intyre, and D. Cline [3] to inject a $\bar{p}$ beam cooled with electrons to transform the high energy proton-synchrotrons in $p\bar{p}$ colliders to search for the intermediate bosons of weak interactions. This project obviously needed the development of a suitable method to construct a cooled antiproton source. Very rapidly it became evident that the electron cooling, suitable to cool protons beams at the level of $\Delta p/p < 10^{-5}$, was not able to cool, in a reasonable time, the very large phase space antiproton beams produced at 3.5 GeV/c from 30 GeV/c protons of Proton Synchrotron (PS). The solution came with the proposal by S. van der Meer [4] of CERN of a new cooling method: the stochastic cooling. This new method, based on the technology of detection, inversion and amplification of electromagnetic signals, was able to cool very rapidly very hot bunches of $\bar{p}$ beam of 3.5 GeV/c to $\Delta p/p < 10^{-3}$; this was sufficient to be inject in the PS to be accelerated to 27 GeV/c and successively injected in the SPS in the reverse proton direction. CERN built very rapidly the antiproton source [5], two rings of 3.5 GeV/c the AC (Antiproton Collector) and the AA (antiproton accumulator) based on stochastic cooling. In 1983 two experiments of CERN UA1, and successively UA2 announced the discovery of the intermediate bosons of weak interactions. It was the first time, after II World War, that a European laboratory reached an important scientific and complex technological goal before the USA labs. In fact, Fermilab also adopt the stochastic cooling and built an antiproton source of 14 GeV/c, but arrived later, still in the end with the 2 TeV $p\bar{p}$ collider they discovered the top quark.

Low energy antiproton physics

In the CERN antiproton workshop the possibility was also discussed to transform the ISR (two-ring $pp$ collider at 30 + 30 GeV/c) in a $p\bar{p}$ collider injecting in one ring the cooled antiprotons. Some ISR experiments installed on the floor measured the elastic and total cross section. I proposed [6] a new experiment to study the charmonium states ($c\bar{c}$), made by heavy quarks $c$, in formation from $p\bar{p}$ annihilation. The experiment consisted in using one ring of the ISR as an accumulator of a $\bar{p}$ beam from 3 to 7 GeV/c interacting with an $H_2$ gas jet target. With this method one could profit of the high resolution of the cooled antiproton beam and form directly also the non vector meson states formed in $p\bar{p}$ annihilation but not formed directly with $e^+e^-$ storage rings, because in this case the interaction was mediated only by a single photon. In $e^+e^-$ the non vector states could be reached through radiative decay from the $\psi$. In this case, however, the measurements of masses and width was limited by the detector resolution. With the cooled $\bar{p}$ we can measure the width of narrow states like $\chi_1$ and $\chi_2$ with a resolution of about 300 KeV, tuning the $\bar{p}$ beam. The background in $p\bar{p}$ annihilation is very high and was eliminated detecting the $e^+e^-$ decay of $J/\psi$ produced in the radiative decay. The collaboration R704 perform the experiment and before the definitive closure of ISR proved the validity of the method [7].
Pietro Dalpiaz

In the CERN antiproton workshop the possibility was also discussed to use the cooled antiprotons to inject in a new accumulator ring capable to decelerate the antiprotons to low energies. CERN decided to construct LEAR (Low Energy Antiproton Ring) [8] that started to work in 1983 and operated until 1995. A bunch of $10^{11}$ antiprotons was injected in LEAR once a day, the $\bar{p}$'s were delivered in a continuous spill with an intensity of $10^6 \text{p/sec}$ up to 15h, with a momentum from 0.18 to 2GeV/c, a $\Delta p/p$ of $2 \cdot 10^{-4}$ and with a very good duty cycle.

In the years of operation some tens of experiments were performed at LEAR on several physics subjects, some of them on hadronic physics [9]. Before the LEAR operations there had been several claims for baryonium states. The first scattering experiments [10] performed at LEAR, PS172 [11] and PS173 [12] did energy scans for elastic, total and annihilation cross sections for $p\bar{p} \leq 600\text{MeV/c}$ to search for new states and check the baryonium claims. The results were negative and the claim not confirmed. The PS172 [13] explored extensively the differential cross sections of the two body $p\bar{p}$ annihilation channels like $\pi^+\pi^-$ and $K^+K^-$, and the amplitude analysis suggested a number of high-spin resonances [14].

The $NN$ dynamics showed big difference with respect to $NN$ system. The $p\bar{p}$ differential cross sections were extensively measured by several experiments [15, 16, 17] in the range of 180 to 1550MeV/c. The analyzing power was measured by PS172 [15] and PS198 [17]. Even at low energy the $p\bar{p}$ differential cross section data show a very strong angular dependence that is not present in $pp$ interactions. Partial wave analysis [16] of data below 300MeV/c gave one of the main results obtained by the scattering experiments at LEAR: the $S$ wave elastic cross section is suppressed and the inelastic is close to its limit; furthermore the $P$ wave is large and is present also at 10MeV excess energy above the $p\bar{p}$ threshold. At higher energy the elastic cross section is more regular and is essentially due to diffraction.

The production of hyperon pairs in $p\bar{p}$ annihilation was studied from 1MeV above threshold up to 1.922GeV/c by PS185 experiment [18]. Also these reactions are dominated by the $P$ wave. In $\bar{A}A$ no evidence for structure was found and one of the intriguing features is the non-zero polarization which is observed at all the energies with a consistently changing shape with increasing energy. In a simple constituent quark model, the proton structure is $uud$: this structure is confirmed at large distance, but at short distance more constituents were revealed, including $ss$ pairs as demonstrated [19] in the study of the ratio $R = \sigma(\bar{p}p \rightarrow \varphi \pi^0 \pi^-)/\sigma(\bar{p}p \rightarrow \omega \pi^+ \pi^-) = 0.019 \pm 0.005$, a very high anomaly with respect the to OZI rules [20] that predicts $R = 0.007 \pm 0.002$. The LEAR experiments ASTERIX [21], Crystal Barrel [22] and OBELIX [23], that studied also the $\bar{n}n$ annihilation, made a detailed study on several annihilation reactions in several channels containing $\varphi$ and $\omega$; they found that $R$ in some cases was 30 to 50 times larger than to the OZI rule predictions. The ratio $R = \sigma(\bar{p}p \rightarrow \varphi \varphi)/\sigma(\bar{p}p \rightarrow \omega \omega)$ was measured by JETSET experiment [24] with $1\text{GeV/c} \leq p_\rho \leq 2\text{GeV/c}$ in 50 points and was found more than two order of magnitude larger than the OZI rule predictions.

Shortly after the discovery of antiproton, B. Pontecorvo [25] pointed out that annihilation in nuclei can lead to find particle configurations not attainable with free nucleons. A typical example is the reaction $\bar{p}d \rightarrow M + N$ where $M \Rightarrow \pi^- , \pi^0 , \eta , \omega , \eta' , \varphi , K$ and $N \Rightarrow p , n , \Lambda , \Sigma$. All these Pontecorvo reactions where ex-
neither of which are believed to be baryon. Barrel and OBELIX data confirmed the broad multi-quark states, $f_{2}(1440)$ and two isoscalar $f_{0}(1370)$ and the $f_{0}(1500)$. These states were confirmed by OBELIX [30] in the coupled channel analysis of $\pi^+\pi^-\phi^0, K^+K^-K^0$ and $K^+K^0\pi^+$ in $p\bar{p}$ annihilation at rest and in $pp$ collisions at the OMEGA facility [31]. The Crystal Barrel and OBELIX data confirmed the broad $f_{0}(600)$ and the narrow $a_{0}(980)$, neither of which are believed to be $q\bar{q}$ state. Together with the isovector $a_{0}(980)$ they are frequently interpreted as a multi-quark states, $KK$ bound states or vacuum scalars. To establish the existence of glueballs was a very difficult task. The lattice gauge theory shows that the lightest glueball is a scalar with the mass in the range $1450-1750$GeV/$c^2$. A combined analysis [32] of the complete set of two body decays of the $f_{0}(1370), f_{0}(1500)$ and $f_{0}(1670)$ (the last is a well established resonance) into pseudoscalar mesons determined the mixing angles and masses of the bare glueball, $1440 \pm 16$MeV/$c^2$. The physical states were found to be

$$f_{0}(1370) \Rightarrow 0.39|gg\rangle + 0.9|s\bar{s}\rangle + 0.14|NN\rangle,$$
$$f_{0}(1500) \Rightarrow -0.69|gg\rangle + 0.37|s\bar{s}\rangle - 0.62|NN\rangle$$
$$f_{0}(1670) \Rightarrow 0.60|gg\rangle - 0.13|s\bar{s}\rangle - 0.79|NN\rangle.$$

A further study [33] including data on scalar meson production in $\gamma\gamma$ interactions, confirm this general picture and suggest an even larger $gg$ component for the $f_{0}(1500)$. In this scenario, it is fair to say that the lightest glueball was discovered at LEAR, although not in a pure state. In spite of such evidence there are alternative scenarios like for example construction of a scalar nonet from the $a_{0}(980),f_{0}(980),f_{0}(1500)$ and $K_{0}^{*}(1430)$. The $a_{0}(1450),f_{0}(1370),f_{0}(1710)$ and $K_{0}^{*}(1500)$ could then form the nonet of scalar radial excitations. In any case the other members of this nonet are not yet found and is can be armed that it is a pity, the fact, that when LEAR experiments started to disentangle these complex problems the LEAR program was closed.

Exotics states could have quantum numbers not accessible to $q\bar{q}$ states like $J^{PC} = 0^{--},1^{++},2^{-+}$. In 1997 the Brookhaven experiment E852 announced [34] the discovery of a resonance, called $\pi_{1}$, with mass $1370$MeV/$c^2$ with exotic quantum numbers $J^{PC} = 1^{--}$, in the reaction $\pi^-p \rightarrow \pi^-pp$ at $18$GeV/$c$ incident pion momentum. The situation was confused by the result [35] from VES coll. at Serpukov. They studied the same reaction at $25$GeV/$c$ and observed a very similar amplitude and phase, but pointed out that a resonance interpretation was not mandatory and a non resonant amplitude could give an acceptable fit, this interpretation was supported by a theoretical model [36]. An essential confirmation of $\pi_{1}$ was given [37] by Crystal Barrel in the reaction $\bar{p}n \rightarrow \pi^-\phi^{0}\eta$ and $\bar{p}p \rightarrow \phi^{0}\phi^{0}\eta$. Fitting only with conventional mesons gave a poor description of the data but the addition of the exotic $\pi_{1}$ allowed an excellent fit, its interference with the dominant $\rho^{-}(770)$ and $\phi^{0}(1230)$ being clearly apparent in the Dalitz plot. The existence of the $\pi_{1}(1370)$ is undoubted, although there is still arguments about whether it is a genuine hybrid or a dynamically generated resonance [38]. The E852 coll. observe [39] another ex-
otic, the $\pi_1(1600)$ in the channels $\rho \pi$ and $\eta' \pi$, this state was confirmed in the same channel and in $b_1(1235)$ by VES coll. [40]; in this last channel it was confirmed also by Crystal Barrel coll. [41] in the reaction $\bar{p}p \rightarrow \omega \pi^+ \pi^- \pi^0$. A partial-wave analysis of $\bar{p}n \rightarrow \pi^- \pi^0 \pi^+ \pi^0$ reaction by the Crystal Barrel coll. [42] showed evidence for a $J^{PC} = 1^{-+}$ signal in the $\rho \pi$ channel with a mass of $1440 \text{MeV}/c^2$ and a width of $400 \text{MeV}$. Its identification with the $\pi_1(1370)$ seems unlikely and its production characteristics are very different. Many other results [9] on vector mesons were obtained by Crystal Barrel and OBELIX coll. and on radiative decays by Crystal Barrel coll. Some of these results are not yet conclusive.

The LEAR antiprotons, studying $p\bar{p}$ annihilation involving neutral kaons, gave the opportunity to the CPLEAR experiment [43] to study the symmetries which exist between matter and antimatter. The experiment was devoted to the study of CP, T and CPT symmetries. A rather complete set of measurements of high precision, allowed to determine the parameters which describe the time evolution of the neutral kaons and their antiparticles, including decay amplitudes, and the related symmetry properties.

The large amount of antiprotons given by LEAR allowed the PS170 experiment [44] to measure accurately the Form Factor of Protons in the Time Like Region (FFP-TLR) from threshold up to $s = 4.2 \text{GeV}^2$ studying the reaction $p\bar{p} \rightarrow e^+e^-$. PS170 had a good system to identify the electrons in a high hadronic background. The measure of the angular distribution showed that in the region studied the Electric ($G_E$) and Magnetic ($G_M$) Form Factors are similar. The $s$ distribution confirm the high value of the FFP-TLR with respect the extrapolation with the dipole model from the FFP of Space like region, already found in previous experiments [45], and do not follow the expected $s^{-\lambda}$ behavior, probably due to the presence of the vector mesons in that region, the data show also a steep increment very near threshold. The dip found in the total multihadronic cross section [46, 47] and the steep variation of the proton form factor near threshold may be fitted with a narrow vector meson resonance, with a mass $M \sim 1.87 \text{GeV}/c^2$ and a width $\Gamma \sim 10-20 \text{MeV}$, consistent with an $NN$ bound state [47]. Recently in the reaction $J/\psi \rightarrow \gamma + X(1860)$ BES found a narrow resonance with $\Gamma_X = 30 \text{MeV}$ decaying $X(1860) \rightarrow p\bar{p}$ at $\sim (4-14)\%$. The effect is a rise of $p\bar{p}$ production near the threshold very similar to the behaviour (FFP-TLR).

Several high precision experiments with antiproton traps and of spectroscopy were carried out at LEAR to measure the antiproton mass, charge, lifetime, and magnetic momentum [49].

A group of physicist from Fermilab [50] proposed a new way to produce antihydrogen atoms. A $\bar{p}$ passing through a strong Coulomb field of a nucleus with high charge $Z$ can create an $e^+e^-$ pair, and occasionally the $\bar{p}$ could capture the $e^+$ and form the antihydrogen. The experiment JETSET proposed this idea at LEAR. The experiment was accepted in 1995 and using only the last 17h of LEAR the experiment PS210 [51] succeeding to produce and observing 9 antihydrogen atoms. The antihydrogen production at CERN had large impact in the media. This fact probably helped in the acceptance and construction in 2000 of the “Antiproton Decelerator” (AD) at CERN [5] , presently the only facility to perform antiproton physics at low energy. The now-defunct Antiproton Collector into an “all-in-one” machine to
collect (at 3.5GeV/c), cool (stochastic and electron cooling) and decelerate $10^7\bar{p}$ to 100MeV/c, every 2 min. The AD physics program \cite{52} is devoted to the high precision measurements of $\bar{p}$ and antihydrogen. Several experiments are installed and collaborations like ATRAP \cite{53} and ATHENA \cite{54} with a very sophisticated techniques trap in the order of $10^8\bar{p}$ and produce typically $10^9$ cooled antihydrogen atoms. With such experimental conditions very important measurement are expected.

After ISR closure, was evident that at CERN it was not possible to study charmonium states with $p\bar{p}$ annihilation. An Italian-USA coll. proposed to install a detector similar to R704, but with large acceptance, in the $\bar{p}$ Accumulator of Fermilab, where bunches of up to $8\times10^{12}\bar{p}$ (stochastically cooled $\Rightarrow \Delta p/p = 10^{-4}$) could be accumulated and could continuously interact with a gas $H_2$ target (with a density of $10^{14}$g/cm$^2$) for more than 24h in the energy range of 2GeV/c $\leq p_\bar{p} \leq 8.9$GeV/c. The experiment E760 \cite{55} was installed in 1990 in a small experimental area especially prepared on the AP50 straight section of the Fermilab $\bar{p}$ Accumulator. The collaboration ran until 2000 with the experiments E760 and E835. The main results \cite{56} are the measurement of the mass with a precision better than $10^{-4}$ of the $\chi_{c0}, \chi_{c1}, \chi_{c2}$, with a precision of $10^{-3}$ of the $\eta_c$ and with the precision of 10% the direct measurement of the width of $\chi_{c0}, \chi_{c1}, \chi_{c2}$ and $\eta_c$.

Another important result \cite{57} was the of the FFP-TLR at high $s^2(<14$GeV$^2$). In that region the FFP-TLR are dominated by $G_M$ and show an evident $q^{-4}$ behaviour, that confirm the presence of 3 valence quark in the proton.

The antiproton physics future

The GSI Laboratory of Darmstadt in Germany has recently approved a proposal \cite{58} to construct FAIR: a group of accelerators that include a new cooled source of $\bar{p}$ with a production rate of $10^7\bar{p}$/sec can accumulate $10^{11}\bar{p}$/day. The $\bar{p}$ produced with a proton beam of 30GeV/c, with an intensity of $10^{13}$ protons per burst. The $\bar{p}$ are employed in different ways, with a direct beam from 0 to 30GeV/c, or in an accumulator where they interact with the nucleus of different ions, this facility will allow to follow the tradition of high precision experiments. A key element of the new facility will be the HESR (High Energy Storage Ring) a new synchrotron able to accumulate, accelerate or decelerate bunches of $\bar{p}$ from 0.8 to 14.5GeV/c. HESR will be equipped with stochastic cooling and an electron cooling operating until 8GeV/c. With that system the $\bar{p}$ beam can be cooled down to $\Delta p/p < 10^{-5}$. It is expected that FAIR can start operations around the year 2012. Two proposals were presented to be installed in HESR. PANDA, already approved, and PAX, still under study. PANDA \cite{59} is a fixed target experiment. The experiment proposes to operate with several types of targets: a Gas-Jet $H_2$, a pellet of $H_2$ and nuclear targets. The experiments with $H_2$ targets can reach a luminosity of $10^{32}$cm$^{-2}$s$^{-1}$ with a beam momentum resolution of $\Delta p/p = 10^{-4}$ and $10^{31}$cm$^{-2}$s$^{-1}$ with a resolution of $\Delta p/p = 10^{-5}$. The magnetic spectrometer has a very large acceptance and it consists of a barrel detector around a solenoidal magnet and a forward detector including a dipole magnet. Both detectors have a tracking system, a RICH-type counter for particle identification, a $\gamma$ detector of $PbWO_4$ with an energy resolution...
better than 2% and a muon detector. The main PANDA physics program consists of the following topics:

a. High-precision charmonium spectroscopy [60]. The capability to study also the charmonium hadronic decays will allow the experiment to collect sufficient statistic to perform precision measurements of mass, width, decay branches of all charmonium states. This will allow a check of QCD predictions at the level of 2%.

b. Search for gluonic excitations (charmed hybrids, glueballs) in the charmonium mass range. The new states announced by [61] $B$ factories show the present interest on the subject.

c. Search for modifications of meson properties in the nuclear medium, and their possible relationship to the partial restoration of chiral symmetry for light quarks.

d. Precision $\gamma$-ray spectroscopy of single and double hypernuclei for extracting information on their structure and on the hyperon-nucleon and hyperon-hyperon interaction.

The PAX proposal [62] intends to use polarized antiprotons produced by filtering with an internal polarized $H$ gas target to have access to a wealth of single and double spin observables, thereby opening a window to physics uniquely accessible at the HESR. This includes a first measurement of the transversity distribution of the valence quarks in the proton, a test of the predicted opposite sign of the Silvers functions, related to the quark distribution inside a transversely polarized nucleon, in Drell-Yan as compared to semi inclusive Deep Inelastic Scattering [63], and the first measurement of the amplitude and the relative phase of the timelike electric and magnetic form factors $G_E$ and $G_M$ of the proton. In polarized and unpolarized $\vec{p}\vec{p}$ elastic scattering open questions like the contribution from odd charge symmetry Landshoff mechanism at large $t$ and spin effects in the extraction of the forward scattering amplitude at low $t$ can be addressed.

To polarize the $\vec{p}$ the PAX collaboration proposes [64] the construction of APR (Antiproton Polarizer Ring) a large acceptance accumulator ring of 100m of circumference with a maximum energy of 50MeV equivalent to a circulating beam of 350MeV/c momentum, with a very large acceptance of 500$\pi$ mm mrad, equipped with stochastic and electron cooling, siberian snake and an $H$ gas polarized target. A beam of $10^{12}\vec{p}$ after passing 18-20h through the polarized target should be polarized at around 30% with intensity reduced to 10%. The APR is inserted in CSR (Cooler Synchrotron Ring) a synchrotron of 3.5GeV/c where the polarized $\vec{p}$ are accumulated. The CSR is inserted in HESR. The $\vec{p}\vec{p}$ interaction occurs in an interaction point of the $\vec{p}$ from the CSR with the protons accumulated in HESR and sent to the CSR. With this asymmetric $\vec{p}\vec{p}$ collider (3.5GeV/c $\vec{p}$ + 14.5GeV/c $\vec{p}$) an $s = 210$GeV$^2$ can be reached covering for the measurement of Drell-Yan pairs the interesting region between charm an bottom resonances. But the asymmetric $\vec{p}\vec{p}$ collider proposed can reach a luminosity of $2 \cdot 10^{30}$cm$^{-2}$s$^{-1}$. The spectrometer proposed [65] is a classical one but with a particularly high rejection for electron to
hadrons. Once all the open problems on $\bar{p}$ polarization and luminosity are convincingly solved, the GSI laboratory will approve the experiment, because the physics case is considered very strong.

The asymmetric $\bar{p}p$ collider ($3.5 \text{GeV}/c \bar{p} + 14.5 \text{GeV}/c p$) proposed by PAX reach $s = 200 \text{GeV}^2$ and can open another very important physics case: the bottomonium spectroscopy. In fact the masses and widths of these states could be compared to QCD predictions [66] at a level better than 1% because the high mass of the $b$ quark with respect to $\Lambda_{QCD}$ makes the $bb$ system very simple to calculate. The measurements could be performed with the spectrometer proposed by PAX that will have a good $e/\pi$ rejection. To perform the complete bottomonium spectroscopy the hadronic decays of the states [67] must be detected. Part of the measurement will be performed with PAX but in some cases PANDA will be used because it is designed to detect hadronic decays of resonances and also because of its higher acceptance. This requires that the luminosity of the asymmetric collider must reach at least $10^{32} \text{cm}^{-2}\text{s}^{-1}$, for that a factor 10 of increment of the intensity of the $\bar{p}$ source is needed.

Conclusions

We can conclude hoping for the revival of $\bar{p}$ physics at GSI. The scenario is very interesting with some outstanding physics cases. Our suggestion is to start thinking from now of ways to increase the $\bar{p}$ intensity: in the present design it is similar to the intensity of the old CERN $\bar{p}$ source, whereas the present Fermilab source is 10 times higher. The increase in $\bar{p}$ intensity will make the presented program stronger.

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The Spin Structure of the Nucleon

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Introduction
For many years now, spin has played a very prominent role in QCD. The field of QCD spin physics has been carried by the hugely successful experimental program of polarized deeply-inelastic lepton-nucleon scattering (DIS), and by a simultaneous tremendous progress in theory. A new milestone has now been reached with the advent of RHIC, the world’s first polarized proton-proton collider. RHIC is poised to help answer many of the important question pertaining to the spin structure of the nucleon. Recently, it has also been proposed to study spin phenomena in transversely polarized $pp$ collisions at the planned GSI-FAIR facility. This talk describes some of the opportunities provided by RHIC and the proposed GSI experiments.

Nucleon helicity structure

What we have learned so far
Figure 1 shows a recent compilation [1] of the world data on the nucleon’s spin structure function $g_1(x, Q^2)$. These give direct access to the helicity-dependent parton distribution functions of the nucleon,

$$\Delta f(x, Q^2) = f^+ - f^- \quad (f = q, \bar{q}, g),$$

which count the numbers of partons with same helicity as the nucleon, minus opposite. From $x \to 0$ extrapolation of the structure functions for proton and neutron targets it has been possible to test and confirm the Bjorken sum rule [2]. Polarized DIS data, when combined with input from hadronic $\beta$ decays, have allowed to extract the unexpectedly small – nucleon’s axial charge $\sim \langle P|\bar{\psi} \gamma^5 \gamma^3 \psi|P\rangle$, which is identified with the quark spin contribution to the nucleon spin.

Things we would like to know
The results from polarized inclusive DIS have also led us to identify the next important goals in our quest for understanding the spin structure of the nucleon [3]. The measurement of gluon polarization $\Delta g = g^+ - g^-$ rightly is a main emphasis at several experiments in spin physics today, since the integral of $\Delta g$ could be a major contributor to the nucleon spin. Also, more detailed understanding of polarized quark distributions is needed; for example, we would like to know about flavor
Figure 1: Data on the spin structure function $g_1$, as compiled and shown in [1].

Symmetry breakings in the polarized nucleon sea, strange quark polarization, the relations to the $F, D$ values extracted from baryon $\beta$ decays, and about the small-$x$ and large-$x$ behavior of the densities. Again, these questions are being addressed by current experiments. Finally, we would like to know how much orbital angular momentum quarks and gluons contribute to the nucleon spin. Ji showed [4] that their total angular momenta may be extracted from deeply-virtual Compton scattering, which has sparked much experimental and theoretical activity also in this area [5].

A new milestone has been reached in spin physics with the advent of the first polarized proton-proton collider, RHIC at BNL. By now, several physics runs with polarized protons colliding at $\sqrt{s} = 200$ GeV have been completed, and exciting first results are emerging. In the following, we will discuss one area that is a major strength of RHIC, namely the measurement of gluon polarization in the proton. For further information on the RHIC spin physics program, see Refs. [6, 7].

Accessing gluon polarization $\Delta g$

The measurement of $\Delta g$ is a main goal of several current experiments. $\Delta g$ has been left virtually unconstrained [8-11] by the scaling violations observed in polarized DIS, due to the very limited lever arm in $Q^2$. This is demonstrated by Fig. 2. One way to access $\Delta g$ in lepton-nucleon scattering more directly is to measure final states that select the photon-gluon fusion process, heavy-flavor production and $ep \rightarrow h^+h^-X$, where the two hadrons have large transverse momentum [12].

RHIC will likely dominate the measurements of $\Delta g$. Several different processes will be investigated [6, 7] that are sensitive to gluon polarization: high-$p_T$ prompt photons $pp \rightarrow \gamma X$, jet or hadron production $pp \rightarrow jet X$, $pp \rightarrow hX$, and heavy-flavor production $pp \rightarrow (QQ)X$. In addition, besides the current $\sqrt{s} = 200$ GeV,
also $\sqrt{s} = 500$ GeV will be available at a later stage. All this will allow to determine $\Delta g(x, \not Q^2)$ in various regions of $x$, and at different scales. All tools are in place now for treating the spin reactions relevant at RHIC at next-to-leading order (NLO) pQCD $[13-16]$. NLO corrections significantly improve the theoretical framework. We emphasize that there have already been results from RHIC that demonstrate that the NLO framework is very successful. Figure 3 shows comparisons of data from PHENIX $[17]$ for single-inclusive pion production $pp \rightarrow \pi^0 X$ with NLO calculations based on the code of $[13]$. As can be seen, the agreement is excellent, even down to $p_T$ values as low as $p_T \geq 1.5$ GeV. A similar level of agreement has been found in comparisons with STAR data $[18]$ for $pp \rightarrow \pi^0 X$ at very forward rapidities, and with PHENIX data $[19]$ for $pp \rightarrow \gamma X$. We note that an agreement between data and NLO calculations like the one seen in Fig. 3 is not found in the fixed-target regime (it has recently been shown that in this regime large logarithmic terms at yet higher orders are important and need to be resummed for a successful theoretical description $[20]$). On the right of Fig. 3 we decompose the mid-rapidity $\pi^0$ cross section into the contributions from the various two-parton initial states $[21]$. It is evident that processes with initial gluons dominate.

Figure 4 shows NLO predictions for the double-longitudinal spin asymmetries $A_{LL}$ for the reactions $pp \rightarrow \text{jet} X$ and $pp \rightarrow \gamma X$ at RHIC, based on the GRSV “theory uncertainty” band displayed in Fig. 2. One can see that the experimental uncertainties expected at RHIC are much smaller than the current uncertainty in $\Delta g$. First results for $A_{LL}$ in $pp \rightarrow \pi X$ have now been reported by PHENIX $[22]$.

### Transversity

Besides the unpolarized and the helicity-dependent densities, there is a third set of leading-twist parton distributions, transversity $[23]$. In analogy with Eq. (1) they measure the net number (parallel minus antiparallel) of partons with transverse polarization in a transversely polarized nucleon:

$$\delta f(x, Q^2) = f^\uparrow - f^\downarrow.$$  

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**Figure 2:** Results for $x\Delta g(x, Q^2 = 5 \text{ GeV}^2)$ from recent NLO analyses $[8-10]$ of polarized DIS. The various bands indicate ranges in $\Delta g$ that were deemed consistent with the scaling violations in polarized DIS in these analyses. From $[7]$. 

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Figure 3: Left: PHENIX data [17] for the cross section for \( pp \rightarrow \pi^0X \) at \( \sqrt{s} = 200 \) GeV. The lines represent the NLO calculation based on the code of [13]. Upper right: contributions to the NLO cross section for \( pp \rightarrow \pi^0X \) from \( gg \), \( qg \), and \( qq \) initial states [21]. Lower right: same decomposition for prompt-photon production \( pp \rightarrow \gamma X \). Taken from [7], to which we refer the reader for details of the calculations.

Transversity corresponds to a helicity-flip structure, which precludes a gluon transversity distribution at leading twist. It also makes transversity a probe of chiral symmetry breaking in QCD [24]: perturbative-QCD interactions preserve chirality, and so the helicity-flip required to make transversity non-zero must primarily come from soft non-perturbative interactions for which chiral symmetry is broken.

In contrast to the distributions \( f \) and \( \Delta f \), we have essentially no knowledge from experiment so far about the transversity distributions \( \delta f \). Again the fact that perturbative interactions in the Standard Model do not change chirality means that inclusive DIS is not useful. Collins, however, showed [25] that properties of fragmentation might be exploited to obtain a “transversity polarimeter”: a pion produced in fragmentation will have some transverse momentum \( k_T \) with respect to the momentum of the transversely polarized fragmenting parent quark. There may then be a correlation of the form \( \vec{S}_T \cdot (\vec{P}_x \times \vec{k}_T) \). The fragmentation function associated with this correlation is the Collins function. It makes a leading-power [25] contribution to the single-spin asymmetry \( A_\perp \) in the reaction \( ep^l \rightarrow e\pi X \):

\[
A_\perp \propto |\vec{S}_T| \sin(\phi + \phi_S) \sum_q c_q^2 \delta q(x) H_1^{+q}(z),
\]

where \( \phi \) (\( \phi_S \)) is the angle between the lepton plane and the \( \gamma^* \pi \)-plane (and the transverse target spin). Recently factorization for semi-inclusive DIS (SIDIS) at small
transverse momentum has been proven \[26\]. HERMES has reported \[27\] clear signs of a nonvanishing Collins asymmetry in $ep$ scattering. Measurements by COMPASS using a deuteron target have been presented as well \[28\]. Very recently, first independent information on the Collins functions has come from BELLE measurements in $e^+e^-$ annihilation \[29\]. It is hoped that combination of these results with those from lepton scattering would eventually give some information on transversity.

Clean and direct information on transversity might be gathered from polarized proton-proton collisions at RHIC, using the Drell-Yan process \[6, 7\]. In $pp$ collisions, however, the Drell-Yan process probes products of valence quark and sea antiquark distributions. It is possible that antiquarks in the nucleon carry only little transverse polarization since the perturbative generation of transversity sea quarks from $g \rightarrow q\bar{q}$ splitting is missing. Also, at RHIC the partonic momentum fractions are fairly small, so that the denominator of $A_T$ is large. NLO studies \[30\] estimate the size of $A_T$ at RHIC to be at most a few per cent.

It has recently been proposed to add polarization to planned $\bar{p}p$ experiments at the GSI-FAIR facility, and to extract transversity from measurements of $A_T$ for the Drell-Yan process \[31-33\]. This clearly is a very exciting idea. Initially, experiments could be performed in a fixed-target mode, using the 15 GeV antiproton beam. At later stages of operations, there are plans for an asymmetric $\bar{p}p$ collider, with an additional proton beam of energy 3.5 GeV. The results from such measurements would be complementary to what can be obtained from RHIC or SIDIS. In $\bar{p}p$ collisions the Drell-Yan process mainly probes products of two quark densities, $\delta q \times \delta \bar{q}$, since the distribution of antiquarks in antiprotons equals that of quarks in the proton. In addition, kinematics in the proposed experiments are such that rather large partonic momentum fractions, $x \sim 0.5$, are probed. One therefore accesses the valence region of the nucleon, where the polarization of partons is expected to be large. Estimates \[33\] for the GSI PAX and ASSIA experiments show that the expected spin asymmetry $A_T$ should indeed be very large, of order 30% or more.

The theoretical framework for GSI kinematics is somewhat more involved than that for RHIC, since in the region to be accessed higher-order corrections to the partonic cross sections are particularly important. The NLO corrections for the transversely
polarized Drell-Yan cross section have been calculated in [34]. In the region of interest here, however, certain logarithmic terms in the partonic cross section become important to all orders in perturbation theory and need to be resummed. Such a “threshold resummation” is a well established technique in QCD [35]. For $A_{TT}$ for the Drell-Yan process it has been addressed in detail recently in [36].

Figure 5 shows results of [36] for the $K$ factors for the unpolarized Drell-Yan cross section at $s = 30$ GeV$^2$ (left) and $s = 210$ GeV$^2$ (right), at NLO, NNLO, and for the next-to-leading logarithmic (NLL) resummed case, along with various higher-order expansions of the resummed result. As can be seen, the corrections are very large, in particular in the lower-energy case. Figure 6 shows the corresponding spin asymmetries $A_{TT}$. $A_{TT}$ turns out to be extremely robust and remarkably insensitive to higher-order corrections. Perturbative corrections thus make the cross sections larger independently of spin. They would therefore make easier the study of spin asymmetries, and ultimately transversity distributions. For further details, including a discussion on the role of nonperturbative effects, see [36]. We finally note that it has recently also been proposed [37] to study the spin asymmetry $A_{TT}$ for the reaction $\bar{p}p \rightarrow \pi^0 X$, which would give additional information on transversity.
Acknowledgments

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A summary is presented of recent results and prospects regarding the exploration of proton structure and QCD at the electron-proton collider HERA and beyond. Emphasis is placed on inclusive cross section and parton distribution measurements, on heavy flavour physics and diffractive phenomena at hard scales.

HERA and its Physics

QCD is the renormalizable, non-Abelian gauge field theory which describes the asymptotically free strong interaction of coloured quarks and gluons. HERA is the first electron-proton collider of energies $E_e = 27.6$ GeV and $E_p = 920$ GeV, equivalent to a fixed target deep inelastic scattering experiment of 54.1 TeV lepton beam energy, thus enabling proton structure to be studied at small Bjorken $x$ and at high momentum transfers $Q^2$. Resolving distances down to $10^{-18}$ m, HERA is the highest resolution microscope of the world. The machine was inaugurated in 1992 and is currently running in its second phase with upgraded specific and integrated luminosity. Operation of HERA and the two collider experiments H1 and ZEUS \cite{1} is scheduled to be terminated in 2007 because the injector, PETRA, has been foreseen to be used as a 3rd generation light source. HERA has an $e^\pm$ beam with longitudinal polarisation between $-0.5$ and $+0.5$ which serves the HERMES experiment, operating with stationary targets, and which is now utilised to study polarisation effects in $ep$ collisions at H1 and ZEUS, as polarised charged current scattering for the first time \cite{2}.

Four basic subjects are investigated at HERA which can only be partially discussed here further: the classic, inclusive deep inelastic neutral ($ep \rightarrow eX$) and charged current ($ep \rightarrow \nu X$) scattering, studies of QCD and parton radiation, searches at the energy frontier and electroweak physics in the spacelike region. Generally the HERA data and analyses represent a triumph of perturbative QCD, which is being tested and developed owing to strong theoretical efforts and the unique data from the HERA experiments. New phenomena were found which were not really expected to occur or to play a role at HERA: i) at low Bjorken $x \sim 10^{-4}$ a new phase of partonic matter was observed characterised by large gluon and also sea quark densities at still small coupling $\alpha_s(Q^2)$. In the region of small $x$, detailed studies of parton radiation dynamics, in forward jet production and in azimuthal de-correlations in dijet events, hint to effects beyond the conventional patterns as prescribed by the DGLAP evolution equations; ii) about 10% of the inelastic events are of diffractive nature in which the proton, despite the violent collision, remains intact; iii) recently, with the study of vector meson production and of deeply virtual Compton scattering (DVCS), parton amplitudes are being measured after decades of measuring only partonic cross sections; iv) finally, new phenomena are observed...
which still deserve clarification, regarding the possible production of pentaquark states and the observation of some excess of peculiar events with isolated leptons and missing transverse momentum.

**Quark Structure of the Proton**

HERA measures the inelastic scattering of electrons or positrons off protons at four-momentum transfers, $Q^2$, from very small values, $Q^2 < M_p^2$, a region termed photoproduction, up to very large values approaching the kinematic limit given by the centre of mass energy squared, $s = 4E_eE_p \simeq 10^5\text{GeV}^2$. Here $M_p$ is the proton mass. At low $Q^2$, this reaction is dominated by single-photon exchange between the positron and the proton. Fig.1 shows the H1 and ZEUS measurements of the single differential cross sections, $d\sigma/dQ^2$, in neutral (NC) and charged current (CC) scattering, based on all the $e^\pm p$ data taken in the first period of HERA operation which ended in 2000. As was anticipated 20 years ago, the NC and CC cross sections indeed fall with $Q^2$ to values which are of similar size when $Q^2$ is of the order of the masses of the exchanged $Z$ and $W$ bosons, $Q^2 \sim 10^4\text{GeV}^2$, mediating the weak interaction. Due to the uncertainty relation, high momentum transfers correspond to probing the proton structure at small distances. From a comparison of the NC measurements presented in Fig.1 with the standard model expectation, limits on the quark radius are obtained as small as $r = 0.85(1.0) \cdot 10^{-18}\text{m}$ from the ZEUS (H1) experiment. Hence, quarks are pointlike down to at least 1/1000 of the proton radius.

Neutral currents proceeding via photon and $Z$ exchange and charged currents being flavour sensitive by the coupling of the exchanged $W^+$ or $W^-$ bosons allow the complete set of quark distributions, up and down quarks and anti-quarks, to be determined. A recent determination in next to leading order (NLO) QCD is shown in Fig. 2. It shows reasonable agreement between the H1 and ZEUS determinations. HERA is the only machine in which these parton distributions can be fully determined in regions free of higher twist and nuclear corrections, and efforts are underway to still increase the precision of these determinations to reconstruct proton’s partonic structure and to obtain accurate predictions for various cross sections at the Large Hadron Collider (LHC).

**Gluon and Strong Coupling Constant**

QCD is most accurately tested in deep inelastic scattering via the scaling violations of the proton structure function $F_2(x, Q^2)$ which can be expressed to leading order as

$$\frac{dF_2}{d\ln Q^2} \propto \alpha_s [P_{gg} \otimes g + P_{qg} \otimes F_2],$$

where $P_{gg}$ and $P_{qg}$ are the appropriate splitting functions. H1 and ZEUS have measured $F_2(x, Q^2)$ in a wide range of $x$ and $Q^2$, to an accuracy of about 2% in the bulk region of $x \sim 0.001$ and $Q^2 \sim 20\text{ GeV}^2$. Roughly, at large $x$ the gluon density is negligible and thus $\alpha_s$ is directly determined by Eq 1. At small $x$ the gluon contribution dominates and therefore $xg(x, Q^2)$ is determined from the derivative of $F_2$. The
Figure 1: Measurements of the neutral and charged current electron- and positron-proton scattering cross sections as a function of $Q^2$ by the H1 and ZEUS experiments.

Figure 2: Determinations of the valence, sea and gluon momentum distributions in the proton, from NLO QCD fits to NC, CC, and to jet data (ZEUS), at $Q^2 = 10 \text{ GeV}^2$ as a function of Bjorken $x$, the parton momentum fraction of the proton. The low $x$ region is dominated by the gluon and sea quark distributions while $u_v$ and $d_v$ dominate the valence-quark region at large $x$. 
uniquely large kinematic range at HERA thus allows the correlation of $\alpha_s(M_Z^2)$ with $xg(x,Q^2)$ to be resolved. This derivative constrains the gluon distribution at low $x$ to about 20% accuracy in the DIS region. Both the rise of $\partial F_2/\partial \ln Q^2$ towards low $x$ at fixed $Q^2$ and the increase of the first derivative with $Q^2$ at fixed $x$ are well described by NLO QCD.

The strong coupling constant is the least well-measured of the fundamental coupling constants. It thus dominates the uncertainty of extrapolations of the electromagnetic, weak and strong coupling constants to a unification scale near the Planck mass [3]. The average $\alpha_s(M_Z^2)$ value to NLO from ZEUS and H1 as determined in inclusive DIS and in jet production currently is $\alpha_s = 0.1186 \pm 0.0011 \text{(exp)} \pm 0.005 \text{(thy)}$. Here the first uncertainty comprising all experimental and model dependent effects is already smaller than the current world average error. A striking peculiarity of this result is the so-called theoretical error. Its size reflects the ad hoc convention that the renormalisation (and factorisation) scale should be varied by factors of 2 and 1/2. This convention is not supported by the data: in both the H1 and the ZEUS QCD analyses, fits are very poor at the extremes of these scale variations and thus the variation prescription is questionable. Furthermore, with forthcoming exact NNLO analyses the scale dependence will be further reduced.

It has been a challenge to still improve the experimental accuracy and to extend the kinematic range of the HERA structure function data using new instrumentation and exploiting the overconstrained determination of the event kinematics as well as the high accuracy in tracking and calorimetry of the HERA collider detectors. Theoretical and experimental progress in DIS is therefore expected to pin down $\alpha_s(M_Z^2)$ to an accuracy of better than 1%. A further significant improvement could be expected with luminous electron-deuteron scattering data from HERA. These would resolve the non-singlet and singlet evolutions and would not require significant nuclear corrections since the spectator proton could be tagged, giving access to accurate electron-neutron scattering data [4]. HERA thus seems to have the potential to measure $\alpha_s$ perhaps nearly an order of magnitude more accurately than the current world average. An interesting problem regards the behaviour of the gluon density at large $x$ which is correlated with $\alpha_s(M_Z^2)$.

**Heavy Flavour Physics**

A completely new field of the physics of parton distributions has been opened at HERA with the observation of sizeable fractions of events related to charm ($\sim 20\%$) and beauty ($\sim 2\%$) production. Based on the observation of large samples of events with $D^+ \rightarrow D^0 \pi_{slow} \rightarrow K \pi \pi_{slow}$ decays, the deep inelastic charm production cross section, related to the charm structure function, $F^2_c = x \sum c_i^2 (c + \bar{c})$, has been measured in a wide range of $x$, between 0.0001 and 0.1, and $Q^2$, between a few GeV$^2$ and a few 1000 GeV$^2$. Recently the first measurement of $F^2_b$ became available based on the characteristic signature of the long lifetime of $B$ particles, as measured in H1’s Silicon strip detector around the interaction region. This and further measurements of charm and beauty production at HERA are stimulating much theoretical activity in describing heavy flavour production near and above threshold within QCD. While near threshold one thinks of heavy quarks being produced in the fusion of
the interacting photon with a gluon from a proton made of $u$, $d$ and $s$ quarks, much above threshold, $Q^2 > m^2_Q$, the heavy quarks appear light and behave as ordinary constituent partons with momentum distributions, $c(x, Q^2)$ and $b(x, Q^2)$, inside the proton. With the photon-gluon fusion process one has found an independent measure for the gluon density in the proton at very low $x$. Much can be learned in heavy flavour studies at HERA about fragmentation, hadronisation and also about exotic particle production as related for example to pentaquarks which may exist. Beauty physics is yet in its infancy at HERA as it relies on the increase of luminosity and further Silicon detectors recently installed.

**Diffraction**

Nearly 20 years ago, a model was formulated in which diffractive deep inelastic scattering is ascribed to the scattering of virtual photons off Pomerons in $ep$ interactions in which the proton stays intact, which causes a large ‘rapidity gap’ between the first produced final state particle and the scattered proton. This process was indeed observed at HERA, for about 10% of the DIS events at low $Q^2$ and $x$. A diffractive structure function, $F_2^{D}(t, x_P, Q^2, \beta)$, was then introduced which factorises into calculable coefficient functions and the distribution of partons in the diffractive exchange (Pomeron). Here $t$ is the four-momentum transfer to the scattered proton (often integrated over), $x_P$ is the fraction of proton’s momentum carried by the diffractive exchange and $\beta$ is the fraction of the Pomeron’s momentum carried by its interacting constituent in the parton model. In QCD hard diffraction is often viewed as two-gluon exchange. Since the gluon distribution rises towards low $x$, a potential unitarity limit of $\gamma^* p$ scattering may be observable earlier in diffraction than in inclusive $ep$ scattering. At the LHC double diffractive scattering may provide a clean event environment for studying or perhaps discovering the Higgs boson or exotic particles [5].

Diffractive scattering can be identified via the rapidity gap or by tagging the non-dissociated proton in the leading (ZEUS) or forward (H1) proton spectrometers. There is a wealth of HERA data on $F_2^{D}$ with increasing accuracy and kinematic coverage which are rather consistent, between the experiments and between the different tagging methods applied. The hard scattering part of virtual photon-Pomeron scattering may be treated similarly to $\gamma^* p$ scattering which allows NLO diffractive pdf’s to be determined from the $Q^2$ evolution and $\beta$ dependence. A striking result is that about 80% of the momentum of the diffractive exchange is carried by its gluonic component, at $Q^2 = 5$ GeV$^2$. The evolution of the diffractive parton distributions has now been shown to agree with NLO QCD up to values of $Q^2$ as large as 1600 GeV$^2$ where the gluon momentum fraction still is about 70%. At higher $Q^2$ hard diffraction contributes 2-3% to the inclusive cross section.

The question is being investigated whether the diffractive parton distributions may be universally applied, in particular to $pp$ scattering. The calculation of single diffractive scattering at the Tevatron using the diffractive pdf’s from H1 was found to overestimate the CDF data by about a factor of 7. Spectator interactions may thus hinder the “pure” diffractive exchange in $pp$ scattering to take place as frequently as naively expected. It is important to verify whether the final state data at HERA
can be predicted based on the pdf's from inclusive diffractive DIS and assuming the factorisation hypothesis to hold. This has been found to be correct in DIS, both with dijet and charm data. In photoproduction, resolved photon interactions may be expected to resemble the configuration studied in \( pp \) scattering. In dijet production \( x_s \) is calculated from the hadronic final state which is adequate for a consistent treatment in NLO QCD and direct production dominates for \( x_s > 0.75 \).

It came as a surprise for both H1 and ZEUS that diffractive dijet production in photoproduction is suppressed relatively to predictions assuming factorisation for all \( x_s \) by a factor of about 2, i.e. both for the resolved and for the direct part.

The mechanism of diffractive scattering and its treatment in QCD is a field of major interest and growing activity. If, for example, ‘absorptive corrections’ were to be applied for diffractive contributions to the inclusive cross section, as has been suggested in \cite{6}, the conventional determinations of the gluon and also the quark distributions in the proton would be misleading and so would be their extrapolation to the LHC region.

A new field of research is the physics of deeply virtual compton scattering (DVCS), \( ep \rightarrow ep\gamma \). Here a parton in the proton absorbs the virtual photon, emits a real photon and the proton ground state is restored. As in this process a momentum \( t \) is transferred to the outgoing photon, the virtual partons, gluons at low \( x \) (characteristic for DVCS at collider experiments) or quarks at larger \( x \) (as studied at JLab or by HERMES at HERA), carry different fractions of the initial proton momentum. The DVCS process thus measures generalised parton distributions which depend on two momentum fractions \( x \) and \( \xi \), as well as on \( Q^2 \) and \( t \). The DVCS process interferes with Bethe-Heitler scattering. This allows parton scattering amplitudes to be measured, instead of cross sections in the classic DIS concept. This interference has been viewed as a possibility to establish holograms of nucleons in leptoproduction experiments \cite{7}. Experimentally, as much as phenomenologically, this field is new and developing rather rapidly with the first measurements being performed at HERA and elsewhere. The measurement of charge and helicity asymmetries allows different types of parton distributions to be accessed which may be related via the ‘Ji sum rule’ to the unmeasured angular momentum contribution to the spin of the proton.

**Beyond \( ep \) at HERA**

The programme proposed recently \cite{4} for a subsequent phase of operation, termed HERA III, has three main components:

i) The precision measurement of the transition from deep inelastic scattering to soft hadron collisions. In the infinite momentum frame DIS probes the partonic structure of the proton, down to distances of 0.001 fm at HERA. In the proton restframe, however, one may view this process as proceeding by the photon splitting into a colour dipole of variable size \( 2/Q \) which interacts with the proton at an energy of \( W^2 \approx s_y = Q^2/x \) which for \( Q^2 = 1 \text{GeV}^2 \) can be as large as about 10000 GeV². The distance at which the splitting occurs, the coherence length (Gribov), is large because of \( L \propto 1/x \). Thus low \( x \), by variation of \( Q^2 \), is sensitive to the transition from soft to hard physics, which occurs at \( Q^2 \approx 1 \text{GeV}^2 \) equivalent to a distance of...
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0.3 fm. Investigation of this phenomenon has to include the study of the two virtual photon polarisation states. This programme, at high accuracy, has not been pursued yet because the HERA II phase has been dedicated to maximising the luminosity by introducing focusing magnets very close to the interaction regions of H1 and ZEUS which removed acceptance to that region, \( Q^2 < 5 \text{ GeV}^2 \).

ii) The measurement of electron-nucleus collisions. Prior to HERA every DIS charged lepton scattering experiment used deuterons to study the neutron structure and the partonic content. HERA has discovered the rise of \( F_2 \propto 4u + d \) towards low \( x \). There are non-perturbative models, like the chiral quark soliton model, which predict up and down anti-quarks not to be equal. While this has been indeed confirmed at larger \( x \sim 0.1 \) common wisdom assumes \((d - u) \to 0\) at low \( x \) but may yet be wrong. It is necessary to measure this in order to understand nucleon structure at low \( x \) and to be able to predict the high energy, low \( x \) cross sections at the LHC (up to the rapidity plateau) and in astroparticle physics (superhigh energy neutrino scattering off isoscalar targets). The \( ed \) programme at HERA would be fascinating and more powerful than at fixed target experiments since, by tagging the spectator proton, \( en \) scattering could be measured nearly free of Fermi motion corrections and, moreover, a diffractive programme would be pursued on \( p, n \) and \( d \) which also would allow the shadowing corrections to be determined for the first time. Extending this programme to heavier nuclei would determine nuclear parton distributions, as is required for ALICE at the LHC and for RHIC, and it would search for the predicted black body limit of DIS, with \( F_2 \to Q^2/\ln(\delta/x) \) and a diffractive scattering component of up to 50\%. Moreover, since the gluon density is amplified in nuclei as \( A^{-1/3} \), one would exceed the unitarity limit \( \sim Q^2/\alpha_s \) and be able to study saturation phenomena which in \( ep \) scattering are not uniquely seen at HERA. The \( eN \) programme, focussing on low \( x \), is a low luminosity programme and would constitute a natural complement to the HERA \( ep \) programme.

iii) The study of the structure of polarised nucleons. The HERA proton beam may be polarised. This would allow measurements of double spin asymmetries to be pursued at HERA. For spin physics that would make a huge difference as compared to fixed target experiments which usually suffer from a narrow kinematic phase space and non-perturbative effects. Asymmetries at large \( Q^2 \), as in CC scattering, are large while spin effects at low \( x \), such as the \( A_1 \) asymmetry, which determines the polarised gluon density in the proton, are proportional to \( x \) and are thus small. Consequently, HERA spin physics would require high luminosities, of the order of \( 1 \text{ fb}^{-1} \), to be available. Polarisation of deuterons may be easier to obtain because of the reduced anomalous magnetic moment which implies that less resonances are to be crossed as compared to the polarised proton case.

A new detector was proposed to be built for low \( x \) physics and the H1 detector was proposed to be kept and upgraded. The fixed cost for making HERA an \( eN \) accelerator complex would be nearly negligible, though not small, when compared to the investment HERA represents. Apart from the spin programme only low luminosity is required. Therefore, for the low \( x \) and the \( eA \) physics, one could operate the machine for only a small fraction of time reducing the cost of its operation in electricity and manpower. With external contributions from the (inter)national community HERA III could still be realised.
Today much of the world’s particle physics attention is devoted and focused to the Large Hadron Collider (LHC), a 7 TeV proton ring collider which leads to typical parton-parton cms energies of $\sqrt{s} \simeq 2xE_p \sim 2$ TeV with a maximum of 14 TeV. There are theoretical predictions which let us hope for the discovery of the Higgs particle which explains the masses at the elementary fermion level (while the colour force, QCD, generates the baryonic matter of the universe). Genuine unification of the fundamental forces within perhaps supersymmetric theories may be found. The LHC is thus the greatest adventure of modern particle physics as a genuine discovery machine with the potential of finding phenomena beyond the current theoretical expectation. If there is nothing new occuring, theoretical dogma will need to be revised and the LHC will be a machine to study QCD at high scales.

The LHC should be accompanied by a linear collider at high energies in order to be able to study the physics at the TeV scale, perhaps the spectrum of SUSY particles, in a rather clean environment. Much effort has been spent following the legacy of Bjoern Wiik in order to develop the technology and design of what is now called the International Linear Collider (ILC). In the current version this is a two-arm 250 to 500 GeV superconducting machine corresponding to a cms energy of up to 1 TeV. Given the cost of the ILC and current plans, it is obvious that the detailed parameters of the ILC can not be decided prior to the LHC finding new physics for which the ILC is suited. Thus the energy range of the linear collider will be an open issue until then. This also implies that there is a decade with essentially the LHC as the only high energy accelerator base for particle physics unless decisions regarding HERA and/or the Tevatron would be revised.

On the time scale of the LHC and the ILC the physics of DIS needs to conquer the TeV scale. It is obvious from the past development of particle physics that lepton-nucleon experiments at each energy level, recently HERA in conjunction with LEP and the Tevatron exploring the Fermi scale of a few 100 GeV, have been of very high importance for particle physics. The physics of DIS at the TeV scale is extremely rich. It has been summarised in a series of studies on a LEP × LHC $ep$ machine [8] and more recently on THERA [9], a HERA × TESLA $ep$ option of the cold linear collider. Since the cross section falls rapidly with $Q^2$, luminosities of the order of a $fb^{-1}$ or more are required to study the smallest distance region accessed by the new accelerators. In case leptoquarks are discovered at the LHC a polarised $e^+ p$ proton machine is ideally suited to study their spectroscopy. At energies as large as 1 TeV or beyond in DIS, major questions of low $x$ physics (regarding parton distributions and the saturation of the rise of the gluon distribution, the nature of diffraction and the heavy quark structure of the photon, for example) can be studied much deeper than at HERA. At high $Q^2$ new effects such as parton substructure at $10^{-19}$ m may suddenly be discovered.

The next generation of colliders is not cheaper than the previous one, and huge efforts are needed to realize any of these steps. An $ep$ machine is most economically realised combined with the ILC electron or the LHC proton beams. It thus is cost effective, in particular if one used the HERA, or the Tevatron, proton ring magnets together with the ILC. The physics of DIS at the TeV energy scale may thus be
realised as a $500 \times 1000 \text{ GeV}^2$ ILCp or a $70 \times 7000 \text{ GeV}^2$ eLHC complex. A symmetric energy machine requires an extended detector in the $e$ beam direction to measure the scattered electron at low $x$. An asymmetric machine requires special detection efforts for the forward going hadronic final state to access the region of large $x$. Detectors for an $ep$ collider at TeV energies do not pose extraordinary difficulties, the proton beam energy determining their size.

With the precision measurements of proton structure and the potential for new physics, deep inelastic scattering will remain a unique and necessary part of particle physics. Not to pursue this field further would be a terrific mistake and irrevocable loss for our attempt to reveal the inner secrets of nature.

Acknowledgement. I would like to thank F. Rathmann and H. Stroeher for the invitation to present HERA and its results to a pleasant and interested community dealing with QCD at lower energies.

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Muon g-2 and Electric Dipole Moments in Storage Rings:
Powerful Probes of Physics Beyond the Standard Model

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EDM collaborations)

Dipole Moments in Storage Rings

Muon g-2: Theoretical Significance

The g-factor of a particle is defined as

$$g \equiv \frac{\text{magnetic moment}}{\text{charge}} \times \frac{\text{angular momentum}}{\hbar}$$ (1)

The Dirac equation predicts $g = 2$ for point-like, spin 1/2 particles. The quantity $g - 2$ probes the difference between the mass and charge distributions of a particle and $g - 2 = 0$ when they are the same at all times. The proton ($g_p = 5.586$) and the neutron ($g_n = -3.826$) differ significantly from the value 2, indicating they are composite particles. Their ratio ($g_p/g_n = -1.46$) being close to the predicted value of -3/2 was the first success of the constituent quark model. The anomalous magnetic moment ($a \equiv \frac{g-2}{2}$) value of the electron is known 350 times more precisely than the muon ($a$) in agreement with the theoretical prediction involving only QED. The $(g-2)/2$ value of the muon is known with 0.5ppm accuracy and because its sensitivity to a certain class of particles scales as $(m_e/m_e)^2 \approx 40,000$ it is necessary to add the contribution of strong and weak interactions of the standard model (SM). Speculative extensions of the SM, like super-symmetry (SUSY), could also have a significant contribution.

The estimated contributions to the anomalous magnetic moment of the muon are the sum of the SM contributions and those coming from new physics: $a_{\mu}(\text{theo}) = a_{\mu}(\text{QED}) + a_{\mu}(\text{had}) + a_{\mu}(\text{weak}) + a_{\mu}(\text{new physics})$, with

- $a_{\mu}(\text{QED}) = 11658470.6(0.3) \times 10^{-10}$
- $a_{\mu}(\text{had}) = 694.9(8.) \times 10^{-10}$ (based on $e^+e^-$ data)
- $a_{\mu}(\text{had}) = 709.6(7.) \times 10^{-10}$ (based on $\tau$ data)
- $a_{\mu}(\text{weak}) = 15.4(0.3) \times 10^{-10}$

with the sum of the SM contributions being

- $a_{\mu}(\text{SM}) = 11 659 181(8)(8.) \times 10^{-10}$ (based on $e^+e^-$ data)
- $a_{\mu}(\text{SM}) = 11 659 196(8) \times 10^{-10}$ (based on $\tau$ data)
Speculative extentions like SUSY also have a potentially large contribution given by \[1\]

\[ a_\mu(\text{SUSY}) = \text{sgn}(\mu) \times 13 \times 10^{-10} \left[ \frac{100\text{GeV}}{m_{\text{SUSY}}} \right]^2 \tan \beta \] (2)

with \(\text{sgn}(\mu)\) the sign of the SUSY \((\mu)\) parameter and \(\tan \beta\) the ratio of the vacuum expectation values of the two Higgs doublets.

**Muon g-2: Experimental Method**

There are three major components of the muon g-2 experimental method \[2\]:

- **Polarize:** Using the parity violating decay \(\pi^- \rightarrow \mu^- + \bar{\nu}_\mu\)
- **Interact:** Precess in a uniform magnetic field
- **Analyze:** Using the parity violating decay \(\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu\)

Pions are produced by colliding energetic protons onto a fixed target. Pions of a certain momentum range are collected and directed into a pion decay channel. The muons resulting from the pion decay can be highly polarized (of the order of 95%) when a small muon momentum bite of 1% is used. These longitudinally polarized muons are directed into a large super-conducting magnet of 7.11m radius. The magnetic field is vertical and has a strength of 1.5T. The radius and strength of this magnet are very specific and driven by the requirement to use muons of a specific momentum \(3.1\text{GeV}/c\), a.k.a. magic momentum, with \(\gamma \approx 29.3\) [3].

For the non-relativistic case the g-2 principle is just the difference between the momentum precession and the spin precession of the muon. The cyclotron (angular) frequency is

\[ \omega_c = \frac{eB}{m} \] (3)

while the spin precession is

\[ \omega_s = \frac{g eB}{2m} \] (4)

and their difference

\[ \omega_a = \omega_s - \omega_c = (\frac{g}{2} - 1) \frac{eB}{m} = \frac{g - 2eB}{2m} \Rightarrow \omega_a = \frac{eB}{m} \] (5)

It turns out that this equation is also valid in the relativistic case when taking into account Thomas’ precession of the accelerated system. For a positive \(a\), like it is the case with the muon, it means that the spin vector gets ahead of the momentum vector in every turn. In order to be able to determine the anomalous magnetic moment \(a\) with high accuracy we need to determine with at least the same accuracy \(\omega_a\), \(e/m\) and \(B\). The last requirement places severe restrictions on the possible magnetic field configurations, with the simplest being that of a high uniformity. A highly uniform magnetic field is not very efficient in storing a large number of muons because of the
absence of vertical focusing. This vertical focusing is provided for by an electrical focusing system (quadrupoles) without adding a significant systematic error when the muon momentum used is the magic one. At this momentum the influence of the horizontal electric field on both the muon momentum vector and the muon spin vector is the same. A small correction arising from the finite momentum width of the stored beam is applied at the end of the data analysis. At low momentum the radial electric field influences the momentum vector more than it influences the spin vector. The opposite happens at very high momentum values (the E-field looks like a magnetic field and it precesses the spin vector more than the momentum vector by the anomalous magnetic moment factor $a$). In between, at $\gamma = 29.3$, there is a happy coincidence where the E-field influences both the momentum and spin vectors the same!

The (positive) muons decay to one positron and two neutrinos, with the preferred direction of the positron (in the muon rest frame) being along the muon spin. This fact has very interesting consequences on the energy spectrum of the positrons depending on the relative angle between the muon spin and momentum vectors. When the muon spin and momentum are parallel, the energy of the positron in the lab frame is maximum (on average) and when they are anti-parallel it is minimum (see Figure 1). The time spectrum of the detected positrons is given in (Figure 2).

**Energy Spectrum of Detected Positrons**

![Energy Spectrum of Detected Positrons](image)

Figure 1: When the spin and momentum vectors are aligned the energy of the positrons in the lab frame is (on average) larger than when the two vectors are anti-parallel. Setting an energy threshold of, e.g., 2GeV modulates the number of particles above that energy with the g-2 frequency.

The main experimental accomplishments that made the muon g-2 experiment at Brookhaven National Laboratory particularly sensitive are several:

1. High muon intensity made possible by the large proton intensity available from the AGS with the proper timing structure.
2. The construction of the largest diameter super-conducting magnet in the world providing a stable magnetic field and the superb NMR system as its monitoring device [4].

3. Direct muon injection, made possible with the fast magnetic kicker with minimal residual magnetic field [5].

4. A super-conducting inflector with a superconducting shield that provided 1.5T DC magnetic field to counter-part the main magnet field and yet it allowed no measurable fringe field in the storage region, just a couple of cm away [6]!

5. Pulsed electric quadrupoles providing vertical focusing with an innovative lead design to quench the trapping of low energy electrons [7].

6. Electromagnetic calorimeters and their detection electronics that could operate at high and low counting rates with adequate gain and timing stability [8].

The final experimental results as well as the theoretical predictions based on both the $e^+e^-$ and $\tau$ data are shown in Figure 3; the total experimental error is 0.5ppm [9]. The experimental value is found to be $1.1659203(8) \times 10^{-10}$. Clearly it would be beneficial to reduce both the theoretical and experimental uncertainties. It is expected that the theoretical uncertainty will be reduced by a factor of 2 in the next years. On the experimental side we have already put in a proposal for an upgraded experiment at BNL with a goal of 0.2ppm, which received scientific approval and is currently awaiting funding approval from the DOE.
Electric Dipole Moments in Storage Rings

The search for an electric dipole moment (EDM) of fundamental particles has been going on since the 1950s. If an EDM was to exist it would have to violate separately parity (P) and time reversal (T) invariance (see Figure 4). T-violation, assuming CPT conservation, means CP-violation which is one of the required conditions, according to Sakharov, for an initially matter-antimatter symmetric universe to evolve to the present day matter dominated universe. EDMs are particularly sensitive to physics beyond the SM. Due to the structure of the SM (a single CP-violating phase plus the fact that the $W^-$ boson comes only in one handedness) the EDMs in the SM

A Permanent EDM Violates both 
T & P Symmetries:

![Diagram showing EDM and symmetries](image)

Figure 4: The existence of an EDM in a particle with spin would violate separately parity (P) and time (T) reversal invariance.
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have negligible values (from a $10^{-31} e\cdot cm$ to $10^{-32} e\cdot cm$ for the electron) as they are high order effects. In most extensions of the SM the above mentioned restrictions do not exist (e.g. in SUSY there are 42 CP-violating phases, with both right and left handed bosons present) and their EDM contributions are first order effects. The expected numerical values are in the neighborhood of the current experimental limits. Obviously the discovery of an EDM will constitute a significant progress in understanding the origin of our cosmos. The usual method for searching for an EDM is depicted in Figure 5.

**Usual Experimental Method**

$$\frac{d\vec{S}}{dt} = \vec{\mu} \times \vec{B} + \vec{d} \times \vec{E}$$

![Figure 5: Strong electric fields are used to probe EDMs. Flipping the electric field direction should change the particle spin precession rate in the presence of an EDM.](image)

The current EDM limits are dominated by the electron [10] ($< 1.6 \times 10^{-27} e\cdot cm$), the neutron [11] ($< 6.3 \times 10^{-26} e\cdot cm$) and $^{199}$Hg [12] ($< 2.1 \times 10^{-28} e\cdot cm$) with approximately the same physics sensitivity. Even though the $^{199}$Hg is numerically the best limit it only translates to a lesser limit for the neutron due to screening (Schi theorem). As a matter of fact screening is the reason that all the EDM experiments have been performed in neutral systems and then the EDM of the individual charged particles has been deduced using theory.

We have now introduced a new sensitive EDM method using directly charged particles in magnetic storage rings. This method uses the fact that magnetic fields Lorentz transform into electric field in the rest frame of the moving particles and therefore they couple to the EDM ($\vec{d}$) causing the spin ($\vec{S}$) vector to precess according to:

$$\frac{d\vec{S}}{dt} = \vec{d} \times \left( \vec{V} \times \vec{B} \right)$$

where, e.g., 1T is equivalent to 300MV/m for relativistic particles, much more than it is possible to achieve for electric fields in the laboratory.

In our muon g-2 experiment we used this effect to place an indirect limit on the muon EDM (see Figure 6). Due to the tilt in the angular velocity vector with respect to the magnetic field direction there is a modulated vertical component. The amplitude of the vertical component depends on the g-2 period, the larger the period the stronger the signal. This is the reason we have proposed to use particles with a
Indirect Muon EDM limit from the g-2 Experiment

Ron McNabb’s Thesis 2003: $< 2.7 \times 10^{-19} \text{e} \cdot \text{cm}$ 95% C.L.

Figure 6: The direction of the angular velocity vector is slightly tilted with respect to the magnetic field direction in the presence of a muon EDM.

momentum lower than the magic momentum (where a radial electric field influences the momentum direction more than the spin direction) to “freeze” the spin in the forward direction (in effect making the g-2 period as long as possible) [2]. We have applied this method to produce a letter of intent with a sensitivity of $10^{-24} \text{e} \cdot \text{cm}$ for the muon [14] (statistics limited) and a proposal with a sensitivity of $10^{-27} \text{e} \cdot \text{cm}$ for the deuteron nucleus [15] (systematics limited) as it is most applicable to particles with small anomalous magnetic moments. The deuteron EDM is the sum of the proton, and neutron EDM plus the CP-violating nuclear forces:

$$d_D = (d_p + d_n) + d_{\text{NN}}$$

A limit of $3 \times 10^{-27} \text{e} \cdot \text{cm}$ was used to compare it with the the present limits of the neutron, electron (Tl) and $^{199}\text{Hg}$ [16] limits. The deuteron EDM is most favorable by a factor of 10 to 1000 depending on the value of the SUSY parameters and the models. The deuteron polarimetry (the analyzer that probes the spin polarization state as a function of time) is described by Onderwater in the same proceedings.

The cost of the proposal was estimated to be $34M mainly due to the large size of the storage ring and the Brookhaven PAC felt it was too expensive for the physics reach.

Since then Yuri Orlov invented [3] another variation (resonance method, see the contribution by Orlov in the current proceedings) of the Storage Ring EDM method which reduces the size of the ring by an order of magnitude and eliminates the major systematic error limitation of the previous method. The potential reach of the method is $10^{-29} \text{e} \cdot \text{cm}$ an unprecedented sensitivity level. The buildup of the vertical spin component is achieved by using RF to modulate the particle velocity in resonance with the g-2 frequency. The method is also applicable to particles with large anomalous magnetic moments. It eliminates the need for the radial electric field, the major source of systematic error of the previous method.

\[ \tan \theta = \frac{\omega_{edm}}{\omega_a} \]
Conclusion

We have shown that the study of dipole moments, both magnetic and electric, in storage rings offer unique opportunities in probing physics beyond the SM. Both methods use similar techniques (particle and spin precession in magnetic storage rings). We are currently investigating the systematic errors associated with the resonance EDM method. So far it looks very promising.

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The Indiana Cooler, 1988 - 2002
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Abstract

The Indiana Cooler was the first storage ring with electron cooling built for nuclear physics experiments with internal targets. I give a short history and a list of the main accomplishments.

1. Conception

Forty years ago, Budker in Novosibirsk proposed to use co-moving electron beams to cool charged particle beams in storage rings. The experimental proof was furnished at Novosibirsk (1974), and was followed by tests at CERN with 46-MeV protons, and at Fermilab at 100 MeV and, later, 200 MeV. The latter result provided the solid ground for a proposal to utilize phase space cooling in nuclear-physics experimentation at the Indiana University Cyclotron Facility (IUCF). In December 1980, IUCF submitted the proposal “The IUCF Cooler-Tripler: proposal for an Advanced Light-Ion Physics Facility” to the National Science Foundation. The plan included the addition of a new cyclotron, the ‘Tripler’, which was dropped in a second version of the proposal.

2. Facility Development

The Indiana Cooler project was funded in 1983 ($6.5M) by the NSF, while the State of Indiana provided the funds for a building addition ($2.7M). Ground was broken the same year and the building was ready for occupancy two years after that. The first full turn of a proton beam was achieved in the fall of 1987, it was shown that the stored beam could be accelerated, and deuterons were stored as well. Finally, on April 16th, 1988 electron cooling was demonstrated. The next day, with an internal hydrogen target in place, it was shown that cooling really counteracts target heating, leading to equilibrium with constant emittance, and that experiments with internal targets were indeed feasible!

The Cooler was a 3.6 Tm storage ring with a circumference of 86.8 m. It featured six straight sections, to house equipment for beam manipulation and internal-target experiments. One of the straight sections contained the electron cooler in which a 10 to 275 keV electron beam of up to 4 A overlapped the stored beam. Beam was injected in the center of a second, dedicated straight section. Beams of p, d, ³He⁺, ³He++, ³Li⁺ at variable energies up to 200 MeV Q²/A were supplied by the existing cyclotron.

To improve the intensity of polarized beam the existing cyclotron was equipped with a new polarized ion source (HIPIOS) in 1994. To overcome the limitation inherent in the cyclotron as a source for beam, a new, dedicated injector was built between 1994 and 1997, jointly funded by the University and the NSF ($3.5M). It consisted of a pulsed, polarized H⁺ or D⁺ source (CIPIOS). The ions were accelerated to 7 MeV with a radio-frequency quadrupole structure, followed by a drift-tube linac, and strip-injected into a small accumulator synchrotron
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(CIS), where they were accelerated and then transferred as a single bunch into the Cooler. The final layout of the facility is shown in fig.1.

In 1999 the NSF announced that operation of the facility will no longer be supported. An exit strategy for a final research program was formulated. The last beam orbited the ring at the end of July 2002.

The first Cooler experiment was conducted with less than 25 µA stripping-injected unpolarized protons on a simple H₂ gas jet target. At the time of the shutdown, up to 1.5 mA of polarized proton or deuteron beam was stored and polarized proton and deuteron targets were available.

3. Technical Developments

3.1. Stored Beam

After electron cooling was demonstrated, it was natural to study it systematically, especially in the presence of heating by an internal target or RF noise. To improve the efficiency of machine operation, a number of injection schemes were developed, in particular schemes in which cooling was utilized [FRI85].

The Cooler also extended the energy range of the existing cyclotron. This was achieved by changing the orbit frequency of the bunched beam, while ramping the bending magnets at the same time. In the beginning, the higher energy was needed for meson production experiments. Later, the ability to change the energy, either up or down, proved important to relate polarization calibration standards to each other.

Throughout the life of the Cooler, accelerator physicists were using the ring as a testing ground for many studies, in particular of the departure of beam dynamics from linearity [CAU92].

3.2. Polarized Stored Beam

Polarized proton beam was injected into the Cooler at low intensity as early as March 1989. This marked the start of a program of studies of depolarizing resonances. It was also shown that forced precessions of the stored beam (‘Siberian Snakes’) are able to remove the effect of depolarizing resonances [KRI89, OHM95]. In this context,
snakes of the 3rd kind (net precession without direction change) were discovered [POL91b].

Ramping through artificial (RF induced) resonances was used to flip the polarization of stored beams [CAU94b], providing a great tool to address systematic errors in polarization measurements, and to preserve the stored beam between subsequent cycles with opposite beam polarization. A two-solenoid snake was installed to prepare longitudinal beam polarization at the location of the target.

The lifetime of polarization was measured in the vicinity of depolarizing resonances, and it was found that vector- and tensor-polarized deuterons have different polarization lifetimes [PRZ03b].

A first attempt to separate stored particles of opposite spin by the Stern-Gerlach effect was unsuccessful. This topic is still alive, and still without an experimental demonstration.

3.3. Unpolarized Internal Target Schemes

The obvious candidate for a thin, internal target is a localized volume filled with a rarefied gas. The localization was achieved by a jet from a cooled nozzle, a few mm from the beam. The jet was operated with H₂, D₂, and N₂ gas and with water vapor.

Self-supporting target foils are too thick for the available cooling force, but inhomogeneous solid targets work if a given beam particle intercepts the target only rarely. Such targets were constructed using a beam of micro-particles [MEY90] or an oscillating, thin fiber.

Skimmer targets consist of a thick piece of the target material that intercepts only the fringe of the stored beam. A graphite skimmer was used to measure proton polarization in the early studies of resonances. In this case, luminosity (and beam lifetime) are adjustable by changing the skimmer position. A positioning device and a feedback scheme were developed to stabilize the interaction rate during a measurement.

A plasma in a magnetic trap was used as a free electron target and the dynamics of electrons in the trap was used as a diagnostic tool for the stored beam [POL93b].

3.4. Beam-Target Interaction

The interplay between internal targets and the properties of the stored beam (lifetime, emittance, energy spread) was of crucial importance for any experiment, and systematically exploring the luminosity boundaries was an important task in the beginning. A systematic study of the lifetime of a stored, cooled beam in the presence of targets of varying thickness and species at various beam energies was conducted, and models were developed to explain the results [POL93]. The insight gained helped in choosing the operating parameters to optimize the time-integrated luminosity of an experiment.

3.5. Polarized Internal Targets

The limited production rate of polarized atoms motivated the idea of the storage cell. Such a cell is simply a long tube, through which the stored beam passes, with a sideways access tube in the middle into which the polarized atoms are injected. The tube is coated with a material that minimizes depolarization of the atoms when they collide with the walls. The storage cells that were developed usually also had to take into account experimental requirements (thin walls for recoil observation, little
material near the beam and remote positioning capability to reduce background) [ROS93].

The first polarized target in the Cooler was operated with optically pumped $^3$He. It was used for a single experiment and then replaced with an atomic beam source for polarized hydrogen atoms (1994), which was later upgraded (2000) to supply also vector- and tensor-polarized deuterium. This target was the workhorse for most of the Cooler research with polarized internal targets. An alternative method to produce polarized hydrogen by spin exchange with optically-pumped Rb was also tested in the Cooler.

Secondary effects that are typical of a dense polarized gas have also been observed. It was shown that polarized H atoms that recombine to H$_2$ retain some of their polarization [WIS01], and that tensor-polarized deuterium atoms lose their polarization by atom-atom-collisions.

3.6. Detector Schemes and Experimental Techniques

The specific demands of internal target experiments required the development of special detectors. A cylindrically symmetric segmented scintillator stack [RIN99] was used to cover most of the solid angle for pion total cross section measurements, and later to measure the azimuthal dependence of the cross section, needed to disentangle different polarization observables. A wire chamber was constructed that featured a hole in the center (for the stored beam to pass) suspended by nothing but the wires and thin foils [SOL89]. Low-energy recoil particles, detected by position-sensitive semiconductor detectors very close to the beam, were used to better define the signature of a reaction.

Ways to monitor the luminosity and the beam polarization had to be found, and new methods to analyze data with polarized beam and target were invented.

4. Nuclear Physics

4.1. Pion Production

The first Cooler experiment was the measurement of the $pp\rightarrow pp\pi^0$ total cross section very close to threshold. It became clear that the internal target environment was particularly well suited to this kind of task because the events of interest could be identified easily (by detecting the two protons in the final channel.), the beam energy had a narrow spread (due to cooling) and was known precisely (from the orbit frequency), and almost all of the available phase space could be covered with a modest detector in the forward direction (with the exception of the hole for the circulating beam).

The first measurement ended in 1990 with the remarkable conclusion that the $pp\rightarrow pp\pi^0$ cross section differed by about a factor of five from existing calculations [MEY92a]. This was eventually traced to the contribution to the NN interaction of the exchange of mesons heavier that the pion [HOR94]. This success inspired an extensive program to measure polarization observables for pion production in pp collisions close to threshold. In the case of $pp\rightarrow pp\pi^0$, this led to a complete map of all observables that can be measured with both protons polarized, providing enough information to pin down all contributing partial wave amplitudes [MEY01b]. Other pion production channels were studied as well, especially the reaction $pp\rightarrow pnp$ [DAE02]. A physics interpretation of these data is still in the future.
As a byproduct of the early pp → ppπ⁰ measurements, data on bremsstrahlung, pp → ppy, far from the quasi-free configuration were also obtained. In those days it was hoped that such information would lead to determination of the off-shell part of the NN interaction.

An early measurement of a total cross section for pion production in the three-nucleon system, pd → pdπ⁰ [ROH93], was interpreted in terms of a quasi-free mechanism. With the availability of polarized deuteron beams and targets, pion production in the three-nucleon system (pd → tπ⁺) was extended to include polarization observables.

Double-pion production, pd → ³Heπ⁺π⁻, was just within the energy range of the Cooler. It was hoped that the formation of the π⁺π⁻ bound state (‘pionium’) could be exploited to determine the ππ scattering length, but the cross section was not sufficiently large to reach this goal [BET96].

Pion production from medium-weight nuclei, one of the mainstays of the research with the cyclotron in the seventies, was revived at the Cooler with a measurement of π and 2π production in p+¹²C by observing the recoil ¹³N nuclei.

The last Cooler experiment was a search for the reaction dd → απ⁰. A non-vanishing cross section was indeed observed (see fig. 3), resulting in quantitative information on the breaking of charge symmetry [STE03].

4.2. Nucleon-Nucleon Scattering

An important task in the early days of the Cooler was to provide a standard in the form of a precise pp analyzing power within the energy range of the Cooler in order to calibrate the stored beam polarization. This standard was exported by energy ramping. An early measurement of pp scattering in the Coulomb-nuclear interference region was sensitive enough to reveal the interaction between the magnetic moments of the protons.

When a polarized internal H target became available, the potential of internal target experiments was clearly demonstrated by a very precise, complete map of pp analyzing powers and spin correlation observables from 200 to 450 MeV [RAT98, PRZ98]. The data set also included observables that required longitudinal beam polarization and hence a Siberian Snake [LOR00]. The quality and quantity of the data was such as to significantly affect the then-current phase shift analyses of the pp interaction.

A re-measurement of a disputed cross section experiment in np scattering was carried out by using the Cooler to produce a tagged neutron beam. To this effect a stored proton beam interacted with a D₂ gas jet target. The two protons from the pd → pππ breakup were observed with position-sensitive solid-state detectors close to the target, and the kinematic parameters of the remaining neutron were determined on an event-by-event basis. The result of this experiment had a bearing on the πN coupling constant [SAR05].

4.3. Three-Nucleon System

With ³He as the first polarized target in the Cooler, it was possible to use the quasi-free knockout of neutrons or protons by polarized protons to study the spin-dependent single-particle wave functions of ³He [MIL95].

In March 2000 the polarized atomic beam source was upgraded to supply a vector- or tensor-polarized deuterium target, and in early 2001, the polarized ion source
(CIPIOS) was developed to deliver a polarized deuteron beam to the Cooler. Having the choice of either polarized protons or polarized deuterons for either the beam or the target provided a unique opportunity to study polarization observables in the three-nucleon system, leading to measured angular distributions for the proton analyzing power, four target analyzing powers, five vector correlation coefficients and seven tensor correlation coefficients in pd scattering at 135 and 200 MeV proton bombarding energy [PRZ04].

The data were compared with Faddeev calculations that exactly predict (for a given NN potential) any scattering or breakup observables. Given the premise that these calculations describe how nature would behave without a three-nucleon force (3NF), discrepancies with the data must be due to the 3NF. However, including (various versions of) a three-nucleon force in the calculation does not lead to an overall improvement with the data (see fig.2). This leads to the conclusion that either the theoretically constructed
Fig. 2: Difference between analyzing power and spin correlation data and an NN Faddeev calculation (the calculation corresponds to the zero line. The reference calculation is based on the CDBonn potential and has been carried out by the Bochum group [WIT01]. The lines show the effect of including a three-nucleon potential in the calculation. The solid and dashed lines correspond to the Tucson-Melbourne TM and TM' three-nucleon potentials, and the dotted line is a calculation with the AV18 3N potential. None of them reproduces the data.
3N potentials are not realistic, or that the difference between the data and the 2N calculation is not really dominated by 3NF effects. Thus, there was no experimental evidence for a 3NF.

A measurement of the breakup reaction $dp \rightarrow ppn$ focused on so-called axial polarization observables that are zero by parity conservation in reactions with a two-body final state [MEY04]. There was some promise that such observables are more sensitive to 3NF effects, however, the conclusion was the same as with the elastic scattering data. A novel method to adapt the calculations to reflect the exact phase space coverage of the experiment was developed for this experiment.

4.4. Other Physics Topics

In the early days, dielectronic recombination, a subject of atomic physics, was studied by storing ions in the ring and using the electrons in the cooling beam as a target [TAN91].

A measurement of the analyzing power of $p^{+12}C$ in the Coulomb-nuclear interference region, using a thin fiber target, provided a test for the use of this process to monitor the proton polarization in RHIC collider.

5. IUCF Today

In the two-and-a half years since the shutdown of the Cooler IUCF has been transformed drastically. Where the Cooler has once been, there is now a facility for radiation testing of electronic components (RERP), and a low-energy neutron source (LENS) for condensed-matter related research. The cyclotron beam is mainly used to supply beam to the new major mid-western proton radiation therapy facility (MPRI). More about today’s IUCF can be learned by visiting “http://www.iucf.indiana.edu”.

![Fig.3: Missing-mass spectra from the reaction $dd \rightarrow X$ at two bombarding energies. The peak corresponds to the charge symmetry violating $dd \rightarrow \alpha \pi^0$ reaction [STE03].](image-url)
6. References

There are about 120 publications in refereed journals directly related to research with the Cooler. Because of space constraints, I only list a few selected publications. A full account will be given in a planned future paper on the saga of the IUCF Cooler.

Physics at (Existing) Storage Rings with Hadronic Probes
CELSIUS experiments

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Since 1989 the CELSIUS accelerator and storage ring at the The Svedberg Laboratory in Uppsala has been used for hadron physics research in the GeV region. The programme includes production and decay of $\pi$ and $\eta$ mesons in light ion collisions. Heavier ion experiments are performed for studies of multifragmentation and particle correlations. Another study concerns deeply bound pionic states in Xenon.

The CELSIUS Ring

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</tr>
<tr>
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<tr>
<td>Maximum rigidity</td>
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</tr>
<tr>
<td>Protons max kinetic energy</td>
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</tr>
<tr>
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</tr>
<tr>
<td>Ions d He N O Ne Si Ar</td>
<td></td>
</tr>
<tr>
<td>max kinetic energy per nucleon for QA&gt;3/4 ions</td>
<td>500 MeV</td>
</tr>
<tr>
<td># stored particles</td>
<td>$1 \times 10^{10}$ – $5 \times 10^{9}$</td>
</tr>
</tbody>
</table>

Figure 1: The CELSIUS cooler and storage ring with cluster-jet and pellet target stations.

CELSIUS

After a recent upgrade, the CELSIUS ring provides protons of kinetic energies up to 1450 MeV and light ions ($A < 20$) of energies up to 510 MeV/nucleon. Some main parameters are given in Fig. 1. By electron cooling a beam size of around 1 mm and a relative momentum spread down to the $10^{-5}$ region is obtained. Protons
of energies up to 500 MeV and light ions up to the maximum energy can be cooled. Experiments are performed at two internal-target stations, one providing a cluster-jet and the other a stream of frozen hydrogen pellets.

**CELSIUS 1988-2005**

<table>
<thead>
<tr>
<th>Experiment Type</th>
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<th>Beam Time</th>
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</thead>
<tbody>
<tr>
<td>Experiments @ cluster-jet</td>
<td>June 89 - April 05</td>
<td>312 h</td>
</tr>
<tr>
<td>Experiments @ pellet-target</td>
<td>November 99 - June 05</td>
<td>312 h</td>
</tr>
</tbody>
</table>

Total beamtime: 272 hours

Beam to exp.s: 202 hours

![CELSIUS beam time statistics](image)

Figure 2: Some statistics on CELSIUS running.

The Spring 2005 is the last semester of operation for CELSIUS and the last run takes place in June. CELSIUS has then, with high reliability, provided the experiments with beam for about 20,000 hours (Fig.2). About 7000 hours has been used for beam development (BD).

**Experiments at the cluster-jet target**

The cluster-jet station provides different nuclear targets from hydrogen and helium up to xenon with thicknesses from $10^{14}$ atoms/cm$^2$ for hydrogen down to $10^{13}$ atoms/cm$^2$ for the heaviest elements. Over the years, many experiments have been performed at the cluster-jet. In Fig.3 some experiments with heavier nuclei are listed. In the same way Fig.4 shows experiments using hydrogen nuclei, both as projectiles and as targets. More details on the different experiments can be found via the TSL www home page [1].

During the last years, the main experimental activity at the cluster-jet has been aiming at detailed studies of multifragmentation in heavy ion collisions using the CHICSi internal detector setup [2] based on 500 silicon detectors and $Gd_2SiO_5$ scintillation crystals. CHICSi is a compact, large solid angle, barrel-shaped detector system, with rotational symmetry around the beam axis, for measurements of...
Heavy ion experiments at the Cluster-jet target

charged particles and fragments from nuclear reactions with detection thresholds down to 0.7 MeV/nucleon. For recent results see the contribution by Bo Jakobsson to this conference.

Fragmentation of beam Si nuclei hitting H and D targets are conducted to measure cross sections relevant for the understanding of Single Event Effect (SEE) problems in microelectronics. Experimental data in the energy range of 100-300 MeV/nucleon are compared with theoretical calculations. Results from this experiment are reported by Yuri Murin at this conference.

Other experiments at the cluster-jet use the accelerator bending magnets to filter out, from the circulating beam, low energy particles scattered at zero degree (ZD). One experiment concerns studies of the deeply bound pionic $1s$ state in xenon in the $Xe(d,^3He)Xe(e-e\text{-bound})$ reaction. An electron cooled deuteron beam with an energy of 499.8 MeV and a momentum resolution $\Delta p/p \approx 4 \times 10^{-4}$ was used. The outgoing $^3He$ was measured by a telescope comprising four germanium detectors. The energy resolution of the telescope for $360\,\text{MeV}$ $^3He$ ions was estimated to be approximately 900 keV. The energy calibration of the experiment was done by means of the $^1H(d,^3He)^e\pi^0$ reaction with the same beam.

A signal consistent with the production of the deeply bound pionic $1s$ state was observed in a first run on natural Xenon [3]. The experiment has then been repeated on isotope pure $^{136}Xe$, where the signal should be more clear. The measured $^3He$
Figure 4: CESLIUS experiments using hydrogen nuclei as projectile and target.

kinetic energy spectrum is shown in Fig.5. The data from the $^{136}\text{Xe}(d,^3\text{He})X$ reaction in the lower part of the figure corresponds to a measuring time of 75 h. The wider peak at approximately 367 MeV corresponds to the $^1\text{H}(d,^3\text{He})^0$ reaction on a small admixture of hydrogen from the pumping system. The narrow peak at approximately 363 MeV corresponds to the production of the deeply bound pionic 1s state in the $^{136}\text{Xe}(d,^3\text{He})^{135}\text{Xe}$ reaction. The total number of events in the peak is in agreement with a cross section of 40 $\mu$b/sr [4]. However, the binding energy deduced for the pionic 1s state, $B=2.9(5)$ MeV assuming a nuclear excitation energy of 0.29 MeV, is lower than theoretically predicted, $B=4.17$ MeV [4].

In a series of experiments studying the two nucleon halo state of the A=6 system. The $^0$ ground state of $^6\text{He}$ and its isobaric analogue state at 3.56 MeV in $^6\text{Li}$ was populated in the pionic fusion reactions $^4\text{He}(d,^6\text{He})\pi^+$, $d(^4\text{He},^6\text{Li}^*)\pi^0$ and $^3\text{He}(^1\text{He},^6\text{Li}^*)\pi^+$. The data on the first two reactions at centre of mass energies between 0.6 and 4.9 MeV above threshold are now analysed. The differential cross section is strongly anisotropic, the pion being emitted preferentially in the direction of the heavy particle in the initial state. These results provide a test of models for the halo state in particular of the wave function describing the motion of the two nucleon halo relative to the alfa-particle like core.

The light ion experiments at the cluster-jet target has been dominated by studies of $\pi$, $2\pi$ and $\eta$ production in different reactions (Fig.4). The WASA/PROMICE collaboration used a subset of the WASA detector and measured among other things the excitation functions for $\eta$ production in pp and pn reactions (Fig.6) [5].
Figure 5: Kinetic energy spectrum of $^3$He ions from the reactions $^1H(d,^3He)\pi^0$ (upper) and $^{136}Xe(d,^3He)X$ (lower).

Experiments at the pellet target

From 1999 the uniquely developed pellet-target system [6] that provides small spheres of frozen hydrogen as internal targets has been used routinely for the CELSIUS/WASA experiments [7]. About one third of the total beam time for experiments has been devoted to experiments at the pellet-target.

The experiments concern detailed studies of production and decays of light mesons. The mesons are produced in p-p, p-d and d-d interactions. An intense beam of pellets is produced a few meters above the CELSIUS beam. The pellets are then guided to the interaction region in a thin pipe (Fig.7). This arrangement allows high luminosity and high detection coverage for meson decay products like $\gamma$s, electrons and charged $\pi$s. The target system is operating close to the design performance with $H_2$ and $D_2$ pellets with a diameter of about 25 $\mu$m, a speed of about 80 m/s and occurring at a rate of 5-10 k/s.

The WASA 4$\pi$ detector facility [8] includes a forward part for measurements of charged target-recoil particles and scattered projectiles, and a central part designed for measurement of the meson decay products. The forward part consists of eleven planes of plastic scintillators and of proportional counter drift tubes. The central part consists of a cylindrical drift chamber and a barrel of plastic scintillators, placed inside of a superconducting solenoid and of an electromagnetic calorimeter of CsI(Na) crystals (Fig.7).

Initially, production of $\eta$, $\pi$, $2\pi$ and $3\pi$ in pp collisions were measured. Also the $\eta$ decay into $3\pi^0$ was measured. Since February 2004, $D_2$ pellets are available and the experiment has been developed for studies of $\eta$ charged-particle decays. $D_2$ pellets as targets allow very clean tagging of $\eta$s for decay studies, by the $pd \rightarrow ^3He\eta$ reaction at threshold.

Data for studies of meson production in pd, dd and in quasi-free pn reactions have now been collected. Recent results on $pd \rightarrow ^3He\pi^+\pi^-$ and $pd \rightarrow ^3He\pi^0\pi^0$ are reported by Mikhail Bashkanov at this conference. Other studies in progress concern $\omega$ and $\eta\pi$ production in pd collisions, $2\pi$ production in dd collisions and a search
for a $\Theta^+$ signal from the reaction $pd \rightarrow p\Lambda\Theta^+$.

**Summary and outlook**

At CELSIUS several developments have been done to exploit high quality stored (cooled) ion beams in internal target experiments. High acceptance detector systems for zero degree detection close to the kinematic threshold has been used extensively. An internal close to 4$\pi$ detector with high sensitivity to slow particles has been developed by the CHIC collaboration. The external 4$\pi$ detector system WASA based on the new pellet target concept has been built and used by the CELSIUS/WASA collaboration.

From the last years of running, many more results are anticipated e.g. on heavy-ion reactions with Si and Ne beams and on different meson production reactions in pd and dd collisions.

After the close-down of CELSIUS some experimental equipment will be used at other laboratories and/or for other applications. Discussions are going on, but it is quite clear that WASA with the pellet system will be moved to FZ Jülich for future experiments at COSY. The cluster-jet will go to GSI Darmstadt and the electron cooler will be used for tests in connection with developments for high energy electron cooling, in particular for the future HESR at GSI.
Figure 7: Left: The pellet-target system with the pellet generator on the top and the pellet dump at the bottom. The pellet pipe diameter is about 5 mm at the scattering chamber. Right: The central part of WASA during assembly. The pellet pipe crosses the cryostat for the superconducting solenoid. Some CsI crystals in one of the calorimeter halves are visible behind.

References


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Introduction

This talk presents selected recent results achieved in the field of hadron physics at COSY, and an outlook on the future physics program at the WASA detector which is being relocated from the CELSIUS ring in Uppsala to COSY in Jülich. The presented experimental results are chosen such that the content of the talk is complementary to the other talks given at this conference on COSY experiments. In the field of hadron physics three internal installations, namely ANKE, COSY-11, and TRIC, are currently operative (EDDA has completed data taking), as well as two external setups, namely COSY-TOF and Big Karl (with the extensions GEM, MOMO and HIRES). As additional new internal detector the WASA setup will be installed, which will add large acceptance photon detection capability to the instrumental equipment at COSY. In the intermediate future, the experimental activity will concentrate on the large installations WASA, ANKE and COSY-TOF. With the particular weight on studies of fundamental questions in hadron and particle physics involving final states with neutral particles at WASA, the rich physics program at COSY opens a perspective into the next decade.

Exotic states with strangeness

Studies of the $\theta^+$ pentaquark at COSY-TOF

According to the quark model hadrons exist either as $qqq$ baryons or as $q\bar{q}$ mesons. All other color-neutral states like e.g. $qq\bar{q}$ (“tetraquarks”), $qqqq\bar{q}$ (“pentaquarks”), or states with constituent gluonic components are usually called exotic, but they are not excluded by QCD. Soliton models [1] predicted the existence of an anti-decuplet family of $q\bar{q}q$ states the three “corners” of which are manifestly exotic ($uudds \equiv \theta^+$, $ddssu \equiv \Xi_c^+$, and $uussd \equiv \Xi_b^+$) since their $S$ or combination of $S$ and $Q$ quantum numbers can not be carried by normal baryons. The predicted masses of the anti-decuplet members were obtained based on the assignment of the $N^*(1710)$ to the non-strange isospin doublet within the anti-decuplet, in particular the $\theta^+$ mass was predicted to be 1530 MeV/$c^2$, its width to be as narrow as 15 MeV/$c^2$. Its production in the $pp \to \Sigma^+\theta^+$ reaction was studied theoretically [2] and a production cross section $\sigma \approx 80$ nb obtained.

As large acceptance geometrical spectrometer with excellent tracking capability, in particular close to the interaction point, COSY-TOF [3] is ideally suited to study strangeness production, detecting displaced $\Lambda \to p\pi^-$ or $K_\Lambda \to \pi^+\pi^-$ decay vertices,
Figure 1: (Left) Efficiency corrected invariant mass spectrum of the $pK^0$ subsystem in the reaction $pp \rightarrow pK^0\Sigma^+$ from Ref. [6]. (Right) $pK^+$ missing mass spectrum of a subsample of the new data showing a background-free $\Lambda$ peak.

or $\Sigma^+ \rightarrow n\pi^+/\pi^0$ decay kinks. Within the hyperon production studies at COSY-TOF [4, 5] the reaction $pp \rightarrow \Sigma^+pK^0$ was measured at incident beam momentum $p_p = 2.95$ GeV/c. A narrow peak was seen in the invariant $pK_\Sigma$ subsystem at $M = 1530 \pm 5$ MeV/c$^2$ at a width below 22 MeV/c$^2$, which was attributed to the $\theta^+$ pentaquark [6] (see Figure 1 (left)). Evidence for the $\theta^+$ was first observed by the LEPS collaboration [7], and confirmed by other experiments, however a number of experiments did not see a signal. For a recent overview see Ref. [8].

In order to clarify the question of existence or non-existence of the $\theta^+$ pentaquark recently another beamtime was carried out with an improved experimental setup and a factor $>5$ more statistics at slightly higher beam momentum $p_p = 3.05$ GeV/c. Figure 1 (right) shows the $pK^+$ missing mass spectrum of a subsample of this dataset allowing a background-free identification of $\Lambda$’s in the $pp \rightarrow pK^+\Lambda$ reaction. The analysis of these data is currently in progress. If the existence of the $\theta^+$ is confirmed, studies of the doubly polarized $p\bar{p} \rightarrow \theta^+\Sigma^+$ reaction are planned, using a modified setup with a frozen spin target. This opens the possibility to determine the parity of the $\theta^+$ in a model-independent way [9].

Evidence for a neutral hyperon resonance $Y^*(1480)$ at ANKE

The ANKE spectrometer [10] consists of three dipole magnets which are operated as chicanes for the circulating COSY beam. The central dipole placed downstream of the target separates positively and negatively charged reaction products from the beam. As target for $pp$ collisions a hydrogen cluster jet target is used. The ANKE detection system [19] consisting of scintillation detectors, multiwire proportional chambers, and range telescopes (on the positive particle side) allows to identify particles with either sign charge, and to determine their momenta. In particular, it is well suited to identify $K^+$ mesons.

The production of excited hyperons was studied [12] in the reaction $pp \rightarrow pK^+Y^{0\pi}$ at incident proton momentum $p_p = 3.65$ GeV/c where the kinematic limit corresponds to $M_{Y^{0\pi}} = 1540$ MeV/c$^2$. In the $pK^+$ missing mass spectrum peaks are observed above a continuum which are due to the known hyperon states $\Lambda(1116)$, $\Sigma^0(1192)$, and $\Lambda(1405)$ together with $\Sigma^0(1385)$. In addition a peak-like structure is
Figure 2: (Left) Missing mass of $pK^+\pi^+$ (upper) and $pK^+\pi^-$ (lower) versus missing mass of $pK^+$ in the reaction $pp \rightarrow pK^+\pi^+X^\mp$. (Right) $pK^+$ missing mass spectrum with $\Sigma^-$ mass cut on the $pK^+\pi^+$ missing mass: a) experimental data points together with full Monte Carlo simulation of all known reaction channels (see b)) plus $Y(1480)$ contribution (shaded histogram); b) decomposition of the simulated spectrum into contributions from the known reaction channels, i.e. $\Sigma(1385)$ (dotted), $\Lambda(1405)$ (dashed), $\Lambda(1520)$ (dash-dotted), and non-resonant phase space production (solid), as well as the $Y^*(1480)$ (shaded histogram); c) difference of measured spectrum and fitted sum of the contributions from the known channels without the $Y(1480)$ contribution. From Ref. [12].

seen at a mass of $\sim 1480$ MeV/c$^2$. The signal of hyperon resonance states relative to non-resonant and instrumental background was further enhanced by requiring a charged pion in the final state, which is emitted in the decay $Y^{\pm}\rightarrow \pi^\pm\Sigma^\mp$. In Figure 2 (left) two-dimensional spectra of $pK^+\pi^+$ missing mass and $pK^+\pi^-$ missing mass versus $pK^+\pi^-$ missing mass are shown for the reaction $pp \rightarrow pK^+Y^{\pm}\rightarrow pK^+\pi^\pm X^\mp$. In the $pK^+\pi^+$ missing mass the $\Sigma^-$ (1197) is clearly seen whereas the $pK^+\pi^-$ missing mass spectrum is dominated by protons from the $pp \rightarrow pK^+\pi^+p$ reaction. Apart from this, a continuum background of e.g. $\pi^0p$, $\pi^0\eta p$, and $\pi^+n$ obscures the $\Sigma^+(1189)$ band in the $pK^+\pi^-$ missing mass spectrum. The $pK^+$ missing mass spectra for both $\pi X$ charge state combinations are analysed for cuts on the $\Sigma$ mass bands in the respective $pK^+\pi^\pm$ missing mass. Figure 2 (right) shows the obtained result for the $\Sigma^-$ band in the $pK^+\pi^+$ missing mass, in comparison to a Monte Carlo simulation which takes into account all final states populated in the reactions $pp \rightarrow pK^+\Sigma^0(1385)$, $pp \rightarrow pK^+\Lambda(1405)$, and $pp \rightarrow pK^+\Lambda(1520)$, as well as a continuum background. As Figure 2 (right) demonstrates, the measured spectrum is not described by a combination of the contributions listed, but additional strength centred at 1480 MeV/c$^2$ is observed. This observation is in agreement with the $pK^+$ missing mass spectrum (not shown here, see Ref. [12] for more details) observed in a $pK^+\pi^-X^+$ final state with a mass cut on $\Sigma^+$ for $X^+$, where the enhancement at 1480 MeV/c$^2$ is also seen. Based on this observation, Ref. [12]
suggests that an excited hyperon is produced with $M(Y^0) = (1480 \pm 15) \text{ MeV}/c^2$ and $\Gamma(Y^0) = (60 \pm 15) \text{ MeV}/c^2$.

In the PDG compilation [3] a $\Sigma(1480)$ state is listed with a one-star rating and described as a “bump” with unknown quantum numbers. Based on the ANKE data the assignment to either a $\Lambda$ or a $\Sigma$ excitation is not possible. This would require further studies such as the search for its charged isospin partners (only existing in case of $\Sigma$), for its $\Sigma^0\pi^0$ decay branch (non-existing in case of $\Sigma$), and the determination of its $\Lambda\pi/\Sigma\pi$ decay ratio ($= 0$ in case of $\Lambda$). The WASA detector reassembled at COSY (see below) will allow to investigate the final states with neutral particles populated in these decays.

Within the quark model it is difficult to accomodate an additional 3-quark hyperon state at masses below $1600 \text{ MeV}/c^2$ [14, 15]. However more information needs to be collected before solid conclusions can be drawn on the exotic nature of the $Y^*(1480)$ state.

High resolution studies at Big Karl

The high resolution spectrometer Big Karl [16] consists of a 3Q2DQ magnetic spectrograph and a focal plane detector arrangement with multiwire driftchambers and scintillator hodoscopes. The magnetic spectrometer acceptance is $\approx 10 \text{ mrad}$, its resolution $p/p < 5 \times 10^{-5}$. The spectrometer can be extended by different detector systems close to the target region which are however not used in the experiments presented here.

Precision determination of the $\eta$ mass

Recently the two-body reactions $p + d \rightarrow t + \pi^+$ and $p + d \rightarrow ^3\text{He} + \eta$ were measured simultaneously, where the particles underlined were detected at the Big Karl focal plane [17]. The incident proton beam momentum $p_p = 1640 \text{ MeV}/c$ was chosen such that these particles have almost identical magnetic rigidity $p/q$ at $\theta = 0^\circ$ in the laboratory frame, and hit the focal plane within a small region. Note that $t$ and $\pi^+$ are emitted as pair in the same reaction. This allows to calibrate simultaneously the incident proton beam momentum and magnetic rigidity of the Big Karl spectrometer. As a result, the $\eta$ mass could be measured with unprecedented accuracy to be $m_\eta = (547.311 \pm 0.028 \text{(stat)} \pm 0.032 \text{(syst)}) \text{ MeV}/c^2$ [17]. Figure 3 (left) shows the history of the $\eta$ mass determination. The new value found at Big Karl [17] is in agreement with much less accurate measurements of 1995 and earlier, but in clear disagreement with the measurement of the NA48 collaboration which found $m_\eta = (547.843 \pm 0.051) \text{ MeV}/c^2$ [18]. The latter result led to a “jump” in the value for $m_\eta$ in the PDG listing of particle properties [3].

Study of the $pn$ interaction close to threshold

Close to threshold, the interaction of the $pn$ system in the spin triplet state is governed by the deuteron bound state at an energy $-B_d = e_t = -2.22 \text{ MeV}$ resulting in a strong $S$-wave final state interaction. In the spin singlet state, theoretical
analyses of the \(pn\) interaction [20] find a slightly unbound state at \(\epsilon_t = 0.07\) MeV. Experimentally, it is however difficult to see the contribution of the spin singlet state in the \(pn\) final state interaction, since the separation of the \(pn\) continuum from the \(d\) bound state requires very good energy resolution. This goal was achieved in a recent measurement of the \(pp \rightarrow \pi^+X\) reaction at Big Karl at a proton beam momentum \(p_p = 1640\) MeV/c [19], as shown in Figure 3 (right). Using final state scattering theory an analytical expression for the energy dependent strength of \(S\)-wave scattering states related to the strength of the bound state can be derived for the spin triplet state [21, 22]. A corresponding analytical expression is expected for the \(pn\) spin singlet state, where the binding energy \(B_d\) of the \(d\) bound state is replaced by the energy of the virtual state \(\epsilon_s\). Its close vicinity to the \(pn\) continuum limit results in a sharp spike at threshold. Such a signal is however not observed resulting in an upper limit for the ratio of spin singlet to triplet contribution \(\xi < 10^{-4}\) [19].

The physics program for WASA-at-COSY

The relocation of the WASA detector from CELSIUS to COSY opens new perspectives in a twofold way: it combines the capability of large acceptance photon detection of WASA with the higher beam energies at COSY. This allows to use the detection capabilities of WASA also in \(\eta'\) and strangeness production beyond the \(\phi\) meson threshold, not accessible in \(pp\) collisions at CELSIUS. A lay-out of the WASA detector setup is shown in Figure 4. A detailed description of the detector is given in Ref. [23], an overview is found in these proceedings [24].

A comprehensive physics program is envisaged for the WASA detector at COSY [25] focussing on the studies of fundamental symmetries. While isospin violation will also be studied in the \(\bar{d}d \rightarrow \alpha\pi^0\) reaction and in the mixing of the scalar mesons \(a_0/f_0(980)\), in this contribution only some aspects of \(\eta\) and \(\eta'\) decays will be discussed.
Isospin violation: $\pi - \eta$ mixing in hadronic $\eta'$ decays

Two sources are responsible for charge symmetry breaking (CSB): the different electromagnetic energies due to the different charge of $u$ and $d$ quarks, and their mass difference $\Delta m = m_d - m_u$ (for a review see Ref. [26]). Whereas the electromagnetic contribution can be calculated to fair accuracy, the quark mass difference is more difficult to be determined from experimental observables. A particularly clean approach is provided by the measurement of isospin violating $\eta'$ decays.

The physical $|\pi^0\rangle$ and $|\eta\rangle$ states are not pure isospin eigenstates but are realized as mixed states of the isospin eigenstates $|\tilde{\pi}^0\rangle$ and $|\tilde{\eta}\rangle$ [27]:

$$\begin{pmatrix} \pi^0 \\ \eta \end{pmatrix} = \begin{pmatrix} \cos \theta_{\pi\eta} & \sin \theta_{\pi\eta} \\ -\sin \theta_{\pi\eta} & \cos \theta_{\pi\eta} \end{pmatrix} \begin{pmatrix} \tilde{\pi}^0 \\ \tilde{\eta} \end{pmatrix},$$

where the mixing angle is related to the quark masses as

$$\sin \theta_{\pi\eta} = \sqrt{3} \frac{(m_d - m_u)}{4(m_u + m_d)}; \quad \bar{m} = (m_u + m_d)/2.$$ 

The mixing angle can be directly deduced from the ratio of isospin forbidden $\eta' \to 3\pi$ decays to the isospin allowed $\eta' \to \eta 2\pi$ modes:

$$R_1 = \frac{\eta' \to \pi^0\pi^0\pi^0}{\eta' \to \eta\pi^0\pi^0}; \quad R_2 = \frac{\eta' \to \pi^0\pi^+\pi^-}{\eta' \to \eta\pi^+\pi^-},$$

with $R_1 = P_1 \sin^2 \theta_{\pi\eta}$ with the corresponding phase space ratio $P_1$. Only an upper limit is known for $R_2$, while a measurement of $R_1$ resulted in $\sin \theta_{\pi\eta} = 0.023 \pm 0.002$ [28]. There is however considerable uncertainty in the literature concerning $\sin \theta_{\pi\eta}$ deduced in different approaches with values ranging from 0.010 to 0.047.

WASA-at-COSY operated at the foreseen luminosity $10^{32} \text{cm}^{-2}\text{s}^{-1}$ will allow to determine $\sin \theta_{\pi\eta}$ to a statistical accuracy of 1% within a 10-12 weeks beamtime.

QCD anomalies: the box anomaly and $\eta/\eta' \to \pi^+\pi^-\gamma$

Non-resonant contributions in $\eta/\eta' \to \pi^+\pi^-\gamma$ are sensitive to the AAAV (A $\equiv$ axial vector, V $\equiv$ vector) box-anomaly of QCD [29, 30], however with much higher...
sensitivity in the $\eta'$ decays. The experimental task is to measure the $\pi^+\pi^-$ mass distribution in this decay to high accuracy, in order to separate the continuum from the $\rho$ meson contribution. Box anomaly parameters have been determined to the best statistical accuracy so far by Crystal Barrel [31] and L3 [32], however with resulting values inconsistent to each other. WASA-at-COSY will outnumber the statistics of the presently available world data on this decay mode by two orders of magnitude in two weeks.

**CP violation beyond the Standard Model:** $\eta \to \pi^+\pi^-e^+e^-$

Within the Standard Model the source of CP violation is a single phase in the CKM mixing matrix determining flavor changing weak couplings. Experimentally, CP violation has only been seen in neutral $K$ and $B$ decays. Violation of CP invariance in flavor conserving processes would point to sources beyond the Standard Model. NA48 has recently reported [33] on the observation of a CP violating asymmetry in $\sin \varphi \cos \varphi$ in $K_L \to \pi^+\pi^-e^+e^-$ decays, where $\varphi$ is the angle between the $\pi^+\pi^-$ and $e^+e^-$ planes in the $K_L$ rest frame. In analogy to the flavor changing $K_L$ decay, one could also search for CP violation in the corresponding flavor conserving decay $\eta \to \pi^+\pi^-e^+e^-$. Flavor conserving CP violating four-fermion operators involving two $s$-quarks have been theoretically studied in Refs. [34, 35], resulting in predicted asymmetries as large as 2%.

The presently published world data on the $\eta \to \pi^+\pi^-e^+e^-$ decay branch is 5 events, while CELSIUS/WASA has an indication for $\sim 25 \eta \to \pi^+\pi^-e^+e^-$ candidates at a preliminary stage of the data analysis [24]. With WASA-at-COSY, at $L = 10^{32}$ cm$^{-2}$s$^{-1}$, this world statistics will be outnumbered by large factors even in one day, with an expected rate of 7000/d for this decay mode.

**Summary**

In this contribution only a small selection of recent activities in hadron physics obtained at COSY could be presented. This encompassed strangeness production at COSY-TOF and ANKE, including studies of the $\theta^+$ pentaquark at COSY-TOF, and of hyperon resonances at ANKE with an evidence for a neutral $Y^*(1480)$ resonance, as well as high resolution measurements of the $\eta$ mass and of the $pn$ interaction close to threshold at Big Karl. Furtheron, an outlook was given on the physics program with WASA-at-COSY, where in particular tests of fundamental symmetries in $\eta$ and $\eta'$ decays were discussed.

**References**


Physics at (Existing) Storage Rings with Hadronic Probes


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Spin Physics Inside the COSY Ring

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Introduction

It is the aim of the ANKE collaboration to carry out a well directed programme [1] of internationally competitive experiments involving polarised beams and targets, by fully exploiting the potential of the outstanding COSY facility. These activities, at the same time, are good preparation for our participation in the PAX@FAIR project [2]. This contribution will present a short description of the apparatus that can be used for this purpose and outline some of the principal experiments that will be undertaken within the scope of this collaboration. A survey is made of the current experimental np spin physics programme with especial emphasis on the recent results from the ANKE facility with the polarised beams.

Experimental Facilities

COSY – COoler SYnchrotron and storage ring [3] accelerates and stores unpolarised and polarised protons and deuterons in a momentum range between 0.3 GeV/c and 3.7 GeV/c. To provide high quality beams, there is an Electron Cooler at injection and a Stochastic Cooling System from 1.5 GeV/c up to the maximum momentum. Transversally polarised beams of protons are available with intensities up to $1 \times 10^{10}$ (with multiple injection and electron cooling and stacking) and polarisations of more than 80%. For deuterons an intensity of about $3 \times 10^{10}$ was achieved in the February 2005 run with vector and tensor polarisations of more than 70% and 50% respectively.

Fast particles can be measured in the ANKE magnetic spectrometer [4] installed at an internal beam position of COSY. Detection systems for both positively and negatively charged particles include plastic scintillator counters for TOF measurements, multi-wire proportional chambers for tracking, and range telescopes for particle identification. A combination of scintillation and Čerenkov counters, together with wire chambers, allow one to identify negatively charged pions and kaons. The forward detector, comprising scintillator hodoscopes, Čerenkov counters, and fast proportional chambers, is used to measure particles with high momenta, close to that of the circulating COSY beam. There is also a detector that can be used as a spectrometer for backward-emitted particles.

Although strip and cluster-jet targets have been standard for use at ANKE, we are currently in the process of installing a polarised internal target (PIT) system [5],
consisting of an atomic beam source, feeding a storage cell, and a Lamb–shift polarimeter. The cell, which will increase tremendously the available luminosity, was tested in February 2005 and the whole apparatus will be ready for commissioning experiments in early 2006. The design is such that the target and polarimeter can be moved in and out of the beam position, depending upon the requirements of the experiment.

One of the major advantages of doing experiments at a storage ring is that very low energy particles emanating from the very thin targets can be detected in silicon tracking telescopes placed in the target chamber [6]. These are used to help in the measurement of elastic scattering, which is vital for luminosity and polarisation calibrations and, for a long target, establishing the vertex position. However, their most exciting use is for measuring the angles and energies of low energy protons (< 10 MeV) that emerge as so-called spectators from the interactions of beam protons with the neutrons in the deuterium target. This information allows one to determine the proton–neutron centre–of–mass energy with high accuracy and will permit the study of a whole range of \( pn \) elastic and inelastic reactions. The development of very thick (5–20 mm) double–sided micro–structured Si(Li) and very thin (69 \( \mu \)m) double–sided Si detectors provides a very flexible system for the use of the telescopes in particle identification and angle and energy measurement which, in the case of protons, will be from about 2.5 MeV up to 40 MeV. Each spectator detector can have typically a 10% geometrical acceptance with respect to a point target and, depending upon the needs of an individual experiment, up to four or six telescopes could be employed.

Although some information on the beam polarisation is available from the source, the standard methodology for determining it will be through the comparison with several reactions with known analysing powers that can be measured simultaneously in ANKE. For example, in the interaction of polarised deuterons with a hydrogen target, the vector and tensor polarisations could each be determined in three different ways at 1.2 GeV [7]. At energies where the calibration reactions are unavailable, it is possible to use the polarisation export technique where, say, the deuteron beam polarisation is measured at 1.2 GeV, the energy is ramped to the region of interest for the physics measurement, before being reduced again to 1.2 GeV, where the beam polarisation is remeasured to check that any depolarisation is unimportant. We have shown [1] that this method works very well for both proton and deuteron beams. The polarisation of the target cell will also be checked through known standards, some of which we ourselves will establish with the polarised beams.

Physics Programme

Although, with the equipment available, many reactions will necessarily be detected simultaneously, we here describe only a few of the most important ones for which there is minimal ambiguity in the interpretation. A more complete compilation, listing our order of priorities, will be found in the document [1].
Proton–Neutron Spin Physics

The nucleon–nucleon interaction is fundamental to the whole of nuclear physics and hence to the composition of matter as we know it. Apart from its intrinsic importance, it is also a necessary ingredient in the description of meson production and other processes. The meticulous investigation of the nucleon–nucleon interaction must be a communal activity across laboratories, with no single facility providing the final breakthrough. However, the mass of EDDA–COSY data on \( pp \) scattering has reduced significantly the ambiguities in the \( I = 1 \) phase shifts up to 2.1 GeV [8]. Nevertheless, the lack of good neutron–proton spin–dependent data make the \( I = 0 \) phase shifts very uncertain above 800 MeV and there are even major holes in the knowledge between 515 and 800 MeV. We propose to add significantly to the elastic scattering data set by making measurements of cross sections, analysing powers, and spin–correlation coefficients near both the forward and backward directions by using the deuteron as a source of quasi–free neutrons. This substitute target has been shown at other laboratories to work well, though some theoretical input is necessary to extract the \( pn \) amplitudes reliably.

Small angle neutron–proton scattering, which is difficult to study with a neutron beam, will be investigated up to 1.1 GeV per nucleon using the beam of polarised deuterons interacting in the polarised hydrogen target. One fast spectator proton will be detected in the ANKE magnetic system and the struck proton in the silicon telescopes.

By using a deuterium target and detecting now the slow spectator proton in the telescopes, the beam energy range could be extended up to \( \approx 3 \) GeV though, to connect with the \( pp \) phase shifts, the range up to 2.1 GeV is the most important. In this configuration the kinematic interval is fixed mainly by the measurement of the fast proton in ANKE \( (4^\circ < \theta_{pp}^{\text{lab}} < 11^\circ) \). Though in both configurations there are significant deuteron corrections, these can be largely handled, and the measurement of the slow proton leads to a good vertex identification even in the long target provided by the target cell. It has already been shown that ANKE is an efficient tool for measuring small angle charge exchange of polarised deuterons, \( dp \rightarrow (pp)n \), where the final \( pp \) pair is at such low excitation \( (\ll 3 \) MeV) that it is almost exclusively in an \( S \) state. In this case the reaction provides a spin filter that selects an \( np \) charge–exchange spin–flip from the \( (3S_1, 3D_1) \) states of the deuteron to the \( ^1S_0 \) of the diproton. A similar enhancement will be seen in the \( dp \rightarrow (pn)p \) reaction at small momentum transfers.

Charge–Exchange Reaction with a Polarised Deuteron Beam

A first measurement of the deuteron–induced charge–exchange reaction was carried out at the ANKE spectrometer using a polarised deuteron beam at \( p_d = 2400 \) MeV/c \( (T_d = 1170 \) MeV) [7]. Two fast protons, emitted in a narrow forward cone with momenta around half that of the deuteron beam, were detected by the forward detector system of the ANKE set–up.

The first step in processing the \( dp \) charge–exchange breakup data is to choose two–track events using the MWPC information. The momentum vectors were determined with the help of the magnetic field map of the spectrometer, assuming
a point-like source placed in the centre of a beam-target interaction region. The charge-exchange process was identified from the missing mass with respect to the observed proton pairs (see Fig. 1) and time difference information. The spectra for all spin modes reveal a well defined peak at $M_{\text{miss}}$ equal to the neutron mass to within 1%. The background was less than 2% and stable, so that the charge-exchange process could be reliably identified.

Figure 1: Missing mass distribution of all observed proton pairs. The inset shows the distribution near the neutron mass for the pairs selected by the TOF.

Using the polarised deuteron charge-exchange break-up reaction $p(d,2p)p$, where the final protons have an excitation energy of less than 3 MeV and hence are in the $^1S_0$ state, we can access the spin-dependent amplitudes of the elementary $np$ elastic scattering. Fig. 2 (left panel) shows SAID predictions for the values of the moduli of the two forward spin-flip amplitudes, as functions of energy. In impulse approximation the forward differential cross section is proportional to $2|\beta(0)|^2 + |\varepsilon(0)|^2$ times form factors [9]. Thus, in the forward direction,

$$T_{20} = \sqrt{2} \left( \frac{|\beta(0)|^2 - |\varepsilon(0)|^2}{2|\beta(0)|^2 + |\varepsilon(0)|^2} \right),$$

so that the ratio of the two forward spin-dependent $np \rightarrow pn$ amplitudes can be deduced from our value $T_{20} = 0.39 \pm 0.04$ shown in Fig. 2 (right panel) along with the predicted $T_{20}$ energy dependence using the SAID input. Alternatively, using our value of $T_{20}$, we obtain $|\beta(0)|/|\varepsilon(0)| = 1.86 \pm 0.15$, to be compared to SAID $1.79 \pm 0.27$. It is clear that our statistical precision is already superior to that present in the World data base. The same type of experiments carried out with a polarised target will determine the relative phases of these amplitudes. Though the selectivity of the $^1S_0$ region is clear, experience at Saclay shows that valuable information on the charge-exchange amplitudes is contained also in the higher $pp$ excitation data.

We have already shown in practice [1] that the charge-exchange reaction can also be carried out in inverse kinematics, with both protons from a deuterium target being detected in the spectator counters. This would allow the energies up to 3 GeV to be used, though over a rather smaller momentum-transfer interval.
Andro Kacharava

Figure 2: Left: Predictions for the moduli of the two independent $np \rightarrow pn$ scattering amplitudes at $t = 0$, taken from the SAID database; Right: The associated prediction of $T_{20}$ for $dp \rightarrow (pp)_{S0}n$ in impulse approximation. The latter is compared to our value of $T_{20} = 0.39 \pm 0.04$ at $\frac{1}{2}T_d = 585$ MeV.

It is important to stress that, with the apparatus available, the studies of the small and large angle elastic neutron–proton scattering will be carried out simultaneously at ANKE.

$p^3d \rightarrow (pp)n$ at Large Momentum Transfers

The ANKE collaboration has a programme for measuring the reaction $p^3d \rightarrow (pp)_{S0}n$ at high momentum transfers. By taking $E_{pp} < 3$ MeV, we can be fairly certain that there is little contamination from higher $pp$ partial waves. In contrast to the small–angle charge exchange reaction, the selection of fast diprotons in the laboratory system corresponds to neutrons emerging with cm angles close to 180° with respect to the incident proton. The kinematics are then very similar to those of backward $pd \rightarrow dp$. This reaction provides two new features compared to $pd$ elastic scattering:

i) The contribution from three–body forces, arising from the excitation of $\Delta$ and $N^*$ resonances in the intermediate state, is suppressed by an isospin factor of three in amplitude.

ii) The uncoupled $S$–wave dominates the internal state of the diproton at $E_{pp} < 3$ MeV. Due to the repulsive nature of the $pp$ force at short distances, it is expected that the $^{3}S_0$ diproton wave function should have a node at a relative $pp$ momenta $q \approx 0.4$ GeV/c. This should be easier to test than in $pd \rightarrow dp$, where minima are filled in by quadrupole effects connected with the deuteron $D$–state. For diproton production there should be regions in energy that are dominated by different mechanisms and that can test separately the ingredients of models.

The unpolarised cross section of the reaction was measured at COSY at proton beam energies from $T_p = 0.6$ to 1.9 GeV [10]. A reasonable agreement with these data is achieved in a model [11] that includes one–nucleon exchange, single scattering, and double $pN$ scattering with the excitation of a $\Delta(1232)$ isobar. This analysis takes into account interactions in the initial and final states by employing modern $NN$ potentials, e.g. CD–Bonn. Older potentials, such as the Paris and Reid Soft
Core (RSC), seem to overestimate the high-momentum components of the $^3S_0$ wave function and this leads to a strong disagreement with the data. Thus, within this model, one has sensitivity to the $NN$ interaction that should be explored further through measurements of the spin dependence of the reaction.

The measured proton analysing power [12] depends sensitively upon interferences, but the deuteron tensor analysing power and spin correlations are much more robust indicators of the reaction mechanism. These have been predicted at 180° in the same model as that used for the unpolarised cross sections [11] and shown in Fig. 3.

Figure 3: Tensor analysing power $T_{20}$, and spin–spin correlation parameters $C_{yx}$, $C_{zx}$ and $C_{zy}$ predicted for different $NN$ potentials within a model that includes one-nucleon exchange, single scattering, and $\Delta$ excitation [11]. The curves correspond to RSC (dotted), Paris (dashed), CD–Bonn (full).

For energies $T_p > 1$ GeV, the $\Delta$ contribution is expected to die away and single-nucleon exchange might then dominate. In this limit $T_{20}$ must change its sign at some energy, whose value will depend upon the form of the $NN$–interaction.

Deriving the Chiral Three–Body Force from $\pi$ Production

Chiral perturbation theory represents the best current hope for a reliable and quantitative description of hadronic reactions at low energies. One important step forward in our understanding of pion reactions at low energies will be to establish that the same short-range $NN \rightarrow NN\pi$ vertex contributes to both $p$–wave pion production and to low energy three–nucleon scattering, where the identical operator plays a crucial role. The connection of pion production operators to three-body forces is illustrated in Fig. 4. In the chiral Lagrangian, at leading and next-to-leading order, all but one term can be fixed from pion–nucleon scattering. The missing term corresponds to an effective $NN \rightarrow NN\pi$ vertex, where the pion is in a $p$–wave and both initial and final $NN$ pairs are in relative $S$ waves [13].
To second order in the pion momentum, nine observables are required to perform the full amplitude analysis in order to extract in a model-independent way the effective coupling constant. Of these, data from TRIUMF and CELSIUS yield seven at a beam energy around 350 MeV. Experiments designed to provide the necessary overconstraints will be carried out at ANKE through measurements of the analysing powers and spin-correlation parameters in the reactions $pp \rightarrow pp\pi^0$ and $pn \rightarrow pp\pi^-$. It should be noted that the diproton detection in ANKE to isolate the $^1S_0$ state is just the same as that needed also for the $dp$ charge-exchange programme described earlier. The resolution on the $pp$ excitation energy is estimated to be around 0.3 MeV and that on the missing mass about 5.5 MeV (RMS) which, at these low energies, will allow us to distinguish unambiguously the pion production reaction from any background. The counting rates are quite high and, even in the $pn \rightarrow pp\pi^-$ case, where the spectator proton has to be detected, more than $10^3$ events per hour could be accumulated over the full range of pion centre-of-mass angles.

Our facility offers the exciting possibility [1] of extracting pion-production amplitudes in a model-independent way and thus determining a vital parameter for chiral perturbation theory.

**Strangeness Production: The $\Lambda$–$N$ Scattering Length**

Effective field theories provide the bridge between the hadronic world and QCD. For systems with strangeness, there are still many open questions and it is not even clear if the kaon is more appropriately treated as heavy or light particle. To improve further our understanding of the dynamics of systems containing strangeness, better data are needed. The insights to be gained are relevant, not only for few-body physics, but also for the formation of hypernuclei, and might even be of significance for the structure of neutron stars. The hyperon–nucleon scattering lengths are obvious quantities of interest in this context.

The IKP theory group has developed a method to enable one to deduce a scattering length directly from data on a production reaction, such as $pp \rightarrow pK^+\Lambda$, in terms of an integral over the invariant $\Delta p$ mass ($m_X$) distribution [14]. Using this method it can be seen that the inclusive Saclay $pp \rightarrow K^+X$ data, which had a

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**Figure 4:** Illustration of the role of the $4N\pi$ contact term in $NN \rightarrow NN\pi$ and three nucleon scattering. Solid lines denote nucleons, dashed lines pions.
mass resolution of 4 MeV, would allow the extraction of a scattering length with an experimental uncertainty of only 0.2 fm. However, the actual value of the scattering length obtained in this way is not meaningful, since it represents the incoherent sum of the $^3S_1$ and the $^1S_0 \Lambda p$ final states with unknown relative weights. It is important to try to separate them.

The $\Lambda N$ triplet final state could be isolated unambiguously by measuring the unpolarised $K^+$ spectrum in the forward direction and this weighted with the incident spin correlation, obtained using a transversally polarised beam and target [1]. This we will achieve by looking at the $\vec{p}d \rightarrow p_{sp}K^+X$ reaction, since the spectator proton ($p_{sp}$) will provide a better determination of the vertex in the long polarised target cell.

In fact, by measuring the $K^+$ production rates in the near-threshold region in hydrogen and deuterium, and the spin-correlation in the deuterium case, we will also determine in a model-independent way the magnitudes of the three $S$-wave spin-isospin amplitudes, two corresponding to the spin-triplet final state and one to the singlet [15]. It is also possible with a deuterium target to measure spin-transfer coefficients from the initial proton or neutron to the final $\Lambda$, and these will fix the relative phases of the three amplitudes. A significant $m_X$ variation in the singlet–triplet interference would point at a strong spin dependence of the $\Lambda n$ final state interactions, though much more theoretical work would be required to extract quantitative differences in the scattering lengths from such data.

Conclusions

There are unique opportunities at ANKE to measure the spin dependence of many polarised reactions, primarily in the proton–neutron sector. This is through the combination of magnetic analysis of fast particles with the detection of slow particles in the silicon telescope array. The proton–neutron programme has already been started at ANKE by using polarised deuterons and protons incident on an unpolarised target and the full programme with a polarised target will be initiated in 2006. Many reactions will be measured simultaneously, but we will concentrate for some time on the nucleon–nucleon programme, where the counting rates are very high, before passing to the pion production and eventually to the more challenging of the strangeness experiments.

The experience that the team will gain in undertaking polarisation measurements will be put to good use in the developments for PAX@FAIR, to which the group as a whole is committed.

References


[5] See the contribution of R. Engels to this proceedings.


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\(\phi\)-meson production in \(pp\) collisions close to threshold

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The Okubo-Zweig-Iizuka (OZI) rule [1] states that processes with disconnected quark lines in the initial or final state are suppressed. Accordingly, the production of \(\phi\)-mesons from initial non-strange states is expected to be substantially suppressed relative to \(\omega\)-meson. The cross section ratio for \(\phi\) and \(\omega\)-meson production under similar kinematical conditions should then be of the order of \(R_{\text{OZI}} = \sigma_\phi / \sigma_\omega = \tan^2 \alpha_V = 4.2 \times 10^{-3}\) [2], where \(\alpha_V = 3.7^\circ\) is the deviation from the ideal \(\phi\)–\(\omega\) mixing angle [3]. However, one may expect that a certain amount of hidden strangeness in the nucleon would manifest itself in a reaction cross section that significantly exceeds \(R_{\text{OZI}}\). These questions have led to a large experimental activity involving different hadronic reactions. Many of these experimental results agree with the forecasts of the OZI-rule [4]. Nevertheless in specific channels in \(\bar{p}p\) annihilation [5] enhancements of \(\phi/\omega\)-ratio by up to two orders of magnitude have been observed and discussed as being either a hint that the \(\phi\)-meson production occurs from hidden strangeness in nucleons [6] or that final-state interactions are significant [7]. A subsequent experiment at the SATURNE II accelerator has also found a large excess from \(R_{\text{OZI}}\) in the reaction \(pd \rightarrow ^3\text{He}X(X = \omega, \phi)\) [8]. Here, the origin of the ratio of these complex systems has more uncertainty than for e.g. the elementary \(\phi/\omega\)-meson production.

A systematic analysis of the \(\phi/\omega\) cross-section ratio in elementary hadronic processes, like \(pp\) collisions and \(\pi N\) interactions, has been performed by Sibirtsev and Cassing [9]. Almost all of the existing data give a \(\phi/\omega\)-ratio of \(3 \times R_{\text{OZI}}\). Only the ratio derived from \(\phi\)-meson production measured at DISTO [10] in \(pp\) collision at an excess energy of 83 MeV shows a value being 7 times larger than \(R_{\text{OZI}}\) (Fig. 2 (b)). However an uncertainty remains regarding the relative contribution of partial waves to the \(\phi\) and \(\omega\)-meson production. Thus the data of the reaction \(pp \rightarrow pp\phi\) at lower excess energy combined with existing data from \(\omega\)-meson production [11, 12] can make the \(\phi/\omega\)-ratio close to threshold more clear due to suppression of higher partial waves. In addition, microscopic model calculations [13, 14] show that the energy dependence of the total cross section at lower excess energy constrains better the not well known \(\phi\)-meson coupling constant to the nucleons (\(\phi NN\)). The ratio of the coupling constants \(\phi NN/\omega NN\) could also provide direct informations about the origin of the \(\phi/\omega\)-production ratio. In this paper, new results on the total cross section for the reaction \(pp \rightarrow pp\phi\) are presented below the energy of DISTO measurements.

The reaction \(pp \rightarrow pp\phi\) at excess energies of \(\epsilon = 19, 35\) and 76 MeV has been studied with the ANKE spectrometer [6, 16] at COSY-Jülich by detecting the \(K^+K^-\) decay mode of the \(\phi\)-meson in coincidence with one of the forward going protons. The times-of-flight and the momenta of positively and negatively charged particles are
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determined with scintillation counters and multi-wire proportional chambers and
have been used for particle identification. The reaction $pp \rightarrow pp \phi \rightarrow ppK^+K^-$ has been
selected by a missing mass cut on the non-detected proton. Estimated background
inside the cut is 3% at $\epsilon=19$ MeV and 10% at $\epsilon=35$ and 76 MeV, respectively. At
each energy about 200-400 $\phi$-mesons have been identified in the invariant mass of
$K^+K^-$ spectrum.

Figure 1: (a) and (b) show the efficiency corrected $K^+K^-$ invariant mass distribution
at excess energies of 19 MeV and 76 MeV. The dashed curves are the non-resonant
contributions based on four-body phase space. The solid line is the sum of non-
resonant contributions and $\phi$-meson production including the detector resolution.
The error bars indicate the statistical uncertainties.

Figure 1 (a,b) shows the efficiency corrected $K^+K^-$ invariant mass distributions
at $\epsilon=19$ and 76 MeV, which have been used to determine the total cross section of
$\phi$-meson production and the fraction of the yield due to the non-resonant $K^+K^-$
production. The determination of the total cross sections has been carried out
on the basis of phase-space distributions. The shape of resonant contribution is
given by the natural width of the $\phi$-meson folded with a Gaussian ($\sigma \approx 1$ MeV/c$^2$),
in agreement with the momentum resolution of the detector system. The total
cross section of $\phi$-meson production has been obtained after including the branching
ratio ($\Gamma_{K^+K^-}/\Gamma_{tot}=0.491$). The statistical uncertainty contribute with 10% to the
total error of the cross-section. The absolute cross-sections have been determined
d by comparing to the $pp$-elastic scattering [17]. The systematic uncertainty of the
normalization was estimated to be 17%.

Figure 2 (a) shows the preliminary result of the total cross sections for the reaction $pp \rightarrow pp\phi$ at $\epsilon=19$, 35 and 76 MeV. The $\phi$ cross section at $\epsilon=76$ MeV is close
to the DISTO data point. The calculations by Kaptari et al. [14] (black line) and
Tsushima et al. [13] (dashed lines) are based on an effective meson-nucleon model.
They consider the meson exchange current and the nucleonic current as well as the
initial and final state interaction. In both calculations the not well known $\phi$NN
coupling constant has been fixed in order to describe the angular dependence of
$\phi$-meson production measured at DISTO [10]. The calculated cross sections - with
the different values of the coupling constant - show a different energy dependence.

In combination with the existing $\omega$-meson production from SPES-III at $\epsilon=3.8$
- 30.1 MeV [11] and COSY-TOF at $\epsilon=92$ and 173 $\text{MeV}$ [12] the $\phi$-to-$\omega$ production
Figure 2: a) The preliminary total $\phi$ cross sections from ANKE are shown together with the DISTO point [10]. The error bars indicate the current systematic uncertainties on the basis of phase-space distributions. The lines are predictions from Kaptari et al. [14] (solid line) and Tsushima et al. [13] (dashed lines) - the later one given as an upper and lower prediction. b) $\phi/\omega$ cross section ratios normalized to $R_{OZI}$. The data points above $\epsilon=1$ GeV are taken from A. Sibirtsev et al. [9]. The black curve is taken from the calculations of Kaptari et al. [14]. The thick dashed horizontal line is a fit taking into account only the high energy data above 1 GeV excess energy whereas the thin dashed lines above and below indicates the range of the systematic uncertainties.

ratio can be given at the measured ANKE and DISTO $\phi$-production excess energies. Therefore the $\omega$ data have been interpolated considering the energy dependence of higher partial waves and pp final state interaction. Figure 2 (b) shows the $\phi/\omega$ production ratio, normalized to $R_{OZI}$, for pp collisions from all existing data. The high energy ratios above 1 GeV were taken from Ref. [9]. The enhanced ratio at $\epsilon=80$ MeV is confirmed by the ANKE cross section. The new $\phi/\omega$-ratio at an excess energy $\epsilon=19$ MeV is around $3\times R_{OZI}$ which is consistent with the data at higher energy and the ratio derived from the $\pi N$ interaction [9]. This may indicate that the nature of the $\phi/\omega$-ratio can be the same as the elementary processes via the pion induced reaction.

To finalized the cross section determination of the $\phi$ measurements at ANKE a further investigation of the differential distributions for all three energies - at each excess energy (19, 35 and 76 MeV) few hundred events - is in progress. Here, the contribution of higher partial waves has to be investigated. Furthermore a new measurement of the reaction $pp\rightarrow pp\phi$ at $\epsilon=76$ MeV has been performed at ANKE in spring this year to investigate the differential distributions with higher statistics. The statistics of the collected $\phi$-mesons was improved from few hundreds by almost one order of magnitude [18].
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According to the Okubo-Zweig-Iizuka (OZI) rule, the production of $\phi$-mesons from an initial non-strange state is expected to be suppressed in comparison to the $\omega$-meson production. The $\phi/\omega$ cross-section ratio within the OZI-rule should be of the order of $R_{OZI}=4.2 \times 10^{-3}$. However, existing experimental data show an apparent excess over $R_{OZI}$ indicating violation of the OZI-rule. This could also be due to an intrinsic $s\bar{s}$ component in the nucleon, which would also manifest itself in a $\phi$-meson production significantly exceeding $R_{OZI}$.

Experiments on $\phi/\omega$-meson production in antiproton-proton annihilation at the LEAR facility [8] revealed a considerably larger ratio (100-250)$\times 10^{-3}$ than the OZI estimation. The enhanced $\phi$-meson yield is strongly correlated to the initial spin-triplet state with no large deviations from OZI-rule in the singlet state, which leads to the suggestion [2] that the $\phi$-meson can be produced through a rearrangement process of a negatively polarized intrinsic $s\bar{s}$ component in nucleons. Several possible tests for this model are discussed in Ref.[2]. Alternatively, rescattering of the intermediate kaon in the annihilation process has been also proposed [3]. In this connection, further insight into the origin of the $\phi/\omega$ ratio could be provided by the $\phi/\omega$-meson production in nucleon-nucleon collisions close to threshold. In the reaction $pp \rightarrow pp\phi$, the entrance channel is a pure isospin-spin triplet state close to threshold due to the suppression of higher partial waves in the final state. Thus the $\phi/\omega$ ratio in $pp$ collision should be increased according to the negatively polarized intrinsic $s\bar{s}$ model. $\phi$-meson production in $pn$ collisions contains both spin-triplet and spin-singlet in the entrance channel. In particular the reaction $pn \rightarrow d\phi$ is a filter for the spin-singlet state. The $\phi/\omega$-ratio should therefore be strongly suppressed compared to the proton-proton case based on the negatively polarized intrinsic $s\bar{s}$ model. In contrast, meson exchange models predict that the ratio was found to be sizable [4, 5, 6]. Data for the reaction $pn \rightarrow d\phi$ does not exist so far and would allow one to discriminate between those theoretical models. In this paper, new results for the reaction $pn \rightarrow d\phi$ are presented, whereas new results on the reaction $pp \rightarrow pp\phi$ are reported in Ref.[7].

The experiment has been performed at ANKE facility [6] using a 2.65 GeV proton beam from COSY. A deuterium cluster-jet target has been used as an effective neutron target. The reaction $pd \rightarrow dK^+K^-p_n$ has been identified by detecting the outgoing $K^+$ and $K^-$ mesons as well as the deuteron. Particle identification has been achieved by the time-of-flight information, provided by scintillation counters, and by the reconstructed momentum. Figure 1 (a) shows the missing mass spectrum of detected particles and indicates a clear peak at the proton mass resulting from the reaction $pd \rightarrow dK^+K^-p_n$. The estimated background is less than 5% inside the cut.
Figure 1: a) Proton missing mass spectrum obtained from the detected $K^+K^-$ and the deuteron. The arrow indicates the cut for the proton mass. b) $K^+K^-$ invariant mass distribution for the selected events. Crosses show the experimental data. The solid histogram is obtained from a Monte-Carlo simulation including the resonant contribution, whereas the shaded area corresponds to the contribution of non-resonant $K^+K^-$ production. The efficiency of the detector system is included in the measured distribution.

The $K^+K^-$ invariant mass spectrum is shown in Fig.1 (b) and $\phi$-meson events are clearly seen above the non-resonant $K^+K^-$ production contribution. About 1700 $\phi$-meson events have been collected in total. The amount of background due to the non-resonant $K^+K^-$ production has been estimated by four-body phase space simulations which fit the invariant mass spectrum together with the resonant process (solid histogram). The non-resonant contribution is less than 10% in the $\phi$ mass region $1.020\pm0.015$ GeV/c². The shape of the resonant contribution is reproduced by the natural width of $\phi$-meson with the experimental mass resolution 1 MeV/c² ($\sigma$), which is consistent with the momentum resolution of the ANKE detector system.

Assuming that the reaction $pd \rightarrow d\phi n$ is due to the interaction between the beam proton and the target neutron, the proton in the final state is a spectator. The kinematics of the reaction $pn \rightarrow d\phi$ can be determined on an event-by-event basis. Figure 2 shows the spectator momentum spectrum for the events inside the $\phi$-meson mass region $\pm0.015$ GeV/c². The histogram has been generated by a Monte-Carlo simulation based on the spectator model including the detector response. It fits the shape of the data well in the momentum range of 0–150 MeV/c, where the model dependence of the deuteron wave function is negligibly small compared with the statistical uncertainty. The spectator model works well for the $\phi$-meson production.

The absolute cross-section normalization has been obtained by two methods. First, the luminosity has been estimated by target density and beam current measurements. The target density has been determined by the frequency shift measurement of the stored proton beam during each measurement cycle. Second, the reaction $pd \rightarrow pX, (X=d, pn)$ has been analyzed from the same data set as for the

*aNote that in principle the low-mass $K^+K^-$ pair could be produced via the scalar meson $a_0/f_0(980)$. However, since their widths are significantly larger than the $\phi$-meson width, we describe the events as “non-resonant”.*
Spectator proton momentum [GeV/c]

0 0.02 0.04 0.06 0.08 0.1 0.12 0.14 0.16 0.18 0.2

Counts

0 50 100 150 200 250 300 350 400 450 500

Figure 2: Momentum spectrum of the reconstructed spectator proton. Crosses show the data, whereas the solid histogram is obtained by a Monte-Carlo simulation based on the spectator model. The deuteron wave function from the BONN model is used.

$\phi$-meson production. The normalization has been determined by comparing data to model calculations based on the Glauber-Franko formalism [9]. Both methods give consistent normalizations within ±5% and currently the estimated systematic uncertainty is 15%, which mainly comes from the acceptance correction for the $pd$ scattering analysis.

Preliminary data for the total cross section of the reaction $pn \rightarrow d\phi$ are shown in Fig.3. The excess energy is determined by $\epsilon = \sqrt{S - m_d - m_\phi}$, where $S$ denotes the total energy of the outgoing deuteron and the $K^+K^-$-meson pair, and $m_d, m_\phi$ is the mass of deuteron and $\phi$-meson, respectively. The horizontal bars indicate the width of the excess energy range, which corresponds to 4-8 times larger values than the excess energy resolution ~ 2.5 MeV ($\sigma$). The vertical error bars show statistical errors. The current estimate of the systematic uncertainty is around 25% due to the luminosity determination and the contribution of non-resonant $K^+K^-$ production. The total cross sections of the reaction $pp \rightarrow pp\phi$ are also shown for comparison and the cross-section ratio $\sigma_{dn}/\sigma_{pp}$ amounts to about a factor of five at an excess energy around 20 MeV, whereas it is a factor of two at 80 MeV. It is worthwhile to note that the ratio is much less than that observed for $\eta$ production [10], indicating that the isospin dependence for $\phi$ production is weaker than for $\eta$ production. The data of the reaction $pn \rightarrow d\phi$ almost follows the energy dependence of phase space.

The cross-section ratio of $\phi/\omega$-meson production in the reaction $pn \rightarrow dv (\nu=\phi, \omega)$ at the same excess energy range is provided by a combination with ANKE results on $\omega$-meson production [11]. The total cross section for $\omega$-production (2.6±2.3) σb at $\epsilon=28^{+16}_{-20}$ MeV and (9.0^{+15}_{-23}) σb at 57^{+21}_{-15} MeV, together with the preliminary data of $\phi$-meson production, leads to the $\phi/\omega$ ratio $R=(3-60)\times10^{-2}$ and $(2-5)\times10^{-2}$, respectively, where the error of the $\omega$-production comes from systematic one. Thus, compared to the ratio that follows from the OZI-rule, the ratio of the reaction $pn \rightarrow dv$ yields a deviation of a factor 4 as a lower limit, which is almost the same as the ratio for the $pp \rightarrow pp\nu$ channel, i.e a factor of 3−7 at $\epsilon = 19−83$ MeV [7]. Consequently, if S-wave $\phi$-meson production is dominant in the measured excess
energy range, the data on nucleon-nucleon collisions do not support the negatively polarized intrinsic $s\bar{s}$ model for the $\phi$-meson production. In contrast, the meson exchange model predicts $(0.3\pm0.4)$ in qualitative agreement to the experimental data. As a future task, the S-wave dominance has to be checked by the differential distribution providing the density matrix $\rho$ in the decay distribution of $\phi\rightarrow K^+K^-$, which could distinguish the S-wave contribution from higher amplitudes. This analysis is in progress. In addition, the uncertainty of the ratio on $pn\rightarrow d\phi$ is strongly dominated by the $\omega$-production data. Thus the improvement of $\omega$-data at lower energy is clearly essential to make a quantitative conclusion for the origin of the ratio, that will be studied in ANKE detector at COSY.

References


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Study of $\omega$ meson production in pp interactions at ANKE

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Heavy meson production in nucleon-nucleon (NN) collisions is of significant interest due to the possibility to probe as well the NN interaction on short distances as the nucleon-meson coupling. In case of $\omega$ and $\phi$ mesons there is special interest in connection with the OZI rule violation which may be interpreted as a considerable contribution of strange quarks to the nucleon wave function. Despite extensive theoretical analysis of $\omega$ and $\phi$ meson production has been performed within the last years [1, 2], experimental data is still very limited. Even for the most studied $pp \rightarrow pp\omega$ reaction the energy dependence of the total cross section near threshold is basically determined by data from SATURNE [3] in the excess energy ($Q$) range below 31 MeV. Up to the COSY-TOF point at $Q = 92$ MeV [4] there is no data and both points, at 31 MeV and at 92 MeV, deviate already from the predicted monotonous cross-section behavior [2].

The ANKE installation at COSY is well suited to measure near threshold meson production. So it is an appropriate task to link the SATURNE data to other points at higher $Q$. With the upcoming installation of the ANKE spectator proton detection system we are able to improve our first result [5] on the $pn \rightarrow d\omega$ total cross-section significantly. In total we can provide a consistent set of data on the $\omega$ production in $pp$ and $pn$ reactions and therefore in both isospin channels. However, as at ANKE the $\omega$ meson can be only identified by the missing mass technique one has to treat a large physical background from multi-pion production. To investigate this background we have recently carried out a short measurement of the $pp \rightarrow pp\omega$ reaction.

Experimental Setup and Data Analysis

The experiment was done at the ANKE installation [6] using the internal hydrogen cluster-jet target and the COSY proton beam. To minimize systematic errors the beam momentum was changing every 10 minutes between 2.85 GeV/c and 2.95 GeV/c corresponding to excess energies of 60 MeV and 92 MeV respectively. One outgoing proton was detected in the ANKE forward detector (FD) which consists of three MWPC's and two layers of scintillators. The other proton was simultaneously detected in the positive side detector (PD) of ANKE where 23 thin scintillators (Start), two MWPC's and one layer of 6 large scintillators (SW) were used only. For normalization purposes proton-proton elastic scattering was measured parasitically in the FD.
Figure 1: The TOF difference between particles detected in the FD and protons in SW scintillators vs. the momentum of particles in the FD.

In the PD protons were selected from other particles, mostly pions, using the time-of-flight (TOF) between Start and SW scintillators. As momenta of particles are less than 1.2 GeV/c the proton and the pion peaks are separated by more than 3 FWHM for any Start-SW combination. To select protons in the FD which accepts momenta up to 2.5 GeV/c, the TOF difference between SW and FD scintillators has to be combined with the momentum reconstruction as shown in Fig. 1. There the TOF of protons selected in the PD was corrected for different trajectory lengths. The strong peak in the momentum distributions of pions which can be seen as a spot in vicinity at 1.75 GeV/c is related to the proton-neutron final state interaction in the $pp \rightarrow pn\pi^+$ reaction. It gives a possibility to control the selection because being misidentified as protons such pions produce a peak in the missing mass distribution at 0.65 GeV/c$^2$ and 0.68 GeV/c$^2$ for 2.85 GeV/c and 2.95 GeV/c respectively.

The accuracy of the missing mass reconstruction was verified using the $pp \rightarrow pp\eta$ and the $pp \rightarrow pp\pi^0$ reaction. For the later one the neutron mass was correctly reconstructed in both possible variants, either when the proton was found in the FD and the pion in the PD or vice versa. The $\eta$-meson mass also was correctly obtained as presented in Fig. 2. The $pp \rightarrow pp\pi^0$ reaction was observed but the pion peak has a large width because momentum uncertainties are significantly amplified due to the small mass of reconstructed particle. Thus, one can expect to find the $\omega$ peak at its nominal position as well. However, in vicinity of the the $\omega$ mass the large background from the multi-pion production is strongly peaked due to the specific

Figure 2: Missing mass distributions of $pp \rightarrow ppX$ reactions measured at 2.85 GeV/c (left) and at 2.95 GeV/c beam momentum (right).
acceptance of the forward detector at ANKE.

To select the $\omega$ peak, the kinematical transformation of experimental missing mass distributions from one beam momentum to another was applied. The first time this approach has been proposed and used in [3]. It consists in an event-by-event Lorentz transformation of both proton momenta from the laboratory system where they were really measured to the laboratory system at another beam momentum. If the phase space of multi-pion production processes is much larger than the experimental acceptance, the shape of the missing mass distribution related to this background is expected to be determined by the acceptance only and to remain the same in both systems. But a resonant peak is shifted by approximately the difference of excess energies. It can be shown that in our case this approach works very well in the range above $0.4 \text{ GeV/c}^2$ for the distributions presented in Fig. 2 which are integrated over the total acceptance. Then removing $\omega$ and $\eta$ peaks from the transformed distribution one can subtract it from the measured one. The result of such subtraction is presented in Fig. 3. The ratio of integral luminosities for each beam momentum was only used here to equalize the background.

As the acceptance of ANKE for the reaction under investigation strongly depends on the angular distribution over the $\omega$ center-of-mass angle ($\Theta_{\omega}^{\text{cm}}$), on the anisotropy in the system of the two protons and their relative kinetic energy ($e_{\text{pp}}$), the same procedure was tested to generate these differential distributions. It was found, however, that in this case the procedure is much more sensitive to such details of experimental acceptance as the efficiency homogeneity, gaps between scintillators and the efficiency of the trigger which must be investigated in more detail. This part of analysis is not completed yet. The current status of the job is presented in Fig. 4.

In average these distributions do not significantly contradict to the results of the phase space simulations in both $e_{\text{pp}}$ spectra and at forward $\Theta_{\omega}^{\text{cm}}$ angles but some structure is still observed at backward angles, especially at $Q=92 \text{ MeV}$. This effect needs further investigation.
Figure 4: Differential distributions of $pp \rightarrow pp\omega$ events along the center-of-mass angle (upper ones) and along the relative kinetic energy of two protons (lower ones) obtained at $Q=60\text{ MeV}$ (left column) and at $Q=92\text{ MeV}$. The results of the phase space simulation of the reaction are shown by lines. The solid line corresponds to the S-wave state of the two protons and the dashed line to the P-wave.

Preliminary Result and Conclusion.

As the distributions in Fig. 4 do not show any significant sensitivity to the relative angular distribution of two protons and taking into account that the analysis is not yet completed, values of the total cross section can be only given preliminary within a range of $2.4 - 4.5 \mu b$ at $Q=60\text{ MeV}$ and $5.6 - 10.8 \mu b$ at $Q=92\text{ MeV}$.

Nevertheless the presented results show that the use of the model-independent treatment of the multi-pion background is possible at ANKE. In the case of differential cross sections it requires a more detailed understanding of the experimental acceptance.

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Introduction

The most remarkable feature – in the frame of the quark model – distinguishing the \( \eta' \) meson from all other pseudoscalar and vector ground state mesons, is the fact, that the \( \eta' \) is predominantly a flavour-singlet combination of quark-antiquark pairs and therefore can mix with purely gluonic states.

A comparison of the close-to-threshold total cross section for the \( \eta' \) production in both the \( pp \to pp\eta' \) and \( pn \to pn\eta' \) reaction constitutes a tool to investigate the \( \eta' \) meson structure and the reaction mechanism and may provide – as suggested in reference [1, 2, 3] – insight into the flavour-singlet (perhaps also into gluonium) content of the \( \eta' \) meson and the relevance of quark-gluon or hadronic degrees of freedom in the creation process.

By the analogy to the \( \eta \) meson production – in case of the dominant isovector meson exchange we can expect that the ratio \( R_\eta = \frac{\sigma(pp-n\eta)}{\sigma(pp-pp\eta)} \) should be about 6.5 [4]. If however \( \eta' \) meson is produced via its flavour-blind gluonium component from the colour-singlet glue excited in the interaction region the ratio should approach unity after corrections for the initial and final state interactions [1].

\( \eta \) and \( \eta' \) meson production in quasi-free reactions

The close-to-threshold excitation function for the \( pp \to pp\eta' \) reaction has already been determined [5, 6, 7, 8], whereas the total cross section for \( \eta' \) meson production in the proton-neutron interaction - a second part of our studies - is still unknown. In August 2004, for the first time we have conducted the measurement of the quasi-free \( pn \to pn\eta' \) reaction at the COSY-11 facility. In order to measure quasi-free \( pn \to pnX \) reaction by means of the proton beam, deuterons are used as a source of
neutrons since a pure neutron target does not exist. The reaction is schematically shown in figure 1.

Nucleons bound inside the deuteron are not in the rest, but they are moving with a Fermi momentum as shown in the fig.2 (left). For the data analysis the proton from the deuteron is considered as a spectator which does not interact with the bombarding proton but rather escapes untouched and hits the detectors carrying the Fermi momentum possessed at the time of the reaction. Since the neutron momentum varies from event to event, the excess energy will also change from event to event. Fermi motion of neutron inside the deuteron enables to scan a large range of excess energies with one constant beam momentum (see fig.2 right), however this requires the determination of the excess energy for each event.

The experiment at the COSY-11 facility is based on the measurement of the four-momenta of the outgoing nucleons, whereas events corresponding to the creation of $\eta'$ meson are identified off-line via the missing mass technique. Protons are registered in two drift chambers and in the scintillator hadoscopes [10, 11]. Neutrons are measured in the neutral particle detector. The spectator protons are measured by the dedicated silicon-pad detector [12, 13]. From the measurement of the momentum vector of the spectator proton one can infer the momentum vector of the neutron at the moment of the collisions, and hence calculate the excess energy [14, 15].

The experiments and the evaluation of the data from the proton-neutron interaction is much more difficult in comparison to the measurements of the proton-proton reactions. To define the full kinematics of the $pn \rightarrow pnX$ events one needs
Figure 3: (left) Missing mass spectra of the $pn \rightarrow pn\eta$ process determined for the excess energies larger and smaller than zero. (right) Missing mass spectrum for $Q$ larger than 0 after the subtraction of the multi-pion background. The solid line, normalized in amplitude to the data points, corresponds to the Monte-Carlo simulation to measure at least one more particle comparing to the analog meson production in proton-proton interaction. Moreover the efficiency for the registration of the quasi-free $pn \rightarrow pn\eta$ process decreases by a large factor in comparison to the $pp \rightarrow pp\eta$ reaction. The elaboration of the data encounters problems of low statistic, however one can extract the number of registered $pn \rightarrow pn\eta$ events from the missing mass distribution provided that the contribution of the continuous spectrum originating from the multi-pion production can be disentangled from the signal resulting from the production of the investigated meson. This can be done by comparison of the missing mass distribution for the negative values of $Q$, when only pions may be created and the missing mass distribution for $Q$ larger than zero [16]. In case of the positive values of $Q$ a signal from the $\eta(\eta')$ meson is expected on the top of the multi-pion mass distribution. Example of application of this method (depicted in details in ref. [16]) in the analysis of the quasi-free $pn \rightarrow pn\eta$ reaction is shown in the fig.3. Figure 3 (left) presents the missing mass spectra for $Q$ larger then zero (solid line) and the corresponding background histograms (shaded area). Figure 3 (right) shows the spectrum of the missing mass for $Q$ larger than zero after the subtraction of the background. One can see a good agreement between the experimental distribution and the simulation. This method will be also used for the extraction of the signal of the $\eta'$ meson production via $pn \rightarrow pn\eta'$ reaction from the data.

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Double-Pionic Fusion to $^3H_e$ - ABC effect revised

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Introduction

About 40 years ago first measurements onto the double-pionic fusion of protons and deuterons to $^3H_e$ particles lead to a big surprise. In the momentum spectra of the $^3H_e$ particles detected by a magnetic spectrometer Abashian, Booth and Crowe [1] found an intriguing excess of strength close to the $\pi\pi$ threshold. Follow-up measurements of these group revealed this enhancement to be of isoscalar nature, since corresponding measurements on the $\pi^+\pi^0$ channel in $pd \rightarrow ^3HX$ yielded a much smaller cross section. Hence it has been speculated, whether some unknown isoscalar resonance (like, e.g., the $\sigma$ meson) could be the origin of the observed enhancement. Later on the effect, meanwhile called ABC effect, was confirmed at Saclay [2], even on other nuclear systems [3] - though in all cases in inclusive single-arm magnetic spectrometer measurements detecting solely the nuclear recoil particle.

The first exclusive measurements of the $pd \rightarrow ^3H_e \pi^+\pi^-$ reaction have been carried out recently at CELSIUS [4] very close to threshold and at COSY-MOMO [5] near threshold. Whereas in the first case the very limited statistics does not permit any definite conclusions, the MOMO data clearly show an excess of strength at high invariant $\pi^+\pi^-$ masses $M_{\pi^+\pi^-}$ as compared to phase space distributions. Though this finding is in contrast to the ABC effect observed at higher energies, it coincides with the observation in $pp \rightarrow pp\pi^+\pi^-$ at the same center-of-mass energy above threshold [6].

Experiment

In order to shed more light on the nature of the ABC effect we have carried out exclusive measurements of the reactions $pd \rightarrow ^3H_e \pi^0$, $^3H_e \pi^0\pi^0$ and $^3H_e \pi^+\pi^-$ at $T_p = 0.895\, GeV$ using the WASA detector [7] with the deuterium pellet target system at the CELSIUS storage ring. The energy chosen corresponds to the one, where the maximum ABC effect has been observed [2]. The detector has nearly full angular coverage for the detection of charged and uncharged particles. The forward detector consists of a straw tracker followed by plastic scintillator quirl and range hodoscopes, whereas the central detector comprises in its inner part a thin-walled superconducting magnet containing a minidrift chamber for tracking and in its outer part a plastic scintillator barrel surrounded by an electromagnetic calorimeter consisting of 1012 CsI (Na) crystals. $^3H_e$ particles have been detected in the forward detector, whereas $\pi^+$, $\pi^-$ and $\gamma s$ (from $\pi^0$ decay) have been detected in the central detector. This way the full four-momenta have been measured for all
particles of an event allowing thus kinematic fits with 4 overconstraints in case of \( \pi^+\pi^- \) production and 6 overconstraints in case of \( \pi^0\pi^0 \) production.

**Results**

Fig. 1 shows the 3D and contour plots of the lab angle versus lab energy \( T_{3He}^{lab} \) for \( ^3He \) particles detected in the forward detector - before kinematic fit and any demand on other particles in the event. Whereas for single \( \pi^0 \) production \( ^3He \) particles are detected only in a very limited angle and energy range of phase space, the \( ^3He \) particles stemming from \( \phi \) production are covered over the full kinematical range up to \( ^3He \) angles \( \Theta_{3He}^{lab} \leq 90^\circ \). In Fig.1 we see a strong enhancement of events at the kinematical limit for \( \pi\pi \) production, i.e. corresponding to small invariant \( \pi\pi \) masses - obviously a clear sign of a strong ABC enhancement in these data.

Next we require that the \( ^3He \) particles are accompanied with 2 or 4 gammas from \( \pi^0 \) decay or a \( \pi^+\pi^- \) pair registered in the central detector. Having now also the four-momenta of the accompanied particles the selected events are overcomplete and kinematical fitting with 4-6 overconstraints can be applied.

Fig. 2 displays the differential distributions for the \( \pi\pi \) invariant masses. As expected from the discussion of Fig. 1 we see a strong enhancement in \( M_{\pi^+\pi^-} \) at low masses towards threshold. In \( M_{\pi^0\pi^0} \) we see such an enhancement, too,
Figure 2: Differential cross sections for the reactions $pd \rightarrow ^3He \pi^0\pi^0$ (left, solid symbols) and $pd \rightarrow ^3He \pi^+\pi^-$ (right, open symbols) for the distributions of the invariant masses $M_{\pi^0\pi^0}$ and $M_{\pi^+\pi^-}$. The shaded areas show the phase space distributions for comparison.

however of considerably smaller size. The enhancement in $M_{\pi^+\pi^-}$ is accompanied with a corresponding one at small opening angles between the pions, meaning that these pions are moving in parallel.

Since the initial deuteron has isospin 0, whereas proton and $^3He$ have isospin 1/2, the reaction acts as an isospin filter and the $\pi\pi$ pair can only be in an $I=0$ or 1 state - in case of $\pi^0\pi^0$ even uniquely in $I = 0$ due to Bose symmetry. From previous $pd \rightarrow ^3H \pi^+\pi^0$ measurements [1, 2], where $I_{\pi\pi} = 1$ necessarily, the isovector contribution in $pd \rightarrow ^3He \pi^+\pi^-$ has been deduced to be very small by using isospin relations between both channels. Hence the ABC enhancement has been assigned to be of isoscalar nature. The discrepancy between the low-mass distributions for $M_{\pi^0\pi^0}$ and $M_{\pi^+\pi^-}$ looks, indeed, as a huge isospin violation in this mass range. In fact, we see that strength starts to build up towards low masses in $M_{\pi^+\pi^-}$, but obviously cannot continue in this channel because of the $\pi^+\pi^-$ threshold. Instead, due to the significantly lower $\pi^0\pi^0$ threshold, we see the strength to continue growing towards smaller masses in the $\pi^0\pi^0$ channel.

Two-step $\Delta\Delta$ calculations [9, 10], which were thought to provide an explanation for the ABC effect, give a double-hump structure in $M_{\pi\pi}$, which obviously is not supported any longer by the new exclusively measured data - not to mention the obvious isospin breaking in the two channels.

From the $M_{\pi\pi}$ spectra in Fig. 2 we note that the low-mass enhancement relative to phase space (which describes the high mass region quite well) is roughly twice as strong in the $\pi^0\pi^0$ channel as in the $\pi^+\pi^-$ channel. An idea which has been put forward already in the first papers [1] on the ABC effect and which again has been brought up recently in connection with the observation of a similar enhancement in $pp \rightarrow pp\pi\pi$ [11], is the possibility of having Bose-Einstein correlations in the $\pi^0\pi^0$ channel. This scenario would provide an maximum enhancement of a factor of two.
for the $\pi^0\pi^0$ channel relative to the $\pi^+\pi^-$ channel at low $M_{\pi\pi}$ masses - as we indeed observe -, however, in this scenario the two pions need to be emitted stochastically by independent sources - a situation, which is hard to accomplish in our case.

Another presumably more realistic explanation for the increased enhancement in the $\pi^0\pi^0$ channel could come from chiral dynamics, according to which pion loops play the dominant role in $\pi\pi$ production giving rise to a dynamically generated $\pi$ meson by $\pi\pi$ rescattering. This scenario has been shown to describe $pp \rightarrow ppp\pi\pi$ quantitatively at energies near threshold [12]. Though this scenario can possibly account for the additional enhancement in the $\pi^0\pi^0$ channel, it cannot explain, why we observe so much strength at all at low masses in the $\sigma$ channel.

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Strangeness production at threshold


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Introduction

The strangeness production near threshold is investigated at the internal experiment COSY-11 in different reaction channels. Recently, the main focus has been to extend measurements of the hyperon production $pp \rightarrow NK^+Y$ in different isospin channels as well as the associated strangeness production in $pp \rightarrow ppK^+K^-$. In general, the low relative momenta of the outgoing particles at threshold gives access to study the hyperon-nucleon $YN$ and the $NK$ systems in detail. This allows to extend the investigations of the strong interaction within SU(3).

The experimental technique is based on the reconstruction of the four momentum for all positively charged ejectiles. Neutrons are detected in addition using a neutral particle detector. The unregistered hyperon or meson is identified by means of the missing mass technique.

Experiment

The magnetic spectrometer COSY-11 [1] at the COoler SYnchrotron COSY [2] is shown in its principal layout in figure 1. The cluster jet target operated with hydrogen or deuterium is mounted in front of a regular COSY dipole used as a magnetic spectrometer. The positively charged ejectiles are bent to the interior of the ring and their four momenta are reconstructed using the information of a set of three drift chambers and a subsequent time of flight measurement. In case of the $pp \rightarrow ppK^+K^-$ reaction, the probability to detect the decaying $K^+$ in the stop counter S3 is too low. Therefore, an indirect method to determine its time of flight by using the information from the fully reconstructed protons is used. The negative kaon is then identified via the missing mass.

For the reaction $pp \rightarrow nK^+\Sigma^+$, additionally the neutron has to be detected which is done in a lead-scintillator arrangement and the unregistered $\Sigma^+$ is deduced from the missing mass technique. More details on the experiment and the explicit analysis can be found in [1, 3, 4].

Hyperon production

The close-to-threshold data [5-7] for $pp \rightarrow pK^+\Lambda/\Sigma^0$ production showed that the
Figure 1: Schematic view of the COSY-11 setup for an exemplary event in $pp \rightarrow ppK^+K^-$, where the kaon decays before reaching the stop scintillator S3. The not shown cluster target is located in front of the left dipole magnet.

ratio $R = \sigma_{tot}(\Lambda)/\sigma_{tot}(\Sigma^0) \approx 28$ exceeds that at high energies by an order of magnitude. The description within different models [8-10] based on one-boson exchange are not able to fully reproduce the energy dependence of $R$. It is therefore necessary to exploit the hyperon production in different isospin channels which provide further constraints to the theoretical descriptions. This is exemplarily illustrated in figure 2. Within the calculations of [8] the excitation function for $pp \rightarrow pK^+\Sigma^0$ can only be reproduced by introducing a destructive interference of the two dominant meson exchanges $K$ and $\pi$ while the constructive interference is far off. Then the predictions for the other isospin channel $pp \rightarrow nK^+\Sigma^+$ are fixed. If the assumed exchange modes are dominant then the cross section for this channel is predicted to be an order of magnitude larger for the negative interference. The measurement of this additional channel will therefore allow for more qualitative judgement on the different scenarios since the isospin channels cannot be adjusted independently.

The COSY-11 collaboration extended their investigations on the hyperon sector with the new reaction channel $pp \rightarrow nK^+\Sigma^0$ at $Q = 13$ and 60 MeV. While the neutron is registered in a neutral particle detector consisting of several modules in a sandwich design from lead and scintillator, the kaon is registered in the main detector. The $\Sigma^+$ is then identified via the missing mass technique. While a preliminary result for the excess energy at $Q = 60$ MeV is shown in figure 3, the full analysis is to be found

Figure 2: Calculations for the two isospin channels $pp \rightarrow pK^+\Sigma^0$ and $pp \rightarrow nK^+\Sigma^+$ for dominant $K$ and $\pi$ exchange [8] with destructive (solid lines) and constructive (dashed lines) interferences of the two amplitudes.

Figure 3: Preliminary result for the excess energy at $Q = 60$ MeV.
in [11]. The total cross section is by more than two orders of magnitude enhanced

\[ \text{pp} \rightarrow nK^+\Sigma^+ \]

The preliminary result for the total cross section for \( \text{pp} \rightarrow nK^+\Sigma^+ \) at \( Q = 60 \text{ MeV} \) is shown in Figure 3. For comparison, the results for the other channels are also shown. Compared to the \( \Lambda \) channel and it will be a stimulating result for theory to explain such a high cross section.

**Associated kaon production**

The investigation of the elementary process \( \text{pp} \rightarrow ppK^+K^- \) has been a long term program at the COSY-11 experiment. At low excess energies, various different aspects motivate these studies, such as the interactions in the \( KK \) or \( pK^- \) systems that can be accessed due to the low relative momentum in the final state. A longer discussion of the physics motivation can be reviewed in [4, 12]. The determination of the cross section at \( Q = 17 \text{ MeV} \) of \( \sigma = 1.80 \pm 0.27^{+0.28}_{-0.35} \text{ nb} \) [12] showed a clear enhancement of more than an order of magnitude compared to the pure phase space expectation. In order to study the strength of this effect, two more data points were measured at \( Q = 10 \) and \( 28 \text{ MeV} \) below the \( (1020) \) threshold.

In Figure 4(a) the missing mass of the identified system \( ppK^+ \) is plotted and a clear peak at the mass of the \( K^- \) is visible. The broad background is known to mainly stem from the excited hyperon production \( pp \rightarrow pK^+\Sigma(1385)/\Lambda(1405) \) where the second proton originates from the decay. From Figure 4(b) showing the excitation function, it is obvious that the data set exceeds the pure phase space drastically (dashed line). Even the inclusion of the strong \( pp \) final state interaction (red dash-dotted line) is not fully reproducing the energy dependence. The same holds for the calculation within a one boson exchange model [10] while it should be noticed that it does not include the \( pp \)-FSI. It has to be seen if further improvements in the theoretical descriptions will lead to an understanding of the excitation function or if other aspects need to be incorporated.

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Figure 4: a) Squared missing mass for the $ppK^+$ system. b) Total cross sections for $pp \rightarrow ppK^+K^-$ including the published data (references given in the plot) and the new data from [4] (triangles).


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Strangeness production in pD interactions at ANKE/COSY

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The $K^+$ production rate in proton–neutron collisions is an important ingredient for the various theoretical calculations of strangeness production in $pA$ and $AA$ interactions. However, the ratio between kaon production in $pn$ and $pp$ reactions, $\sigma_n/\sigma_p$, varies from one to six in different theoretical models [1, 2, 3]. It has recently been suggested that close to threshold the ratio might even approach a factor of ten [4]. Unfortunately, experimental data on strangeness production in $pn$ interactions and reactions on light nuclei are very poor.

Using the magnetic spectrometer ANKE [5], placed at an internal target position of cooler synchrotron COSY–Jülich, experimental data on the $K^+$ production in $pd$ and $pp$ collisions have been collected at proton beam momenta of 2.055, 2.095, 2.600, 2.700, 2.806, 2.950 and 3.463 GeV/c. The ANKE spectrometer consists of three dipole magnets that separate forward–going charged reaction products from the circulating beam and allows one to determine their emission angles and momenta. The spectrometer, with its detection and data acquisition systems, leads to the suppression of a background that is $10^6$ times higher and thus to the identification of the rare production of $K^+$ with momenta in the range $100 < p_{K^+} < 600$ MeV/c.

The cluster–jet target, using $H_2$ or $D_2$ as target material, provided areal densities of up to $5 \times 10^{14}$ cm$^{-2}$. For the analysis of all the $pd \rightarrow K^+X$ data discussed in this work, the delayed–veto technique has been used. The detectors and corresponding data–analysis procedures for the $K^+$ identification are described in detail in Ref. [6].

Double differential cross sections for $K^+$ production in $pd$ collisions at $2.600, 2.700$ and $2.806$ GeV/c are shown in Fig. 1. For the extraction of the information about strangeness production on the neutron, a naive phase space model has been used that assumes that kaons are produced independently on the proton or neutron which are moving inside the deuterium nucleus. Only the six main $K^+$ production reaction channels have been taken into account in this analysis; other reaction channels have small total cross sections at these momenta. The model of Ref. [2], suggests that the ratio between $K^+$ production on the proton and neutron is equal to two. The sum of the phase space contributions for these six channels, weighted with the total cross sections taken from Ref. [2] and including this factor of two, is shown by the curve marked $\sigma_n = 2 \times \sigma_p$ in Fig. 1. However, in order to improve the agreement between experimental data and simulations, we varied the $\sigma_n/\sigma_p$ parameter and found the best fit at all three momenta for $\sigma_n/\sigma_p \sim 4$. The details of the analysis, as well as a description of the model, can be found in Ref. [7].

Double differential cross sections for inclusive $K^+$ production have been extracted from the data collected on deuterium and hydrogen targets at our highest momentum.

For a complete collaboration list see: http://www.fz-juelich.de/ikp/anke
of 3.463 GeV/c. From this analysis, where the luminosity was determined using pp elastic and pd diffraction scattering events, a ratio of two was found between \( K^+ \) production on the proton and deuteron.

At the low momenta of 2.055 and 2.095 GeV/c, kaon production is not possible in pp collisions but might occur in pd due to the Fermi motion in the target. Double differential cross sections built from the experimental data collected at these momenta have been used to estimate total \( K^+ \) production cross section on the deuteron using a Fermi-smearing model. In this model the reaction is assumed to occur through the \( pN \rightarrow K^+\Lambda N \) reaction on either a proton or neutron moving in the deuteron. Other channels involving \( \Sigma \) production are negligible here. The phase space event generator PLUTO [8], which incorporates the deuteron momentum distribution and final state interactions (\( pn \) and \( NA \)) has been used for the total cross section estimation. Experimental data as well as theoretical curves are shown in Fig. 2a.

The energy dependence of the near-threshold pp \( \rightarrow K^+\Lambda p \) total cross section was modelled by phase space distorted by the \( \Lambda p \) FSI. It was smeared by the deuteron wave function in order to get an estimation of the proton contribution to the pd \( \rightarrow K^+X \) total cross section below the pp threshold. The results of these calculations compared with the total cross section deduced from the experimental data are shown in Fig. 2b. A ratio of \( \sim 10 \) between \( K^+ \) production on the deuteron and proton would be necessary within the framework of this model to give agreement.

However, the Fermi smearing model used in the analysis does not describe well the experimental momentum distribution of protons correlated with the kaon. Furthermore, approximately twenty events corresponding to the exclusive pd \( \rightarrow K^+\Lambda d \) reaction have been found at both energies. A crude estimation of the total cross section for this latter reaction using a pure phase space distribution suggests that the \( K^+\Lambda d \) channel represents roughly 20% of the total \( K^+ \) production rate on the deuteron and this cannot be explained by a final state interaction within the single scattering model. Further model development is therefore needed to describe of these sub-threshold low data, possibly involving two-step mechanisms as have been used to model the analogous pd \( \rightarrow \eta pd \) reaction [10].

The analysis of the double differential cross sections suggests different ratios between \( K^+ \) production on the proton and neutron at different beam momenta.
Figure 2: a) Double-differential cross section for $pd \rightarrow K^+X$ production at 2.055 and 2.095 GeV/c compared with model calculations;b) Experimental $pp \rightarrow K^+A_p$ data taken from Ref. [9]. When smeared with the deuteron momentum-space wave function it leads to the curve which predicts the dependence of the total cross section for $pd \rightarrow K^+X$ on the excitation energy $Q$ in the $pp$ system. This is compared to our results at 2.055 and 2.095 GeV/c.

The ratio of one found at the highest beam momentum, which is largely independent of any model considerations, can either be interpreted in terms of a strong energy dependence of the investigated parameter or as a weakness of the models used in the analysis of the data at lower momenta. However, it should be stressed that the contributions of the basic reaction channels do change significantly over the momentum range we have studied.

Events of $pd \rightarrow dK^+\Lambda$ reaction found at the lowest beam momenta are a first indication for such a reaction channel that will have to be taken into account in model descriptions.

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Role of \((2N)\) Clusters in Subthreshold \(K^+\) Production

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Irrespective of the large amount of experimental data on \(K^+\)-meson production in proton-nucleus \((pA)\) collisions at energies below the elementary \(pN\rightarrow K^+NA\) threshold at \(T_p=1.58\) GeV, which has been collected since the first measurements in 1988 [1], the nuclear kaon-production mechanisms are far from being understood. Data on inclusive \(K^+\) production can be equally well reproduced by different models that involve either multi-step processes, cooperation between several target nucleons, or high momentum components of the nuclear wave function. Thus, new types of experiments, selectively exploring features of one or the other mechanism, are mandatory, for example an experiment which simultaneously detects \(K^+\) and the accompanying deuteron. Detection of such correlated kaon-deuteron pairs provides a clear signature for the two-step mechanism; in the first step, pions with typical energies of more than 500 MeV are produced in \(pN_1\rightarrow NN\pi\) reactions, and in a second step these energetic pions produce \(K^+\) mesons via \(\pi N_2\rightarrow K^+\Lambda\) or \(\pi N_2\rightarrow K^+\Sigma\) processes. Such two-step reactions should dominate at energies far below threshold since the intrinsic nucleon momentum can be utilized twice. A rather flat background of coalescent deuterons should not be a problem below 1.3 GeV, since two-step deuterons are expected to be strongly peaked with an average momentum corresponding to the kinematics of the \(pN\rightarrow d\pi\) reaction. Besides the two-step mechanism, a cluster-like formation might show up at lower energies. For example, a production on a two-nucleon cluster close to the corresponding threshold would give a non-flat momentum distribution for deuterons.

The results of a first experiment on \((K^+d)\) correlations from \(pC\) interactions at a proton beam energy of 1.2 GeV gave a first direct experimental evidence for the two-step process \((pN_1\rightarrow d\pi, \pi N_2\rightarrow K^+Y)\) as well as an indication for the cluster mechanism \((p(2N)\rightarrow K^+d)\) for \(K^+\)-meson production [2]. It has also been suggested [2] that the underlying kinematics can be exploited to distinguish between these reaction mechanisms. The deuteron momentum spectra are shown in Fig. 1. The shape of the deuteron momentum distribution, measured in coincidence with \(K^+\) mesons in the full energy range, is described as a combination of the 2-step and cluster mechanisms sitting on the flat background of coalescent deuterons (see Fig 1a).

To further test this conjecture, the kinematical features of both mechanisms were exploited. Deuterons, produced in the first step of the multi-step process have a rather wide angular distribution (more than 35°) and the shape of the deuteron peak weakly depends on the deuteron emission angle within 10–15°. Thus, the intensity of the central peak should be proportional to the solid angle covered by the deuteron detector, and it should strongly depend on the part of the kaon momentum spectrum accepted for correlations with deuterons. The latter is due to the fact that in order to produce kaons with a certain momentum in a second chance collision a limited range of pion momenta is needed. For possible \((2N)\) cluster mechanisms, the beam energy
Figure 1: Deuteron momentum spectra measured for the reaction $pC \rightarrow K^+dX$ at $T_p = 1.2$ GeV and different cuts on the deuteron emission angles and kaon momenta. 

- a) The circles are the experimental data ($\theta_d < 8^\circ$), the solid line is the fit to the data, the dotted line shows a contribution of the 2-step process, while shaded areas correspond to the cluster mechanism. 
- b) The deuterons (circles) are measured within 8 degrees, $p_K > 400$ MeV/c. 
- c) $\theta_d < 4^\circ$, $p_K < 400$ MeV/c. The dashed lines indicate the fitted background distribution. The figure has been taken from Ref. [2].

of 1.2 GeV is less than 60 MeV above the threshold for the $pd \rightarrow dK^+X$ reaction. Since the binding energy of a $(2N)$ cluster should be at least as large as for two individual nucleons, the excess energy should be even smaller. As a result, the deuterons from the cluster mechanism must have a much narrower, strongly forward peaked angular distribution. They correlate with kaons of momenta less than 400 MeV/c, the kinematical upper limit for kaons from the $2N$-cluster mechanism. A cut on the low-momentum part ($<400$ MeV/c) of the kaon spectrum and on correlated deuterons within a reduced angular acceptance ($4^\circ$ instead of $8^\circ$) should thus reduce the deuteron peak from the two-step mechanism ("cluster cut").

The experimental results after applying such cuts are presented in Figs. 1b,c and confirm these naive kinematical considerations. Deuterons, correlated with the most energetic kaons having momenta of 400–610 MeV/c ("2-step cut"), form a 250 MeV/c wide peak (see Fig. 1b) corresponding to the kinematics of the two-step mechanism via the $pN \rightarrow dX$ reaction. Moreover, even within the moderate statistical accuracy of our experiment two peaks are observed (see Fig. 1c) in the deuteron momentum distribution when analysing their correlations with low energetic kaons within a limited angular acceptance. These two were attributed to the cluster mechanism. Since the statistical significance of the data in Ref. [2] is too low to draw unambiguous conclusions about the cluster process and, in particular, about the properties of the involved $(2N)$ clusters, a larger data sample has been collected in the meantime.

The deuteron momentum distribution within the "cluster cut" is presented in Fig. 2 for the data sample including data from both beam times. As it is seen the statistics is still insufficient to make unambiguous conclusions about cluster mechanism. A finer binning of this distribution would be required in order to prove the existence and explore the properties of possible two-nucleon clusters. Furthermore, the shape of the momentum distribution of deuterons detected in the full kinematical range ($\theta < 8^\circ$, no cut on the $K^+$-meson momentum) does not indicate a necessity for anything in addition to the 2-step mechanism (open circles in Fig. 3).
Figure 2: Deuteron momentum spectra measured for $pC$ collisions at $T_p = 1.2$ GeV. The same cuts as in Fig. 1c are applied: $v_d < 4^\circ$, $p_K < 400$ MeV/c.

Although the statistical significance is insufficient for understanding of possible contribution of the cluster mechanism, it allowed to use a finer binning for the distribution without cuts (see Fig. 3). This is extremely important to determine the width of the peak corresponding to the 2-step production process. It has been predicted that two-step deuterons should have an average momentum corresponding to the kinematics of the $pN \rightarrow d\pi$ reaction and a typical width of about 200 MeV/c [3]. A fit to the experimental data (solid line in Fig. 3) results in the following characteristics: maximum=$(1006 \pm 10)$ MeV/c and width=$(111 \pm 12)$ MeV/c. While the position of the maximum is in very good agreement with the prediction, its width is nearly a factor two smaller.

It is also expected that within the “2-step cut” the two-step peak should be shifted towards lower deuteron momenta, since for energetic kaon production pions with high momenta are needed. Experimental findings favor this expectation (see closed squares in Fig. 3). The dashed line indicating a fit to the data results in $(944 \pm 11)$ MeV/c for the maximum and $(101 \pm 14)$ MeV/c for the width. Thus, a position of the peak is changed by $\sim 50$ MeV/c due to the mentioned kinematical constraint. The width of the momentum distribution associated with the two-step mechanism together with a value of the shift of the distribution are good input parameters for refined model calculations.

Analysing the shape of the distributions presented in Fig. 3 one can see that there is almost no space left for the cluster mechanism. Even if (depending on the mass of cluster) the shape of the momentum spectrum for the latter is not much different from the one from the two-step process, the maximum of this distribution should not change depending on the part of the kaon momentum spectrum accepted for correlations with deuterons. So, the contribution of the cluster mechanism, if it exist at all, is rather small at this energy.
Figure 3: Deuteron momentum spectra measured for $pC$ collisions at $T_p = 1.2$ GeV. The open circles are the experimental data for the uncut kaon momentum distribution, closed squares correspond to the subset of the data sample with $p_K > 400$ MeV/c. The solid and the dashed lines indicate fits to the corresponding experimental distributions.

Besides the peak associated with the two-step production, the momentum spectrum of deuterons has another peculiarity: a small peak with a maximum at $\sim 700$ MeV/c. Its strength remains, when only high momentum kaons are selected, so its origin is correlated with energetic kaons. The nature of this peak is not understood yet.

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Study of the $pp\eta$ system using the HBT interferometry method


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It is quite interesting to know, what is the dependence between the reaction mechanism and the size of the particles emission source. We try to establish to what extent this knowledge may be useful for determining the mechanism of the $\eta$ meson production in the collisions of nucleons. One of the possible mechanisms of the $\eta$ meson production via the $pp \rightarrow ppp$ reaction is a direct production of the $\eta$ meson at the interaction region and the other creation possibility believed to be dominant is the production of this meson via the resonant state $S_{11}(1535)$ [1, 2, 3]. In the latter scenario, the effective size of the emission region is expected to be larger than in the former one.

A large enhancement in the excitation function of the $pp \rightarrow ppp$ reaction observed close to the kinematical threshold indicates a strong attractive interaction within the $pp\eta$ system [1]. The effect can be described assuming, that the proton-proton pair is produced from a large object of a 4 fm radius [4]. Therefore, a study of the $pp\eta$ system is particularly interesting in the context of the search for the Borromean states. As Borromean we call a bound three-body system in which none of the two-body subsystems is bound. In nuclear physics the $^{11}\text{Li}$ ($^9\text{Li} + \text{n} + \text{n}$) and $^6\text{He}$ ($\alpha + \text{n} + \text{n}$) nuclei have been found to have such a property [5], and recently a nanoscale Borromean rings were constructed in a wholly synthetic molecular form [6, 7].

At present it is still not established whether the low energy $pp\eta$ system can form a Borromean or resonant state. Recently the COSY-11 collaboration published high statistics data for the $pp \rightarrow ppp$ reaction which will be used to elucidate this question [8]. These data are presently evaluated using the well known intensity interferometry method, commonly referred to as the HBT effect [9]. This technique permits to determine the size of the source from which the protons are emitted. It is based on the correlation function of the relative momenta between the two protons, which relates the space-time separation of the particles at the emission time to their momenta $p_1$ and $p_2$. This function can be expressed in terms of pair-
and single-particle cross section [9]:

\[ R(p_1, p_2) = C \cdot \frac{d^6\sigma/d^3p_1d^3p_2}{(d^6\sigma/d^3p_1)(d^3\sigma/d^3p_2)} - 1, \]  

where C denotes the overall normalization constant. The shape of two-proton correlation function calculated including Coulomb interaction and Pauli exclusion principle depends on the spatial size of the source. In a present analysis we consider only the projection of the \( R \) function onto one dimension corresponding to the relative momentum of emitted protons \( q = |\vec{p}_1 - \vec{p}_2| \). In the calculations we tentatively assumed a simultaneous emission of the two protons and approximated the effective spatial shape of the emission zone by the Gaussian distribution. In such case the standard deviation of this distribution - hereafter referred to as \( r_0 \) - constitutes the measure of the dimension of the source. For the simulations we adapted a computing procedure written by R. Lednicky [10, 11], which already has been successfully applied (example in ref. [12]). Figure 1 (left panel) displays proton-proton correlation functions calculated for the \( pp \to ppX \) reaction, assuming four different sizes of the emission source. One can see that the height of the peak at \( q \approx 40 \text{ MeV/c} \) depends significantly on the value of \( r_0 \) and therefore the magnitude of this maximum may serve as a measure of the volume of the reaction zone. Of course, generally the size of the reaction zone can be extracted by the comparison of the experimental and simulated correlation functions treating \( r_0 \) as a fitting parameter.

Since in the experiment the single particle yield has not been measured, it is not possible to determine directly the denominator of equation 1. Therefore, in order to facilitate an extraction of the considered correlation function from the data, an alternative function \( R(q) \) can be defined [9] as a ratio of the reaction yield \( Y_{pp\pi}(q) \) to the uncorrelated yield \( Y^*(q) \):

\[ R(q) + 1 = C^* \frac{Y_{pp\pi}(q)}{Y^*(q)}, \]  

Figure 1: **Left:** Theoretical correlation functions of two protons for \( r_0 = 1.0, 2.0, 4.0 \) and 7.0 fm. **Right:** The experimental two protons correlation function calculated from data [8] for the \( pp \to ppX \) reaction.
where $C^*$ denotes an appropriate normalization constant. In practice, $Y^*(q)$ can be obtained via event mixing techniques, taking momentum of one proton from event $m$, and the momentum of the second proton from event $m+k$, where $k$ is arbitrarily chosen. In the experiment devoted to the $pp \rightarrow pp\eta$ reaction the four-momenta of two protons are being measured and the unobserved meson is identified via the missing mass technique [8, 13, 14]. High statistics in such experiment allows to derive the distributions of differential cross sections free of the multi-meson production background [8, 13]. To demonstrate the quality of the data, an example of the missing mass distribution as a function of $q$ is shown in figure 2 (left panel). The correlation function derived from the data is presented in figure 1 (right panel). A determined experimental spectrum shows a maximum at a value of $q$ as predicted by simulations.

The correlation function for the $pp \rightarrow pp\eta$ reaction was evaluated free of the multi-pion production background, by counting each measured $pp \rightarrow ppX$ event with the weight corresponding to the probability that it is due to the $pp \rightarrow pp\eta$ reaction. This probability was extracted as a function of measured missing mass value separately for each of the 25 studied intervals of relative momentum. Missing mass spectrum for one of protons relative momentum intervals is presented in figure 2 (right panel).

The probability $\omega_i$, that $i^{th} pp \rightarrow ppX$ event with a missing mass $m_i$, and relative momentum of $q_i$ corresponds to $pp \rightarrow pp\eta$ reaction reads:

$$\omega_i = \frac{N_\eta}{N_\eta + N_B} (m_i, q_i),$$

(3)

where $N_\eta$ stands for the number of events corresponding to the $pp \rightarrow pp\eta$ reaction and $N_B$ is number of multi-pion production background events.

A rough comparison between theoretical correlation functions and the experimental one shown in the figure 1 indicates that the size of the reaction volume can
be approximated by the Gaussian distribution with $r_0 \approx 3$ fm. However, in order to draw the final conclusions, we need to take into account an experimental spread in the theoretical calculations and establish how acceptance corrections can modify experimental correlation function.

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Introduction

Close to threshold data on the $pd \rightarrow ^3\text{He} \eta$ reaction are of great interest to study the strong attractive $\eta$-nucleus interaction at low energies, which might be a signal for the existence of quasi-bound $\eta$-nucleus states. First observed at the SPES-IV and SPES-II spectrometers at SATURNE ([1,2]), the $\eta$-production in the reaction channel $pd \rightarrow ^3\text{He} \eta$ reveals remarkable features. Additionally to the unexpected high cross section, the shape of the excitation function reveals a maximum very close to the production threshold and a large drop of the production amplitude within only a few MeV above threshold, which clearly deviates from pure phase space expectations. In contrast, the angular distributions of the emitted $\eta$ mesons in the center of mass system appeared to be consistent with pure phase space expectations and exhibit no contributions from higher partial waves.

In order to describe this unexpected near threshold behaviour, a two-step model based on a double-scattering reaction mechanism has been proposed by Kilian and Nann ([3]). Calculations by Fälldt and Wilkin ([4]), exploiting this approach, succeeded to reproduce the threshold cross section within a factor of 2.4. However, in order to reproduce the observed rapid drop of the production amplitude with increasing energy, the two-step approach had to be refined by a strong $\eta^*-\text{He}$ final state interaction (FSI) with a large $\eta^*-\text{He}$ scattering length.

Further measurements performed at higher excess energies of $\sim 50$ MeV by the COSY-GEM-Collaboration ([5]) and between 22 MeV and 120 MeV by the WASA/PROMICE collaboration ([6]), resulted in non-isotropic angular distributions and total cross sections that are underestimated by the description of the refined two-step model fitted to the SPES data. A different reaction mechanism based on the excitation of the $N^*(1535)$ has been suggested ([5]), however, it fails to reproduce the observed shape of the previously determined excitation function. Here we present results on the $\eta$-production in proton-deuteron collisions performed using
Heinz-Hermann Adam

the COSY-11 facility at COSY-Jülich (FZJ). With five new data points measured at intermediate excess energies between \( Q = 4.6 \) and \( Q = 40.2 \) MeV, we are able to close the gap between measurements carried out at SPES-II (SATURNE) below an excess energy of 7 MeV (isotropic emission) and results from WASA/PROMICE (CELSIUS) and GEM (COSY) above excess energies of 20 MeV (non-isotropic angular distributions).

In contrast to all these investigations on \( \eta \)-production, only little is known for the corresponding case of the \( \eta' \)-meson. Only one data point close to threshold measured by Bertini et al. ([7]) is available, with two cross sections measured in total, the second ([8]) far above threshold at \( \sim 600 \) MeV Q-value. Therefore the underlying reaction process for \( pd \to ^3\text{He} \eta' \) is experimentally completely uninvestigated. But despite this lack of experimental data, predictions for the \( \eta' \)-excitation function, based on a two-step process, are available e.g. from Kondratyuk and Uzikov ([9]). As these and other calculations lack the existence of detailed near threshold cross section and production amplitude data, especially in view of possible FSI-effects, four new data points, ranging from 5 to 40 MeV \( \eta' \)-excess energy, are currently under evaluation by the COSY-11 collaboration. These new data will allow to study the corresponding production amplitude with respect to the absolute scale and a possible deviation from phase-space expectations, similar to the \( \eta \) case. The determination of the excitation function in the near-threshold region is also desirable for studies on the dominant production mechanism and for the confirmation of theoretical predictions.

**Experiment and Results**

The reaction channels \( pd \to ^3\text{He} \eta/\eta' \) have been studied using the COSY-11 installation ([10]) at COSY (Jülich) ([11]) by detection of the emitted \(^3\text{He} \) nuclei and identification and reconstruction of the produced mesons using the missing mass technique.

**Results on the \( \eta \)-meson production**

Over the range of studied excess energies \( (Q = 4.6, 10.4, 14.7, 19.5 \) and \( 40.2 \) MeV) a transition from a rather flat angular distribution at the two lowest energies to a highly anisotropic behaviour for the highest measured excess energy of 40.2 MeV is observed.

By determining the integrated luminosity via the \( pd \to pd \) elastic scattering ([13], [14]) it was also possible to derive total cross sections and production amplitude information for each of the measured excess energies. The obtained production amplitudes close the open gap between the SATURNE data at low energies and the higher energy data from WASA/PROMICE and GEM (figure 1).
Physics at (Existing) Storage Rings with Hadronic Probes

Figure 1: Average production amplitude squared $|f|^2$ as function of the cms momentum of the emitted $\eta$ mesons for the pd$\rightarrow^3$He $\eta$ reaction. The solid and dashed lines represent fits to the data based on a strong $\eta$-$^3$He FSI and a resonance model description respectively.

Outlook

The data on the pd$\rightarrow^3$He $\eta'$ reaction are still under evaluation. Although the analysis routine is similar to the $\eta$-analysis, the proved procedure for selection of pd$\rightarrow^3$He X events from background is more complex due to the overall higher particle energies. A first very preliminary view of the extracted missing mass spectra for an $\eta'$-excess energy of $Q = 10$ MeV reveals a clearly visible $\eta'$-peak on top of the already understood multi-pion background, as well as a signal of the $\omega$-meson.

Acknowledgments

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References:

Figure 2: Missing mass spectra of selected pd→³He X-events at an ς' excess energy of Q=10 MeV. A signal at the ς' mass is clearly visible on top of a background originating from multi-pion production. Besides the ς' also the ω-meson is visible in the lower missing mass region.


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Information on the problem with cosmic radiation induced Single Event Effects (SEEs) in space electronics has been known for a long time, it was only in the recent years that this problem was recognized by the microelectronics industry that focuses on terrestrial applications [1, 2]. The fundamental nuclear physics related to SEEs is in general understood [3]. The microscopic origin of SEEs is always traced down to the energy deposition from ionizing particles in a small, sensitive volume and subsequent charge released by a sensitive node of the device which can change the state of the circuit. Experimental measurements and theoretical simulations of the heavy recoils from nucleon-nucleus reactions are particularly important since the energy deposited by these recoils is a major source of secondary radiation. While in the past much effort has been devoted to the study of light particle emission (e.g. H and He isotopes) in intermediate-energy inelastic proton-nucleus collisions, very few experiments [5, 6] have been performed to study the characteristics of slow recoils, also of stable ones (e.g. Al, Mg, etc.) which are most effective in causing single event upsets (SEUs) in silicon chips. A major experimental difficulty in experiments with Si as target, is the identification of the heavy fragments with short ranges (of the order of 10 μm or less). The lack of direct data on recoil spectra (double differential cross sections) renders it difficult to make systematic checks on standard nuclear reaction models [3, 7-9].
Experimental Setup at CEPSIUS

An experimental setup has been developed at The Svedberg Laboratory (TSL), Uppsala, Sweden, to measure the production of recoil ions, using an inverse kinematics scheme. This operates at the CEPSIUS nuclear accelerator and storage facility of TSL. It consists of four detector systems designed for the registration of reaction products emitted in collisions of 100A-470A MeV Si ions with atoms of the internal hydrogen cryogenic cluster-jet target of CEPSIUS. Secondary particles are registered simultaneously by the Small Angle Detector (SAD), Forward Wall Detector (FWD), Zero Angle Detector (ZAD), and the Spectator Tagging Detector (STD).

Figure 1: Layout of the experiments on Si+H and Si+D reactions at TSL

SAD detects fragments of the Si ions emitted at angles $0.6^\circ - 1.1^\circ$. Here the unique features of CEPSIUS are fully exploited. SAD consists of a telescope with two 300 um custom-made silicon strip detectors (SSD) and a 5 mm thick plastic scintillator. The first SDD has circular and the second radial strips, with a total of 16 of each type. Plastic scintillators are used as triggers of the readout cycle and for timing. The position of the particle, registered simultaneously by both detectors, is thus giving 512 pixels. The charge of the recoil is identified from SSD pulse amplitude analysis. In working position SAD is positioned at a distance from the cooled beam of 12 mm.

The Zero Angle Detector (ZAD) is also a telescope made up of two silicon strip detectors and one plastic scintillator. Here we take the advantage of the technique...
developed at TSL [10] to use the quadrant after the cluster-jet target of CELSIUS as a magnetic spectrometer. ZAD is positioned at 22757 mm from the target, at the focal plane of the spectrometer [11]. The strips of ZAD make up a 32x32 rectangular net. The vertical strips of one of SSD are used to register projectile-fragments, identify the charge (Z) and determine the position (X) of the hit point with respect to the nominal beam centerline. The electronic schemes of SAD and ZAD are identical. The Forward Wall Detector (FWD) [12] is used for the detection of light secondaries ($A < 5$) emitted within the polar angle of $3.9^\circ - 11.7^\circ$ in coincidence with the recoil, registered by SAD. The CHICSi detector [13] is used for tagging the SAD data to the spectator-protons emitted within $60^\circ - 120^\circ$.

**Experimental Results**

Good quality 200A and 300A MeV Si beams were accelerated, cooled and stored at CELSIUS. This allowed the fragment detectors to be located very close to the cooled beam. The Si ion beam current was around 100 $\mu$A and the hydrogen target thickness around $2 \times 10^{14}$ atoms/cm$^2$. Data on both 200A and 300A MeV Si+H and Si+D reactions are under analysis.

![Figure 2: Charge distributions of recoils measured by SAD in study of 300A MeV Si+D reaction (see the text for details)](image)

Figure 2 demonstrates charge distributions of recoils measured in a the 300A MeV Si+D reaction. Here SAD inclusive data (dark colors) are compared with that obtained in coincidence with the hydrogen and helium isotopes registered by the FWD (l.h.s.) and by one of the CHICSi telescopes (r.h.s). The bottom panels compare the the inclusive and semi-inclusive yields of recoils by showing the ratio of the recoil rate without and with the production of H,He or a low energy spectator-like proton registered by CHICSi. The coincidence events probe the Si fragmentation induced by the quasi-free neutron of deuterium. These events reproduce to a certain
degree the SEE events. Results from a complete analysis of the data are to appear soon.

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The smallest storage rings, Traps

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Introduction

For the trapping of ions as well as the production and trapping of antimatter atoms elec-
"tromagnetic traps (penning traps, nested traps, Ioffe traps) are commonly used
which in fact act as the smallest possible macroscopic storage rings.

The ATRAP experiment [1] (see Table 1) at the CERN antiproton decelerator AD
aims for a test of the CPT invariance by a comparison of the 1S{2S two-photon
transition of hydrogen (H0) to antihydrogen (H0) atom spectroscopy. The H0 produ-
tion is routinely operated at ATRAP [2, 3] in a nested Penning trap config-
uration. Detailed studies concerning shape parameters of the antiproton (p)
and positron (e+) clouds, N-state distribution of the produced Rydberg H0
and H0 ve-
locity have been performed to improve the production efficiency of useful
H0 atoms.

The ATRAP experiment is divided into two phases:
ATRAP–I using the super conducting magnet of the former TRAP collaboration at
LEAR and ATRAP–II with a new superconducting magnet with a central bore as
large as 0.5 m in diameter giving ample space for further installations like detectors,
Ioffe-trap, and laser access. ATRAP-I served successfully for: trapping cold e+ and
cold p, overlapping of these two clouds, cooling p with e− and e+, and finally combin-
ing p and e+ to form H0 atoms. For the first time ever ATRAP has measured
the velocity of slow H0 [4] produced in three-body recombinations. Comparing the
data to a simple model calculation indicates an kinetic energy of the H atoms of ≈
200 meV (2400 K in temperature units). ATRAP succeeded in demonstrating an
entirely new method for producing slow H0 [5]. This method is distinguished from
the three-body recombination especially since it is expected that the temperature
of the H0 is as low as the p from which they form.

For high precision measurements of atomic transitions cold antihydrogen in the
ground state is required which has to be trapped due to the low number of avail-
able antihydrogen atoms compared to the cold hydrogen beam used for hydrogen
spectroscopy. The trapping of neutral antihydrogen atoms works via the force on
the magnetic moment in a magnetic field gradient which drives the atoms towards
the minimum of the magnetic field for a state with spin orientation parallel to the
field direction. To ensure a high antihydrogen trapping efficiency a magnetic trap
has to be superposed the nested Penning trap. A basic question in such a config-
uration is the possibility to keep the charged particle clouds, the antiprotons and the
positrons, in the stabilizing solenoid field which is strongly distorted by the varying
field of the magnetic trap.

Table 1: The ATRAP Collaboration

<table>
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<th>Institution</th>
<th>Members of the Collaboration</th>
<th>Main task</th>
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</thead>
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<tr>
<td>Harvard University</td>
<td>N. Bowden*, G. Gabrielse</td>
<td>Nested Penning trap for $\bar{p}$</td>
</tr>
<tr>
<td>USA</td>
<td>P. Oxley*, A. Speck,</td>
<td>$e^+$, production of $B^0$, superconducting magnet</td>
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<td></td>
<td>D. LeSage, N. Guise, J.N. Tan*</td>
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<tr>
<td>York University</td>
<td>E. Hessels, D. Comeau, C. Storry</td>
<td>PPAC-system, superconducting magnet</td>
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<tr>
<td>Canada</td>
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<tr>
<td>Research Centre</td>
<td>F. Goldenbaum, D. Grzonka</td>
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<tr>
<td>MPI for Quantum Optics, Garching, Germany</td>
<td>T.W. Hensch, H. Pittner, J. Walz</td>
<td>laser spectroscopy</td>
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</table>

* until 2002 or 2003

**Stacking and cooling of antihydrogen atoms**

Antiprotons enter into the trap via a degrader of about 100 μ Beryllium to reduce the 5 MeV particles to energies which are optimized for trapping them in a 4 keV potential. Here a very large amount of $\bar{p}$’s is lost via annihilation and that is why the community at the AD is preparing a proposal for a further deceleration ring ELENA [6] to minimize such losses. If ever reality such a ring should be placed between the AD and the experiments. The deceleration scheme is shown in figure 1 demonstrating that about each 90 seconds a bunch of fast extracted $\bar{p}$’s ($\approx 3 \times 10^7$ $\bar{p}$’s in $\approx 80$ ns) is delivered to the experiments after appropriate stepwise stochastic –

![Basic AD Deceleration Cycle](image-url)
and electronic cooling.

As a first step towards $\tilde{H}^0$ production antiprotons are captured and cooled with electrons within the Penning trap, where a 5.4 Tesla magnetic field is directed along the vertical axis of a stack of copper ring electrodes cooled to liquid helium temperature. When a bunch of $\tilde{p}$'s from the AD enters the trap is opened by grounding the degrader as indicated in figure 3 (right). Before the $\tilde{p}$'s can return to the entrance, reflected from the potential barrier at the top of the trap, the potential at the window degrader is turned on to negative potential and thus the $\tilde{p}$'s are trapped. Up to about 20000 antiprotons are typically captured in the long potential well.

The cyclotron motion of electrons cools via spontaneous emission of synchrotron radiation with a $0.1 \, s$ time constant and therefore for electron cooling of the $\tilde{p}$'s electrons were loaded before in short wells. After the trapped $\tilde{p}$'s are cooled into the electron wells the potential barrier is reduced again for the next injection of a stack of new $\tilde{p}$'s from the AD. Figure 2 demonstrates that a large number of $\tilde{p}$'s can be accumulated by this stacking method showing a linear increase with the number of $\tilde{p}$ bunches injected, here up to 32.

Finally, figure 3 shows a systematic study of the time dependence of $\tilde{p}$ cooling with positrons [7] in a potential structure as given in the left part of the figure. Such interaction between the two species of antihydrogen $\tilde{p}$ and $e^+$ is a crucial condition for producing $\tilde{H}^0$ atoms and must be regarded as an important step.

Cloud parameters

By combining measured parameters of the trapped particle clouds with some relations valid for charged plasmas very detailed informations like the density, axial
extent, rotation frequency, diameter, aspect ratio, and angular momentum of the trapped antiproton and positron clouds results. Such data are important for an optimization of the $\hat{H}$ production. For these investigations [8] the clouds were launched and re-caught after passing through the 5 mm diameter ball valve. The transfer efficiencies for $\bar{p}$ and $e^+$ are given in figure 4 showing that for $e^+$'s the efficiency decreases by a factor of two when increasing the number of positrons to 1.7 million, whereas the transfer efficiency stays constant up to 50000 $\bar{p}$'s. Recently ATRAP succeeded in greatly increasing the number of positrons available for experiments to about 5 million – by re-using the positrons from repeated cycles of antihydrogen production.

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Neutral and charged pion production in the S-matrix approach

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Retardation effects and off-shell dependencies of the rescattering operator in neutral pion production were recently investigated[1] within the framework of time-ordered perturbation theory (TOPT). Various approximations to the result obtained from TOPT were analysed. The central problem underlying this study is that the final- and initial-state interaction diagrams do not define a single effective operator. Since in the time-ordered diagrams energy is not conserved at individual vertices, each of these diagrams defines a different off-energy shell extension of the pion rescattering amplitude. This problem is not present in the S-matrix derivation of the effective rescattering operator (for definition of the S-matrix approach and detailed discussion see Ref. [1] and references therein).

In this work, we applied this approach to charged and neutral pion production in \( pp \) collisions, in which the spin/isospin channels filter differently the rescattering mechanism. As in Ref.[1], the chiral perturbation theory rescattering amplitude[2] is employed. The contributions from the single-nucleon (so-called, impulse approximation: IA), \( Z \)-diagrams and \( \Delta \)-isobar mechanisms are also included.

The contributions of all the mechanisms considered are shown on Fig. 1. For the reaction \( pp \rightarrow pp\pi^0 \) the IA term (dashed line) is suppressed. On the other hand, the IA and rescattering mechanisms (dotted line), which interfere destructively, are clearly not enough to describe the data, and the \( Z \)-diagrams (dashed-dotted line) are found to be very important in reproducing the cross section. The \( \Delta \)-isobar, when included explicitly (solid line) plays a significant role, even at energies close to threshold, improving the description of the data.

The convergence of the partial wave series of Table 1 is shown on Fig. 2. As expected, the contributions with \( J > 0 \) start to play their role only about 20MeV above threshold. Including all contributions with \( J \) up to \( J = 3 \) yields a reasonably converged results. The effect of the potential used for distorting the \( NN \) final and initial states is studied on Fig. 3. Although the cross sections for the first channel considered differ for the Bonn B and CD Bonn potential (dotted and dashed-line, respectively), and this deviation is increasing with \( T_{lab} \), when all the contributions to \( J = 0 \) are included (dashed-dotted vs. solid line), the results for the cross section for both potentials are very close.

For the reaction \( pn \rightarrow pp\pi^- \), the convergence rate of the partial wave series is not as uniform as for \( pp \rightarrow pp\pi^0 \) (Fig. 4). Although \( J = 0 \) is enough to describe
Table 1: The lowest partial waves for $pp \rightarrow pp\pi^0$. $S(S')$, $L(L')$ and $J(j')$ are the spin, the orbital momentum and the total angular momentum of the initial(final) $NN$ pair, respectively. $l'$ is the angular momentum of the pion relative to the final $NN$ pair.
Figure 2: Cross section for $pp \rightarrow pp\pi^0$. The dotted, dashed-dotted, dashed and solid line correspond to the cross section for the Bonn B NN potential and to all contributions up to $J = 0, 1, 2, 3$, respectively.

Figure 3: Effect of the $NN$ interaction on the convergence of the partial wave series for $pp \rightarrow pp\pi^0$. The dotted(dashed) line corresponds to the cross section for the first channel considered, $^3P_0 \rightarrow (^1S_0)s$ for the Bonn B (CD Bonn) potential. The solid(dashed-dotted) line corresponds to the contribution up to $J = 0$ for the Bonn B (CD Bonn) potential. The $\Delta$-isobar is not included.
the data close to threshold, the contributions with higher $J$ included underestimate the cross section, in particular for larger $T_{lab}$. The origin of this discrepancy may be the non-inclusion of the coupled $N\Delta$ channels, which play for sure an important role and must be included in a further analysis.

To sum it up: the S-matrix approach is successful in describing the cross section for $\pi^0$ and $\pi^-$ production. For both reactions, the convergence of the partial wave series is quite satisfactory and $J = 0$ is enough to describe the data close to threshold. If one includes all contributions with $J = 0$ (not just a single dominant channel), the results do not depend much on the choice of the $NN$ interaction. For charged pion production, in which the $\Delta$ is known to play a decisive role (in particular for $\pi^+$), a complete coupled-channel $N\Delta$ calculation will be needed to describe the data. Also, the S-matrix approach should be tested by more sensitive polarisation observables.

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Interaction of $K^-$-mesons with light nuclei

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Introduction

Low-energy $KN$ and $KA$ interactions have gained substantial interest during the last two decades. Data on the $K^-p$ scattering length $a(K^-p)$ from KEK [1, 2]

$$a(K^-p) = (-0.78 \pm 0.18) + i(0.49 \pm 0.37) \text{ fm},$$

and the DEAR experiment at Frascati [3]

$$a(K^-p) = (-0.468 \pm 0.090 \text{ (stat.)} \pm 0.015 \text{ (syst.)}) + i(0.302 \pm 0.135 \text{ (stat.)} \pm 0.036 \text{ (syst.)}) \text{ fm}$$

show that the energy shift of the $1s$ level of kaonic hydrogen is repulsive, $\text{Re } a(K^-p) < 0$. Nevertheless, it is possible that the actual $K^-p$ interaction is attractive if the isoscalar $\Lambda(1405)$ resonance is a bound state of the $KN$ system [4, 5]. A fundamental reason for such a scenario is provided by the leading order term in the chiral expansion for the $K^-N$ amplitude which is attractive.

Furthermore, very recently a strange tribaryon $S^0(3115)$ was detected in the interaction of stopped $K^-$-mesons with $^4\text{He}$ [6]. The width of this state was found to be less than 21 MeV. According to Ref. [7] this state can be interpreted as a candidate of a deeply bound state $(\bar{K}NN)^{2-0}$ with $I=1, I_z=-1$. It is clear that further searches for bound kaonic nuclear states as well as new data on the interactions of $\bar{K}$-mesons with lightest nuclei are thus of great importance.

The $K^-d$, $K^-^3\text{He}$, and $K^-\alpha$ scattering lengths and loosely bound $K^-$-nucleus states

Calculations of the $K^-d$ scattering length have recently been performed within the Multiple-Scattering Approach [8, 9, 10] as well as with Faddeev Equations [9, 11]. The results of Refs. [8] and [9] if using the same input are in good agreement. Moreover, the calculations of Barrett and Deloff [9] within the framework of Faddeev equations gave practically the same result as in the Multiple Scattering Approach, with the value for $A(K^-d)$ in the range $-0.75 \div 0.85 + i(1.10 \div 1.23) \text{ fm}$. 
In Ref. [12] the real and imaginary parts of the $\bar{K}^0d$ scattering length have been extracted from the data on the $\bar{K}^0d$ mass spectrum obtained from the reaction $pp\to d\bar{K}^0K^+$ measured recently at COSY [13]. Upper limits on the $K^-d$ scattering length have been found, namely $\text{Im}A(K^-d) \leq 1.3$ fm and $|\text{Re}A(K^-d)| \leq 1.3$ fm. It has also been shown that the limit for the imaginary part of the $K^-d$ scattering length is strongly supported by data on the total $K^-d$ cross sections. The results for the imaginary part of the $K^-d$ scattering length from Refs. [10] and [11] violate the upper limit found in Ref. [12].

The calculations of the $K^-\alpha$ and $K^-\bar{3}\text{He}$ scattering lengths have been performed using five parameter sets for the $KN$ lengths shown in Table 1. The results from a $K$-matrix fit (Set 1), separable fit (Set 2) and the constant scattering length fit (CSL) denoted as Set 3 were taken from Ref. [14]. We also study the CSL fit from Conboy [15] (Set 4). Recent predictions for $\bar{K}N$ scattering lengths based on the chiral unitary approach of Ref. [16] are denoted as Set 5.

<table>
<thead>
<tr>
<th>Set</th>
<th>Ref.</th>
<th>$a_0(KN)$[fm]</th>
<th>$a_1(KN)$[fm]</th>
<th>$A(K^-\alpha)$[fm]</th>
<th>$A(K^-\bar{3}\text{He})$[fm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>[14]</td>
<td>$-1.59 \pm 0.76$</td>
<td>$0.25 \pm 0.57$</td>
<td>$-1.80 \pm 0.90$</td>
<td>$-1.50 \pm 0.83$</td>
</tr>
<tr>
<td>2</td>
<td>[14]</td>
<td>$-1.61 \pm 0.75$</td>
<td>$0.32 \pm 0.70$</td>
<td>$-1.87 \pm 0.95$</td>
<td>$-1.55 \pm 0.90$</td>
</tr>
<tr>
<td>3</td>
<td>[14]</td>
<td>$-1.57 \pm 0.78$</td>
<td>$0.32 \pm 0.75$</td>
<td>$-1.90 \pm 0.98$</td>
<td>$-1.58 \pm 0.94$</td>
</tr>
<tr>
<td>4</td>
<td>[15]</td>
<td>$-1.03 \pm 0.95$</td>
<td>$0.94 \pm 0.72$</td>
<td>$-2.24 \pm 1.58$</td>
<td>$-1.52 \pm 1.80$</td>
</tr>
<tr>
<td>5</td>
<td>[16]</td>
<td>$-1.31 \pm 1.24$</td>
<td>$0.26 \pm 0.66$</td>
<td>$-1.98 \pm 1.08$</td>
<td>$-1.66 \pm 1.10$</td>
</tr>
</tbody>
</table>

Table 1: The $K^-\alpha$ scattering length from Ref. [17] and new results for $K^-\bar{3}\text{He}$, calculated for different sets of the elementary $\bar{K}N$ amplitudes $a(KN)$ ($I = 0, 1$).

The results of the calculations are listed in the last two columns of Table 1. These results are very similar for Sets 1–3. The $K^-\alpha$ and $K^-\bar{3}\text{He}$ scattering lengths are in the range $A(K^-\alpha) = -(1.8 \div 1.9) + i(0.9 \div 0.98)$ fm and $A(K^-\bar{3}\text{He}) = -(1.3 \div 1.8) + i(0.83 \div 0.94)$ fm, respectively. The results for Set 4 are quite different: $A(K^-\alpha) = -2.24 + i1.58$ fm and $A(K^-\bar{3}\text{He}) = -1.52 + i1.80$ fm. The calculations with Set 5 are close to the results obtained with Sets 1–3.

Unitarizing the constant scattering length, we can reconstruct the $K^-X$ scattering amplitude within the zero range approximation (ZRA) as

$$f_{K^-X}(k) = \left[A(K^-X)^{-1} - ik\right]^{-1},$$  \hspace{1cm} (3)

where $X = \alpha$ or $\bar{3}\text{He}$, $k = k_{K^-X}$ is the relative momentum of the $K^-X$ system. The denominator of the amplitude of Eq.(3) has a zero at the complex energy $E^* = E_R - i\Gamma_R/2 = k^2/(2\mu)$, where $E_R$ and $\Gamma_R$ are the binding energy and width of a possible $K^-X$ resonance, respectively. Here $\mu$ is the reduced mass of the $K^-X$ system.

In case of the $K^-\alpha$ system we find for Sets 1 and 4 a pole at the complex energies $E^* = (-6.7 \pm 18/2)$ MeV and $E^* = (-2.0 \pm 11.3/2)$ MeV, respectively. The calculations with Set 5 also result in a loosely bound state, $E^* = (-4.8 \pm 114.9/2)$ MeV. Similar results have been obtained for the $K^-\bar{3}\text{He}$ system. Note that assuming a strongly attractive phenomenological $KN$ potential, Akaishi and Yamazaki [18]
predicted a deeply bound $K\alpha$ state at $E^*=(−86−i34/2)$ MeV, which is far from our solutions. This problem can be resolved assuming that the loosely and deeply bound states are different eigenvalues of the $K\alpha$ effective Hamiltonian. Our model for the $K\alpha$ scattering amplitude is valid only near threshold, i.e. when $kA(K\alpha)\ll 1$. The ZRA cannot be applied for the description of deeply bound states when the pole of the scattering amplitude is located far away from the threshold. If the same procedure were applied to the $K^{-3}H$ system we would find a similar loosely bound state. This state together with recently discovered deeply bound state, the $S^0(3115)$, can be considered as different eigenvalues of the $K^{-3}H$ effective Hamiltonian. In any case it is very important to measure the $s$-wave $K\alpha$ scattering length in order to clarify the situation concerning the existence of bound $K\alpha$ states.

The $K^-\alpha$ FSI in the reaction $dd\to\alpha K^-K^+$

In Refs. [17, 19] it was argued that the reaction $dd \to \alpha K^-K^+$ near threshold is sensitive to the $K^-\alpha$ final state interaction. We calculated the $K^-\alpha$ invariant mass spectrum at excess energy 50 MeV. The result is shown in Fig. 1. The solid line shows the calculations for pure phase space, i.e. for a constant production amplitude and neglecting FSI effects. The dash-dotted and dashed lines show the results obtained for the $K^-\alpha$ FSI calculated with the parameters of Sets 1 and 4, respectively. All lines are normalized to the same total cross section of 1 nb. It is clear that the FSI significantly changes the $K^-\alpha$ mass spectrum.

![Figure 1: The invariant $K^-\alpha$ mass spectrum produced in the $dd\to\alpha K^-K^+$ reaction at excess energy 50 MeV. The solid line describes the pure phase space distribution, while the dash-dotted and dashed lines show our calculations with $K^-\alpha$ FSI for parameters of Set 1 and 4, respectively. The short-dashed line shows the result obtained using the modified $KN$ scattering lengths in nuclear medium.](image)

Akaishi and Yamazaki [18] argued that the $KN$ interaction is characterized by a strong $I=0$ attraction, which allows the few-body systems to form dense nuclear objects. The optical potential proposed by Akaishi and Yamazaki for deeply bound nuclear states contains the following effective $KN$ scattering lengths in the
medium: $a_{KN,\text{med.}}^0 = +2.25 + i0$ fm, $a_{KN,\text{med.}}^1 = 0.48 + i0.12$ fm. We used these modified scattering lengths to calculate the enhancement factor for the $K^-\alpha$ FSI in the $d\bar{d} \rightarrow K^+K^-\alpha$ reaction. The short-dashed line in Fig. 1 demonstrates a very pronounced deformation of the $K^-\alpha$ invariant mass spectrum. Such a strong in-medium modification of the $KN$ scattering length apparently can be tested at COSY.

References


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Physics at (Existing) Storage Rings with Electromagnetic Probes
The Da\(\Phi\)ne project

The INFN Frascati National Laboratory (LNF) in Italy is nowadays for various, important aspects the product of the efforts devoted to the Da\(\Phi\)ne project, started in 90’s. Three detectors have been built and have taken data at Da\(\Phi\)ne: a general purpose detector for particle physics, KLOE, a hypernuclear physics detector, FINUDA, and a detector for the investigation of low energy kaon-nucleon interaction, DEAR.

Da\(\Phi\)ne\(^1\) is an \(e^+e^-\) collider at the center of mass energy of the \(\Phi\) resonance, 1.02 GeV. The \(\phi\)-factory is a source of monochromatic, correlated kaon pairs; in fact, visible production cross section of the \(\Phi\) meson at this energy is about 3 \(\mu\)b and 83% of the decays are into kaon pairs while the remaining are 3-pion and radiative decays. Besides the measurement of neutral and charged kaon decays, the versatility of the Da\(\Phi\)ne project allows for a rich physics program, including measurements of kaonic atoms, hadronic cross section, radiative \(\phi\) decays and hypernuclei spectroscopy, among other topics. Many of the interesting processes have cross sections of O(100) pb or smaller. For such precision measurements the collider has been designed to achieve a luminosity exceeding \(10^{32}\) cm\(^{-2}\)s\(^{-1}\) and the detectors to provide thousands of well measured events per second.

In order to minimize beam-beam interactions, Da\(\Phi\)ne is constituted by two independent rings intersecting with a horizontal crossing angle of 25 mrad in two straight sections, the Interaction Regions (IR1 and IR2). A maximum of 120 bunches can be stored; however a gap of about 10 bunches is needed to get rid of the ions produced by the electron beam. The injection system includes the Linac, the intermediate damping ring and the 180-m-long transfer lines. The KLOE detector is permanently installed in IR1, while the DEAR and the FINUDA detectors share IR2. Two synchrotron-light beam lines for Infrared and X-rays are also operational.

The history of Da\(\Phi\)ne can be summarized through its achievements in terms of peak luminosity, reported in Fig.1. At present, typical Da\(\Phi\)ne currents in collision are \(\sim1.4\) A for positrons and \(\sim1.7\) A for electrons, in 109 bunches. With these values, a peak luminosity of \(1.26\times10^{32}\) cm\(^{-2}\)s\(^{-1}\) has been achieved. The performance has been obtained thanks to the continuous work aimed at increasing beam currents while keeping low background rates. Simulations and machine measurements have been used to understand beam dynamics and beam-beam interactions effects. Longitudinal bunch-by-bunch and transverse feedbacks are fundamental to operate with stable high currents. Both, optimization of beam parameters (e.g. orbit, linear and nonlinear dynamics), and hardware devices (e.g. scrapers and IR masks) are needed in order to keep low the background at the IR. The colliding currents, in spite of
the intrinsic sensitivity of beam dynamics at low energy, are comparable to those obtained at the B-factories. Coupling correction, tuning of the working point, lower IR beta functions and nonlinear dynamics studies have contributed to the present performance.

A summary of the delivered luminosities is in Tab.1, while Fig.2 shows the time sharing between KLOE, DEAR and FINUDA.

The DAΦNE complex includes also the Beam Test Facility (BTF)\textsuperscript{2} operational since November 2002, that is a beam transfer line capable to deliver electrons or positrons in a wide intensity range, from single particle up to \(10^{19}\) particles per pulse, and energy from few tens of MeV up to 750 MeV. The facility is particularly suitable for testing particle detectors, allowing energy calibration and efficiency measurements. In the last two years many experiments (e.g. AGILE, AIRFLY, APACHE, BTeV, CaPiRe, CRYSTAL, FLAG, LCCal, LHCb, MCAL, MEG, NANO, RAP, SIDDHARTA) carried out successfully the study of detector prototypes with different beam conditions in terms of intensity and energy.

**DEAR and SIDDHARTA experiments**

DEAR\textsuperscript{3} (DAΦNE Exotic Atom Research) is the experiment at DAΦNE devoted to measurements in the field of kaonic atoms. Strong interactions between kaon and proton are responsible of the different energy and width of the \(1s\) level on respect...
to the values due to the electromagnetic coupling. So far, the X-rays produced by the de-excitation of kaonic Nitrogen and kaonic Hydrogen have been studied by the DEAR apparatus, consisting of a gaseous target viewed by an array of 16 CCDs operating at 165 K with an energy resolution of 150 eV. Besides the pattern of kaonic Nitrogen transitions\(^4\) DEAR performed the most precise measurement of kaonic Hydrogen X-ray transitions to the 1s level (the K-complex), disentangling for the first time individual transitions (K\(\alpha\), K\(\beta\), etc). The accuracy of the DEAR results, achieved with 68 pb\(^{-1}\) of integrated luminosity in year 2002, was limited by the signal/background ratio, due to the slow, non-triggerable CCD detectors.

The SIDDHARTA\(^5\) (Silicon Drift Detector for Hadronic Atom Research) experiment will continue the research program initiated by DEAR, pushing the precision on the kaonic Hydrogen measurements to the eV level, and performing the first measurement on kaonic Deuterium. The antikaon-nucleon isospin dependent scattering lengths, of interest for \(\chi PT\), will be extracted using both, the Hydrogen and the Deuterium transition lines. The SIDDHARTA X-ray detectors, Silicon Drift Detectors (SDD) with energy resolution of \(140\) eV at 6 keV, will allow to trigger on the coincidences between positive kaons and X-rays at 1 \(\mu s\) level, improving the signal fraction in the data acquisition rate. Presently, the SDD detectors are being constructed and tested, and the related electronics is being designed. The SIDDHARTA program includes the measurement of kaonic Helium as well, and feasibility studies of the measurements on other exotic atoms. The SIDDHARTA data taking is scheduled during year 2007.

The status report on the kaonic atom program at DA\(\Phi\)NE has been presented by J. Marton at this Conference.

**FINUDA experiment**

FINUDA\(^6\) (FLsica NUcleare a DA\(\Phi\)NE) is the first hypernuclear physics experiment carried out at an \(e^+e^-\) collider. At DA\(\Phi\)NE A-hypernuclei are produced by the \(K_{\text{stop}}^+ + ^A Z \rightarrow \Lambda^A Z + \pi^-\) reaction. The low energy negative kaons from \(\phi\) decays are easily stopped by a thin (200 \(\div\) 300 mg/cm\(^2\)) nuclear target. The positive kaons, with opposite momenta, are used to tag the reaction and to trigger the experiment.
At present, after the end of the activities at KEK and at BNL, the only running hypernuclear factories are DAΦNE at LNF, and CEBAF at JLab. FINUDA is a high acceptance, high resolution magnetic spectrometer measuring the hypernuclear levels from the momentum spectra of the $\pi^-$ emitted in hypernuclear formation. The FINUDA detector is sensitive also to the charged particles and the neutrons following $\Lambda$ decays, thus performing studies on the hypernuclear decay modes. Two arrays of bi-dimensional Si-microstrips are placed before and after the target station for precise measurement of the kaon stopping point.

An integrated luminosity of about 250 $\text{pb}^{-1}$ has been collected during the 2002-2003 data taking, when $^6\text{Li}$, $^{12}\text{C}$, $^{27}\text{Al}$ and $^{51}\text{V}$ targets have been exposed to the $K^-$ beams. $^{12}\text{C}$ spectrum has been successfully measured, providing information on the spectrometer performance and improving the knowledge of the hypernuclear levels. $^6\text{Li}$ is unstable for proton emission and decays into $^5\text{He} + p$, or $^4\text{He} + p + n$, or $^3\text{H} + p + p$. The search for deeply-bound kaonic systems has been carried out with the Li-target data, which shows evidence of the formation of such bound states.

A new FINUDA run, with the collection of the order of 1 $\text{fb}^{-1}$ of integrated luminosity, is scheduled in year 2006. Trigger performance will be improved by the upgrade of the scintillator readout and new Be and H$_2$O targets will be installed to perform Be and O hypernuclear spectroscopy. The $K^-\Lambda p$ bound states could be confirmed on the basis of ten times larger statistics, and topics like non-mesonic $^3\Lambda\text{He}$ decays and the searches for neutron-rich hypernuclei will be addressed by the analysis of the new data set.

A detailed report on the FINUDA results has been given at this Conference by L. Benussi.

**KLOE experiment**

The KLOE (KLOng Experiment) experiment has been designed primarily for precise measurements of the Klong decays. Kaon pairs are produced at DAΦNE in a state with well defined quantum numbers (those of the photon) and are emitted almost back to back. These unique features allow for the determination of the nature of each produced kaon by looking at the decay of its companion in the opposite direction (tagging), as well as to perform quantum interferometry measurements. The research program of the experiment includes measurements of numerous decays of charged and neutral kaons, radiative $\phi$ decays, and the measurement of the hadronic cross section, among other topics.

The KLOE detector is composed of a large drift chamber and a hermetic electromagnetic calorimeter immersed in the 0.52 T field of a superconducting solenoid.

The requirements for the tracking system are very demanding to guarantee good resolution for low-momentum tracks and low absorption for photons over the large volume needed to have reasonable acceptance for the Klong decays, since the mean decay length of the Klong at DAΦNE is 3.4 m. The drift chamber, 2 m radius, 4.2 m length, for a gran total of 52140 stereo wires, provide a spatial resolution of 150 $\mu$m in the transverse plane while in the z-direction the resolution is about 2 mm. The requirement of high transparency poses severe constraints in the choice of materials and thickness of the chamber walls, in Carbon fibers. The drift chamber
is filled with a He-based gas mixture that has been chosen to reduce the effects of multiple scattering, photon conversion and kaon regeneration. The transverse momentum resolution $\sigma(p)/p$ is better than 0.4% for large-angle tracks.

The lead-scintillating fiber calorimeter was designed to detect with very high efficiency photons with energy as low as 20 MeV, and to accurately measure their energy and time of flight. Particularly relevant is the performance in terms of time resolution, which scales as $57 \text{ ps}/\sqrt{E(\text{GeV})}$. The calorimeter consists of the barrel and the end-caps; the modules of the end-cap are C-shaped to minimize dead zones, a solution which provides a solid angle coverage of 98%.

The $\phi$ production cross section is about 3 $\mu$b so that the event rate from $\phi$ decays at the reference luminosity of $5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ is 1.5 kHz, to which a similar yield of Bhabha events plus machine background and cosmic rays must be added. With an average event size of 2.7 kB, KLOE needs a data acquisition capable to handle with high efficiency a throughput of 10 Mbytes per second, a data processing environment with file servers providing a bandwidth of order of 100 MBytes/s, and a data storage in the Petabyte range. The high precision needed for the measurements requires a careful control of the systematics so that billions of well simulated events, including the most realistic description of the beam background, must be generated.

KLOE has demonstrated to fulfill the experimental requirements producing several important physics results with the $\sim 450 \text{ pb}^{-1}$ collected in years 2001-2002. These span from rare or medium-rare $K_S$ and $K_L$ decays$^{11}$ to charged kaon decays$^{12}$ and to the study of the nature of scalar and pseudoscalar mesons through radiative $\phi$ decays$^{13}$. In particular, the measurements of the semileptonic decays of charged and neutral kaons, and also the measurement of the $K^+ \rightarrow \mu\nu(\gamma)$ decay, together with a novel determination of the semileptonic form factors and with the improvement in precision of the $K_L$ and $K^+$ lifetimes will provide a more strict test of the unitarity of the first row of the CKM matrix. The preliminary results on this topic are summarized in Fig.3.

The $\Phi$ radiative decays to scalar mesons, the iso-scalar $f_0(980)$ and the iso-vector $a_0(980)$, have been searched for, respectively, in $\pi^0\pi^0\gamma$, $\pi^+\pi^-\gamma$, and in $\eta\gamma\gamma$ final states. Several models are being compared with data distributions based on large samples, of the order of $10^5$ events. The visible cross section for the $\Phi \rightarrow \eta(\eta')\gamma$ decays at DAΦNE is 40(0.08) nb and 40(0.08) millions of monochromatic $\eta(\eta')$ mesons are produced with 1 fb$^{-1}$ of integrated luminosity. The study of both, the charged, and the neutral decays is in progress. In particular, the dynamics of $\eta \rightarrow \pi^+\pi^-\pi^0$ is being investigated and the measurement of the branching ratio of the $\eta \rightarrow \pi^0\gamma\gamma$ showing a marginal agreement with the Crystal Ball results$^{15}$, is being finalized. Another important, published result is the measurement at the percent level of the $e^+e^- \rightarrow \pi^+\pi^-\gamma$ cross-section below 1 GeV which has relevant implications in the theoretical interpretation of the muon magnetic anomaly$^{16}$.

Perspectives

Since 1999 DAΦNE has delivered luminosity to the experiments with increasing performance. KLOE has collected 450 pb$^{-1}$ in years 2001-2002, DEAR 68 pb$^{-1}$ in 2002, and FINUDA 250 pb$^{-1}$ in 2003-2004. A second round of data collection has
started in May 2004 with the aim of delivering about 2 fb$^{-1}$ to KLOE within the end of 2005, 1 fb$^{-1}$ to FINUDA during 2006, and few hundreds of pb$^{-1}$ to SIDDHARTA in 2007. An accelerator experiment to exploit the Strong Radio Frequency Focusing concept is expected to enrich the know-how on the high-luminosity frontier of the meson factories in the same period. After these short-term achievements the mission of DANE, as it is, can be considered concluded.

Three possible options in a longer term perspective have been envisaged:

1. the optimization of DAΦNE operation, enriched by minimal upgrades needed to increase the beam energy from 0.51 to $\sim$1.2 GeV for the study of the $NN$ threshold. The facility could be commissioned in 2008. It fulfills the requirements of the proposal to study the nucleon form factors near threshold, of the continuation of the experiment on kaonic atoms, and of the hypernuclear spectroscopy on medium-high atomic-number nuclei with FINUDA. Such an option presents the best compatibility with the development of a Synchrotron Radiation user facility, and with the operation of the Beam Test Facility sharing the Linac;

2. the construction of a new Φ factory exceeding $10^{33}$ cm$^{-2}$ s$^{-1}$ in luminosity, possibly capable to reach the energy for the study of the $NN$ threshold as well. Integrated luminosities of at least 30 fb$^{-1}$ open the possibility to achieve new results in the field of kaon physics. In particular, the study of rare $K_S$ decays and $K_L-K_S$ interferometry represent the highlights of the particle-physics program of this option. The project could also be well suited for the experiment on the kaonic atoms and for the hypernuclear program with a modified FINUDA setup (FINUDA2) including Germanium detectors to perform high-resolution $\gamma$-spectroscopy for the measurement of the level structures with
energy resolution of few keV;

3. the construction of a $\tau$-charm factory ($\tau$F), running at $(3 \leq \sqrt{s} \leq 4)$ GeV, delivering an instantaneous luminosity of $10^{34}$ cm$^{-2}$ s$^{-1}$. The project, although challenging and slightly over-dimensional for the present LNF infrastructures, is less critical from the accelerator point of view than a $\Phi$-factory above $10^{35}$ cm$^{-2}$ s$^{-1}$. Discussions involving a wide community are needed in order to clarify the feasibility and the scientific interest of this machine, the least studied so far.

The discussion on the interest and the feasibility of the programs 1. and 2. has been issued in a dedicated workshop at Alghero in September 2003 and in several international conferences$^{18}$.

Accelerator design studies for the energy upgrade and the luminosity optimization of the $\Phi$-factory are advancing and should be finalized in the drafting of a Design Report by the end of 2005. Also the Letters of Interest for the continuation of the KLOE, FINUDA and SIDDHARTA programs should be circulated in the same period.

Conclusions

The experiments at DAΦNE are carrying out a broad physics program in the field of kaon physics and are performing measurements on kaonic atoms, hadronic cross sections, radiative $\phi$ decays, and hypernuclei spectroscopy as well.

The next three years will be crucial for the activities at DAΦNE, that will demand strong efforts in order to deliver the expected integrated luminosity of good-quality data, to maintain the detectors for a successful data taking, and to produce maximum scientific output from data analyses.

The discussion on new initiatives following the completion of the DAΦNE program is in progress with the aim to prepare in year 2006 a roadmap for the mid-term future.

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GeV photon beam experiments at the SPring-8 laser-backscattering facility

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A polarized high energy photon beam is produced by laser-induced backward Compton scattering on the electron beam of 100 mA and 8 GeV at SPring-8. Since 2000, the experiments have been running to study the particle and nuclear physics with this laser-electron-photon (LEP) beam of energy ranging from 1.5 GeV to 2.4 GeV. Some experimental results and the present status are reported.

6.2.1 INTRODUCTION

SPring-8 (Super Photon ring-8 GeV) in Nishiharima, Japan, is the third generation synchrotron radiation facility with the world’s highest energy. We have constructed a multi-GeV photon beam line dedicated to the particle and nuclear physics in one of its 62 beam lines, which is called LEPS (Laser-Electron Photons at SPring-8). The photon beam produced by means of laser-induced backward Compton scattering (BCS) from 8 GeV electrons has some advantages. One is the rather flat energy distribution with small spreading angles as shown in Fig. 1, where the BCS photon energy is calculated for a 351-nm laser. This is unlike the Bremsstrahlung beam which has huge high-intensity low-energy photons. We can measure forward angles even including $0^\circ$ with small radiative $e^+e^-$ backgrounds. Another advantage is the high polarization of photon beam. When the laser is fully polarized, the LEP is also nearly 100 % polarized at the maximum energy. The photon energy can be determined by tagging the recoil electrons using one of the bending magnets in the storage ring and position detectors.

Figure 1: BCS photons for the 351 nm laser and 8 GeV electrons. (Left) Energy of the BCS photon as a function of scattering angle. (Right) Differential cross section of the BCS photon.
There are three facilities in the world with such a high-energy laser-backscattering photon beam, LEGS at BNL, GRAAL at ESRF, and LEPS at SPring-8. These facilities cover the different energy regions (see Fig. 2). Figure 2 shows various threshold energies for meson-photoproductions and hyperon-photoproductions with $K$ and $K^*$. In the LEPS energy region ($1.5 \text{ GeV} \leq E_{\gamma} \leq 2.4 \text{ GeV}$), $\phi$ meson channel and some hyperon resonance channels, for instance, $\Lambda(1405)$ and $\Theta^+$ (penta quark) are open. Therefore some of the key words in the LEPS experiments are the forward angle measurements, polarization observables, and strangeness.

![Figure 2: Photoproduction threshold energies for mesons and hyperons.](image)

### 6.2.2 DETECTOR SYSTEM

The laser light is injected to the storage ring through several mirrors and the inverse Compton $\gamma$-rays come to the experimental hutch about 70 m downstream of the collision point between two bending magnets. The intensity of the beam is about $2.5 \times 10^6$ photons/sec for 5-W Ar laser. The tagging rate is typically $10^6$ Hz.

The LEPS forward spectrometer system is shown in Fig. 3. When a photoreaction occurs in the target, momenta and scattering angles of outgoing charged particles at forward angles are determined with tracking detectors (silicon-strip vertex detectors (SSD) and three multiwire drift chambers (DC1-3)) and a large dipole magnet. The TOF plastic scintillator wall is used to give the velocity information. A start counter for the trigger and a aerogel counter for the electron veto are located just downstream of the target. The detailed experimental setup is described elsewhere [1-3]. The first physics run started with a 50-mm thick liquid hydrogen target in 2000.
6.2.3 EXPERIMENTAL RESULTS

Photon beam asymmetry for the $K^+$ photoproduction

A new resonance structure around $W=1.9$ GeV was indicated in the cross section data of the $p(\gamma, K^+)\Lambda$ reaction at SAPHIR [4]. Moreover the new CLAS data suggested the possible existence of more than one resonance [5]. This stimulated the theoretical investigation and some new calculations were performed including missing resonances $D_{13}$ [6,7]. Since it is difficult to draw a strong conclusion on the existence of new resonances only from the cross section data, the LEPS collaboration has searched the missing nucleon resonance by measuring the beam polarization asymmetry of the $K^+$ photo-production off proton, which is sensitive to the different model calculations.

Figure 4: Missing mass spectrum for the $\gamma p \to K^+ X$ reaction.
Figure 4 shows the missing mass spectrum of the \( p(\gamma, K^+)X \) reaction. \( \Lambda(1116) \) and \( \Sigma^0(1193) \) peaks can be seen with clear separation and hyperon resonances \( \Sigma(1385)/\Lambda(1405) \) and \( \Lambda(1520) \) are also seen. The photon beam asymmetries (\( \Sigma \)) for \( \Lambda \) and \( \Sigma^0 \) have been obtained by taking data for both the vertically and horizontally polarized beam. The observed asymmetries are not reproduced by any existing theoretical calculations. Polarization observables are strong tools to pin down the missing baryon resonances. The detailed results and discussions are described in Ref. [2,3].

**Photoproduction of \( \phi \) mesons near the threshold**

The \( \phi \) photo-production near the threshold is one of the main subjects of the LEPS experiments at the first stage. Although at high energies the photo-production of \( \phi \) mesons is dominated by a Pomeron-exchange process based on the vector dominance model [8], other processes, like a meson (\( \pi, \eta \)) exchange, a scalar 0\(^{++}\) glueball exchange and \( s\bar{s} \) knock-out, possibly contribute at low energies. Since the meson exchange contribution is relatively small due to the OZI suppression in case of \( \phi \)-mesons, the \( \phi \) photoproduction is useful to get information on the exotic mechanisms like a glueball exchange. The decay angular distribution of vector mesons for the linearly polarized beam is an ideal observable to know the parity of exchange particles. If the decay plane is parallel to the polarization vector of photons, it indicates the natural-parity exchange, and if the plane is perpendicular, it shows the unnatural-parity exchange like \( \pi \) and \( \eta \).

![Energy dependence of \( (d\sigma/dt)_{t=-|t|_{\text{min}}} \). The LEPS data are represented by closed circles. The solid curve is a theoretical prediction including the Pomeron trajectory, \( \pi \) and \( \eta \) exchange processes [9].](image-url)
mesons are clearly identified by the $K^+K^-$ invariant mass spectra in both the $KK$-mode and $Kp$-mode detections for the hydrogen target. Differential cross sections obtained for each energy bin are fitted by an exponential function. The energy dependence of the differential cross sections at $t = |t|_{\text{min}}$ is plotted in Fig. 5. A peaking structure is seen around $E_y = 2$ GeV. Data are compared with the prediction of a model including the Pomeron exchange, $\pi$ and $\eta$ exchange processes [9]. The model calculation is inconsistent with the present data although it describes the data rather well at higher energies. The analysis of the decay angular distribution has shown the helicity-conserving natural-parity exchange contributions are still dominant in our energy range even for the local maximum region [10].

Until now the photo-production has been measured not only for the liquid hydrogen but also the liquid deuterium, and some nuclear targets (Li, C, Al, and Cu). The experiment with nuclear target and the associated analysis have been described in Ref. [11], where the modification of properties in nuclear medium is discussed.

**Search for the penta-quark $\Theta^+$**

The most exciting result in the LEPS experiments is the discovery of a candidate of exotic baryon resonance states with $S = +1$, which is now called $\Theta^+$. This state is first predicted by Diakonov et al. using the chiral soliton model [12] and found around the mass of 1.54 GeV with the width of less than 25 MeV in the missing mass spectrum of the reaction $\gamma n \rightarrow K^-\Theta^+ \rightarrow K^-K^+n$, after the correction for the Fermi motion of neutrons in the carbon target [13]. The LEPS result has been confirmed by more than a dozen of experiments in other facilities, although a lot of negative results are also reported with good statistics from high energy facilities. (e.g., see Ref. [14].) Very recently a shocking result has been reported from CLAS at Jlab. The new CLAS data for the $p \rightarrow K_S\Theta^+$ mode has shown no peak, which is inconsistent with the previous SAPHIR data.

We have continued the $\Theta^+$ search for the new data set using a 15-cm liquid D$_2$ target as well as a liquid H$_2$. They are analyzed in two mode. The first mode is the same as the previous one, $\gamma n \rightarrow K^-\Theta^+$ for neutrons in deuterons. After the $\phi$ exclusion cut, $\Theta^+$ still seems to exist in the $K^-$ missing mass spectrum after the Fermi-motion correction. The second mode is a new mode which is free from the correction for the Fermi motion. The $\Theta^+$ is identified by the $K^-p$ missing mass from the $\gamma + d$ reaction, especially for the $K^-p$ coming from $\Lambda(1520)$. The possible reaction mechanism is two step process, for example, at first $\gamma p \rightarrow \Lambda^*K^+$ occurs and then $K^+$ interacts with neutron to produce $\Theta^+$. In fact, $K^+$ momentum spectrum is soft for the forward-going $\Lambda(1520)$.

The invariant mass spectrum for $p + K^-$ detected by the forward spectrometer is shown in Fig. 6 for the $\gamma + d$ reaction. The $\Lambda(1520)$ peak is clearly seen above the non-resonant $pK^-$ background. Closed circles in Fig. 7 shows the missing mass distribution in the $d(\gamma, pK^-)$ reaction when selecting the $\Lambda(1520)$ region in the $pK^-$ invariant mass spectrum. In this mode the major background must come from the quasifree $\Lambda(1520)$ photoproduction, and its effect can be well estimated using the liquid H$_2$ data. Non-resonant $pK^-$ contribution to the missing mass in the $d(\gamma, pK^-)$ is estimated using the side-bands in Fig. 6. The line histograms in Fig. 7 correspond
Figure 6: Invariant mass spectrum of proton and $K^-$ for the $\gamma + d$ reaction. A peak corresponding to $\Lambda(1520)$ is clearly seen. Different dark areas show the peak region and side-band regions, respectively.

Figure 7: Missing mass distribution in the $d(\gamma, pK^-)$ reaction for $\Lambda(1520)$ region (closed circles). Three histograms are the quasifree $\Lambda(1520)$ production (lower), the missing mass for the side-band regions in Fig. 6 (middle), and the sum of both histograms (upper), respectively.

to these background contributions. Above the sum of estimated backgrounds, a significant peak is clearly seen around the mass of 1.53 GeV with the width of less than 10 MeV, which can be regarded as $\Theta^+$ in the $d(\gamma, \Lambda(1520))\Theta^+$ reaction. There also exists a broad excess around 1.6 GeV.

We plan to take more data with a time projection chamber (TPC-II) which covers a large acceptance and the 3-GeV LEP beam by using a short wave-length laser in order to study $\Theta^+$ in a wider kinematic region. When the $\Theta^+$ is produced via the vector $K^*$ meson production, decay asymmetry of $K^*$ may be useful to determine the parity of $\Theta^+$ [15].

**Other experiments**

Data taking of other several experiments has been completed, for example, the study for the non-charged meson resonances through the detection of $\pi^0$ or $\eta$ using a large solid-angle electro-magnetic (EM) calorimeter, which consists of 252 lead/SCFI (scintillating fiber) modules [16]. Hyperon resonances, especially $\Lambda(1405)$ have also been studied for a proton target [17] and nuclear targets, because the nature of $\Lambda(1405)$ is still mystery whether it is a $KN$ bound state or an SU(3)-singlet quark state. The nuclear-target experiment has just been finished using the time-projection chamber (TPC-I). The TPC-I has a very small bore (23-mm diameter) in order to detect the decay charged $\Sigma$ from $\Lambda(1405)$ for the separation of $\Lambda(1405)$ and $\Sigma(1385)$ [18]. They are still in analysis mode.
Physics at (Existing) Storage Rings with Electromagnetic Probes

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Introduction

FINUDA (Fisica NUcleare a DANE) is an non focusing magnetic spectrometer devoted to hypernuclear physics. The aim of FINUDA is to study simultaneously the formation and decay of hypernuclei produced by the strangeness exchange reaction induced by the stopped $K^-$ coming from the decay of the $\phi(1020)$ mesons produced at the DAΦNE $\phi$-factory. An hypernucleus is a many-body system composed of conventional (non-strange) nucleons and one or more hyperons ($\Lambda$, $\Sigma$, or $\Xi$). A $\Lambda$ hyperon embedded in a nucleus is stable for mesonic decay and strong interaction; therefore it survives for a while, maintaining its own identity among other nucleons. In addition it can deeply penetrate inside the nucleus since the Pauli principle is not effective due to the strangeness degree of freedom. For these reasons hypernuclei can provide invaluable information concerning the behavior of a baryon deeply embedded in nuclear matter. The FINUDA apparatus, described in detail in [1] and references therein, consists of an inner section surrounding the interaction-target region, an external tracker, an outer scintillator array and a superconducting solenoid providing a magnetic field of 1.0 T. The whole tracking volume ($\sim 8 \text{ m}^3$) is immersed in a He atmosphere to minimize Multiple Coulombian Scattering. The geometry of the spectrometer, the position of the detectors and the value of the maximum magnetic field have been optimized for maximizing the momentum resolution and acceptance for the prompt $\pi^-$ from hypernuclear formation $K_{\text{stop}}^+ + A Z \rightarrow A\Lambda Z + \pi^-$. For such $\pi^-$ (250-280 MeV/c), the design momentum resolution is $\Delta p/p = 3.5 \times 10^{-3}$ (FWHM), corresponding to a resolution of 830 keV in the hypernuclear energy levels.

Results on $^{12}\Lambda C$ hypernuclear spectroscopy

The first FINUDA data taking started on December 1st 2003 up to March 22, 2004. DAΦNE[2] delivered in total an integrated luminosity of 250 pb$^{-1}$, of which 33 were used for machine tuning, 10 for FINUDA detector debug, the useful data correspond to 190 pb$^{-1}$. The maximum daily integrated luminosity delivered to FINUDA was 4.0 pb$^{-1}$, with a maximum peak instantaneous Luminosity of $6 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1}$. The analysis started with a detailed study of the $^{12}\Lambda C$ hypernucleus, which will be used as a reference; the whole sample of $\sim 3 \times 10^7$ collected events has been processed selecting hypernuclear candidate events for the formation of hypernuclei by means of the following requirements selected to optimize the signal-to-noise ratio:
1) a negative track from a K⁻ (pion candidate), 2) a fitted track with 4 points in the spectrometer, 3) a forward track, i.e. not crossing back the interaction/vertex region, 4) the particle momentum reconstructed and corrected for the energy loss in the crossed materials, 5) quality cuts on track fitting. Background reactions giving a π⁻ following K⁻—Nucleus interactions have been simulated and the corresponding events have been reconstructed and selected following the same selection criteria of the data hypernucleus formation candidates. The obtained spectra are then converted into Λ binding energy spectra. Hence the shape background spectrum is parameterized and subtracted from the experimental one; the results is shown in Fig.1(a): two prominent peaks at \( B_\Lambda \approx 11\) MeV and 0 MeV correspond to the ground state \( (s_\Lambda) \) configuration and to the excited state of the \(^{12}\)C hypernucleus with the \( \Lambda \) in the p-shell \( (p_\Lambda) \). The FINUDA spectrum has been fitted with seven Gaussian curves all with the same sigma, fixed and set at \( \sigma_E = 550 \) keV (\( \Delta E = 1.29 \) MeV, \( \Delta p/p = 0.4\% \)), given by the peak at \( B_\Lambda = 0 \). In the fit the Gaussian widths were constrained to be the same and equal to \( \sigma_E \). The FINUDA fit result on \(^{12}\)C is compared (Fig.1(b)) with the result of experiment KEK-E369[3] which used the \((\pi^+, K^+)\) hypernuclear production mechanism: peaks \#1, \#2, \#5, \#6 in Fig.1(b), while in the region between peak \#2 and \#6 of FINUDA data does not match the data in E369 spectrum. The capture rate for \(^{12}\)C formation is \((1.01 \pm 0.11(stat) \pm 0.1(sys)) \times 10^{-3}/K_{stop}\) for the ground state and \((2.1 \pm 0.17) \times 10^{-3}/K_{stop}\) for the \(p_\Lambda\) state. The measured ground state capture rate measured by FINUDA agrees very well with the value \((0.98/\pm 0.12) \times 10^{-3}/K_{stop}\) measured at KEK [3].

**Study of kaon-bound \( K^-pp \) states**

The existence of \( \bar{K} \)-nucleus bound states crucially depends on the shape of the \( \bar{K} \)-nucleus optical potential. There is a controversial interpretation of existing experimental data from theoretical point of view; some authors deduce a shallow potential
while others [5, 6] claim it is very deep. If the K⁻-nucleus potential is as deep as 200 MeV K⁻-nucleus bound states could be experimentally visible. Recently Akaishi and Yamazaki [5] discussed the possibility of formation of discrete nuclear K⁻ bound states in few body systems and they derived a very deep K⁻ nucleus interaction. The resulting binding energies for these light systems are so large (≥ 80 MeV) that the main decay channel of the I=0 K⁻N pair to Σπ is forbidden; as a consequence the deeply bound state becomes narrow enough (∼ 20 MeV for the $^3\Sigma^+$ state) to be experimentally visible. Recently two experimental groups reported [7] possible signatures of deeply bound kaonic states but their results are still subject to some ambiguities about whether the K⁻ was really bound or not. FINUDA can measure directly the invariant mass of the bound system by detecting its decay products. Our initial study is focussed on the search for a deeply-bound $K^-pp$ system. When a K⁻ interacts with two protons, one expects, ignoring final state interaction, a hyperon-nucleon pair (+p, +N) to be emitted with a back-to-back angular correlation. Our analysis is focused on the search of Λp, back-to-back events and

Figure 2: backgroung subtracted momentum distribution of π⁻'s when in coincidence with (π⁻p) pairs with invariant mass matching the Λ mass.

is based on the following steps: i) selection of ppπ⁻ events; ii) selection of (π⁻p) pairs with invariant mass corresponding to the Λ mass; iii) selection of Λ − p pairs emitted with back-to-back opening angle (cos(θ_{open}) ≤ −0.86). The θ_{open} opening angle distribution between a Λ and a proton (not shown) is strongly peaked around cos(θ_{open})=−1, which clearly indicates that most of the Λp events are coming from an intermediate “K⁻pp” system almost at rest. If the reaction process were simply a two-nucleon absorption process, the mass of the system should be close to the sum of a kaon and two proton masses, namely 2.37 GeV/c², minus the separation energy of the two protons, which amounts to approximately 30 MeV. A significant mass decrease of the K⁻pp system is observed instead with a lot of strength accumulated below the K⁻pp absorption peak. The main background contribution coming from the $K^-pp \rightarrow \Lambda + p$ two nucleon absorption, which shows up as a peak at about 2.34 GeV, has been simulated and filtered with the same reconstruction cuts of the experimental data. The background was subtracted after normalizing it to the experimental data at the $K^-pp \rightarrow \Lambda + p$ absorption peak. The result is shown in Fig.2: the Λ − p invariant mass distribution is sensibly shifted toward lower values with respect to the absorption peak with two wide structures peaked at
about 2.290 GeV and 2.190 GeV, 50 MeV and 75 MeV wide respectively (Lorentzian fit). The higher peak can be interpreted as a $K^-p$ bound state, with a binding energy of approximately 90 MeV (value obtained without applying any acceptance correction). Events from $K^-p \rightarrow \Sigma^0 + p$ can contribute to the $\Lambda p$ invariant mass via the $\Sigma^0 \rightarrow \Lambda \gamma$ decay: they should still present a $p$ back-to-back correlation and the distribution should be shifted by $\sim 74$ MeV and broadened because of the missing $\gamma$.

Conclusion

In this proceeding have been presented some preliminary results from the analysis presently being performed on data collected at the DAΦNE $\phi$-factory with the FINUDA spectrometer. The first effort of the collaboration was put in the analysis of the $\Lambda$ hypernuclei formation on $^{12}$C. The analysis results compare well with the best existing literature data, which allowed us to prove FINUDA’s ability to perform high resolution hypernuclear spectroscopy. Data analysis on several different nuclear targets is under way. As to be underlined the capability of FINUDA to fully reconstruct multitrack events with high momentum resolution, which allows to dramatically reduce backgrounds and make exclusive measurements. Another topic presented regards the search for deeply bound kaonic nuclei. FINUDA have searched for $K$-bound ($K^-p$) states by studying the invariant mass of a possible decay channel, namely $\Lambda - p$ events emitted back-to-back. Although the analysis is not completed, (i.e. no acceptance corrections have been made), it can be stated that the $\Lambda - p$ invariant mass distribution presents a strong accumulation ($\sim 2290$) of strength below the $(K^-p)$ total free mass.

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Kaonic Atoms at DAΦNE: DEAR and SIDDHARTA

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Introduction

Precision measurements of X-ray transitions in hadronic atoms, like pionic hydrogen and kaonic hydrogen, are used to extract the meson-nucleon scattering lengths near zero energy. Whereas in the pionic hydrogen case high accuracy in the experimental observables (shift $\epsilon_1$ and width $\Gamma_1$ of the ground state due to strong interaction) is already reached, the kaonic hydrogen case is still waiting for high precision measurements. Furthermore, no experimental studies on kaonic deuterium were performed up to now. Therefore, the goal of the SIDDHARTA project (silicon drift detector for hadronic atom research by timing application) - which is the natural continuation of the DEAR project [1] - are precision measurements at the percent level of $\epsilon_{1s}$ and $\Gamma_{1s}$ in kaonic hydrogen as well as in kaonic deuterium. From these quantities the desired isospin dependent scattering lengths can be determined. In the light of experimental findings of deeply bound kaonic systems at KEK [2] and at FINUDA/LNF [3] the information about the $\Lambda(1405)$ sub-threshold resonance is important. This resonance is responsible for the repulsive character of the kaon-proton interaction [4] and is considered as doorway for the formation of kaonic nuclear clusters [5].

The DAΦNE electron-positron collider at Laboratori Nazionali di Frascati (LNF)
provides a unique source of negative kaons from $\Phi$ meson decay. With a branching ratio of $\sim 50$ percent nearly mono-energetic charged kaons are emitted back-to-back [6]. For the further stage of the experiment the correlation between the kaon pair and the X-ray will be used to efficiently suppress the background events. The combination of the unique features of DAΦNE and the new detector system will open the way to study the low-energy kaon-nucleon interaction at utmost precision.

Kaonic hydrogen

The principle of the DEAR experimental method to detect kaonic X-rays is straightforward. Kaonic atoms are produced by stopping negative charged kaons in a cryogenic gas target. The kaonic atoms are formed in high $n$ states. The subsequent electromagnetic cascade itself is a non-trivial interplay of different processes - radiative X-ray transitions predominantly take place in the last steps. The cryogenic gas target provides high density and therefore high kaon stopping efficiency and furthermore high yields of kaonic X-rays. This target volume is surrounded by an array of X-ray detectors characterized by high energy resolution and high X-ray efficiency. The DEAR experiment uses CCDs which fulfill these demands but background suppression is only possible by discriminating pixel clusters (clusters of more than 2 hit pixels) which are due to charged particles or high energetic $\gamma$ rays. The DEAR collaboration showed the functionality of the setup by measuring X-rays from kaonic nitrogen and succeeded in measuring X-rays from 3 kaonic nitrogen transitions for the first time [7]. After this proof of the experimental method, we measured the X rays emitted from kaonic hydrogen by using a cryogenic hydrogen target (density 3 percent of liquid density). Due to high X-ray background the careful study of the background data was important, see [8]. The analysis yielded the following values for the strong interaction shift and width : 

\begin{align}
\epsilon_{1s} &= -193 \pm 37(\text{stat.}) \pm 6(\text{syst.}) \text{eV} \\
\gamma_{1s} &= 249 \pm 111(\text{stat.}) \pm 30(\text{syst.}) \text{eV}
\end{align}

Our results verify the repulsive character of the interaction kaon-proton found in the KpX experiment at KEK [9] but we get smaller values and also smaller error bars.

These most precise results obtained up to now raised considerable interest and triggered new theoretical studies [10, 11, 12, 13, 14]. By using a relativistic field theoretical model [10] the DEAR data can be reproduced. On the other hand the careful analysis of scattering data and the DEAR data [12] finds $\epsilon_{1s}$ compatible with the DEAR result but finds larger values for the width.

SDDs and New Setup

In order to suppress the X-ray background efficiently new X-ray detectors SDDs providing timing capabilities are in development now. Large area SDD detectors (1 cm$^2$) exhibit high efficiency and energy resolution comparable with that of CCDs.
Figure 1: Comparison of the DEAR result with former experimental results obtained by X-ray spectroscopy of kaonic hydrogen. Indicated is also the precision goal of SIDDHARTA.

(~150 eV/66 keV). An array of ~200 SDDs will surrounding the target gas volume. By applying a triple coincidence (see fig. 2, left) we expect a background suppression by ~3 orders of magnitude, thus giving a signal to background ration of 10:1 for kaonic hydrogen and about 1:1 for kaonic deuterium (assuming a $K_\alpha$ yield of ~0.2). A new dedicated target-detector system is in development now. Monte Carlo studies of the X-ray spectrum of kaonic deuterium showing the kaonic deuterium X-ray spectrum (fig.2, right). For a measuring time of about 30 days about 3000 $K_\alpha$ events can be recorded thus opening the way to high precision measurements.

Figure 2: Scheme of triple coincidence to be applied in SIDDHARTA (left). Monte-Carlo simulation of kaonic deuterium $K$-lines (right) with a $K_\alpha$ yield of 0.2 percent.

Summary and Outlook

DEAR was one of the first experiments at DAΦNE showing the successful production X-ray spectroscopy of kaonic atoms. After the study of kaonic nitrogen X-ray a measurement of the kaonic hydrogen spectrum was successfully performed yielding the most precise values for $\epsilon_{1s}$ and $\Gamma_{1s}$. Large area SDDs and a newly designed setup are in development now. A new precision experiment on kaonic hydrogen and the first ever on kaonic deuterium are envisaged in the framework of the SIDDHARTA
project. Furthermore, within SIDDHARTA measurements on kaonic helium isotopes and a feasibility study of sigmaonic atoms are planned.

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Results on Deeply Virtual Compton Scattering at HERMES

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We report our latest results on single-spin and beam-charge azimuthal asymmetries in the hard electroproduction of photons at the HERMES experiment using 27.6 GeV HERA positron/electron beams. The asymmetries are attributed to the interference of the Bethe-Heitler and deeply virtual Compton scattering (DVCS) processes. The single-spin and beam-charge asymmetries have been measured for unpolarized/polarized hydrogen and deuterium targets which can give access to the DVCS amplitudes of protons and neutrons. The DVCS process can be described in terms of generalized parton distributions (GPDs). A new recoil detector will be installed in the HERMES experiment in 2005 which will improve the kinematic resolution by detecting the recoil proton in the DVCS process.

1. Introduction

Recent interest in hard exclusive processes has resulted from the theoretical description of these processes in terms of the Generalized Parton Distribution (GPD) formalism [1-2]. This formalism offers a consistent description of nucleon structure. It incorporates as limiting cases the well-known nucleon form factors determined from elastic scattering as well as parton momentum distributions (PDFs) determined from measurements of inclusive and semi-inclusive deeply inelastic lepton-nucleon scattering (DIS). Interest in the GPD framework has also been motivated by the fact that the unknown total angular momenta of the quarks and gluons within the nucleon are encoded in the GPDs [3]. The latter allows in principle access to the orbital angular momentum of the quarks using the knowledge of their intrinsic spin contribution to the nucleon’s spin.

One of the theoretically cleanest channels with which to probe GPDs is Deeply-Virtual Compton Scattering (DVCS), in which a highly virtual photon is absorbed on a parton within the target, which produces a single real photon in the final state, along with the intact recoiling nucleon (nucleus).

2. DVCS measurement at HERMES

Measurement of the DVCS process is intrinsically mixed with that of the Bethe-Heitler (BH) process, in which a real photon is radiated by the incoming or outgoing lepton rather than the quark. The cross section for the leptoproduction of real photons is therefore proportional to the square of the sum of the amplitudes:

$$d\sigma \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{BH}^{*}\tau_{DVCS} + \tau_{DVCS}^{*}\tau_{BH}$$

At HERMES kinematics the BH process dominates over DVCS in the cross section. However, the DVCS amplitude can be studied via the interference term by measuring various cross section asymmetries and their dependences on the azimuthal
angle $\phi$, defined as the angle between the lepton scattering plane and the photon production plane. The interference term $\tau_{cBH}^c BH + \tau_{DVCS}^c BH (I)$ can be written in a series of Fourier moments in $\phi$ [4]

$$I \propto \pm \left( c_0^c + \sum_{n=1}^{3} c_n^c \cos(n\phi) + \sum_{n=1}^{3} s_n^c \sin(n\phi) \right)$$

where sign $+(-)$ stands for the electron(positron) beam, $c_0^c$, $c_n^c$ and $s_n^c$ are given by a linear combination of the Compton form factors (CFFs), which in general depend on the beam helicity and target polarization. The CFFs can be expressed as convolutions of coefficient functions with the GPDs.

By flipping charge and helicity of the beam, HERMES accesses correspondingly the real and the imaginary part of the CFF $H$ while the imaginary part of the CFF $eH$ can be determined by flipping only the target helicity. The expressions for the beam-charge asymmetry (BCA), beam-spin asymmetry (BSA) and longitudinal target-spin asymmetry (LTSA) in leading order and leading twist are

$$d\sigma(e^+p) - d\sigma(e^-p) \simeq \cos(\phi) \text{Re}H$$
$$d\sigma(\bar{e}^+p) - d\sigma(\bar{e}^-p) \simeq \sin(\phi) \text{Im}H$$
$$d\sigma(e^+\bar{p}) - d\sigma(e^-\bar{p}) \simeq \sin(\phi) \text{Im}\bar{H}$$

(3)

It should be noted that HERMES is the only experiment which measures BCAs due to its unique ability to flip between electrons and positrons.

HERMES is an internal target experiment in the 27.6 GeV electron or positron beam at HERA[5]. In order to extract the above mentioned asymmetries from the data, events were selected if they contained one photon and one scattered lepton track. Photons were identified by the energy deposition in the calorimeter and preshower counter in the absence of a track. The following requirements were imposed on the lepton kinematics $Q^2 > 1 \text{ GeV}^2$, $W > 3 \text{ GeV}$. The opening angle $\Theta_{\gamma\gamma}$ between the virtual and real photon was limited to a range of 5 to 45 mrad.

Since the recoiling nucleon (or nucleus) was not detected, the exclusive DVCS events were selected imposing an additional constraint on the missing mass $M_x$. The exclusive region was defined as $1.5 < M_x < 1.7 \text{ GeV}$ (negative $M_x$ values are obtained as a consequence of the finite energy resolution of the spectrometer).

3. Azimuthal asymmetries from HERMES

Azimuthal asymmetries with respect to the beam spin have been reported on hydrogen [6] as well as on deuteron [7]. The $\phi$ dependence of the beam-charge asymmetry $A_C$ for the deuterium target is shown in Fig.1 (left), together with the results of the fits to the data. One sees the expected $\cos\phi$ behavior. The comparison of the $\cos\phi$ amplitudes $A_C^{\cos\phi}$ on deuterium and hydrogen derived from the fits in four bins in $-t$ (the square of the four-momenta transfer to the target) are shown in Fig.1 (right). For both targets, the amplitudes become sizable only at higher values of $-t$. The effect from the coherent scattering on the deuteron could be expected in the first $-t$ bin, but are not apparent. The difference in asymmetries at large $-t$ values can be explained by the contribution from the incoherent scattering on the neutron inside the deuteron. The data are compared with different model predictions [8,9].
asymmetry $A_C$ for the hard exclusive electroproduction on target (left). For small $|t|$ the $\cos\phi$ amplitudes for proton and deuteron are similar (right).

Dependences of the longitudinal target-spin asymmetry and deuteron targets. In Fig.3 the extracted $-t$ amplitudes for both the proton and deuteron targets. In case of $A_{UL}^{\sin 2\phi}$ all models show disagreement, which can be explained by the fact that only the Wandzura-Wilczek twist-3 contribution to this amplitude.

$$A = s_0 + s_1 \sin \phi + s_2 \sin 2 \phi$$

Figure 1: Beam-charge azimuthal asymmetry $A_C$ for the hard exclusive electroproduction of photons from deuterium target (left). For small $|t|$ the $\cos\phi$ amplitudes for proton and deuteron are similar (right).

Figure 2: Longitudinal target-spin azimuthal asymmetry $A_{LU}$ for the hard exclusive electroproduction of photons from hydrogen (left) and deuterium (right) targets.

In 2005 HERMES will install a recoil detector around the HERMES gas target which will enable us to detect the recoil proton in DVCS processes [10] and thus distinguish them from events with resonances in the final state.

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Figure 3: Comparison of the t-dependences of $A_{UL}^{\sin \phi}$ (left) and $A_{UL}^{\sin 2 \phi}$ (right) for hydrogen and deuterium targets with model predictions from [8-9].

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Atomic and Nuclear Physics
Recent Achievements and Future Mass Measurements in Storage Rings

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Abstract: A unique method of fast Mass Spectrometry of Individual Ions is described. The revolution time of a single ion circulating in the isochronously tuned storage ring can be precisely measured, and the mass of a nuclide with a half-life down to $10^2$ s can be directly determined. A rich harvest of masses for exotic nuclides, even some hitherto unknown, has been obtained. Many of the measured nuclides are situated along the expected path of the astrophysical r-process. The unprecedented potential of this method can be used in planned storage rings.

Introduction

Over the last decades, storage rings have become unique installations, providing fascinating results in fundamental research. They still have unexhausted potential to be at the forefront of research in the future. The FAIR (Facility for Antiproton and Ion Research), proposed at GSI \cite{1}, addresses multidisciplinary investigations through the use of storage rings. As the new facility could provide an increase in secondary radioactive beam intensity by a factor of $10^5$, the unique breakthroughs in the regions of extremely exotic nuclides up to borderlines of existence is expected.

The project ILIMA \cite{13} within the framework of FAIR, dedicated to measurements of masses and half-lives for very exotic nuclides, has been triggered by abundant achievements in the storage ring ESR at GSI during the last few years.

The storage ring provides the attractive opportunity to distinguish masses of circulating ions by their revolution frequencies. Two ingenious methods have been pioneered at GSI: Schottky mass spectrometry of cooled revolving ions \cite{3, 4} and TOF measurements of uncooled ions running in an isochronously tuned storage ring \cite{5, 6}.

The aim of this article is to elucidate those recent achievements in the domain of mass measurements at the ESR, which may pave the way and provide key links to the next generation facilities which are planned in the world.

Mass Spectrometry of the Individual Ions (MSI$^2$)

Basics of MSI$^2$ in the Ring Lattice

Two individual ions with different mass-to-charge ratios $m/q$ injected into the ring will circulate there with differences in their revolution times given in the first order by the equation \cite{7}:

$$\frac{\Delta t}{t} = \frac{1}{\gamma^2} \frac{\Delta (m/q)}{m/q} + \left( \frac{\gamma^2}{\gamma^2 - 1} \right) \frac{\Delta v}{v}.$$
This equation gives the basic relations between the properties of a storage ring setting (transition point $\gamma_l$) and the properties of individual ions that are circulating in the ring ($m/q$, $t$, velocity $v$, and the Lorentz factor $\gamma$).

The revolution time becomes a direct measure of the $m/q$ value when the second term in the given equation is much smaller than the first term. The second term can be decreased by reducing the relative velocity difference to a value of $10^{-6}$, or by tuning the storage ring in such a way that the ring transition point $\gamma_l$ becomes close to the Lorentz factor $\gamma$.

The first method has been performed by the beam-cooling in Schottky Mass Spectrometry (SMS) [4]. The second approach was proposed for a storage ring in [5] and has been implemented recently at ESR [6].

Radioactive ions of many different $m/q$-values produced on the external target populate the interior of the storage ring. The multicomponent beam stored in the ring is a prerequisite for an "in situ" spectra calibration. The SMS, which uses the cooling method, is restricted in time with a lower limit of $\approx 5$ s. About 10 additional seconds are required to detect the frequency signal of a single ion by pick-up probes after many averages. Therefore, this method is slow and acceptable only for relatively long-lived nuclides. The most favored condition for this method occurs when a large number of ions of fixed $m/q$ are present, so that a good Schottky signal may be observed and the frequency peak position may be deduced with high precision. Indeed, a rich harvest of masses measured by SMS belongs to relatively long-lived nuclides (see the last presentation of measured data in [8]). Meanwhile, the mass surfaces for heavy short-lived exotic neutron-deficient nuclides have been determined mainly by a synergetic combination of directly measured mass data with the known $\alpha$-decay energy surface [9].

One can ask whether we need faster mass-spectrometry. Half-life and production yield graphs towards the drip-lines (see, e.g., [1]) show that both quantities simultaneously decrease quite considerably. Fig.1 presents the behavior for nuclides of three elements from different mass areas. As can be seen in this figure, the nuclides with unknown masses (in the grey area) have small production cross-sections and, as a
rule, have half-lives shorter than the cooling limit of 5 s. Only very heavy nuclides are still accessible with SMS, however, their production cross-sections are small (1 µb level, shown in Fig.1, corresponds to one produced ion per spill of injected beam into ESR). Therefore, further advancement to exotic nuclides will require the development of a fast method which, at the same time, should serve for measurements of individual nuclides.

![Diagram](image)

Figure 2: Information flow from signal of individual ions to mass spectrum.

**Fast Mass Spectrometry of Individual Ions at the Storage Ring**

As we are trying to measure the revolution time for individual ions, the detector should produce a signal which exceeds the background during a short measurement time. Such a detector was constructed [10] and used for mass measurements of uncooled ions [6].

The ion circulating in the ring repeatedly passes through a thin carbon foil mounted in the ring aperture. Electrons produced at any passage are isochronously guided by crossed electric and magnetic fields onto two microchannel plates installed on both sides of the foil. The signal-to-noise ratio for each turn (corresponding to ≈0.5 µs for ion energy of 400 A·MeV) already exceeds a factor of ≈5 for this detector, which opens the way for the detection of very short-lived individual nuclides. As the ion is relativistic, the energy losses in a foil with thickness ≈20 µg/cm² will not strongly change the revolution time during hundreds of turns (≈ hundreds of µs) after which because of energy loss, multiscattering and charge-exchange processes, the ion can be lost.
Is this short time span sufficient for precise measurements? In order to answer this question, let’s estimate the mass resolution for this MSI. As the best time resolution of the TOF-detector was determined to be \( \approx 50 \) ps [11], one can deduce mass-resolution \( \Delta m/m = 3 \times 10^{-4} \) for one ion per one turn. For one thousand turns one can expect a value of \( 10^{-5} \), which has been achieved in the latest experiments [11].

The revolution time becomes a measure for the masses of many individual ions if they circulate in the same orbits (with the same magnetic rigidity). An isochronously tuned storage ring will provide the recurrence of revolution times for different ion spills, which should increase the statistical precision. Individual ions of the same nuclide injected with different velocities in one-by-one spills will circulate with the same time in the isochronous conditions \( \gamma = \gamma_t \) [5, 12].

Thus, the combination of the TOF-method with the isochronously tuned storage ring provides a fast (down to \( \approx 10 \) \( \mu \)s) Mass Spectrometry of Individual Ions. This system has been tested in the late 1990’s [6], and the first results on mass measurements in light neutron-deficient nuclides have been presented in [13]. The main remarkable observation of these investigations was that only a small part of the injected ions was circulating in the isochronous mode. For this region of \( m/q \)-values the relative changes of revolution times correspond to \( \Delta \tau/\tau \leq 10^{-5} \).

To expand the high precision to unisochronous mode, it was originally proposed [14] that \( \Delta v/v \) would be determined for each ion either by measuring the ion flight-time over the injection and/or over an ejection flight path, or by injecting only ions...
with equal $\Delta v/\gamma$ by using, e.g., accelerating or deflecting RF-cavities.

Information handling from signal to mass spectrum for fast MSI$^2$ is shown in Fig. 2. Here the flow of information starts at the TOF-detector, proceeds through the stamping and tracing of signals, then progresses to the determination of revolution times for individual ions and ends by determination of a histogram deduced from one-by-one beam spills into the ESR. This is followed by a mass identification and unknown mass direct determination with an internal calibration in the mixed spectrum, containing nuclides with known and unknown masses.

**Mass Measurements by the Fast MSI$^2$**

First experiments with $^{84}$Kr-fragments [13, 15] yielded measured mass values for some of the neutron-deficient nuclides in the medium-weight region. New masses for $^{48}$Mn and $^{68}$As (out of 10 measured) have been determined with a precision of 100 keV.

However, the first extensive measurements with the fast MSI$^2$ have been performed recently [16, 17] in order to determine the masses for exotic neutron-rich nuclides. Ions of $^{70}$Zn and $^{238}$U with relativistic energies of $\approx 400$ A MeV and intensities of $\approx 10^9$ per spill from SIS-18 were shot onto a Be-target. Inverse reaction products have been roughly separated in-flight by the Fragment Separator (FRS) [18] and single ions of a large m/q variety injected into the ESR. Thus, in the zinc-fragmentation single ions of 102 nuclides have been identified, whereas in the uranium-fission the number of observed nuclides was 280. The nuclide with the shortest half-life identified in the spectra was $^{14}$B (14 ms). The broad band TOF-spectrum of individual ions from uranium fission for one of the fixed Bp-settings is shown in Fig. 3. Zoomed spectra, corresponding to two parts of the isochronous region of the spectrum, are shown as well. They represent the histogram of revolution times for individual ions collected from different beam-spills with a measurement time of 100 $\mu$s on average. Altogether the masses for 45 exotic neutron-rich nuclides in the half-life interval from 0.1 s to 2 s have been determined for the first time [11].

The high potential of the fast MSI$^2$ method is also demonstrated by the determination of mass values for one dozen of exotic isotopes of Zn, Se, Mo, Ru, Rh, Pd, Te and La with unknown properties. The nuclides $^{82}$Ga, $^{83}$Ge, $^{85}$As and $^{86}$As, whose masses have been measured for the first time, are situated beyond the $^7$ waiting...
Impressive results were obtained for products of Zn-fragmentation [16]. Fig. 4 shows that the expected r-process path just intercepts many measured nuclides (grey squares). This path has been determined with the assumption of fulfillment of the steady flow concept and in accordance with the probabilities of transformation (experimental β-decay and empirical nγ-rates) [19] nuclide by nuclide.

The determined path fits the population of potential "r-process only" stable nuclides well and corresponds to astrophysical conditions: a temperature $T_9 \approx 1$ and a neutron density of about $10^{21}$ cm$^{-3}$. On the other (neutron-deficient) side of the chart of the nuclides, measured nuclides are intercepted by the rp-process path [15].

A surprising result was obtained when values measured directly by fast MSI$^2$ [17] were compared to previously known data [20]. As can be seen from Fig. 5 there are differences for many nuclides. Such big discrepancies have been observed also in Penning-trap measurements [21, 22] (see figure). Since the information on the masses of heavy neutron-rich nuclides in [20] is drawn up mainly from indirect measurements by means of β-decay spectroscopy, it should be used cautiously.

Figure 5: Deviations of measured mass values from Atomic Mass Evaluation (AME)-data [20]. The data from Penning-trap measurements of [21] in the mass region $A\approx 100$ and of [22] in the mass region $A\approx 150$ are also shown. Error bars on the picture include both measured errors and ones evaluated by AME.
Conclusions

Fast Mass Spectrometry of Individual Ions is presented by TOF-measurements of circulating nuclides in the isochronously tuned storage ring at GSI. Being extremely sensitive, this method allows the direct mass measurement of single ions with half-lives down to $\approx 10 \, \mu s$, which paves the way to extremely exotic nuclides situated very far off the $\beta$-stability line. The fast MSI$^2$ method contrasts sharply with other MSI$^2$ that also deal with individual nuclides, such as SMS and Penning Trap (PT), which are slow MSI$^2$. SMS has time restrictions ($\geq 10 \, s$) because of cooling and measuring times, whereas TP needs some time ($\geq 100 \, ms$) for measurement of a ”resonance curve”. Therefore, the fast MSI$^2$ turns this method into unique tool for direct precise mass measurements and opens a new chapter in nuclear mass-spectrometry.

The unprecedented potential of fast MSI$^2$ is demonstrated by the measurements of exotic short-lived nuclides, some of which were hitherto unknown. Many of the measured nuclides are situated at the expected r- and rp-process paths.

Figure 6: A sketch of the storage rings that will be used in the ILIMA-measurements and the reachable regions for mass measurements in the chart of nuclides.

Outlook

Fast MSI$^2$ is well suited to the new project ILIMA (Isomeric beams, Lifetimes and MAsses) [13]. The main feature of the installation is that the function of ESR will be split among the two storage rings, one of which, CR, will be used for isochronous
tuning and stochastic pre-cooling, whereas the other ring, NESR, will be used for subsequent electron cooling of the ionic beam (see Fig.1). A TOF-detector will be installed inside the CR. SMS will also be used for mass and half-life measurements of relatively long-lived nuclides. The production of pure relativistic high spin beams for reaction studies in the internal target in NESR is also foreseen. A rich harvest of \( \approx 1500 \) new masses can be gathered by these two methods and new physics properties can be discovered.

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References


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Determination of Nuclear Ground State Properties with Large Atomic Cross Sections – Isotopic Shift Measurements by Means of Dielectronic Recombination

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In August 2005 a pilot experiment of isotopic shift measurements with Li- and/or Be-like (3 or 4 electrons) neodymium ions is scheduled at the heavy-ion storage ESR of GSI. A novel technique which makes use of the unique properties of the atomic electron-ion collision process of dielectronic recombination (DR) will be employed. In this contribution a brief description of this novel approach and its implementation at the electron cooler of the ESR will be given.

In the literature several techniques for the determination of nuclear charge radii can be found. Among these are: elastic electron scattering [1, 2], the spectroscopy of muonic atoms [3], optical [4, 5] or X-ray spectroscopy [6, 7]. In many cases the different approaches yield values for the nuclear rms charge radii, which are not in agreement with each other. Therefore, great effort has been spent to produce a consistent set of nuclear rms charge radii from a combined analysis of the different methods as published, e.g., in [8, 9, 10, 11]. A review about the different techniques, extensive tables and further references can be found in the literature cited above.

The utilization of DR of highly-charged few-electron ions for the study of nuclear-size effects is a novel alternative to the these methods. For \( Z > 50 \), a precision comparable with those of the established methods can be expected. Utilizing the electron cooler of a heavy-ion storage ring as a target for free electrons, the collision kinematics between the co-propagating cooler electrons and the stored heavy-ions leads to a high precision and a high resolution, in particular for low collision energies (\( E_{\text{cm}} \lesssim 1 \text{ eV} \)). Moreover, the large atomic DR cross sections and the 100\% detection efficiency for the recombined ions allows for the performance of DR measurements with sufficient counting statistics even with as few as \( \sim 10^4 \) stored ions. Special emphasizes should be given to the possibility to access also radioactive species if their lifetime is sufficiently long to cool these ions (\( \sim 10 \text{ s} \)). The new opportunities at FAIR, with high production rates of radioactive ions from the SuperFRS and a dedicated electron target at the storage ring NESR [12, 13], will furthermore increase precision and range of accessible species.

DR is a two-step resonant electron-ion recombination process where in the initial radiationless dielectronic capture (DC; time-reversed autoionization) a doubly excited intermediate state is formed. If, in a second step, this intermediate state decays radiatively below the autoionization threshold, DR is completed. DR experiments at storage rings are fundamentally different from classical spectroscopic methods, as no photons are detected (‘spectroscopy without a photon in sight’). In fact, resonance spectra are obtained by detecting the recombined ions, produced by
the resonant capture of the cooler electrons. Correspondingly, an increased rate of recombined ions is detected at relative electron-ion energies equal to the DR resonance energies. At the ESR electron cooler, the desired energy difference between the collision partners is introduced by applying a sequence of voltages to a drift tube in the overlap region of the two beams, thus changing the energy of the electrons. Energy calibration is associated with a determination of the electron accelerating voltages in the cooler and is independent of any calibration lines. In particular, if an s-core-electron is excited during the initial dielectronic capture (DC) process, the comparatively large overlap of atomic and nuclear wavefunctions leads to strong nuclear-size contributions. In L-shell ions (Li-like, Be-like . . . ) isotopic shifts of DR resonances associated with 2s → 2p core excitations range from a few meV for Z = 50 up to several hundred meV in uranium [19]. In DR, nuclear-size effects do not lead to a shift of a single transition, but to a shift of a complete resonance pattern with typically more than 50 well resolved resonance structures, partially on the level of the natural linewidths [14].

In the last decade, measurements of DR at heavy-ion storage rings have evolved into a well established tool for the investigation of atomic structure and collision dynamics of highly-charged heavy-ions, i.e. of relativistic and QED effects [15, 16, 17]. E.g., for the Li-like ions 197Au76+, 208Pb79+ and 238U89+ we succeeded to determine the 2s1/2 − 2p1/2 splitting (‘Lamb-shift’) with high precision. In these measurements, the resonance energies of the doubly excited autoionizing states, formed during the initial DC, were extrapolated to the series limit. The series limit of the associated 2p1/2 nl Rydberg states directly corresponds to the energy of the underlying core excitation 2s1/2 = 2p1/2. With this method a statistical uncertainty of about 0.030 eV and a systematic error of 0.070 eV could be obtained. In total, the experiment is about a factor of 2–3 more accurate than the best available QED calculations [18]. The biggest uncertainties in the calculations stem from yet uncalculated higher-order QED contributions as well as from experimental errors for the charge radius of the nucleus. As an example, for 238U89+ we could obtain for the energy splitting ∆E(2s1/2 − 2p1/2) = 280.516(34)(65) eV. The total contribution to this transition energy, which results from the finite size of the nucleus is calculated to be 33.35(7) eV (about 12 %) [18]. This uncertainty of 70 meV includes the error of the experimental value for the 238U nuclear charge radius of <r2>1/2 = 5.8604(23) fm [3] and a model uncertainty (for details see [18]). Solely from these numbers, the sensitivity of DR of L-shell ions to the nuclear charge radius is apparent. Provided that higher QED contributions will be available in the future, DR measurements could be a competitive approach to obtain charge radii even on an absolute scale. For relative measurements like isotopic shift measurements the changes of QED contributions along an isotopic chain can be neglected in most cases. At the same time, also experimental uncertainties largely cancel out. Due to the simplicity of the electronic structure, no distinct DR calculations have to be performed for the evaluation of the DR spectra with respect to isotopic shifts. The change in the nuclear radius can directly be deduced from the energy shifts of the resonances by applying the formulae from [19]. In addition, for the L-shell systems under consideration a reliable and well tested theoretical description of the DR process is available. DR rate coefficients calculated in a fully relativistic Multi-Configuration Dirac-Fock (DR-MCDF) approach
Figure 1: DR of Li-like $^{89+}$ in the energy range of the $1s^22p_{3/2}5l_{5/2}$ resonance group [21]. In addition to the experimental results (full circles) calculations from Steih et al. [22] for two different charge radii are displayed. Please note that the rate coefficients for experiment and theory are on independently absolute scales. Besides a shift of -0.4 eV, no fitting of the theoretical curves to the data points has been performed. In the calculations the literature values $\langle r^2 \rangle_{142}^{150} = 5.86$ fm for the uranium isotope $^{238}$U (full line) as well as $\langle r^2 \rangle_{142}^{150} = 5.81$ fm for the isotope $^{233}$U (dotted line, grey area) are assumed [3].

show an excellent agreement with the experiment (Fig. 1). In order to visualize the isotopic effect for DR (volume shift only) the calculations for $^{89+}$ are performed for two different uranium isotopes, $^{233}$U and $^{238}$U. As already mentioned, DR experiments have their highest resolution and accuracy at very low collision energies. In addition, the non-resonant process of radiative recombination (RR) which manifests itself in a sharply peaking recombination rate at zero relative energy, this point of the energy scale can be fixed with very high precision. Therefore, it is desirable to perform the first series of isotopic shift measurements with ions which possess resonances in this energy range. In order to find the most promising ion for precise energy-shift measurements, our previous DR studies of Li-like ions [16, 17] have been extended to Be-like configurations [20]. Theoretical studies suggest that neodymium (Z=60) is the most interesting candidate for a pilot experiment: Besides DR resonances at about 0.5 eV for Be-like $^{56+}$ there are also low-energy resonances for Li-like $^{57+}$ at about 2.5 eV. Neodymium has 7 stable isotopes with natural abundances larger than 5% (Fig. 2). In addition, the isotope $^{142}$Nd has a closed neutron shell. Thus, the attachment of additional neutrons leads to a strong increase of the charge radius [5]. The corresponding expected isotopic shifts are also indicated in the figure. The charge radii $\langle r^2 \rangle_{142}^{150} = 1.324$ fm$^2$ for this estimate resulted from measurements of muonic X-rays [9]. Accordingly, the square radius changes by $\delta \langle r^2 \rangle_{142}^{150} = 1.324$ fm$^2$ when switching between the outermost stable isotopes $^{142}$Nd and $^{150}$Nd. In contrast, the corresponding value from optical spectroscopy is $\delta \langle r^2 \rangle_{142}^{150} = 1.205(5)$ fm$^2$ [5].

The compilation of several other data sets for the Nd charge radii in [10] does not shed more light on the situation. Our combined experimental and theoretical DR studies will hopefully help to resolve these discrepancies in the near future.
Nd ($Z = 60$):

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Natural Abundance</th>
<th>Estimated Isotopic Shifts</th>
</tr>
</thead>
<tbody>
<tr>
<td>142</td>
<td>27.3 %</td>
<td>4.914 fm 0.32 meV</td>
</tr>
<tr>
<td>143</td>
<td>12.2 %</td>
<td>4.924 fm 3.2 meV</td>
</tr>
<tr>
<td>144</td>
<td>23.8 %</td>
<td>4.941 fm 8.8 meV</td>
</tr>
<tr>
<td>145</td>
<td>8.3 %</td>
<td>4.953 fm 12.7 meV</td>
</tr>
<tr>
<td>146</td>
<td>17.2 %</td>
<td>4.968 fm 17.7 meV</td>
</tr>
<tr>
<td>147</td>
<td>5.7 %</td>
<td>4.998 fm 27.6 meV</td>
</tr>
<tr>
<td>148</td>
<td>11 d</td>
<td>5.047 fm 43.9 meV</td>
</tr>
<tr>
<td>149</td>
<td>17 h</td>
<td></td>
</tr>
<tr>
<td>150</td>
<td>5.6 %</td>
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</tr>
</tbody>
</table>

Figure 2: Chart of stable neodymium isotopes with their natural abundances. Charge radii form muonic atoms [9] and estimated isotopic shifts for $2s \rightarrow 2p$ excitations in L-shell ions are indicated. The nuclear size calculations were performed according to [19].

References


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Schottky Mass Measurements of Neutron-Rich $^{238}$U Projectile Fragments

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Abstract

The FRS-ESR facility at GSI is an ideal tool for nuclear structure studies with stored exotic nuclei. A new experiment with time-resolved Schottky Mass Spectrometry has been performed. The masses and half-lives of neutron-rich $^{238}$U projectile fragments in the element range from neodymium to uranium were addressed. The experiment and the preliminary results are presented.

Introduction

Nuclear masses and lifetimes of exotic nuclei are basic quantities which are essential for the understanding of nuclear matter and the creation of the elements in stars. The masses are of a great interest, because they reflect the complex interaction of the nucleons and the forces acting among them in the nuclear medium. Systematic precision measurements yield new insights into the basic nuclear properties such as the limits of their existence, the shell structure, the shapes, and pairing correlations.

Today the challenge is to measure the masses and lifetimes of exotic nuclei close to the borders of their existence. These nuclides can be characterized by small
production cross-sections and short lifetimes. The time-resolved Schottky Mass Spectrometry (SMS) in a storage ring has been developed at GSI for such measurements. The SMS has proven its ability to cover large areas on the chart of nuclides in one experiment [1, 2]. In this contribution we present first results from a recent experiment in which we addressed the masses and half-lives of neutron-rich $^{238}\text{U}$ projectile fragments.

**Experiment**

The exotic nuclides were produced via projectile fragmentation of a 670 MeV/u $^{238}\text{U}$ primary beam in the 4 g/cm$^2$ $^9\text{Be}$ production target placed in front of the fragment separator facility FRS [3]. The intensity of the primary beam was about $2 \times 10^9$ particles/spill. The neutron-rich projectile fragments were separated in flight and injected into the storage ring ESR [4]. The primary beam and the produced fragments emerge from the target as highly-charged ions with none or very few electrons. The injection into the ESR was optimized with the primary beam and the magnetic fields of the FRS-ESR facilities were fixed at the constant magnetic rigidity of 7.9 Tm throughout the experiment. In the ESR the fragments were stored and electron cooled. The time required for the electron cooling restricts the nuclides that can be accessed with the SMS. For our low intensity fragment beams this time is of the order of a few seconds [1]. A schematic layout of the experimental facility is presented in Figure 1.

Except for a short test beam time [6], the neutron-rich fragments were the objective of a SMS experiment for the first time. In contrast to the measurements of neutron-deficient fragments, see e.g. [1, 2], the charge states of the primary beam

![Figure 1: The layout of the experimental facility. The synchrotron SIS [5], fragment separator FRS, and cooler-storage ring ESR are highlighted. The primary beam, production target, and the degrader used in the experiment are indicated.](image-url)
are also transmitted to the ESR. Since they are very abundant, they can hinder fast
electron cooling and limit the frequency resolution. To circumvent these problems,
an additional separation criterion was applied at the FRS during a part of the ex-
periment. A thin 0.5 mm plastic degrader was placed at the middle focal plane thus
enabling the $Bp - \Delta E - Bp$ separation method [3]. This method allows to transmit
only the selected fragment and a few neighboring nuclides into the ESR.

The electron cooling process compresses the phase-space volume of stored beams
and the initial longitudinal velocity spread is reduced to typically $\Delta v/v \approx 5 \times 10^{-7}$.
By selecting the cooler voltage we define the velocity of the merged electrons and
thus the velocity of the cooled ions. In order to cover the range of stored fragments
from neodymium to uranium, the cooler voltages were varied from 190 kV up to
220 kV in steps of 2 kV.

The revolution frequencies of stored ions were measured by means of the time-
resolved SMS [2]. The frequency bandwidth of 320 kHz was simultaneously mea-
sured, which is sufficient to cover the entire frequency acceptance of the ESR. The
data acquisition and the data analysis are similar to the ones described in Ref. [2].

First Results

Although the data analysis is still in progress, the identification of spectra from a few
settings was already done. As an example, a part of the identified Schottky frequency
spectrum is presented in Fig. 2. Only the most abundant lines are labelled with the
corresponding identification. In the inset, a zoom of $^{228}\text{Fr}$ and $^{228}\text{Ra}$ frequency lines
is shown. The mass value of $^{228}\text{Fr}$ nuclide is presently unknown [9]. It should be

![Figure 2](image_url)

Figure 2: Part of the Schottky frequency spectrum measured in the new experiment.
For clarity, only the most abundant lines are labelled. The identification of the peaks
is based on the the Atomic Mass Evaluation AME'03 [9].
noted that already in the test run we could measure for the first time the masses of three nuclei [6].

Summary and Outlook

The experimental program at the FRS-ESR has been very successful over the last years [12]. It has now been extended with the SMS measurements of neutron-deficient nuclides. The nuclides from Nd to U were covered in this first run [7].

There are several nuclear structure investigations foreseen with our new data, e.g. the shell closures at \( Z=82 \) for protons and at \( N=126 \) for neutrons, the odd-even staggering of binding energies which has a clear isospin dependence in neutron-deficient nuclides [8]. With the developed single particle method [2, 10], which has a mass resolving power of \( 2 \times 10^6 \), new long-lived isomeric states are expected in the mass region around \( A=180 \) [11].

In the future, it will be possible to access even more neutron-rich nuclides in the framework of the accepted ILIMA [13] project at the new FAIR facility [2].

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The liquid-gas phase transition from emulsion to storage ring experiments

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Astrophysics attempts to describe supernovae evolution and neutron stars, require better knowledge of nuclear equation-of-state (EOS) parameters like the compression modulus (K), specific heat ($C_V(P)$), entropy (S) and temperature (T) around the liquid-gas phase transition etc. Laboratory attempts have so far been concentrated on studies of the disintegration of excited (pieces of) nuclei prepared in (multi)hadron - nucleus collisions. These attempts are discussed in this talk.

Past - from emulsion to electronic multidetectors

Multibody decay of strongly excited (pieces of) nuclei was first observed in nuclear emulsions exposed to protons. When the process was more systematically studied and better verified in light nuclei exposures [1], the name multifragmentation was introduced and its properties described [2]. This name is now commonly used for cold- as well as hot- as well as slow multibody decay. With enough statistics of impact parameter selected events, critical behaviour could be studied. Fig. 1 shows the Au (projectile) breakup at 10.7A GeV in the $Z^{max}$ - Z distribution (2:nd moment, $S_2$) space. The population is non-structured in a minimum-bias sample but dominated by a liquid and gas-like branches when peripheral events are selected. This strengthened the idea of a phase transition but stressed the difficulties to handle large fluctuations due to limited statistics and large surface effects.

Electronically trigable multidetector systems (Plastic ball at LBL and ALADIN, INDRA and CHIMERA detectors at European accelerators), made systematic studies of "caloric curves" possible. The most popular one is $T(e^*)$ ($e^*$ is excitation energy per nucleon) although the determination of both parameters is hard. Some results [4] have a surprisingly good support by theoretical predictions based on statistical multifragmentation [5] but lately differences in the form of the caloric curve have been reported [6]. Do they depend more on empirical methods and event selection critera than on choice of reactions and "prepared emission sources"?
Present - slow ramping experiments at CELSIUS

Using the CHICSi detector at the cluster-jet target of the CELSIUS ring, we obtained recently basic information for various caloric curves in fixed energy [7] and slow ramping (excitation function) experiments. CHICSi has a very low energy cut-off (900A keV) and Fig. 2 shows the angular dependence of the charge distribution of the lowest energy ($\epsilon < 7$A MeV) fragments in 200A MeV Ne + Ar reactions. Increasing steepness with increasing angle informs us, that in impact parameter averaged event samples, source mixing (equilibrium + pre-equilibrium) appears even for these low energy fragments.

We have chosen to compare data with a single-step (Nuclear) Molecular Dynamics model (NMD) and a complete three-step model (CFEM) [8]. The latter describes the dynamical part as an intranuclear nucleon-nucleon cascade progressing over short time (here 100 fm/c). Then a fast statistical breakup (SMM) produces heavier fragments. Any single-step model predicts too wide $Z$ distributions (Fig. 2) and so does CFEM after SMM disintegration. Only after final-state evaporation (solid histogram) is good agreement achieved. This is further stressed in double differential cross sections, mass distributions etc [7].

This agreement makes it plausible that CFEM provides a trustworthy "back-
ground" to EOS investigations. A few attempts to derive the $T(\epsilon^*)$ function from measurements on double isotopic ratios [4, 6] and slopes of emitted particles and photons have been performed. Empirical $T(\epsilon^*)$ curves show however quite different slopes in the $\epsilon^*$ region 2 - 10 MeV [6], where the transition is expected [5], but never with zero $dT/d\epsilon^*$ (specific heat). The double isotope ratio method of determining $T$ claims a rise of 2 - 3 MeV while the kinetic temperature method gives a rise of 4 - 6 MeV over the critical $\epsilon^*$ region (see Fig. 3 in ref. [6]).

Our first excitation function data represent the $p + Xe$ reaction where no compression is expected and the preparation of the excited nucleus is easier to describe. The number of nucleon - nucleon (NN) collisions is calculated (straight line optical calculation with incoherent addition of phases) and empirical inelasticity, $i(\epsilon_{NN})$ is used,

$$\epsilon^* = \epsilon_{inc} \cdot \left(1 - \int_0^{b_{max}} (1 - i)^{N_{NN}(b)} db\right)$$

and the isotopic double ratio [9],

$$R = \frac{N(A_i, Z_i)/N(A_i + \Delta A, Z_i + \Delta Z)}{N(A_j, Z_j)/N(A_j + \Delta A, Z_j + \Delta Z)}$$

where $(\Delta Z = 0, \Delta A = 1)$ isotopes with well known binding energies (BE) and spin (S) are used. Now, $T = B/\ln(a-R)$ where $B = BE(A_i, Z_i) - BE(A_i+1, Z_i) - [BE(A_j, Z_j) - BE(A_j+1, Z_j)]$, $a = 2.2$ and $B = 13.3$ MeV for $^6\text{Li} - ^4\text{He}$.

Results are compared to complete CFEM calculations in Fig. 3. Both show flat $\epsilon^*(T)$ curves from 2.5 to 8 MeV excitation but a constant shift in $T$ of about 1 MeV is noticed. Slow ramping measurements in a limited emission phase-space thus indicate a flat, "first-order like" transition in disagreement with other data.
Figure 3: $e^*(T)$ from semi-central p + Xe events at 200 - 1400 MeV black points: data, open points: CFEM calculations [8], points at $e^* = 22$ MeV: Ne + Ar [7].

Future - more complete storage ring data?

The differences in EOS data are intriguing. Do they depend on choice of T parameter or reaction or selection of fragments? Slow ramping experiments with internal detectors at storage rings seems quite useable and proton beams in extended energy range as well as very heavy ion ($A > 100$) beams should be introduced in this work.

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EDM Search
RESONANCE METHOD OF EDM MEASUREMENTS IN STORAGE RINGS

Yuri F. Orlov

EDM measurements in storage rings can be made using: (1) a g-2 ring designed for measurement of $a=(g-2)/2$, which has been done for muons [1]; (2) a ring where g-2 rotations are canceled by a radial electric field [2], which has been investigated in detail by this EDM collaboration; and (3) a resonance EDM ring—the subject of this report [3]. We think we understand the main conceptual issues of this design.

The basic formulas are the same for the three methods:

$$\frac{dS}{dt} = e \left( aB + \left( \frac{mc}{F} \right)^2 - a \right) \vec{V} \times \vec{E}$$

$$\omega_a = \frac{e}{mc} \left[ aB + \left( \frac{mc}{F} \right)^2 - a \right] \vec{V} \times \vec{E}$$

$$\omega_e = \frac{e}{2mc} \eta \left[ \vec{V} \times \vec{B} \right]$$

Ideally, $B = B_V$, $V = V_L$, $E = E_R$, $\omega_a = (\omega_a)_V$, $\omega_e = (\omega_e)_R$. For deuterons, $a=-0.14301$.

Central to all three methods is detecting how the component $S_V$ changes in time:

$$\frac{dS_V}{dt} = e \frac{1}{2mc} \eta \left[ \vec{V} \times \vec{B} \right]$$

The last expression shows how the different methods work.

The main disadvantage of the g-2 ring method is that $S_V$ oscillates as quickly as $g-2$ rotates, so a steady development of $S_V$ due to the EDM is not possible. In the case of the second method, $E_R = \frac{ab \eta}{(mc/p)^2 - a} V/e$. With such $E$, the angle between spin and orbit on the plane remains constant in time. Thus, ideally, the spin rotates only on the vertical plane and only due to EDM: $\omega_a = \omega_a^V$. The main disadvantage of this method is that the ring is too big. (The size of the resonance EDM ring is one order smaller, see Fig. 1.) Also, the tolerance of undesigned $\theta_R = E_V/E_R$ is rather tight. (In the resonance EDM ring, the similar tolerance of $\theta_B = B_R/B_V$ is at least one order looser.)

The resonance method of EDM solves most of the problems of the other two methods. In this method, $\omega_a = (e/ma)B = (e/ma)a \gamma \omega_C \neq 0$. There are no electric fields, either, except the RF fields of the usual RF cavities. Instead, we introduce forced synchrotron oscillations, the same for all particles, with the frequency and phase of $g-2$. Then the velocity of every particle is a classical superposition:

$$V = V_0 + (\Delta V)_{free} \cos (\omega_L t + \phi_L) + (\Delta V) F \cos (\omega_a t + \phi_a).$$

As for the spin, $S_L = S_{L0} \cos (\omega_L t + \phi_L)$. (where $\omega_a \neq \omega_L$). Thus,
\[
\frac{dS_V}{dt} = \omega_L S_L = -\frac{eB_V}{2mc} S_{LO} \cos(\omega_a t + \phi_a) \times \\
[(\Delta V)_f \cos(\omega_a t + \phi_a) + (\Delta V)_f \cos(\omega_L t + \alpha_L) + V_0] = \\
-\frac{eB_V}{4mc} S_{LO}(\Delta V)_f + \text{non-resonance terms,}
\]

(6)

(In our deuteron EDM ring, \( (\Delta V)_f/V_0 = 0.02; B_V = 2T; R \approx 1m \). The goal is \( \delta d_D \approx 10^{-20} \text{e} \cdot \text{cm}; \delta \eta \approx 2 \times 10^{-11} \). The origin of this major spin resonance perturbation is the following: In order to expose EDM, we use velocity, hence momentum oscillations

Radial magnetic field perturbations in the dipoles are the only serious first-order effects imitating EDM. After some improvements of the lattice, we hope to ideally adjust. It is important that the dispersion fields if the particles are 100\% polarized, and if the related frequencies and phases grow the average, and that there are no spin resonances caused by the cavity RF fields if the particles are 100\% polarized, and if the related frequencies and phases are ideally adjusted. It is important that the dispersion D-function equal zero inside every RF cavity.

The existence of such resonance has been confirmed by simulations (Y. Semertzidis) and analytically. It has also been shown (mostly by Y.S.) that oscillations of the vertical magnetic field, like \( B_V = B_{V0} \cos(\omega_a t + \phi_a) \), produce zero effect on the average, and that there are no spin resonances caused by the cavity RF fields if the particles are 100\% polarized, and if the related frequencies and phases are ideally adjusted. It is important that the dispersion D-function equal zero inside every RF cavity.

Enhancement factor \( \sim 3000 \) at such a betatron tune is caused by: (1) the increase of the Courant \( \beta \)-function, \( \beta^2_{cor}/\beta^2_N \sim 45 \), and (2) the proximity of the vertical betatron resonance at \( \nu_y = \nu_a \). We will check any non-EDM growth of \( \langle (S_V) \rangle \) and \( \langle S^2_V \rangle - \langle S_V \rangle^2 \) in the normal half-beam, say, every 100ms, and correct the corresponding perturbation in the ring. Then we will repeat these operations for the correcting half-beam.
Fig. 1

$\frac{1}{4}$ of an EDM ring

M - Magnets (focusing edges, homogeneous B)
RFQ - RF quadrupoles, $(\partial B/\partial x)_{\text{max}} \sim 20$ gauss/cm
F - usual focusing quadrupoles

$R = 1.167488m$ (for $B = 2T$)

Accelerating RF’s, sextupoles, etc. are not shown.
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Spin rotation and birefringence effect for a particle in a high energy storage ring and measurement of the real part of the coherent elastic zero-angle scattering amplitude

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It is well known in experimental particle physics how to measure a total spin-dependent cross-section of proton-proton (pp) and proton-deuteron (pd) or proton-nucleus (pN) and deuteron-nucleus (dN) interactions. However, measurement of the real part of coherent elastic forward scattering amplitude $\Re f(0)$ arouses some difficulties.

It has been shown in ([1, 2] and references therein) that there is an unambiguous method which makes the direct measurement of the real part of the spin-dependent forward scattering amplitude in the high energy range possible by the effect of proton (deuteron, antiproton) beam spin rotation in a polarized nuclear target and on the phenomenon of deuteron spin rotation and oscillation in a nonpolarized target.

Spin rotation and oscillation experiments also allow to carry out new experiments to study P- and T-odd interactions ([1, 2] and references therein).

Considering evolution of the spin of a particle in a storage ring one should take into account several interactions. The equation for the particle spin wavefunction considering all these interactions is as follows:

$$i\hbar \frac{\partial \Psi(t)}{\partial t} = \left( \hat{H}_0 + \hat{V}_{EDM} + \hat{V}_{E} + \hat{V}_{B} + \hat{V}_{nucl}^{E} + \hat{V}_{nucl}^{B} \right) \Psi(t)$$  \hspace{1cm} (1)

where $\Psi(t)$ is the particle spin wavefunction, $\hat{H}_0$ is the Hamiltonian describing the spin behavior caused by interaction of the magnetic moment with the electromagnetic field (equation (6.2) with the only $\hat{H}_0$ summand converts to the Bargmann-Myshel-Telegdy equation), $\hat{V}_{EDM} = -d \left( \vec{S} \times \vec{B} + \vec{E} \right) \vec{S}$ describes interaction of the particle EDM with the electric field $\hat{V}_{E} = -\frac{i}{2} \alpha_{ik}(E_{eff})_i(E_{eff})_k$ describes interaction of the particle with the electric field due to the tensor electric polarizability (where $\alpha_{ik}$ is the electric polarizability tensor of the particle, $E_{eff} = (\vec{E} + \vec{B} \times \vec{E})$ is the effective electric field; the above expression can be rewritten as $\hat{V}_{E} = \alpha_S E_{eff}^2 - \alpha_T E_{eff}^2 \left( \vec{S} \vec{n}_E \right)^2$, $\vec{n}_E = \frac{\vec{E} + \vec{S} \times \vec{B}}{|\vec{E} + \vec{S} \times \vec{B}|}$, where $\alpha_S$ is the scalar electric polarizability and $\alpha_T$ is the tensor electric polarizability of the particle. A particle with the spin $S \geq 1$ also has the magnetic polarizability which is described by the magnetic polarizability tensor $\beta_{ik}$ and interaction of the particle with the magnetic field due to the tensor magnetic polarizability is $\hat{V}_{B} = -\frac{1}{2} \beta_{ik}(B_{eff})_i(B_{eff})_k$, where $(B_{eff})_i$ are the components of the effective magnetic field $B_{eff} = (\vec{B} - \vec{S} \times \vec{E})$; $\hat{V}_{B}$ could be expressed as: $\hat{V}_{B} = \beta_S B_{eff}^2 - \beta_T B_{eff}^2 \left( \vec{S} \vec{n}_B \right)^2$, $\vec{n}_B = \frac{\vec{B} + \vec{S} \times \vec{E}}{|\vec{B} + \vec{S} \times \vec{E}|}$, where $\beta_S$ is the scalar magnetic polarizability and $\beta_T$ is the tensor magnetic polarizability of the particle.
\( \hat{V}_B^{\text{nucl}} \) describes the effective potential energy of particle interaction with the nuclear pseudomagnetic field of the target ([1, 2] and references therein).

\( \hat{V}_E^{\text{nucl}} \) describes the effective potential energy of particle interaction with the nuclear pseudoelectric field of the target ([1, 2] and references therein).

It should be emphasized that \( \hat{V}_B^{\text{nucl}} \) and \( \hat{V}_E^{\text{nucl}} \) include contributions from strong interactions as well as those caused by weak interaction violating P (space) and T (time) invariance.

Let us consider particles moving in a storage ring with low pressure of residual gas (10\(^{-10}\) Torr) and without targets inside the storage ring. In this case we can omit the effects caused by the interactions \( \hat{V}_B^{\text{nucl}} \) and \( \hat{V}_E^{\text{nucl}} \).

Let us consider a particle with \( S = 1 \) (for example, deuteron) moving in a storage ring. According to the above analysis spin behavior of such a particle cannot be described by the Bargman-Myshel-Telegdy equation. The equations for particle spin motion including contribution from the tensor electric polarizability were obtained in ([1, 2] and references therein). Considering that deuteron possesses also the tensor magnetic polarizability and adding the terms caused by it to the equations obtained in ([1, 2] and references therein) finally we get:

\[
\begin{align*}
\frac{d\Theta}{dt} &= \frac{e}{mc} \left[ \vec{P} \times \left( \left( a + \frac{1}{2} \right) \vec{B} - a \frac{\vec{E}}{\gamma} \right) \vec{\beta} - \left( \frac{g}{2} - \frac{\gamma}{\gamma + 1} \right) \vec{\beta} \times \vec{E} \right] + \\
&+ \frac{\alpha}{\gamma} \left[ \vec{P} \times \left( \vec{E} + \vec{\beta} \times \vec{B} \right) \right] - \frac{\alpha}{\gamma} \frac{\vec{B}_\text{eff}}{k} \left[ \vec{n}_E \times \vec{n}_E^* \right] - \frac{\alpha}{\gamma} \frac{\vec{B}_\text{eff}}{k} \left[ \vec{n}_B \times \vec{n}_B^* \right], \\
\frac{d\Theta}{dt} &= -\left( \varepsilon_{ikl} \hat{P}_i \Omega_\nu + \varepsilon_{ikl} \hat{P}_j \Omega_l \right) - \\
&- \frac{\alpha}{\gamma} \frac{\vec{B}_\text{eff}}{k} \left[ \vec{n}_E \times \vec{P}_j \right] n_{E,k} + n_{E,l} \left( \vec{n}_E \times \vec{P}_k \right) - \\
&- \frac{\alpha}{\gamma} \frac{\vec{B}_\text{eff}}{k} \left[ \vec{n}_B \times \vec{P}_j \right] n_{B,k} + n_{B,l} \left( \vec{n}_B \times \vec{P}_k \right),
\end{align*}
\]

(2)

where \( m \) is the mass of the particle, \( e \) is its charge, \( \vec{P} \) is the spin polarization vector, \( P_{xx} + P_{yy} + P_{zz} = 0 \), \( \gamma \) is the Lorentz-factor, \( \vec{\beta} = \vec{v}/c \), \( \vec{v} \) is the particle velocity, \( a = (g - 2)/2 \), \( g \) is the gyromagnetic ratio, \( \vec{E} \) and \( \vec{B} \) are the electric and magnetic fields in the point of particle location, \( \vec{E}_{\text{eff}} = (\vec{E} + \vec{\beta} \times \vec{B}) \), \( \vec{B}_{\text{eff}} = (\vec{B} - \vec{\beta} \times \vec{E}) \), \( \vec{n} = \vec{E}/k \), \( \vec{n}_E = \frac{\vec{E} + \vec{\beta} \times \vec{B}}{[\vec{E} + \vec{\beta} \times \vec{B}]} \), \( \vec{n}_B = \frac{\vec{E} - \vec{\beta} \times \vec{B}}{[\vec{E} - \vec{\beta} \times \vec{B}]} \), \( n_{E,k} = P_{ik} n_k \), \( n_{E,l} = P_{ik} n_k \), \( n_{B,k} = P_{ik} n_k \), \( \Omega_\nu, \Omega_\nu(d) \) are the components of the vector \( \Omega(d) \) (\( r = 1, 2, 3 \) correspond to \( x, y, z \), respectively).

\[
\vec{\Omega}(d) = \frac{e}{mc} \left( \left( a + \frac{1}{2} \right) \vec{B} - a \frac{\vec{E}}{\gamma} \right) \vec{\beta} - \left( \frac{g}{2} - \frac{\gamma}{\gamma + 1} \right) \vec{\beta} \times \vec{E} \right] + \\
+ \frac{\alpha}{\gamma} \left( \vec{E} + \vec{\beta} \times \vec{B} \right).
\]

(3)

From (2) it follows that the magnetic polarizability leads to spin rotation with two frequencies \( \omega_1 \) and \( \omega_2 \) instead of \( \Omega \) and, therefore, experiences beating with the frequency \( \Delta\omega = \omega_1 - \omega_2 = 2\sqrt{\Omega^2 \Omega'^2} = \frac{\alpha \vec{B} \times \vec{E}}{k} \).

According to the evaluation ([1, 2] and references therein) the tensor magnetic polarizability \( \beta_T \sim 2 \cdot 10^{-40} \), therefore for the beating frequency \( \Delta\omega \sim 10^{-5} \) in the field \( B \sim 10^4 \) gauss.
Measurement of the frequency of this beating makes possible to measure the tensor magnetic polarizability of the deuteron (nuclei).

Thus, due to the presence of tensor magnetic polarizability the horizontal component of spin rotates around $\mathbf{B}$ with two frequencies $\omega_1, \omega_2$ instead of expected rotation with the frequency $\Omega$. The resulting motion of the spin is beating: $P_1(t) \sim \cos \Omega t \sin \Delta \omega t$.

This is the reason for the component $P_3$ caused by the EDM to experience the similar beating.

Another class of experiments deals with the use of polarized targets. Preparing such experiment one should remember that density of polarized gas target is lower than nonpolarized that and for example for COSY density of polarized target is $j = 10^{14} \text{cm}^{-2}$.

When a particle (proton, antiproton, deuteron ...) propagates through the target with polarized nuclei an effect of particle spin precession occurred. It is stipulated by the fact that in a polarized target the particles are characterized by two refraction indices ($N_1$ for particles with the spin parallel to the target polarization vector and $N_2$ for particles with the opposite spin orientation , $N_1 \neq N_2$). According to the ([1, 2] and references therein), in the target with polarized nuclei there is a nuclear pseudomagnetic field and the interaction of an incident particle with this field results in particle spin rotation. The experiments with slow neutrons proved the existence of this effect ([1, 2] and references therein).

The effective potential energy of a particle in the pseudomagnetic nuclear field $\mathbf{G}$ of matter can be written as:

$$\hat{V}_{nucl} = -\hat{\mu} \mathbf{G},$$

where $\hat{\mu}$ is the magnetic moment of the particle and $\mathbf{G}$ can be expressed as ([1, 2] and references therein) $\mathbf{G} = \mathbf{G}_s + \mathbf{G}_w$, $\mathbf{G}_s = \frac{2\mu_0}{\mu_n} \rho [A_1 \langle \mathbf{j} \cdot \mathbf{n} \rangle + A_2 \langle \mathbf{j} \times \mathbf{n} \rangle + ...]$, $\mathbf{G}_w = \frac{2\mu_0}{\mu_n} \rho [b_1 \langle \mathbf{j} \times \mathbf{n} \rangle + b_2 \mathbf{n} + b_3 \mathbf{n} \times \mathbf{n} + b_4 \mathbf{n} + b_5 \mathbf{n} \times \mathbf{n} + ...]$, where $\mathbf{n} = \mathbf{v}/v$, $\mathbf{j}$ is the spin of nuclei of matter, $\langle \mathbf{j} \rangle = S_{\text{nucl}} \mathbf{j}$ is the average value of nuclear spin, $\mathbf{n}$ is the components $n_{ij} = \langle Q_{ij} \rangle n_{ij}$, where $\langle Q_{ij} \rangle = S_{\text{nucl}} Q_{ij}$ is the polarization tensor.

It is easy to see that interaction (4) looks like the interaction of a magnetic moment with a magnetic field, thus the field $\mathbf{G}$ contributes to the change of the particle polarization similar a magnetic field does. It should be especially mentioned that $\hat{V}_{nucl}^B$ contains both the real part, which is responsible for spin rotation, and imaginary part, which contributes to spin dichroism (i.e. beam absorption dependence on spin orientation). The detailed analysis of the effects caused by the nuclear pseudoelectric field was done in [1].

Interaction with the field $\mathbf{G} = \mathbf{G}_s + \mathbf{G}_w$ contains two summands: the first $\mathbf{G}_s$ corresponds to the strong interaction, which is T,P-even, while the second $\mathbf{G}_w$ describes spin rotation by the weak interaction, which has both T,P-odd (the term containing the constant $b_3$) and T-odd, P-even (the term containing the constant $b_5$) terms.
If either vector or tensor polarization of a target rotates then the effects provided by \( \vec{G}_s \), \( \vec{G}_w \) periodically depend on time i.e. equation (6.2) converts to:

\[
i\hbar \frac{\partial \Psi(t)}{\partial t} = \left( \hat{H}_0 + \hat{V}_{EDM} + \hat{V}_E + \hat{V}_B + \dot{\hat{V}}_{\text{nucl}}(t) + \ddot{\hat{V}}_{\text{nucl}}(t) \right) \Psi(t). \tag{5}
\]

This equation coincides with the well-known equation for the paramagnetic resonance. Thus, if we have the strong magnetic field orthogonal to the weak nuclear pseudomagnetic field \( \vec{B} \perp \vec{G} \) and \( \vec{G} \) either rotates or oscillates with the frequency corresponding to the splitting, caused by the field \( \vec{B} \), the resonance occurs and this leads to the conversion of horizontal spin component to the vertical one with the frequency determined by the frequency of spin precession in the field \( \vec{G} \) [2]. Thus we can measure all the constants containing in \( \vec{G}_s \) and \( \vec{G}_w \): constants \( A_i \) give the spin-dependent part of elastic coherent forward scattering amplitude of proton (deuteron, antiproton) that is important for the projects at GSI and COSY; amplitudes \( b_i \) provides to measure the constants of T-, P-odd interactions.

First of all we should pay attention to the effects caused by the T-odd nucleon-nucleon interaction of protons (antiprotons) and deuterons with polarized nuclei and, in particular, interaction described by \( V_{PT} \sim \vec{S} [\vec{P}_N(t) \times \vec{n}] \), where \( \vec{P}_N(t) \) is the polarization vector of target. The interaction \( V_{PT} \) leads to the spin rotation around the axis determined by the unit vector \( \vec{n}_T \) parallel to the vector \( \left[ \vec{P}_N(t) \times \vec{n} \right] \). Spin dichroism also appears with respect to this vector \( \vec{n}_T \) i.e. a proton (deuteron) beam with the spin parallel to \( \vec{n}_T \) has the absorption cross-section different from the absorption cross-section for a proton (deuteron) beam with the opposite spin direction.

P-even T-odd spin rotation, oscillation and dichroism of deuterons (nuclei with \( S \geq 1 \)) caused by the interaction either \( V_{PT} \sim (\vec{S}[\vec{P}_N(t) \times \vec{n}]) (\vec{S}\vec{n}) \) could be observed [1]; P-even T-odd spin rotation and dichroism for a proton, deuteron (nucleus with the spin \( S \geq 1/2 \)) \( V_{PT} \sim b_5 [\vec{n} \times \vec{n}_1(t)] \) could be observed ([1, 2] and references therein) in paramagnetic resonance conditions, too.

Study of spin rotation and birefringence effect for a particle in a high energy storage ring provides for measurement as the real part of the coherent elastic zero-angle scattering amplitude as well as tensor electric and magnetic polarizabilities.

We proposed the method for measurement the real part of the elastic coherent zero-angle scattering amplitude of particles and nuclei in a storage ring by the paramagnetic resonance in the periodical in time nuclear pseudoelectric and pseudomagnetic fields.

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Polarimeter Development for Ring EDM Search

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Introduction

The development of a sensitive deuteron polarimeter is part of a project aimed at
the search for a permanent electric dipole moment (EDM) on the deuteron using
a storage ring\cite{1}. A detailed description of this project is presented by Semertzidis
and Orlov elsewhere in these proceedings; we limit ourselves to a brief summary.

Particles circulating in a magnetic field experience a large electric field ($\vec{E}^{\ast} = \gamma(\vec{v} \times \vec{B})$). This motional electric field can be orders of magnitude larger than
fields obtainable in the laboratory. The interaction of this electric field with the
EDM induces a spin precession in the plane \textit{perpendicular} to the plane of the orbit.
Without further effort, the time to observe this precession would be severely limited
because the interaction between the magnetic moment and the magnetic field leads
to a many orders of magnitude faster spin precession \textit{in} the plane of the ring.

To allow time for the EDM precession to build, two techniques are considered.
First, following the “frozen spin” concept laid down by Farley \textit{et al.} in Ref. \cite{2}, the
radius of the particle orbit can be changed by imposing an outward radial electric
field $E_r$ in all the bending magnets. With an adjustable circumference, the revolution
frequency can be controlled independent of the magnetic field $B_z$ and it becomes
possible to match the cyclotron and spin precession frequencies. In the particle
frame only the spin precession due to the EDM will be left.

For the second method, the spin precession in the orbit plane is not frozen.
Instead, a modulation of the particle’s velocity is set up, which leads to a modulation
of the motional electric field. Synchronization of this modulation with the spin
precession causes a resonance in which the modulated motional electric field interacts
coherently with the rotating EDM, “pulling” the spin out of the ring plane.

For both methods, the signal of an EDM is the growth of a vertical polarization
component in the circulating deuteron beam, assuming one starts with the beam
polarized along the direction of the deuteron momentum. The polarimeter must
sample the polarization continuously. Great care must be taken to avoid or minimize
the sensitivity of the polarimeter to perturbing influences.
Polarimeter Concept

The expected magnitude of the EDM is practically zero and consequently we will most likely only see the onset of a precession cycle, *i.e.* a linear growth of the vertical polarization component. The proposed limit on the deuteron EDM of $10^{-27} - 10^{-29} \, \text{e} \cdot \text{cm}$ corresponds to a growth of the vertical polarization at the level of less than 1 part in $10^5$ in a few seconds.

The statistical precision $\sigma_d$ one may obtain on the growth rate depends on several factors, such as the initial polarization of the beam $P_0$, the beam storage time $\tau$, the polarization coherence time $\tau_p$, the strength of the electric field in the center-of-mass $E^e = v B_x - E_r$, the analyzing power of the polarimeter $A$, the number of particles used to make the measurement $N$ and the efficiency of the polarimeter $\epsilon$. The uncertainty can be described in good approximation (for the frozen spin technique; a similar relation holds for the “resonant method”) by

$$\sigma_d \approx \frac{4h}{\sqrt{\gamma \epsilon E^e P_0 A \sqrt{N}}} \quad (1)$$

Clearly, the polarimeter must have a large efficiency and analyzing power and may not affect the beam storage time adversely. As a matter of fact, optimal precision is obtained for a beam storage time that is half the spin coherence time.

The most promising concept for a polarimeter relies on the spin-dependence in the nuclear scattering amplitude. Scattering of medium energy deuterons (50–200 MeV) from nuclei in the carbon to oxygen range shows nearly maximal analyzing powers over a wide range of scattering angles (beyond 30–40°). Long storage times (100–1000 s) are reached by slowly extracting through Coulomb scattering from a thin gaseous target placed directly into the circulating beam. Extracted particles are intercepted by a thick analyzer target placed around the beam. This annular target serves at the same time as a collimator and defines the acceptance of the storage ring. Any particle that leaves the acceptance of the ring will eventually, possibly after several turns, collide with this target. Particles scattered from the analyzing target will be collected in a segmented detector system. For the analyzer target we consider carbon the prime candidate. The design of the storage ring is fixed at a momentum of $p = 0.7 \, \text{GeV}/c$ (or $T = 126 \, \text{MeV}$), where a good balance between polarimeter efficiency and the cost of the ring is expected.

The optimization of the efficiency of the polarimeter involves several aspects of the setup, primarily the thickness of the target and the angular acceptance of the detector system. Optimization of the target thickness requires knowledge of the scattering cross section and analyzing powers as a function of the deuteron energy, at the beam energy of 126 MeV and below. The angular dependence of both the cross section and analyzing power is necessary to optimize the acceptance of the detector system.

Measurements

Essentially no experimental deuteron-carbon scattering data exist in the energy range of interest, except for some elastic scattering measurements at and below
Figure 1: Preliminary cross section (left), vector analyzing power (middle) and figure-of-merit (right) for elastic scattering of deuterons from carbon. The data set at 70 MeV was extracted from Ref. [3].

70 MeV[3]. At 110 and 120 MeV elastic cross sections are available[4], and inelastic channels were included at 170 MeV[5]. These data suggest that, in order to avoid a change of sign in the analyzing power, the deuterons should exit the target between 50 and 60 MeV. Large positive analyzing powers are expected at angles backward of 30° in the elastic scattering channel as well as in the reaction channels below 30 MeV of excitation in the recoil nucleus.

To fill this void, an experiment was performed at the AGOR facility of KVI. Scattering data were collected at deuteron beam energies of 80 and 110 MeV, with a vector polarization of about $i t_{11} = 0.44$. The experiment was done at the site of the in-beam polarimeter[6], which was used to measure the beam polarization. Two telescopes were added to the setup, consisting of a plastic scintillator passing detector and a stopping NaI detector. Measurements were made in 3° steps over the range where we expected the analyzing power to be rising for the elastic channel, with some additional settings. The polarization direction was reversed periodically to allow for the cancellation of systematic errors arising from asymmetries in the detector efficiencies.

The combination of scintillator and NaI signals allowed for particle identification. Loci were seen for proton, deuteron, and tritons. There are a large number of protons at roughly half the incident deuteron energy that come from deuteron breakup in the field of the nucleus. Energy spectra for the three particle groups were separated to obtained particle yields and asymmetries. In fig. 1, the cross section and vector analyzing power are shown, together with the figure-of-merit, $\sigma A^2$. From these data it was learned that despite small analyzing power, including small angle scattering data may still enhance the overall efficiency, especially at larger energies. In the summer of 2005, additional data were therefore collected at scattering angles down to 10°. Preliminary analysis of these data confirm that the analyzing power does indeed remain significant down to very small scattering angles.

Also the deuteron inelastic and break-up channels and the $(d,p)$ transfer reaction show large analyzing powers, especially at the higher energies (see fig. 2).
Conclusion and Outlook

From the recent measurements it seems entirely feasible to construct a polarimeter with an efficiency of the order of several percent and an average analyzing power of some tens of percent. Further optimization of the detector configuration is in progress. As the polarimeters form an integral part of the experiment, special consideration is given to the specific conditions in which the polarimeter will operate. Also, inclusion of the polarimeter in a feedback loop to control the magnetic moment induced spin precession must be considered.

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References


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Future Projects (Physics)
Stored Particle Atomic Physics Research Collaboration:
Atomic Physics with Stored Highly-Charged Heavy Ions at
the Future FAIR Facility

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Abstract

The envisioned program of the research collaboration SPARC (Stored Particle Atomic Research Collaboration at the future GSI accelerator facility FAIR will be discussed. This future international accelerator Facility for Antiproton and Ion Research has key features that offer a range of new and challenging opportunities for atomic physics and related fields. In SPARC we plan experiments in two major research areas: collision dynamics in strong electromagnetic fields and fundamental interactions between electrons and heavy nuclei up to bare uranium. In the first area we will use the relativistic heavy ions for a wide range of collision studies. In the extremely short, relativistically enhanced field pulses, the critical field limit (Schwinger limit) for lepton pair production can be surpassed by orders of magnitudes and a breakdown of perturbative approximations for pair production is expected. For medium and low energies, the cooler rings NESR - a “second-generation” ESR - and the low-energy ring LSR, with optimized features and novel installations such as an ultra-cold electron target and dense internal jet-targets will be exploited for collision studies. Fundamental atomic processes can be investigated in a kinematically complete fashion for the interaction of cooled heavy-ions up to bare uranium with photons, electrons and atoms. The other class of experiments will focus on structure studies of selected highly-charged ion species, a field which is still largely unexplored. The properties of stable and unstable nuclei will become accessible by atomic physics techniques along with precision tests of quantum electrodynamics (QED) in extremely strong electromagnetic fields. Another important scenario for this class of experiments will be the slowing-down, trapping and cooling of particles in the ion trap facility HITRAP. This will enable not only high-accuracy experiments in the realm of atomic and nuclear physics but as well highly-sensitive tests of the Standard Model.

Introduction and Overview

At the proposed new accelerator Facility for Antiproton and Ion Research the investigation of extreme atomic conditions becomes accessible with highly-charged
very-heavy ions over an energy range from rest to the relativistic regime [1]. These studies are needed for our understanding of the processes ongoing in extreme states of matter, as the majority of matter in the universe exists as stellar plasmas. There high temperatures, high atomic charge states and highest field strengths prevail. Conditions that become available at FAIR [4] will provide the highest intensities of relativistic beams of both stable and unstable heavy nuclei, in combination with the strongest electromagnetic fields, thus allowing extending atomic spectroscopy virtually up to the limits of atomic matter. In the different accelerator structures, the ions, after having stripped off most of their electrons can be decelerated basically to rest. The wide ranges of ion energies and electromagnetic field strengths that will become available are demonstrated in Fig. 2.

At high, relativistic energies, the FAIR facility will be unique by providing the heaviest ions over a wide energy range from 1 to 30 GeV/u. In the special case of pair production there are very few and only inclusive measurements of pair production available in the intermediate relativistic regime of a few GeV/u. Here, even the target charge dependence is not well understood, whereas at extreme energies, in the region beyond hundred GeV/u, there is good agreement between theory and experiment. The new facility will be worldwide the only one capable of filling this important gap. Utilizing the high luminosity of the future GSI facility, beyond inclusive cross section studies also differential aspects of atomic processes at high energies become accessible, for which the electromagnetic interaction differs significantly from the low-energy regime. A measurement of the impact parameter dependence for both inner-shell ionization and excitation processes will enable the separation of the longitudinal and the transversal field contributions to the interaction. For such investigations, precise spectroscopy of photons as well as of electrons and positrons is required (energy diagram and basic atomic processes which occur in relativistic
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Figure 2: Ion energies and Lorentz factors $\gamma$ that can be obtained with the different FAIR facilities. The adiabaticity value $\eta = 1$ (specific kinetic ion energy corresponding to the mean velocity for an electron bound with $E_{\text{BR}}$ in the uranium K shell) is indicated. On the right hand scale the electric field strengths that are reached in collisions, in bound states and with lasers are shown. Note LSR, USR, and HITRAP are storage ring and trap installation located in the FLAIR building.

ion-atom collisions, compare Fig. 3a). The photon and electron emission gives the details of the specific excitation mechanism in those fields. One may also mention the possibility to search for recombination followed by $e^+ - e^-$ pair production instead of photon emission. This higher-order process, requiring high collision energies, is similar to dielectronic recombination, but with one electron being excited from the negative continuum into a bound state.

The new facility will provide intense beams of stable and unstable isotopes up to uranium at the highest charge states. At the NESR storage ring these ions can be stored and cooled at energies of 760 MeV/u down to 4 MeV/u and at the LSR (LSR: Low-Energy Storage Ring even down to 0.5 MeV/u). For the low-energetic ions (below 100 MeV/u) the possibility to extract them into the dedicated low-energy Cave exists. The storage rings NESR and LSR in their combination with the facilities installed have a decisive advantage over other experimental techniques as they allow to address fundamental process which become feasible at this time only in inverse kinematics: fully differential photoionization cross sections - including polarization - for the heaviest ions in arbitrary charge states, recombination, complete differential cross sections for the short wavelength limit of electron-nucleus bremsstrahlung and fully differential $(e,2e)$ cross sections for ions by mapping the complete momentum balance of all emitted particles. Also, the combination of these very heavy, highly-charged ions with the low collision energies, where the Sommerfeld parameter $q/v$ becomes very large, is an additional unique feature not available at any other machine. Furthermore, spectroscopy in the NESR will be a key instrument for frontier experiments on highly-charged ions and radioactive isotopes.

A singular opportunity is given by the combination of the SIS 12/100/300, the NESR storage ring and the PHELIX laser facility. In contrast to the typical experimental situation in gas targets, the storage ring provides precise control of the initial
Figure 3: a): Energy diagram of the single-particle Dirac equation and basic atomic processes which occur in relativistic ion-atom collisions. b:) Expectation value of the electric field strength $<E>$ for a K-shell electron in H-like ions as a function of the nuclear charge number $Z$.

ion species and diagnostics of the final states of the ions and of ejected electrons on the single-event level. This will enable research at truly undisturbed single-ion condition, where the only interacting partners will be the laser field, the highly charged ion, and the detached electron. The proposed FAIR facility with its intense heavy ion beams, in combination with novel experimental techniques such as excitation by X-ray or laser photons, mono-energetic electron beams, high-resolution spectrometers, or channelling in crystals gives world-wide unique opportunities for atomic spectroscopy. This will enable the exploration of the fundamental QED corrections to binding energies, magnetic moments, and the magnetic interactions in the strong field regime (compare Fig. 3b)).

The new accelerator complex at GSI will enable another important step by a large increase of the photon frequency range and by allowing spectroscopy for a wide variety of radioactive beams that is not available otherwise. The present limitations for the application of wavelength-restricted lasers will most certainly be widely removed. For instance, in the SIS300 ring the accessible transition energy range will be increased considerably due to a large Doppler shift. Furthermore, a completely new regime of laser cooling of heavy relativistic highly-charged ions can be opened.

The HITRAP Facility [3] where highly-charged ions can be brought practically to rest will be the only facility world-wide where bare $U$ nuclei can be trapped in a strong magnetic field. The highly-charged ions will be cooled down to cryogenic temperatures. There the g-factor of a single electron bound in the potential of an arbitrary stable or unstable nucleus like $^{238}U$ nucleus and others can be determined. Measurements of the hyperfine splitting (HFS) in hydrogen-like ions will give information about the distribution of the nuclear magnetization within the nucleus. By optical pumping within the HFS-levels of the ground state, the nuclear spins of ra-
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Figure 4: Setup for combined laser-excitation X-ray spectroscopy experiments showing the laser excitation at known photon energy and the measurement of the energy of the backscattered photon.

Radioactive nuclides can be polarized with high efficiency, opening unique possibilities to study questions of the Standard Model of fundamental interactions.

Experimental Concepts

Laser Experiments at SIS100/300

Laser cooling and spectroscopy installation at SIS100/300 will mostly use Li-like very heavy ions. Laser interaction with highly-charged ions stored in SIS100/300 benefits tremendously from the relativistic Doppler boost experienced in the ion rest frame when counter-propagating beams are used (compare Fig. 4. This advantage is twofold: on the one hand, the Doppler boost will increase the peak intensity in laser-ion interaction experiments at ultra-high intensities and shorten the pulse length in the ion rest frame for ultra-fast spectroscopy. On the other hand, this boost will allow for the use of standard laser systems in the visible range for the optical excitation of ground-state transitions of highly-charged ions in the X-ray range. Precision spectroscopy of heavy few-electron systems will become possible, complementary to the X-ray laser experiments proposed to be performed at NESR, as well as laser cooling, a unique cooling technique for relativistic ion beams. Laser cooling of highly charged ions in the SIS100/300 holds the promise of producing ultimate beam quality in terms of temperature, divergence and density. Even beam crystallization might become possible due to the favorable lattice symmetry of the synchrotron. Especially for experiments at the luminosity limit, like the investigation of nuclear effects due to the interaction with well focused, ultra-intense laser pulses, this combination will considerably facilitate the planned experiments.
Collision Experiments using Relativistic Beams from SIS100

For atomic physics experiments and applications in radiobiology, space and materials research a dedicated experimental Cave for extracted beams from SIS100 will be available. The investigation will concentrate on atomic structure (resonant coherent excitation) and collision studies at moderate and high-relativistic energies (ionization, capture, and pair production) as well as on irradiation of individual samples for biological or solid material research.

For atomic physics experiments with highly-charged, few-electron ions the cave will be equipped with a charge state spectrometer allowing for charge state separation behind a reaction target for beam energies up to about 1 GeV/u ($\approx 20$ $\text{Tm}$). For this purpose, beside a beam line from SIS100 also a direct beam line from SIS12 to the cave has to be installed. The current experimental program in Cave A has shown, that life-time measurements and experiments on precise photon and electron spectroscopy and on channelling strongly profit from coincidence measurements with the final projectile charge state. Here, beam intensities of up to $10^9$ ions/spill with spill lengths of the order of 1 sec are required. For atomic physics experiments at even higher beam energies of up to $\approx 10$ $\text{GeV}/u$, e.g. resonant coherent excitation using channelling techniques and investigation of different channels for pair production, no charge state separation is foreseen and the desired beam intensity amounts to $10^8$ ions/spill.

Experiments with Stored and Cooled Ions at the NESR

The New Experimental Storage Ring NESR is shown in Fig. 4. The NESR can be supplied with highly-charged heavy ions from SIS12 and with exotic nuclei.
Figure 6: Simplified scheme of the various experimental facilities located inside the FLAIR building.

Experiments using decelerated and cooled Highly Charged Ions with rigidities below 4.5 Tm (< 130 MeV/u for ions and < 700 MeV for antiprotons, respectively) extracted from the NESR will be accommodated in the so called FLAIR building Facility for Low-Energy Antiproton and Ion Research which is placed in the neighborhood of the NESR. This building is designed such that it includes the experimental areas requested by the experiments with low-energy heavy ions within the SPARC collaborations as well as for low-energy antiprotons promoted by the FLAIR collaboration [4]. Within the building the low-energy atomic physics cave for experiments

Experiments with Cooled, Decelerated and Extracted Ions

Experiments using decelerated and cooled Highly Charged Ions at the NESR have a variety of installations and projects with following requirements: The number of ions per cycle should reach $10^{10}$ at medium Z. The momentum spread after electron cooling is supposed to be less than $10^{-4}$. The beam energy should range from 760 MeV/u to the low energy limit, reached by deceleration to 3 MeV/u. Fast and slow beam extraction is needed. The lifetimes of stored ions are of utmost importance. Thus, an excellent vacuum of $10^{-11}$ mbar is needed. The electron target should have an ultra-cold electron beam. The resulting energy spreads should be as low as a few 10 meV at collision energies below 1 eV and smaller than 5 eV at 100 keV. One should reach 300 keV in the center-of-momentum frame. At the gas jet target ion-atom reaction mechanisms as well as the ionic structure will be studied; Photon Spectrometer such as crystal spectrometers for soft and hard X-rays (3-120 keV), low-temperature calorimeter and Compton polarimeter will be installed. An Electron Spectrometer for electrons from 100 keV to MeV energy and an Extended Reaction Microscope for imaging recoils and slow and fast electrons in the range of meV should operate at the Internal Target. Here, in addition, laser spectroscopy will be applied. At the electron target the atomic assisted electron-electron interaction will be studied. Here also laser techniques and X-ray spectroscopy will support the experiments.
with cooled and decelerated ions (down to 4 MeV/u) from NESR will be located as well as the HITRAP facility. In addition, it is planned to use an additional storage ring for further deceleration of the heavy ions (as low as 300 keV/u) but also for antiprotons (300 keV). For this task the CRYRING, a facility at the Manne Siegbahn Laboratory at Stockholm University seems to be ideally suited. This Low-Energy Storage Ring (LSR) will deliver electron cooled low-energy beams for experiments in the various experimental location within the FLAIR building: Low-Energy Atomic Physics Cave, experimental areas for direct, fast of slow-extracted antiproton beams from the LSR, the HITRAP, the USR (a Ultra-Low Energy Storage Ring) and traps for antiproton experiments. Both HITRAP as well as the USR might also be used for particle deceleration to rest, as e.g. needed for the trap experiments with antiprotons. A simplified scheme for the various experimental facilities located inside the FLAIR building is given in Fig. 6.

Summary

A condensed description of the main aspects of the planned atomic physics research activities at the future FAIR facility was given along with a short overview of the various experimental installations to be used, including storage rings and traps. These activities of the SPARC collaboration comprise the investigation of relativistic collision dynamics, the test of Quantum Electrodynamics in extremely strong electromagnetic fields, the use of atomic physics techniques for the determination of properties of stable and unstable nuclei, and ideas to test the predictions of fundamental theories besides Quantum Electrodynamics. As documented by the rich program of the SPARC collaboration, the new FAIR facility provides challenging and unique opportunities for atomic physics research in the realm of extrem electromagnetic fields.

References


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Nuclear and Hadron Physics with Antiprotons - PANDA@FAIR

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Introduction

At the Gesellschaft für Schwerionenforschung (GSI) [1] in Darmstadt, Germany, a new facility is currently designed and built. The Facility for Antiproton and Ion Research (FAIR) [2] comprises a new possibility for GSI: the production of secondary antiproton beams. This species of beams could be exploited by several experiments, the first one, which was present already at the early stage of the project [3], is PANDA (antiproton annihilation at Darmstadt) [4].

The Facility

This section describes the part of the facility particularly with regard to PANDA; details about the full facility can be found in [2,3]. To produce the antiproton beams, a primary beam of protons will be used. Therefore, a new proton linear accelerator will be built, which injects the protons in a first synchrotron ring (the existing, upgraded SIS), followed by the acceleration to the energy of 30 GeV in the new SIS100. An intensity of several $10^{13}$ protons per second is envisaged. These protons hit a production target, and the produced secondary antiprotons will be accumulated and cooled using two subsequent storage rings. Then the antiprotons will be accelerated in the SIS100 to the desired energy from the experiment, and finally injected in the High Energy Storage Ring (HESR), where the experiment will be located. Another possibility which is considered foresees to omit the acceleration in the SIS100 but rather transfer the antiprotons at a fixed energy into HESR, where the acceleration/deceleration will be done, applying a synchrotron operation mode to the ring.

The HESR, a 15 Tm ring, should provide antiprotons in the momentum range from 1.5 to 15 GeV/c. The design luminosity is $2 \times 10^{32}$ cm$^{-2}$s$^{-1}$. The ring will be equipped with electron cooling (for lower beam momenta) and stochastic cooling to ensure excellent beam quality. For the so-called high precision mode, a momentum spread of $\leq 10^{-5}$ should be yielded, whereas at design luminosity this condition is relaxed by a factor $\approx 10$. PANDA will operate as a fixed internal target experiment at HESR.
Overview: The Physics Program

Figure 1 shows in an overview the mass range to be exploited by PANDA with antiproton annihilations on a proton target in the above mentioned antiproton momentum range. The maximum antiproton momenta of previous experiments at CERN (LEAR) and FNAL (E760/E835) are indicated below.

PANDA will take data in an energy range which corresponds to a transition region between perturbative and non-perturbative QCD – this is characterized having the hadrons as relevant degrees of freedom, and the confinement of quarks; the fact that the mass of the observed hadrons is much bigger than the sum of the bare quark masses plays a crucial role together with the self-interaction among the gluons.

To shed light on these phenomena, PANDA will investigate the following main topics:

- Spectroscopy of Charmonium
- Search for Glueballs and Hybrids
- Charm in Nuclei
- Double Λ Hypernuclei

Additional topics are also included in the research program:
- D-meson spectroscopy (e.g., rare decays),
- CP-violation (D-mesons, AΣ),
- Generalized Parton Distributions (p̅p → γγ),
- Transversity (asymmetries in Drell-Yan p̅p → μ⁺μ⁻),
- The timelike electromagnetic form factor of the proton,
Hadron Physics

Charmonium Spectroscopy

Figure 2 shows the mass spectrum of the charmonium states as a function of their quantum number. The transitions are indicated by the arrows, the dashed blue horizontal lines show the threshold for the free decay in D-mesons. PANDA will pursue a systematic study of the complete spectrum with high statistics and high precision. Especially, open questions like the width of the $h_c$ state, the establishment of the states above the $D\bar{D}$ threshold, and radiative deexcitation modes, will be studied.

Since PANDA will make use of the $pp$ reaction, the direct formation of all states in the spectrum is possible, whereas for experiments at $e^+e^-$ colliders the formation is restricted to the quantum numbers of the virtual photon. This means also that a resonance scan for all the states is only limited to the momentum resolution of the antiproton beam.

Glueballs and Hybrids

QCD predicts, besides the ordinary states, also the existence of objects like glueballs (formed by gluons) and hybrids (formed by quarks and gluons). Glueballs have been searched for quite some time in the light quark sector, there are candidates (like the $f_0(1500)$), but the mixing with other states in that mass region makes it difficult to perform an unique identification.

PANDA will accomplish dedicated experiments for the search for glueballs and hybrids in the charm quark mass region. In Figure 3, predictions for glueball states (red dots [6], black dots [7], here, the error bars indicate the predicted width) together with the charmonium states (blue lines) are shown. The quantum numbers underlayed with color are exotic quantum numbers, which do not appear for pure $q\bar{q}$ states. The observation of a state with exotic quantum numbers hence will be a clean signature for a non-conventional state. Furthermore, the mixing with other states might be not that pronounced as in the light quark range (less states, smaller widths). For the charmed hybrids, the situation is similar, there are predictions from lattice QCD, e.g. [8]. Also here, some states have exotic quantum numbers.
Charm in Nuclei

The systematic study of the properties of charmed mesons (D) and charmonium (c\bar{c}) in nuclear matter (\rho = \rho_0) will be done for the first time with PANDA.

In the light quark sector, there is evidence for a mass modification and a mass splitting between the different charges for pions [9] and kaons [10] in the nuclear medium. This phenomenon might be due to a (partial) restoration of the chiral symmetry in nuclear matter. Figure 4 shows schematically the effect going from \rho = 0 (left) to \rho = \rho_0 (right).

For the D-mesons a theory prediction [11] is shown; one might expect also a mass shift and a mass splitting in the D-meson system.

In Figure 5 a calculation [12] of the cross sections for D^- (below) and D^+ (above) in the annihilation of an antiproton on a \(^{197}\text{Au}\) nucleus is shown. In analogy to the K^+ production, an enhanced production yield with respect to the elementary process (green line, \(\overline{p}N\)) is predicted as well as different yields for D^- and D^-. The experimental strategy for these measurements would be the study of the D^± production as a function of the \(\overline{p}\) momentum and the mass number \(A\) of the target nucleus.

Experimental consequences of a possible D\bar{D} attractive mass shift are shown in Figure 6. Under the assumption of a small mass shift of the c\bar{c} states, a lowered D\bar{D} threshold would yield to an increased phase space for the decay in D\bar{D}, for states
like the $\psi(3770)$ it will open a $D\bar{D}$ decay branch, resulting in an increased width and a decrease of the branching ratio in dileptons.

Concerning a possible mass shift of the charmonium states, a theory model [13] predicts even a significant mass shift, as bigger as higher the mass of the state, e.g. $-120$ to $-140$ MeV for the $\psi(3770)$, which could be observed looking to the decay in dileptons, or for the $\chi_{c0,1,2} \rightarrow J/\psi\gamma$, respectively.

The measurement of the $J/\psi$ dissociation cross section in nuclei will also be essential for the high energy heavy ion collisions, where the suppression of $J/\psi$ production is interpreted as one of the signatures for the formation of a quark-gluon plasma. PANDA could perform a complete set of measurements of the $J/\psi$ (and $\psi'$ ...) yields in $\bar{p}$ annihilation on different nuclear targets.

**Double $\Lambda$-Hypernuclei**

Exploiting the annihilation of a 3 GeV/c $\bar{p}$ on a nucleus producing a $\Xi^-$ hyperon pair, numerous $\Lambda\Lambda$ hypernuclei can be produced at PANDA. The slow $\Xi^-$ (3 GeV/c is close to threshold) will be captured in a secondary target in the atomic orbit of a nucleus, where it cascades down to the nucleus, finally in a reaction with a proton, two $\Lambda$ hyperons are produced in the nucleus. With a certain probability, they form a $\Lambda\Lambda$ hypernucleus. For the identification of the hypernucleus and the spectroscopy of its nuclear levels precision spectroscopy using Germanium detectors (EuroBall, VEGA type) will be applied. Figure 7 shows a sketch of the described reaction.

The $\Xi^-$ will serve as a tagger of the primary reaction, either by measuring the hyperon itself or the kaons produced in an annihilation inside the primary target nucleus. This experiment will give the unique opportunity to study the $\Lambda\Lambda$ and $\Lambda N$ interaction, as well as the investigation of the existence of a bound six quark (uuddss) state ($H$-particle, [14]).

Similar to the $\Xi\Xi$ case, at a $\bar{p}$ momentum of 5.5 GeV/c $\Omega\bar{\Omega}$ can be produced. The long-lived $\Omega$ $S=-3$ hyperon ($c\tau = 2.46\text{cm}$) is of particular interest since with $J = \frac{3}{2}$ it has a non-vanishing static quadrupole moment. If one captures a $\Omega^-$ in an atom of the secondary target, the study of the hyperfine splitting might be possible.

**The Detector Design**

To investigate the described physics program, a multipurpose detector is needed. It should be able to deal with different targets, cover an angular range as complete as
possible, identify charged ($e^\pm$, $\mu^\pm$, $\pi^\pm$, $K^\pm$, $p$, $\ldots$) and neutral particles ($\gamma$, $\pi^0$, $\eta$, $\ldots$) over a wide momentum range from 100 MeV/c to 8 GeV/c, be capable to stand $10^7$ interactions per second, resolve secondary decay vertices ($D^+, D^0, K^0_s, \Lambda, \Sigma, \ldots$) and be modular to a certain extent (hypernuclear physics setup, see below), furthermore have a sophisticated and efficient trigger system.

Figure 8 shows a cross-sectional view of the present design [5]. The beam is coming from the left. The setup is subdivided in a target spectrometer (using a superconducting solenoid of 2 T) and a forward spectrometer (comprising a dipole of 2 Tm bending power).

**Target**

Perpendicular to the beam pipe a target pipe will be placed, in which a stream of frozen hydrogen (or deuterium) pellets [15], a cluster jet [16] or a wire/fibre target can be implanted. The crossing of the two pipes is the interaction point.

**Tracking Detectors**

Directly at the cross of beam- and target pipe, close to the interaction point, a microvertex tracking detector, using silicon pixels and silicon strip techniques, will be adopted. Further out in radius, on outer tracking system, made from straw tubes (11 double layers of 6 and 8mm straw diameter, partly skewed) is planned. As an alternative option the use of a TPC with GEM readout as outer tracking device is under study. The tracking detectors will be completed by (multiwire) drift chambers for particles going to forward angles.
Particle Identification

For the particle identification, the target spectrometer will be equipped with an electromagnetic calorimeter (probably PbWO$_4$ crystals) with a barrel and forward and backward endcap sections. In front, a Čerenkov detector of the DIRC technique as well as a time-of-flight barrel are placed. In addition, for the forward angles, a RICH type detector will be installed. Going to even more forward angles, an electromagnetic followed by a hadron calorimeter will sit, and an additional Čerenkov detector, which might be replaced be a time-of-flight detector. Using the iron yoke of the magnets and the forward calorimeters as hadron absorbers, muon detectors will be implemented in target and forward spectrometer.

Hypernuclear Physics Setup

For the hypernuclear physics experiment, the upstream part from the target pipe, i.e. the backward endcap of the electromagnetic calorimeter, will be replaced by a part of beam pipe holding the primary target (e.g. Ni foil), with the secondary target outside the vacuum - this target will be sandwiched by target material (e.g. Be, Li, C) and active tracking layers (Si strip). Finally, a number of Ge detectors for the $\gamma$ spectroscopy will cover the backward acceptance. A possible setup is shown in Figure 9, where the beam comes from the right; the small cuboid is the secondary target, with eight Ge detectors looking to it.

References:


[15] Nordhage, Ö.; contribution to this conference

[16] Khoukaz, A.; contribution to this conference

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The PAX Proposal:
Physics with Polarized Antiprotons at GSI

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Abstract

Polarized antiprotons produced by spin filtering with an internal polarized gas target provide access to a wealth of single- and double-spin observables, thereby opening a window to physics uniquely accessible with the HESR at FAIR. This includes a first measurement of the transversity distribution of the valence quarks in the proton, and a first measurement of the moduli and the relative phase of the time-like electric and magnetic form factors $G_{E,M}$ of the proton. In polarized and unpolarized $pp$ elastic scattering open questions like the contribution from the odd charge-symmetry Landshoff-mechanism at large $|t|$ and spin-effects in the extraction of the forward scattering amplitude at low $|t|$ can be addressed.

Introduction

The possibility to achieve polarized proton-antiproton interactions at the at the High Energy Storage Ring (HESR) at the future Facility for Antiproton and Ion Research (FAIR) in Darmstadt (Germany) has been proposed last year by the PAX Collaboration [1]. Polarized antiproton-proton interactions will provide unique access to a number of new fundamental physics observables, which can be studied neither at other facilities nor at HESR without transverse polarization of protons and antiprotons.

Physics case

Transversity

The transversity distributions is the last leading-twist missing piece of the QCD description of the partonic structure of the nucleon. It describes the quark transverse polarization inside a transversely polarized proton [2]. Unlike the more conventional unpolarized quark distribution $q(x,Q^2)$ and the helicity distribution $\Delta q(x,Q^2)$, the transversity $h_1^T(x,Q^2)$ can neither be accessed in deep-inelastic scattering of leptons off nucleons nor can it be reconstructed from the knowledge of $q(x,Q^2)$ and $\Delta q(x,Q^2)$. It may contribute to some single-spin observables, but always coupled to other unknown functions. The transversity distribution is directly accessible uniquely via the double transverse spin asymmetry $A_{TT}$ in the Drell-Yan production of lepton pairs. The theoretical expectations for $A_{TT}$ in the Drell-Yan...
process with transversely polarized antiprotons interacting with a transversely polarized proton target at HESR are in the 0.3–0.4 range [3, 9]; with the expected beam polarization achieved using a dedicated low-energy antiproton polarizer ring (APR) of $P \approx 0.3$ and the luminosity of HESR, the PAX experiment is uniquely suited for the definitive observation of $h_1^T(x, Q^2)$ of the proton for the valence quarks. The determination of $h_1^T(x, Q^2)$ will open new pathways to the QCD interpretation of single–spin asymmetry (SSA) measurements [5].

**Magnetic and electric form factors**

The origin of the unexpected $Q^2$–dependence of the ratio of the magnetic and electric form factors of the proton as observed at the Jefferson laboratory [6] can be clarified by a measurement of their relative phase in the time–like region, which discriminates strongly between the models for the form factor. This phase can only be measured via SSA in the annihilation $pp \rightarrow e^+ e^-$ on a transversely polarized target [7, 8]. The first ever measurement of this phase at PAX will also contribute to the understanding of the onset of the pQCD asymptotics in the time–like region and will serve as a stringent test of dispersion theory approaches to the relationship between the space–like and time–like form factors [9, 10, 11]. The double–spin asymmetry will allow independently the $G_E - G_M$ separation and serve as a check of the Rosenbluth separation in the time–like region which has not been carried out so far.

**Hard scattering**

Arguably, in $p\bar{p}$ elastic scattering the hard scattering mechanism can be checked beyond $|t| = \frac{1}{4}(s - 4m_p^2)$ accessible in the $t$–$u$–symmetric $pp$ scattering, because in the $pp$ case the $u$–channel exchange contribution can only originate from the strongly suppressed exotic dibaryon exchange. Consequently, in the $pp$ case the hard mechanisms [12, 13, 14] can be tested at $t$ almost twice as large as in $pp$ scattering. Even unpolarized large angle $pp$ scattering data can shed light on the origin of the intriguing oscillations around the $s^{-1/2}$ behavior of the $90^\circ$ scattering cross section in the $pp$ channel and put stringent constraints on the much disputed odd–charge conjugation Landshof mechanism [15, 16, 17]. If the Landshof mechanism is suppressed then the double transverse asymmetry in $pp$ scattering is expected to be as large as the one observed in the $pp$ case.

**Experimental setup**

**Accelerator scheme**

The possibility to test the nucleon structure via double spin asymmetries in polarized proton–antiproton reactions at the HESR ring of FAIR at GSI in Darmstadt (Germany) has been suggested by the PAX collaboration with a Letter of Intent submitted on January 15, 2004 [1]. The physics program of PAX has been positively reviewed by the QCD Program Advisory Committee (PAC) on May 14–16, 2004. Following the QCD–PAC report and the recommendation of the Chairman
Figure 1: The proposed accelerator set-up at the HESR, with the equipment used by the PAX collaboration in Phase I: CSR, APR, beam transfer lines and polarized proton injector. In Phase II, by adding two transfer lines, an asymmetric collider is set up. It should be noted that, in this phase, also fixed target operation at PAX is possible.

of the committee on Scientific and Technological Issues (STI) and the FAIR project coordinator, the PAX collaboration has optimized the technique to achieve a sizable antiproton polarization [18] and a Technical Proposal for experiments at GSI with polarized antiprotons [19].

The overall machine setup of the HESR complex is schematically depicted in Fig. 1. Its main features are:

1. An Antiproton Polarizer (APR) built inside the HESR area with the crucial goal of polarizing antiprotons, to be accelerated and injected into the other rings. The polarization method is based on spin-filtering of the circulating beam by an internal target to the storage ring. This technique has been successfully demonstrated with protons [20] and tests are foreseen to optimize it for an antiproton beam.

2. A second Cooler Synchrotron Ring (CSR, COSY–like) in which protons or antiprotons can be stored with a momentum up to 3.5 GeV/c. This ring shall have a straight section, where a PAX detector could be installed, running parallel to the experimental straight section of HESR.

3. By deflection of the HESR beam into the straight section of the CSR, both the collider or the fixed–target mode become feasible.

It is worthwhile to stress that, through the employment of the CSR, effectively a second interaction point is formed with minimum interference with PANDA. The proposed solution opens the possibility to run two different experiments at the same time.

**Staging**

The PAX collaboration proposes an approach that is composed of two phases. During these the major milestones of the project can be tested and optimized before the
final goal is approached: An asymmetric proton–antiproton collider, in which polarized protons with momenta of about 3.5 GeV/c collide with polarized antiprotons with momenta up to 15 GeV/c. These circulate in the HESR, which has already been approved and will serve the PANDA experiment. The proposed phases are the following:

[Phase I]

A beam of unpolarized or polarized antiprotons with momentum up to 3.5 GeV/c in the CSR ring, colliding on a polarized hydrogen target in the PAX detector. This phase is independent of the HESR performance.

This first phase, at moderately high energy, will allow for the first time the measurement of the time-like proton form factors in single and double polarized \( pp \) interactions in a wide kinematical range, from close to threshold up to \( Q^2 = 8.5 \text{ GeV}^2 \). It would enable to determine several double spin asymmetries in elastic \( p^+p^- \) scattering. By detecting back scattered antiprotons one can also explore hard scattering regions of large \( t \): In proton–proton scattering the same region of \( t \) requires twice the energy. There are no competing facilities at which these topical issues can be addressed. For the theoretical background, see the PAX Technical Proposal [19] and the recent review paper [21].

[Phase II]

This phase will allow the first ever direct measurement of the quark transversity distribution \( h_1 \), by measuring the double transverse spin asymmetry \( A_{TT} \) in Drell–Yan processes \( p^+\bar{p}^- \rightarrow e^+e^- X \) as a function of Bjorken \( x \) and \( Q^2 \)

\[
A_{TT} \equiv \frac{d\sigma^{11} - d\sigma^{\perp\perp}}{d\sigma^{11} + d\sigma^{\perp\perp}} = \frac{\hat{a}_{TT} \sum_q e_q^2 b_q^2(x_1, M^2)\bar{b}_q^2(x_2, M^2)}{\sum_q e_q^2 q(x_1, M^2)\bar{q}(x_2, M^2)},
\]

where \( q = u, d, \bar{u}, \ldots, M \) is the invariant mass of the lepton pair and \( \hat{a}_{TT} \), of the order of one, is the calculable double–spin asymmetry of the QED elementary process \( q\bar{q} \rightarrow e^+e^- \). The most promising scenario forsees a beam of polarized antiprotons from 1.5 GeV/c up to 15 GeV/c circulating in the HESR, colliding on a beam of polarized protons with momenta up to 3.5 GeV/c circulating in the CSR. Deflection of the HESR beam to the PAX detector in the CSR is necessary (see Fig. 1). By proper variation of the energy of the two colliding beams, this setup would allow a measurement of the transversity distribution \( h_1 \) in the valence region of \( x > 0.05 \), with corresponding \( Q^2 = 4\ldots100 \text{ GeV}^2 \) (Fig. 2).

\( A_{TT} \) is predicted to be larger than 0.3 over the full kinematic range, up to the highest reachable center–of–mass energy of \( \sqrt{s} \sim \sqrt{200} \) (Fig. 2).

The cross section is large as well: With a luminosity of \( 5 \cdot 10^{30} \text{ cm}^{-2}\text{s}^{-1} \) about 2000 events per day can be expected. For the transversity distribution \( h_1 \), such an experiment can be considered as the analogue of polarized DIS for the determination of the helicity structure function \( g_1 \), i.e. of the helicity distribution \( \Delta g(x, Q^2) \); the kinematical coverage \( (x, Q^2) \) will be similar to that of the HERMES experiment.

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\(^a\)A first estimate indicates that in the collider mode luminosities in excess of \( 10^{30} \text{ cm}^{-2}\text{s}^{-1} \) could be reached. We are presently evaluating the influence of intra–beam scattering, which seems to be one of the limiting factors.
Future Projects (Physics)

Figure 2: Left: The kinematic region covered by the $h_1$ measurement at PAX in phase II. In the asymmetric collider scenario (blue) antiprotons of 15 GeV/c impinge on protons of 3.5 GeV/c at c.m. energies of $\sqrt{s} \sim \sqrt{200}$ GeV and $Q^2 > 4$ GeV$^2$. The fixed target case (red) represents antiprotons of 22 GeV/c colliding with a fixed polarized target ($\sqrt{s} \sim \sqrt{25}$ GeV). Right: The expected asymmetry as a function of Feynman $x_F$ for different values of $s$ and $Q^2 = 16$ GeV$^2$.

Detector

An extensive program of studies has been started to investigate different options for the PAX detector configuration, aiming at an optimization of the achievable performance. The primary goal of the PAX experimental program is to carry out a direct measurement of the $h_1$ transversity distribution. The proposed detector, described in the PAX technical proposal and shown in Fig. 3, is well-suited to provide large invariant-mass $e^+e^-$ pair detection, from both Drell-Yan reactions and $pp$ annihilations. In addition, such a detector is able to efficiently detect secondaries in two body reactions, like elastic scattering events, where the over-constrained kinematic simplifies the event reconstruction and reduces the particle identification requirements. Alternative detector scenarios, e.g. with $e^+e^-$ Drell-Yan pair detection capability, with an instrumented forward section or with extended hadron particle identification, are also under study. The present detector concept fulfills the following driving principles:

- Large acceptance. Good azimuthal coverage and symmetry are needed to be sensitive to the dependence of the observables on the angle between production plane and target spin orientation.

- Sensitivity to electron pairs. The overwhelming hadronic background requires excellent lepton identification.

- Use of a toroidal magnet. The spectrometer magnet should not affect the transverse spin orientation of the beam and provide an environment to ensure the operation of the Čerenkov detector. The toroid has almost negligible
figure 3: Left: Conceptual design of the PAX detector employed to estimate the performance and to show the feasibility of the transversity measurement in the asymmetric antiproton-proton collider at PAX. The artistic view is produced by GEANT. Right: Expected precision of the $h_1^T(x)$ measurement for one year of data taking in the collider mode at PAX. A luminosity of $2 \cdot 10^{30}$ cm$^{-2}$s$^{-1}$ and a polar angle acceptance between 20° and 120° were assumed. The top panel shows the precision achievable within the full $Q^2 > 4 GeV^2$ kinematic range, whereas the bottom panel shows the precision achievable in the restricted $Q^2 > 16 GeV^2$ range.

fringe-fields outside the active volume, both internally along the beam line and externally inside the tracking volume.

**Signal estimates**

A detailed Monte Carlo study has been started to test the feasibility of the Drell-Yan measurement with the proposed detector layout in Phase II. The achievable precision of the ratio between the transverse $h_1^T$ and the well known unpolarized $u(x)$ distributions of the proton, in different intervals of the Bjorken-x and after one year of data-taking is shown in Fig. 3. The $h_1^T$ distribution can be measured in a wide x range, from $x = 0.7$ down to $x = 0.05$, practically covering the whole valence region and extending to low value of x, where the theoretical predictions show the largest deviations. It should be noticed that in principle the beam energies in the two rings of the collider can be tuned to best explore different x intervals. Indeed the highest sensitivity is achievable for $x \approx 1/\sqrt{Q}$.

The situation is more favorable for the measurements of electromagnetic form factors and $pp$ elastic scattering foreseen in Phase I, as, in these cases, luminosity and cross-sections are such to guarantee high rates [19]. In Phase-I a (polarized) antiproton beam with momentum up to 3.5 GeV/c scatters off a polarized internal gaseous target in the CSR ring. For single spin asymmetries (SSA) and double spin asymmetries (DSA), the statistical error scales as:

$$\Delta_{SSA} = \frac{1}{Q \sqrt{N_{SSA}}} \quad \Delta_{DSA} = \frac{1}{PQ \sqrt{N_{DSA}}}$$

(2)

where $Q=0.8$ is the proton target polarization and $P=0.3$ is the expected antiproton
beam polarization, $N_{SSA}$ ($N_{DSA}$) is the number of collected events in single (double) polarization mode.

Using the $p\bar{p} \rightarrow e^+e^-$ cross section measured by PS170 [22] and the estimated luminosity for the fixed target mode [19] it is possible to estimate the running time to get a precise measurement of the relative phases of the time-like electric and magnetic form factors of the proton. Table 1 lists the running time required to reduce the absolute error down to $\Delta A = 0.05$ for few indicative beam momenta accessible in the CSR. Note that the CSR ring can safely run the polarized antiprotons down to 200 MeV/c.

Table 1: Required beam time (in days) to reduce the absolute error to $\Delta A = 0.05$. DSA = Double Spin Asymmetry, SSA = Single Spin Asymmetry.

<table>
<thead>
<tr>
<th>$P_{beam}$ (MeV/c)</th>
<th>DSA (dd)</th>
<th>SSA (dd)</th>
</tr>
</thead>
<tbody>
<tr>
<td>549</td>
<td>2.9</td>
<td>0.3</td>
</tr>
<tr>
<td>900</td>
<td>4.7</td>
<td>0.5</td>
</tr>
<tr>
<td>3600</td>
<td>132</td>
<td>13</td>
</tr>
</tbody>
</table>

An estimate for the rate of hard $pp$ elastic scattering in the PAX kinematic conditions of Phase I can be done starting from the cross-section measured by E838 [23]. For a momentum transfer of $t_{E838} = 5 GeV^2$ a cross-section of $10^{-4} mbGeV^2/c^2$ has been measured. The rescaling of the cross section to the maximum momentum transfer achievable at PAX ($t_{PAX} = 3.9 GeV^2/c^2$) in conjunction with the estimated luminosity for the fixed target mode ($\mathcal{L} = 1.5 \times 10^{31} cm^{-2}s^{-1}$) gives an even rate of the order of 1 Hz for an interval of $\Delta t = 0.1 GeV^2/c^2$. Only a few hours of data taking are than requested to reach a precision of 0.05 in the double-polarized asymmetry.

Conclusion

The PAX Collaboration has presented a rich and innovative physics program to be realized in the upcoming FAIR hadron facility. The storage of polarized antiprotons at HESR will open unique possibilities to test QCD in hitherto unexplored domains and make of FAIR a facility without competitors.

References


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FLAIR, a Facility for Low-energy Antiproton and Ion Research

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Abstract

The FAIR facility for beams of ions and antiprotons at Darmstadt will provide antiproton beams of intensities that are two orders of magnitude higher than currently available. The low-energy antiproton physics community has recognized the opportunity to create a next-generation low-energy antiproton facility and has submitted a proposal for a facility called FLAIR which was very positively evaluated in spring of 2005. FLAIR will be able to provide cooled antiproton beams well below 100 keV kinetic energy, which will allow for a much higher rate of trapped antiprotons and therefore greatly advance the currently performed experiments. Furthermore, the availability of continuous beams will make many new experiments possible. This talk gives an overview of the layout and physics program of the proposed facility.

INTRODUCTION

Low-energy antiproton physics is currently being done at the Antiproton Decelerator (AD) of CERN, Geneva. Due to the low intensity (≈ 10^5 \( \bar{p} / s \)) and the availability of only pulsed extraction, the physics program is limited to the spectroscopy of antiprotonic atoms and antihydrogen formed in charged particle traps or by stopping antiprotons in low-density gas targets. Furthermore, the output energy of the AD (5 MeV kinetic energy) is still significantly higher than the < 100 keV energy best suited for these experiments.

At FAIR, the planned Facility for Antiproton and Ion Research at Darmstadt, it will become possible to create a next-generation low-energy antiproton facility to overcome these limitations by providing cooled beams at higher intensities and a factor 100 lower energy. In addition the new facility should have the possibility of slow (i.e., continuous) extraction, which will allow nuclear/particle physics type experiments requiring coincidence measurements to be performed.

In 2004 a letter of intent [1] and in 2005 a technical proposal [2] have been submitted to GSI, Darmstadt, for a facility called FLAIR (Facility for Low-energy Antiproton and Ion Research) that is described in the following. Both documents have been evaluated very positively by the program advisory committee of GSI. FLAIR consists of two storage rings, a magnetic (LSR) and an electrostatic (USR) one, and a universal trap facility (HITRAP), cf. Fig. 1. These components of the facility can provide stored as well as fast and slow extracted cooled beams at energies between 30 MeV and 300 keV (LSR), between 300 keV and 20 keV (USR), and cooled particles at rest or at ultra-low (eV–keV) energies (HITRAP). This will allow a large
variety of new experiments to be performed, as described in Sec. 6.2. Among the
unique experiments only possible at such a facility are nuclear physics studies using
antiprotons as a hadronic probe to investigate the structure of nuclei, including
radioactive isotopes produced at the future facility, and many atomic-collision type
experiments with internal targets in both storage rings with effective intensities as
large as $10^{10}$ $\overline{p}$/s. An important synergetic aspect is that the whole structure will
also be used to study highly charged ions, including storing, cooling (LSR, USR)
and trapping them in Penning traps like HITRAP [3] and investigating them in a
dedicated area for heavy ions. These experiments are part of the physics program
of the SPARC collaboration [4] (see talk by Th. Stöhler at this conference).

**LAYOUT AND PERFORMANCE OF THE FACILITY**

The key features of the proposed facility at Darmstadt (cf. Fig. 1) are:

- **High-brightness, high-intensity, low-energy antiproton beams.**
  - High antiproton intensity due to **accumulation**.
  - Cooled $\overline{p}$ beams down to **300 keV** using LSR.
Future Projects (Physics)

- Electrostatic storage ring (USR) for atomic collision experiments and deceleration and cooling to 20 keV.
- HITRAP for efficient deceleration of \( \bar{p} \)s from 4 MeV to rest and extraction of \( \bar{p} \)s from a cooler trap at keV energies.

- Both slow and fast extraction from LSR and USR at energies between 30 MeV and 20 keV.

The antiproton production method at the future facility [2] (see talk by P. Beller) is similar to the scheme used for LEAR at CERN. \( 10^8 \) antiprotons will be produced every 5 seconds, will be collected in the CR storage ring and accumulated in the RESR. Already within the foreseen scheme of FAIR it is possible to decelerate antiprotons to 30 MeV in the NESR. The FLAIR proposal assumes that \( \bar{p} \) will then be transferred to the FLAIR facility for further deceleration in the LSR storage ring, in the electrostatic storage ring USR, and in the HITRAP facility. The number of antiprotons that can be decelerated in the storage rings is determined by the space charge limit at low energies. For the case of FLAIR, antiproton rates of \( \sim 10^6/s \) extracted both fast and slow at energies down to 20 keV will be available. This corresponds to about 10% of the production rate at FAIR, so that FLAIR can operate in parallel to other experiments using antiprotons. The \( \bar{p} \) can be either directly stopped in low-density gas targets using thin windows, or trapped with high efficiency in charged particle traps. The same rate of antiprotons can be obtained at rest in HITRAP or extracted at ultra-low (eV–keV) energies. This scheme gives about a factor 100 more antiprotons per unit time stopped in gas targets or trapped in ion traps as compared to the present AD at CERN where no dedicated accumulation and multi-stage deceleration rings are utilized. The availability of such beams will tremendously increase the number of experiments possible at this facility.

Antiprotons can be extracted either slow or fast from the LSR and used in several beamlines for e.g. deceleration and cooling in the HITRAP facility, or for stopping them in low-density gas targets. In addition, an electrostatic storage ring is foreseen (USR), which will be used for deceleration, slow and fast extraction, and for atomic physics experiments with internal targets. The energy range of 300 - 20 keV (using electron cooling) makes it a unique tool for many atomic collision experiments which are only possible in such a low-energy storage ring, where effective intensities (i. e. the number of stored particles \( N_{\text{stored}} \) times the revolution frequency \( f_{\text{rev}} \)) of \( R_{\text{eff}} = N_{\text{stored}} f_{\text{rev}} \) of \( R_{\text{eff}} = 10^{10} \bar{p}/s \) are reached for in-ring experiments.

PHYSICS PROGRAM OF FLAIR

The physics of FLAIR covers a wide range in atomic, nuclear and particle physics and has potential medical applications. It is described in detail in the FLAIR letter of intent [1] available from the FLAIR web page. In the following a brief overview will be given.
Precision spectroscopy of antiprotonic atoms and antihydrogen

This is the current topic of the Antiproton Decelerator (AD) at CERN. The main goal here is to study fundamental symmetries and interactions by providing high-precision data of particle and antiparticle properties for tests of CPT symmetry and QED calculations. Antiprotonic atoms have been used for some time to test CPT symmetry between proton and antiproton properties (for a review, see [6]). The most accurate test of proton/antiproton properties is the measurement of their cyclotron frequency $\omega_c \propto Q/M$ ($Q, M$ denoting charge and mass) by the TRAP collaboration at LEAR, yielding an accuracy of better than $10^{-10}$ [7]. Separate CPT limits on $Q$ and $M$ can be set by combining this measurement with the recent precision laser spectroscopy of antiprotonic helium by the ASACUSA collaboration at the Antiproton Decelerator (AD) of CERN, which are now at a level of $10^{-8}$ [8]. The major recent experimental improvement came from using a radio frequency quadrupole decelerator (RFQD [9, 10]) to decelerate $\bar{p}$ from 5 MeV to $\sim 100$ keV which allowed to stop them in more dilute gases. Further improvements can be expected at FLAIR from the high-quality cooled antiprotons beams at this energy or below.

The ultimately highest precision of a CPT test with antiprotonic atoms is likely to be achieved using antihydrogen. The production of large amounts of cold antihydrogen at the AD has been reported in 2002 by both the ATHENA and ATRAP collaborations at the AD [11, 12, 13], but it is still expected to take several years until precision spectroscopy can be performed. After a shutdown in 2005, the AD is expected to run until 2010, so that initial results on spectroscopy can be expected at the AD. The ultimate goal is to measure the 1S-2S two-photon laser transition [14, 15] and the ground state hyperfine splitting [16] to accuracies similar to the ones achieved for hydrogen ($10^{-14}$ [17] and $10^{-12}$ [18, 19], resp.), yielding a very sensitive test of the CPT theorem. New ideas like the use of a cusp trap for antihydrogen formation [20] are being proposed. To achieve the ultimate precision, the trapping and laser cooling of neutral antihydrogen atoms is required. The development of these techniques will surely take many more years to accomplish.

Once trapped and laser-cooled antihydrogen is available, other challenging experiments can be performed. Among them is the gravitation of antimatter [21], which is a long standing question that has never been answered experimentally, because in the case of charged particles, gravitational effects are covered by the many orders of magnitude stronger electromagnetic interaction. Collisions between antihydrogen and matter atoms as well as the creation of larger antimatter systems like $\bar{H}^+$ (one antiproton and two positrons, equivalent to the well known $H^-$ ion) are of big interest for atomic collision theory.

Atomic collision physics

This field will greatly benefit from the availability of ultra-slow, cooled antiproton beams in storage rings. This will enable for the first time ever the detailed study of ionization processes with antiprotons in kinematically complete experiments. The energy loss can be investigated at ultra-low energies to answer open questions about
Antiprotons as hadronic probes

In nuclear physics, the antiproton is used as a hadronic probe to study the nuclear structure. X-ray spectroscopy of the low-lying states of $\bar{p}p$ or other light atoms \cite{22} gives important information on the nucleon-antinucleon interaction in the low-energy limit, where scattering experiments cannot provide precise values. These data are vital for the improvement of QCD calculations in the low-energy (hence non-perturbative) region. X-ray spectroscopy of heavy antiprotonic atoms can be used to obtain information about the density ratio of neutron and protons at the nuclear periphery, i.e. to investigate neutron halo or skin effects. The PS209 experiment at LEAR has in this way provided benchmark data for nuclear structure calculations over a wide range of nuclei \cite{23}. This technique is much more sensitive than others like total absorption cross section measurements, and further systematic measurements with stable isotope targets will provide a more complete and systematic picture of the nuclear surface. Since halo effects are expected to be more pronounced in nuclei with a large neutron excess which are unstable, the application of this technique to unstable radioactive ions \cite{24} available at FLAIR via the Super-FRS will generate important contributions to the study of the structure of nuclei far from stability.

Concerning the particle physics point of view, the elementary antinucleon-nucleon interaction processes still present a few unclear aspects \cite{25}, in spite of the wealth of physics results produced at LEAR. In particular, some anomalous effects have been observed close to the nucleon-antinucleon threshold which are likely related to the interplay between quark and antiquark degrees of freedom – that could be, for instance, responsible of the existence of quasi-nuclear subthreshold nucleon-antinucleon bound states, long sought for at LEAR without large success. FLAIR would be a good place to further study these processes.

The study of baryon-baryon interactions as a basic tool for investigations of the strong interaction can be extended to the hyperon sector, where much less data exist than in the nucleon sector. Especially few data exist on strangeness $S = -2$ systems. Stopped antiprotons are very efficient for the production of $S = -2$ systems via the double strangeness and charge exchange reaction $(\bar{K}^*, K)$ \cite{26}. With a sizeable branching ratio the annihilation of antiprotons results in the production of a $\bar{K}^*$ “beam” which interacts with another nucleon via $\bar{K}^*N \rightarrow K\Xi$. The momenta of the $K^*$ are well matched for the production of slow $\Xi$ particles which undergo efficient $\Xi N$ interactions. The proposed studies will result in detailed information of $S = -2$ baryonic and possible dibaryonic states.
Medical applications

Recently, interest has been shown in the medical application of antiprotons for tumor therapy. This comes from the fact the antiprotons, in addition to depositing energy via their energy loss like other charged particles, annihilate when stopped in material. The annihilation produces residual nuclear fragments of high charge and low energy, which deposit a large biological dose in the immediate surrounding of the $p$ stopping distribution. Since the cooled low-emittance antiproton beams can be stopped in a well-defined region, the presumably large energy deposited locally makes them a suitable tool for tumor therapy. A test experiment is under way at the AD of CERN [27] and, if this effect is confirmed, the method can be extended at FLAIR where the high-energy antiproton beams (50 – 300 MeV) needed to penetrate deep enough into human tissue are available directly from the NESR.

CONCLUSIONS

FLAIR will be a unique next-generation low-energy antiproton and ion facility. Cooled antiprotons down to 20 keV both in storage rings and extracted will revolutionize low-energy antiproton physics. Continuously extracted beams at these energies will enable nuclear and particle physics type experiments currently not possible at the AD of CERN. The availability of short-lived exotic nuclei at the future facility at Darmstadt creates synergies by using antiprotons as hadronic probes for nuclear structure. Using the same facility, atomic physics experiments with highly charged ion will be possible both in beams and at rest in HITRAP.

Acknowledgements

I would like to thank the members of the FLAIR steering committee and community who contributed to the combined effort to write the letter of intent and technical proposal and who are working towards the creation of this new facility.

References


Future Projects (Physics)


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Transversity and its conjugate T-odd distribution via unpolarized and single polarized Drell-Yan processes

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Abstract

The Drell-Yan (DY) processes with unpolarized colliding hadrons and with the single transversely polarized hadron are considered. An approach to direct (without any model assumptions) extraction of both transversity and its conjugate T-odd parton distribution functions (PDF) is proposed. Of a special importance are DY processes with the participation of antiproton. For the such processes, the preliminary estimations performed for PAX kinematics demonstrate that it is quite real to extract both transversity and its conjugate T-odd PDF in the PAX conditions.

The advantage of DY process for extraction of PDF, is that there is no need of any fragmentation functions. While the double transversely polarized DY process \( H_1 H_2 \rightarrow l^+ l^- X \) allows to directly extract the transversity distributions (see ref. [1] for review), in the single polarized DY \( H_1 H_2 \rightarrow l^+ l^- X \) the access to transversity is rather difficult since it enters the respective cross-section in the complex convolution with another unknown T-odd PDF (see below). At the same time it is, certainly very desirable to manage get the transversity PDF from unpolarized and single-polarized DY processes as an alternative possibility. Besides, T-odd PDF are very intriguing and interesting objects in themselves, so that it is very important to extract them too.

The main goal of this paper is to develop free of any model assumptions approach which would allow to completely disentangle PDF corresponding the unpolarized and single-polarized DY processes.

Let us first consider the results of ref. [3] for both unpolarized and single-polarized DY processes. In that paper the Collins-Soper frame\(^d\) is used (see Fig. 3 in ref. [3]), where one deals with three angles \( \theta, \phi \) and \( \phi_{S_2} \). Two angles, \( \theta \) and \( \phi \), are common for both unpolarized and polarized DY processes. These are the polar and azimuthal angles of lepton pair. Third angle, \( \phi_{S_2} \), does appear when hadron two is transversely polarized, and this is just the azimuthal angle of \( S_{2T} \) measured with respect to lepton plane.

We consider here the case of pure transverse polarization of hadron two, so that we put \( \lambda_1 = 0 \) and \( |S_{1T}| = 1 \) (\( \lambda_2 = 0 \) and \( |S_{2T}| = 1 \) in our notation) in the respective Eqs. of ref. [3] (Eqs. (21) and (22) in ref. [3]) for unpolarized and single

\(^d\)see [1] for detail of the respective kinematics
polarized cross-sections. Besides, taking into account only the dominating electromagnetic contributions and neglecting (just as in ref. [3]) the “higher harmonic” term containing $3\phi$ dependence, one gets the following simplified equations for the QPM unpolarized and single-polarized cross-sections:

\[
\frac{d\sigma^{(0)}(H_1 H_2 \to lX)}{dt d\phi_s \, dx_1 dx_2 q_T} = \frac{\alpha^2}{12Q^2} \sum_q e_q^2 \\
\times \left\{ (1 + \cos^2 \theta) \mathcal{F}[f_1 f_2] + \sin^2 \theta \cos(2\phi) \mathcal{F} \\
\times \left( 2 \hat{h}_{k_1} \cdot h_{k_2T} - k_{1T} \cdot k_{2T} \right) \right\}, \tag{1}
\]

and

\[
\frac{d\sigma^{(1)}(H_1 H_2 \to lX)}{dt d\phi_s \, dx_1 dx_2 q_T} = \frac{\alpha^2}{12Q^2} \sum_q e_q^2 \\
\times \left\{ (1 + \cos^2 \theta) \mathcal{F}[f_1 f_2] + \sin^2 \theta \cos(2\phi) \mathcal{F} \\
\times \left( 2 \hat{h}_{k_1} \cdot h_{k_2T} - k_{1T} \cdot k_{2T} \right) \right\} \\
+ (1 + \cos^2 \theta) \sin(\phi + \phi_s) \mathcal{F} \left( \hat{h}_{k_1} \cdot \frac{h_{k_2T} f_1 f_2}{M_1 M_2} \right) \\
- \sin^2 \theta \sin(\phi + \phi_s) \mathcal{F} \left( \hat{h}_{k_1} \cdot \frac{h_{k_2T} f_1 f_2}{M_1 M_2} \right). \tag{2}
\]

Here $\hat{h} \equiv q_T/(q_T^2)$, $h_{1q}(x, k_T)$ is the $k_T$-dependent transversity distribution, while $h_{1q}(x, k_T)$ and $f_{1q}(x, k_T)$ are $k_T$-dependent T-odd PDF (see ref. [1] for review). The convolution product is defined as [3]

\[
\mathcal{F}[f_1 f_2] \equiv \int d^2k_{1T} \, d^2k_{2T} \, \delta^2(k_{1T} + k_{2T} - q_T) \\
\times [f_1(x, k_{1T}^2) f_2(x, k_{2T}^2) + (1 \leftrightarrow 2)]. \tag{3}
\]

Let us first consider the purely unpolarized DY process. Notice that Eq. (1) is very inconvenient in application because of the complicated $q_T$ and $k_T$ dependence entering Eq. (1) via the convolution, Eq. (3). To deal with Eq. (1) the model

\[
h_{1q}^\perp(x, k_T^2) = \frac{\alpha_T}{\pi} \frac{M_H M_H^*}{k_T^2 + M_H^2} e^{-\kappa k_T^2} f_1(x), \tag{4}
\]

where $M_C = 2.3 \text{ GeV}$, $\alpha_T = 1 \text{ GeV}^{-2}$ and $M_H^*$ is the hadron mass, was proposed in ref. [3]. With a such assumption one then calculates [3], [4] the coefficient $\kappa \equiv \nu/2$ at $\cos 2\phi$ dependent part of the ratio

\[
R \equiv \frac{d\sigma^{(0)}/d\Omega}{\sigma^{(0)}}, \tag{5}
\]
which allows to explain the anomalous $\cos 2\phi$ dependence [6], [7] of the unpolarized DY cross-section. However, the author of ref. [3] stresses that Eq. (4) is just a “crude model”. Besides, Eq. (4) can not help us to extract the quantity $h_2^+$ from the unpolarized DY process.

Thus, to avoid these problems, we propose to extract from unpolarized DY process the properly integrated over $q_T$ ratio (c.f. Eq. (5))

$$R = \frac{\int d^2q_T |q_T|^2 / M_1 M_2 |d\sigma^{(0)}/d\Omega|}{\int d^2q_T \sigma^{(0)}},$$

parameterized as

$$\hat{R} = \frac{3}{16\pi} \left( \gamma (1 + \cos^2 \theta) + \hat{k} \cos 2\phi \sin^2 \theta \right),$$

that should be compared with the equation (see refs [3],[6])

$$R = \frac{3}{16\pi} (1 + \cos^2 \theta + \nu/2) \cos 2\phi \sin^2 \theta (\nu \equiv 2\kappa).$$

By virtue of Eq. (1), the coefficient $\hat{k}$ at $\cos 2\phi$ dependent part of $\hat{R}$ reads

$$\hat{k} = \int d^2q_T |q_T|^2 / M_1 M_2 \times \sum_q \frac{c_q^2 F^2 [(2\mathbf{h} \cdot \mathbf{k}_{1T} \mathbf{h} \cdot \mathbf{k}_{2T} - \mathbf{k}_{1T} \cdot \mathbf{k}_{2T})/M_1 M_2]}{\sum_q c_q^2 F [f_1 f_2]} \left( \int d^2q_T \right)^{-1}.$$
for the $n$-th moment of $k_T$-dependent PDF. Thus, one can see that the numerator of $\hat{k}$ is factorized out in the simple product of the first moments of $h_1^+$ distributions. This allows to directly extract these quantities from $\hat{k}$ which should be measured in unpolarized DY. This, in turn (see below), allows to directly extract the transversity so that one easily gets

\[ \text{and define the following asymmetries} \]

\[ A_{h(j)} = \frac{1}{\sum_q e_q^2 F \left[ \frac{h_{l_1} x f_{l_1}^q}{h_{l_1} x f_{l_1}^q} \right]} \]

\[ \text{where the single-polarized cross-section is given by Eq. (2). It is clear that in the difference} \]

\[ \frac{\sigma(S_{2T}) - \sigma(-S_{2T})}{} \]

\[ \text{and} \]

\[ \text{sin}(\phi) \text{ and sin}(\phi + \phi_S) \text{ survive (and are multiplied by two). Besides, the properly chosen weights: sin}(\phi) \text{ and sin}(\phi + \phi_S), \text{allow to separate the contributions containing} \]

\[ h_1^+ \text{ and } f_{1T}^q \text{ PDF with the result} \]

\[ A_{h} = \frac{1}{\sum_q e_q^2 F \left[ \frac{h_{l_1} x f_{l_1}^q}{h_{l_1} x f_{l_1}^q} \right]} \]

\[ A_{f} = \frac{1}{\sum_q e_q^2 F \left[ \frac{h_{l_1} x f_{l_1}^q}{h_{l_1} x f_{l_1}^q} \right]} \]

\[ \text{The asymmetries like} \]

\[ A_{f} \text{ given by Eqs. (12), (14) and their application with respect to Sivers function} \]

\[ f_{1T}^q(x, k_T) \equiv -(M/2|k_T|)|\Delta_{f_1}^q(x, k_T)| \]

\[ \text{extraction from the data were considered in detail in refs. [5, 9], so that we concentrate here on the asymmetry} \]

\[ A_{h} \text{ given by Eqs. (12) and (13).} \]

\[ \text{Notice that asymmetry} A_{h} \text{ given by Eqs. (12), (13) is inconvenient in application because of the complicated} q_T \text{ and} k_T \text{ dependence entering the convolution. It is much more convenient to deal with the properly integrated over} q_T \text{ asymmetry (just as in ref. [8] in the case of SIDIS and in ref. [9] in the case of Sivers PDF extraction from the single polarized DY):} \]

\[ \hat{A}_{h} = \frac{\int d\Omega d\phi \sigma_{S_{2T}} \sin(\phi + \phi_S)[\sigma(S_{2T}) - \sigma(-S_{2T})]}{\int d\Omega d\phi \sigma_{S_{2T}} \sin(\phi + \phi_S)[\sigma(S_{2T}) + \sigma(-S_{2T})]} \]

\[ \text{so that one easily gets} \]

\[ \hat{A}_{h} = -\frac{1}{2} \sum_q e_q^2 \left[ \frac{h_{l_1}^{(1)}(x_1) h_{l_1 q}(x_2) + (1 \leftrightarrow 2)}{h_{l_1} x f_{l_1}^q(x_1) f_{l_1}^q(x_2) + (1 \leftrightarrow 2)} \right] \]

\[ \text{The analogous weighting procedure was applied in the case of transversely polarized SIDIS by the HERMES collaboration [8].} \]
The system of Eqs. (19) and (20) is the main result of this paper. Measuring the

\[
\bar{h}_1^{\perp}(1) \quad \text{and} \quad h_1.
\]

Among variety of DY processes, DY processes with antiproton (\(\bar{p}p \rightarrow l^+l^-X\), \(\bar{p}p \rightarrow l^+l^-X\), \(\bar{p}p \rightarrow l^+l^-X\)) have essential advantage because the charge conjugation symmetry can be applied. Indeed, due to charge conjugation, antiquark PDF from the antiproton are equal to the respective quark PDF from the proton. Thus, Eqs. (10), (16) in the case of \(\bar{p}p\) collisions are rewritten as

\[
\hat{k} \bigg|_{\bar{p}p^l \rightarrow l^+l^-X} = \frac{8\sum_q e_q^2 \left[ \bar{h}_1^{\perp}(1)(x_1)h_1^{\perp}(1)(x_2) + \bar{h}_1^{\perp}(1)(x_1)\bar{h}_1^{\perp}(1)(x_2) \right]}{\sum_q e_q^2 \left[ f_{1\bar{q}}(x_1)f_{1\bar{q}}(x_2) + f_{1\bar{q}}(x_1)f_{1\bar{q}}(x_2) \right]},
\]

and

\[
\hat{A}_h \bigg|_{\bar{p}p^l \rightarrow l^+l^-X} = \frac{1}{2} \frac{8\sum_q e_q^2 \left[ \bar{h}_1^{\perp}(1)(x_1)h_1^{\perp}(1)(x_2) + \bar{h}_1^{\perp}(1)(x_1)\bar{h}_1^{\perp}(1)(x_2) \right]}{\sum_q e_q^2 \left[ f_{1\bar{q}}(x_1)f_{1\bar{q}}(x_2) + f_{1\bar{q}}(x_1)f_{1\bar{q}}(x_2) \right]},
\]

where now all PDF refer to protons. Neglecting squared antiquark and strange quark PDF contributions to proton and taking into account the quark charges and up quark dominance at large \(x\), Eqs. (17) and (18) are essentially given by

\[
\hat{k}(x_1, x_2) \bigg|_{\bar{p}p^l \rightarrow l^+l^-X} \approx \frac{8h_1^{\perp}(1)(x_1)h_1^{\perp}(1)(x_2)}{f_{1u}(x_1)f_{1u}(x_2)},
\]

and

\[
\hat{A}_h(x_1, x_2) \bigg|_{\bar{p}p^l \rightarrow l^+l^-X} \approx -\frac{1}{2} \frac{h_1^{\perp}(1)(x_1)h_1u(x_2)}{f_{1u}(x_1)f_{1u}(x_2)}.
\]

The system of Eqs. (19) and (20) is the main result of this paper. Measuring the quantity \(\hat{k}\) in unpolarized DY (Eqs. (6), (7)) and using Eq. (19) one can obtain the quantity \(\bar{h}_1^{\perp}(1)\). Then, measuring SSA, Eq. (15), and using the obtained quantity \(\bar{h}_1^{\perp}(1)\), one can eventually extract the transversity distribution \(h_1\) using Eq. (20). Let us stress once again that now there is no need in any model assumptions about \(k_F\) dependence of \(\bar{h}_1^{\perp}\) distributions. In practice one should apply Eqs. (19) and (20) at the points \(x_1 = x_2 \equiv x\) (i.e., \(x_F \equiv x_1 - x_2 = 0\), so that

\[
\bar{h}_1^{\perp}(1)(x) = f_{1u}(x)\sqrt{\frac{k(x, x)}{8}},
\]

and

\[
h_1u(x) = -4\sqrt{2} \frac{\hat{A}_h(x, x)}{\sqrt{k(x, x)}} f_{1u}(x).
\]

To estimate the possibility of \(\bar{h}_1^{\perp}(1)\) and \(h_1\) measurement, the special simulation of DY events with the PAX kinematics [2] are performed. The proton-antiproton

\footnote{The large \(x\) values is the peculiarity of the \(\bar{p}p\) experiments planned at GSI – see ref. [2]}

\footnote{The different points \(x_F = 0\) can be reached changing \(Q^2\) value at fixed \(s \equiv x_1x_2Q^2 \equiv \tau Q^2\).}
collisions are generated with the PYTHIA package [10]. Two samples are prepared: for the collider mode (15 GeV$^2$ antiproton beam colliding on the 3.5 GeV$^2$ proton beam) and for fixed target mode (22 GeV$^2$ antiproton beam colliding on an internal hydrogen target). Each sample contains about 100 K pure Drell-Yan events. The kinematical plots are shown in Figure 1. The events were weighted with the ratio of DY cross-sections given by Eqs. (5) and (8), where $\nu$ dependences of $q_T$ and $x_1$ correspond to ones (and are in a good agreement) from ref. [6] and are presented in Fig. 2. The angular distributions of $\hat{R}$ (Eqs. (6) and (7)) for both samples are studied just as it was done in ref. [6] with respect to $R$ (Eqs. (5), (8)). The results are shown in Fig. 3. The value of $\hat{k}$ at averaged $Q^2$ for both modes are found to be 

$$1.2 \pm 0.2$$ for collider mode and 

$$1.0 \pm 0.2$$ for fixed target mode.

The quantity $h_{1u}^{(1)}$ is reconstructed from the obtained values of $\hat{k}$ using Eq. (21) with $x_F = 0 \pm 0.04$. The results are shown in Fig. 4. Notice, the obtained values of $h_{1u}^{(1)}$ are in accordance (in order of value) with the respective values obtained with the model (4) for $h_{1u}^{z}(x, k_T)$. Indeed, for example for the fixed target mode ($Q^2_{\text{average}} \simeq 5$ GeV$^2$, so that $x_1 \simeq x_2 \simeq 0.2$ at the point $x_F \simeq 0$) the results from the simulations and from the model (4) are $h_{1u}^{z(1)} \simeq 1$ and $h_{1u}^{z(1)} \simeq 0.5$, respectively.

Using the obtained values of $h_{1u}^{(1)}$ we estimate the expected SSA given by Eq. (20). The results are shown in Figs. 5 and 6. To estimate the $h_1$ values entering SSA we follow the procedure of Ref. [11].

In summary, the approach to direct access to transversity and its conjugate T-odd PDF is proposed. Within this approach one need not any model assumptions about $k_T$ dependence of $h_1^z$. One can directly extract both $h_1$ and first moment of $h_1^z$ from the single-polarized and unpolarized DY processes, due to these quantities enter the measured $\hat{k}$ and SSA $A_\bar{h}$ in the form of simple product instead of complex convolution. The preliminary estimations for PAX kinematics show the possibility to measure both $\hat{k}$ and SSA $A_\bar{h}$ and then to extract the quantities $h_{1u}^{(1)}$ and $h_1$. Certainly, the estimations of values of $\hat{k}$ and $A_\bar{h}$ obtained in this paper are very preliminary and show just the order of values of these quantities. For more precise estimations one needs the Monte-Carlo generator more suitable for DY processes studies (see, for example, ref. [4]) than Pythia which we used (with the proper weighting of events) here.

Notice, that the proposed approach can be also applied to DY processes: $\pi^- p \rightarrow \mu^+ \mu^- X$ and $\pi^- p \rightarrow \mu^+ \mu^- X$, which could be study [12] in the COMPASS experiment at CERN.


References


Figure 1: The kinematical plots for generated DY events. The black and red colors correspond to collider and fixed target modes, respectively.
Figure 2: $q_T$ (left) and $x_1$ (right) dependences of reconstructed for collider mode simulations quantities $\mu$ and $\nu$ entering Eq. (8).

Figure 3: $k$ versus $x_1$ for $x_F = 0$. Data is obtained with MC simulations for collider (closed circles) and for fixed target mode (open circles).
Figure 4: $t_{\text{beam}}^{(1)}$ versus $x_1$ for $x_F = 0$. Data is obtained with MC simulations for collider (closed circles) and for fixed target mode (open circles).

Figure 5: SSA given by Eq. (20) versus $x_F$ for collider mode for three values of $Q^2$: 50 GeV$^2$ (lower curve), 25 GeV$^2$ (middle curve) and 9 GeV$^2$ (upper curve).

Figure 6: SSA given by Eq. (20) versus $x_F$ for fixed target mode for three values of $Q^2$: 16 GeV$^2$ (lower curve), 9 GeV$^2$ (middle curve) and 4 GeV$^2$ (upper curve).

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Perspective of Research on HIRFL-CSR


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Abstract

The project of HIRFL-CSR is under commissioning. The first turn beam has been tuning smoothly in beginning of this year. Therefore, the first Beam for experiment is expected will be ready in 2005. The main parameters of HIRFL-CSR are optimized that maximum energy is about 20% higher (1100AMeV for C and 520AMeV for U) than origin design, the 3.7GeV/C proton beam will be ready in future. There will be some new features at HIRFL-CSR complex which new generation electron cooler, capability to perform RIB reaction experiment inside the experimental ring (CSRe). Besides research of the heavy ion, radioactive ion beam, high charged state atomic physics, the interactive sciences & application, the research of hadron physics and high energy density matter are introduced also. Hence, the mini 4π detector is under designed inside main ring (CSRm). The cluster experiment inside of CSRe is under discussion.

1, Introduction

HIRFL-CSR (Cooling Storage Ring at Heavy Ion Research Facility in Lanzhou) project is proposed in STORI96\cite{1,2}. During that time, its main research programs focused on the heavy ion physics, which is including the research of nuclear physics with RIB, the nuclear matter under extreme condition, the atomic physics with highly charged state heavy ion, the astrophysics and some applications of irradiative biological, material and other sciences with heavy ion. With the progressing of physics and technique, HIRFL-CSR is optimized as Fig.1 after that time. Its main parameter is listed in Tab.1.

<table>
<thead>
<tr>
<th>Table 1, Main parameters of CSR</th>
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<tr>
<td><strong>Ion Species</strong></td>
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<tr>
<td>Energy (AMeV)</td>
</tr>
<tr>
<td>(Bmax=1.6T)</td>
</tr>
<tr>
<td>520(\text{^{238}\text{U}^{72+}})</td>
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<tr>
<td>∆P/P</td>
</tr>
<tr>
<td>δP/P(entrance)</td>
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<td>Émitance</td>
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Therefore, HIRFL-CSR research programs are extended as:
1. Nuclear Structure and Nuclear Matter;
2. Hadron Physics with proton 3.7GeV/C and 1.1AGeV heavy ion;
3. Atomic Physics with high charged heavy ion beams;
4. High Energy Density Matter Driven by heavy ion;
5. Irradiative Biological, material and other sciences.

2, HIRFL-CSR Accelerator Facilities Status[3]

HIRFL-CSR project consists of the inject beam line between the exist HIRFL system[4] and new facilities, main Cooling Storage Ring (CSRm), 2nd Radioactive Ion Beam separator RIIBL-II, experimental Cooling Storage Ring (CSRe) and upgrading of the exist HIRFL system. The experiment will be perform in both rings: CSRm, CSRe with internal target and the external target in two experimental sites, one locates after the beam extracted from CSRm, another locates after RIB being separated.

2.1, Improvement of Existing HIRFL System

The main goals of the improvements on existing cyclotron system are increase the beam intensity, beam quality and efficiency. It focus on the following items:
A, the improvements of SFC vacuum from $10^{-7}$ to $10^{-8}$ mbar to increase efficiency of accelerate heavier ion;
B, the reduction of stray magnet field about 75% to less than 4 gauss to decrease the beam losses at LEBT;
C, LEBT is also optimized so that the injection efficiency from ECR ion source to SFC reach 10% to 40%;
D, About factor 2 higher beam injection efficiency from SFC to SSC is abtained by successful add a new rebuncher between SFC and SSC cyclotron;
E, the post beam transport line are also improved to increase the beam efficiency by switching beam in time.

Therefore, all ions from carbon to uranium are accelerated at HIRFL system of SFC and SSC. The higher beam intensity are obtained as that the beam extracted from SFC could reach $10^{13}$pps for the light ions $^{40}$Ar, $10^{12}$pps for medium ions $^{86}$Kr. The beam intensity of SSC reach one order less than that SFC obtained.

2.2, HIRFL-CSR Progress

HIRFL-CSR started in April 2000 and optimized during construction period. About 20% higher than original design of CSR maximum energy is due to the maximum field of the magnet dipole could increase from 1.4 T to 1.6 T in qualify field distribution. The all CSR hardware are installed and CSRm is under commissioning. The proton beam is considered to accelerate at CSR complex since the physics requirement and without radiation protect problem. Besides the multiple multi-turn injection and RF stacking injection designed in origin, the striping inject is adopted to inject light ion in higher efficiency and shorted injection time.
Inject beam line is used to transport the lower energy beam from existing HIRFL system to CSRm as fig.1. The beam is bent from 1st floor to sub-floor by a pair of 60° dipoles in vertical direction. Total length of this beam line is about 61.09 meter. The vacuum, at this section, transit from $10^{-8}$ to $10^{-11}$ mbar in oil free. This beam line has been installed about three years ago. $\sim1.5\times10^{-11}$ mbar UHV has been achieved at the entrance point of CSRm for about two year.

CSRm is a cooler synchrotron with 161.20 meter in circumference and used to collect the beam from existing HIRFL system, cool down by electron cooler, then, accelerate to given high energy and has been installed end of Feb.2004 (Fig.2). The main performances of devices are met design as follow\cite{5,6,7,8}: D-pole of integral field BL accuracy $<\pm1.5\times10^{-4}$, Q-pole gradient $K/K$ accuracy $<\pm1.5\times10^{-6}$; power supplier of long term stability $10^{-4}$~$-6$, cycle to cycle repetition error $<\pm4.0\times10^{-4}$; vacuum $10^{-9}$~$-10$ mbar without baking, $10^{-11}$ mbar after baking, $10^{-12}$ mbar with titanium pump; RFs frequency range from 0.25~1.7MHz with $V_{\text{max}} = 8.25kV$ and 6.0~14MHz with $V_{\text{max}} = 25kV$ respectively. All setup were alignment at very high accuracy (error $\pm0.1mm$). So far, CSRm is under commission by 7AMeV $^{12}$C beams. The first turn beam has been tuning smoothly in beginning of this year.

RIBlL-II locate between the storage ring CSRm and CSRe and used to transport beam from CSRm to CSRe, external experimental sites, produces the radioactive ion beam (RIB) and high charged state ion beam (HCI) in the primary target. RIBLL-II is designed as double achromatic type beam transport line and similar as RIBLL, which has operated for 8 years. Its total length is about 111.98 meter and divides as four parts by different function. There are 4 beam lines to experimental setup, where 1st one directly transport beam to experimental site-I without bending; 2nd, 3rd transport beam to experimental site-I by bending 10° and 20° respectively; fourth transport beam to experimental site-II after RIB separating.

CSRe, with 128.96 meter in circumference, is designed as the high accuracy ($10^{-6}$) and high sensitive spectrometry, as shown in fig.3. The configuration of CSRe is similar as ESR at GSI, except increase the momentum acceptances at the entrance point of ring. This different could improve the RIB collected inside the ring and open RIB reaction experiment with internal target in high accuracy. Its energy could be varied by decelerating injecting beam energy. The main performances of CSRe are similar as those of CSRm even heavier magnet devices, C type dipole, large power supplier, big vacuum chamber and 300keV electron cooler.

The new feature of HIRFL-CSR complex are new generation electron cooler, capability to perform RIB reaction experiment inside the experimental ring (CSRe). There are two electron coolers at HIRFL-CSR. New generation electron cooler ($V_{\text{max}} = 35kV, 300kV$, as fig.4) produces about 3A electron beam with full and hollow structure in cross section, magnetic field inside the solenoid reaches ratio of horizontal to vertical component $10^{-6}$ and the efficiency of current collector is 99.99 %. It has been installed in more than 2.5 year and kept UHV better than $2\times10^{-11}$ mbar at CSRm and 1.5 year at CSRe. Many times offline test shows its quit confident quality. The increment of the acceptance at entrance point of CSRe from $\pm0.15\%$ to $\pm0.5\%$ that increase about 10 times acceptance to RIB. This improvement correspondence increase RIB intensity in significant.
2.3, Operation Mode

Since <1% beam injects to CSRm, CSRe and >90% beam remains in HIRFL; b, energy range from 1AMeV to 1100MeV/u, event 3.7GeV/c for proton beam; c, many beam species: ion, RIB, HCI, Cluster...; d, multi-field: nuclear, atomirradiation, biology... HIRFL-CSR system can operation in different operation modes according experimental requirement:

1. CSRm + external target;
2. CSRm+RIBLL-II + external target
3. CSRm+CSRe + internal target (high accuracy);
4. CSRm+RIBLL-II+CSRe + internal target (high accuracy)
5. CSRm+CSRe+Electron Cooler + laser (high accuracy)

3, Experiment Perspective

There are four zones are designed to perform the experiment as Fig.5. CSRe is the high accuracy and high sensitive spectrometry by measuring the internal target (fig.6) reaction products; the site-II design as external target experiment with ion beam and RIB; about three external experiment setup will be installed at site-I; CSRm hadron experiment is internal target experiment with light ions such as proton, deuteron, helium. The first two setups will be ready in this year and last setups will be completely in following years.

3.1, CSRe experiment

CSRe is idea setup to perform high accuracy experiment of nuclear structure, high charged state atomic physics. Its experimental setup consists of 300 keV electron cooler (corresponding ion beam energy <547AMeV), which is used to cooling the ion beam in high quality and a electron target, gas jet internal target with thickness >1~10\(^{13}\)/cm\(^2\) for gases (H, N, Ne, Ar), beam diagnostic devices used as power detector (like transparent beam monitor, Schotky noise spectrometry...) and some kind of electron, x ray, ions, neutron... detectors.

The beginning of nuclear structure experiments at CSRe are nuclear mass, lifetime measurement, RIB reaction experiment with internal target. The reaction products could be measured by \(\gamma\) telescope, charged particle detector and neutron detector arrangement in downstream of internal target. It is proposal that measurement of nuclear shape by Fraunhofer diffraction scattering with high precisely >800 MeV proton beam.

The high charged state atomic experiments at CSRe are most kind of atomic structure, electron recombination experiments with high charged heavy ion. the atomic experiment could be perform at internal target by collision of two ions or ion+electron+laser at electron cooler. the reaction products could be measured by \(\beta\), x ray, \(\gamma\) and charged ion.
3.2, Site-II Experiment

The starting version of site-II experiment are most of nuclear structure and nuclear matter experiments. It is designed as fig.7. The external target locates after the first double achromatic section of RIBLL-II. The 4 segments Glove HG detectors surround the reaction target. RIB will be determined by tracking detector mount in upstream of target. In downstream, there is a big dipole used to bend charged products. These charged products could be identified by magnet rigidity and TOF in various position. The large neutron wall is mount at about 12 meter downstream of target straightly to measure neutron by TOF and pulse high if it is stop inside neutron wall completely.

In near future, the mini 4\(\pi\) CsI array will be surround target to get more information of nuclear structure. The TPC detector will be considered to set after target and before neutron wall in order to perform the hadron or nuclear medium effect in higher energy beam at CSR.

3.3, Site-I Experiment

There are 3 experimental setups at site-I (fig.1). Big setup is the cancer therapy by heavy ion. Simple fixed point therapy setup will be ready in next year, which is similar as that at GSI. Another fixed therapy setup designs as treating in horizontal and vertical beam. finally, a gantry therapy setup is considered for future developing.

Two other external target experiment will be irradiate experimental setup. One of them will be used to irradiate material in general and other will be used to perform the high energy density matter experiment.

3.4, CSRm Experiment

CSRm is similar as COSY complex which is prefer for hadron experiment. The preliminary physics program at CSRm are: 1, Rare decay modes: such as \(\omega, \eta, \eta', K^+, K^-, \phi, \ldots\); 2, Spectroscopy: such as \(N^{++}, \Delta^{++}\) to look for their missing resonances;...; 3, Search multi-quark state; and 4, Symmetries of C, CP.

CSRm detector setup is Mini-4\(\pi\) internal target (pellet, polarization or solid foil) detector system as designed in fig.8 in preliminary. This detector is based on the internal target spectrometry surrounding the reaction region, which covers \(\phi\) about 340\(^\circ\) and \(\theta\) from 15\(^\circ\) to 150\(^\circ\), and a solenoid as momentum analyzer. In forward zone, \(\theta\) from 5\(^\circ\) to 15\(^\circ\), a position sensitive hadron calorimeter, which timing resolution is better than 100 ps, locates about 1.5 meter downstream of internal target.

The internal target spectrometry (fig.8) consists of a timing project chamber (TPC), starting radial from 15 cm to 35 cm surrounding beam pipe, as tracking detector; a plastic scintillator bar time of flight (TOF) detector and detection of internally reflected Cherenkov light (DIRC) detector in middle layer, used as charged particle identification and an CsI scintillator crystal of electromagnetic calorimeter (EMC) ranging radial from 45cm to 70cm to measure photon. In the forward top end of this setup, there are two multi-wire drift chamber to tracking charged reaction products in forward zone. And similar TOF and DIRC detector to identify and
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measure its starting timing in forward zone. In backward end of this setup, there are some CsI to serve as part of EMC.

Since it is the fixed target experimental setup, the pellet internal target is mount in 50 cm upstream of spectrometry center. For the polarization target experiment, the pellet target will not work and backward CsI EMC will be moved away. The polarization target will mound in 1 meter upstream of this spectrometry. By this kind arrangement, the polarization experiment will have power forward detection setup, but not one in other zone.

The CSRm experimental setup aims to measure the most final products of $e^\pm$, $\pi^\pm$, $k^\pm$, $\gamma$, proton, neutron and light nuclei. This configuration is under optimizing now and staring soon.

4, Future Development

The future development of HIRFL-CSR are optimization and integral this configuration according the physics requirement and high operation efficiency. Obviously, It need have intens beam injector to complete HIRFL-CSR. A 15AmeV LINAC is considered as upgrade project in future. The polarization light ion beam will be one of items in future upgrade.

The cancer therapy by heavy ion has quit successful at GSI and HIMAC which is one of the important research item at HIRFL-CSR. In order to enhance the reliability of HIRFL-CSR complex, the small booster (12MeV/u) is proposed to set in upstream of CSRm as the red drawing inside of HIRFL experimental hall in fig.1. This item consists of laser ion source, Vandgraf static electric accelerator and booster. This development will benefit not only for cancer therapy but also for hadron research and others by more flexible operation mode.

It is also worth to have a straight beam line, after first RIBLL-II separator direction, to inject the primary beam or HCl beam into CSRe since RIBLL-II separator is used for experiment quit often and usually operate in not very high vacuum. This will cause difficult and lower efficiency operation.

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Fig. 1, Layout of HIRFL-CSR

Fig. 2, Side view of CSRm
Fig. 3 Overview of CSRe

Fig. 4, 300keV electron cooler at CSRe
Experiment at CSR

CSRm: 1.1 A GeV (^{12}C_{6+}), 2.8 GeV (p)

CSRe: 0.76 A GeV (^{12}C_{6+})

Fig.5, Overview of CSR experiment

Fig.6 Internal gas jet target at CSRe
Fig. 7, External target experiment at site-II

Fig. 8, Preliminary design of CSRm internal target spectrometry
Nuclear Structure Studies on Exotic Nuclei by Light-Ion Induced Direct Reactions with Stored Radioactive Beams

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Motivation and Research Objectives

The experimental conditions at the future facility FAIR [1, 2, 3] will provide unique opportunities for nuclear structure studies on nuclei far off stability, and will allow for exploring new regions in the chart of nuclides of high interest for nuclear structure and astrophysics. In particular, the predicted intensities of radioactive beams provided by the new superconducting fragment separator SFRS, and the corresponding luminosities will allow for the investigation of direct reactions with stored and cooled radioactive beams at internal H, He, etc. targets of the new storage ring NESR. This technique enables high resolution measurements down to very low momentum transfer and provides a gain in luminosity from accumulation and recirculation of the radioactive beams.

The objective of the EXL-project (EXotic nuclei studied in Light-ion induced reactions at the NESR storage ring), which is part of the NUSTAR-program [4] (NUclear Structure, Astrophysics and Reactions) at FAIR, is to capitalise on light-ion induced direct reactions in inverse kinematics by using novel storage ring techniques, and a universal detection system providing high resolution and large solid angle coverage in kinematically complete measurements.

To address the key physics issues of the EXL project (formulated in details in [2, 5, 6]), such as the investigation of:

- nuclear matter distributions near the neutron drip line (halo -, skin - structures),
- isospin-dependence of single-particle and shell structure (magic numbers, shell gaps, spectroscopic factors),
- nucleon-nucleon correlations, clusters,
- new collective modes (different deformations for protons and neutrons, giant resonance strengths),
- in-medium interactions in asymmetric and low-density nuclear matter,
- astrophysical r- and rp-processes (Gamow-Teller strength, neutron-capture),

a variety of light-ion induced direct reactions, such as for example elastic scattering (p, p), (α, α), etc., inelastic scattering (p, p'), (α, α'), etc., charge exchange reactions (p, n), (3He, t), (d, 2He), etc., quasi-free scattering (p, 2p), (p, pn), (p, po), etc., and transfer reactions (p, t), (p, 3He), (p, d), (d, p), etc., need to be investigated.

Having in mind that for most of these reactions the relevant nuclear structure in-

* The EXL collaboration: http://ns.ph.liv.ac.uk/~mc/EXL/collaboration/EXL-collaboration.html
formation is located in the region of moderate to very small momentum transfer, it becomes obvious from Fig 1 that the use of cooled stored beams interacting with a thin internal gas target is mandatory for most of these investigations, as it provides

- high resolution detection of low energy recoil particles,
- high luminosities due to the continuous beam accumulation and recirculation,
- low-background conditions due to pure, windowless $^{1,2}$H, $^{3,4}$He, etc. targets.

The EXL Detector Setup

Within the Technical Proposal [6], recently submitted to the FAIR management, the design of a complex detection setup was investigated with the aim to provide a highly efficient, high-resolution universal detection system, applicable to a wide class of reactions. The apparatus foreseen being installed at the internal target of the NESR storage cooler ring is displayed in Fig. 2. It includes a Si-detector array for recoiling target-like reaction products, completed by gamma-ray and slow-neutron detectors, as well as forward detectors for fast ejectiles and an in-ring spectrometer for the detection of beam-like reaction products. Whereas the design of the forward detectors and in-ring spectrometers are based on technology already currently available at the present LAND setup [7] at GSI for the investigation of reactions with radioactive beams at external targets, and at the present storage ring ESR, respectively, the design and construction of a highly-efficient, universal recoil and gamma detector system will be one of the most challenging tasks of the present research project. In particular, the detector components need to fulfill strong demands concerning angular and energy resolution, energy threshold, dynamic range, granularity, vacuum capability, etc., partly not available from standard detection systems.

A schematic view of the detector setup surrounding the internal gas-jet target is displayed in Fig. 3. It is foreseen to separate two regions of the setup with different
Figure 2: Schematic view of the EXL detection systems. Left: Setup built into the NESR storage ring. Right: Target-recoil silicon detector surrounding the internal gas-jet target.

vacuum conditions by a thin window. The inner "high vacuum" part will house the silicon particle array which will be bakeable to temperatures in the vicinity of 130°C in order to reach a vacuum of at least $10^{-8}$ - $10^{-9}$ mbar. The outer "low vacuum" part of the detector chamber will house the array of scintillation detectors, which is dedicated to detect the gamma-rays, as well as the residual energy of fast recoil particles, which punch through the silicon detectors. A vacuum of about $10^{-5}$ mbar will be sufficient for that part of the scattering chamber. Different regions A-E of the lab-angular range correspond to a colour code as defined in Fig. 3. Except for the regions C and D, where particle tracking is foreseen, the angular resolution will be determined in all other regions by the dimension of the gas-jet target and the distance of the detectors from the beam-target interaction point. The choice of the detector geometry and detector types for the different regions A-E are optimized with respect to the kinematical conditions and demands on energy and angular resolution for the various types of reactions to be studied (for details see [6]). For angular regions A, B and E telescopes consisting of double-sided silicon strip detectors, 300 μm thick, and 9 mm thick lithium-drifted silicon detectors behind are foreseen, whereas regions C and D will be equipped with tracking detectors consisting of double-sided silicon strip detectors, 100 (300) μm thick. To optimise the detection efficiency of the recoil detector, a maximum solid angle cover allowed by the installations needed for the gas-jet target is investigated. At angles close to $\theta_{lab} = 90^\circ$ a coverage of at least $\phi = \pm 45^\circ$ in azimuthal angle is foreseen, which can be increased in forward and backward directions. A first attempt at a possible 3D detector geometry is displayed in Fig. 2. It should be pointed out that this concept is subject to further detailed investigations in the near future to define a final optimum solution.

The scintillator hodoscope consisting of about 1500 individual crystals, built of scintillator material (CsI or others) is supposed to detect $\gamma$-rays emitted from excited beam-like reaction products, as well as the residual kinetic energy of fast target-like reaction products, which punch through the silicon detectors discussed above. Concerning the detection of $\gamma$-rays, aside of the $\gamma$-sum energy for missing-mass
reconstruction in case the excited beam-like reaction product is particle unstable (for example after GR excitation), the detector has also to provide \( \gamma \) - multiplicities and individual \( \gamma \) - energies for spectroscopic purposes. By detecting the \( \gamma \)-rays from the decay of excited beam-like reaction products it also serves in separating elastic and inelastic reaction channels in cases of low-level spacing where the angular and energy resolution of the silicon detectors are not sufficient to resolve these reaction channels. It is clear from these considerations that only a highly efficient, high-resolution device will satisfy the demands formulated above. An almost \( 4\pi \) coverage, sufficient detector thickness for \( \sim 80\% \) \( \gamma \)-detection efficiency at \( E_\gamma = 2 - 4 \) MeV and for stopping of up to 300 MeV protons, an energy resolution of 2-3\% for \( \gamma \)-rays and 1\% for fast protons are required. In the case of \( \gamma \)-rays, the line broadening due to the Doppler shift, most substantial at highest beam energies, imposes a high detector granularity.

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The ELISe experiment at FAIR

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The ELISe experiment

The ELISe objective is to capitalize on elastic, inelastic, and quasi-free electron scattering on unstable, short-lived nuclei by using intersecting ion and electron storage rings and an electron spectrometer operating in conjunction with a detector system for reaction products, providing high resolution and large solid angle coverage. The experiment is foreseen to be installed at the New Experimental Storage Ring (NESR) at FAIR where cooled secondary beams of radioactive ions will collide with an intense electron beam circulating in a small electron storage ring.

![Figure 1: The ELISe experiment: A LINAC with variable steps in energies fills an electron storage ring, that intersects with the New experimental storage ring (NESR). At the interaction zone a electron spectrometer is situated whereas the recoiling ions are detected in the first dipole arc of the NESR after the interaction zone.](image)

Expected Luminosities

The main two challenges in the foreseen experimental programme \cite{1} are to reach sufficient luminosities for electron-ion scattering experiments in the ELISe setup and
to build an in-ring spectrometer that combines a large solid angle coverage with a very high resolution of $\delta p/p \approx 1 \cdot 10^{-4}$ together with a angular resolution of 1 mrad. These requirements are given by the collider kinematics where angular and energy resolution gets coupled. We have performed a full simulation of the production,

![Figure 2: Expected luminosities for the electron-ion collider in the interaction zone. A full simulation is done for each isotope, calculating optimized degrader settings for the separator and deducing losses due to transmission and nuclear and atomic transport and storage process in order to answer this question. The production yields have been already calculated for the conceptual design report [2] by K.-H. Schmidt and collaborators. This data together with another data set specifying the production method (i.e. fission or fragmentation), provided by the author, was used to estimate the ion optical transport through the separator, where a simple parameterisation could be used. The resolution for the ion-optical separation depends strongly on the total degrader thickness in units of the range of the ions through the separator. The range has been calculated and has been used to determine the degrader thickness in g/cm for a given ratio. This ratio has been provided by the ion-optics group calculating the Super-FRS. The absolute thickness could now be used to compute degrader losses by electromagnetic and nuclear break-up reactions. Here the BCV parameterization has been used to calculate the nuclear interaction cross section. The electromagnetic has been simplified by assuming that the break-up process proceeds only through the GDR. The total cross section was computed using a parameterization for the GDR and folding it with the number of available equivalent photons. The injection limit into the ring system has been taken into account. The nuclear lifetime has been extracted from the Lund table of Isotope,
the atomic life times in the NESR where calculated with a code provided by the atomic physics group. A result of these calculations is shown in Figure 2, where one can see that the reachable luminosities do not depend very much on neutron and proton number in a large range, and than drop down towards shorter lifetimes and lower production yields at the drip-lines. The featureless behaviour can be explained with the current injection limits into the storage rings. The expected luminosities allow for a viable experimental programme covering all proposed experiments for ELISe.

The electron spectrometer

A test bench system has been defined for the spectrometer system, consisting of a in-ring pre-deflection system (the analogue of a septum magnet) and a dipole spectrometer stage with associated instrumentation. A design for the pre-deflection system has been determined. The system consists of a specially shaped, magnet with super conducting coils, that provides both (i) a field close to zero on the beam axis, so that the circulating beams are not disturbed, and (ii) a dipole field in the two gaps situated left and right from the beam axis in order to deflect scattered electrons, starting at a laboratory angle of about 5°. The electrons are hereby deflected to exit the pre-deflector magnet in perpendicular direction to the beam axis. From there a second magnetic stage (in the test bench system a simple dipole bending in vertical direction) is used to analyse the electrons by their momenta. Straw tube tracking detectors can be used at the exit of the pre-deflection system and at the focal plane.

Figure 3: Final resolution of the non-optimized test-bench system. The nominal resolution of $\delta p/p \approx 1 \cdot 10^{-4}$ can almost be achieved. Necessary improvements are discussed in the text.

A tracking MC simulation has been performed for this system, taking into account all possible effects induced by the material placed in the electron trajectories, and the results are shown in Figure 3. Even with a non-optimized set-up – no higher order corrections to the magnetic systems have been introduced – the resolution meets almost the requirements, thus showing the feasibility of this core-component.
of the experimental setup. In summary, two major issues for the electron-ion collider have been tackled. The next steps will be to sue the gathered information in order to come up with a full simulation of the foreseen experiments at the ELISe experiment.

Summary

A feasibility study has been performed for the very challenging electron - radioactive ion scattering experiment (ELISe) at the FAIR facility. It turns out, that a vast amount of ions can be covered with a physics programme addressing (i) elastic scattering to determine charge distributions, (ii) inelastic scattering to selectively excite these nuclei or to perform (e,e’X) experiments. It can thus be shown, that the experiment will enable us for the first time to perform electron scattering on rare isotopes in complete kinematics, therefore opening a new field in nuclear structure research.

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Mass measurements by an isochronous storage ring at the RIKEN RI beam factory

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Precision direct mass measurements of short-lived RI beams are planned at the RIKEN RI beam factory. A new scheme based on individual injection into an isochronous storage ring is presented. The principle and conceptual configuration are addressed.

Introduction

Nuclear masses are one of the most essential quantities for understanding nuclear properties. Mapping the mass surface over the nuclear chart provides a crucial test of nuclear models. Systematic measurements may shed light on new knowledge, such as the development of shell closure, shape and pairing effects, and decay properties. Nuclear masses also play an important role as basic input for network calculations of element synthesis, such as the r-process in stars. The challenge is to measure nuclear masses of exotic nuclei far from stability, which have been available due to the developments of the RI beam techniques in worldwide accelerator facilities.

The RIKEN RI beam factory (RIBF) is under construction for such nuclear structure physics and nuclear astrophysics research programs \cite{1}. The facility consists of a cyclotron complex and the BigRIPS fragment separator \cite{2}. Various kinds of rare RI beams can be produced via projectile fragmentation or fission of a high-energy (350 MeV/u) uranium beam. The primary beam intensity will eventually reach up to 1 p\textmu A, which would allow us to study exotic nuclei at and near the dripline. Such developments of the techniques stimulate direct mass measurements of exotic nuclei. Major techniques applied are ion optical traps and the time-of-flight method in the spectrometers or cyclotrons, as well as Schottky and isochronous mass spectrometry in the storage ring. Recent trends of the mass measurement techniques are reviewed in the literature \cite{3}.

In this paper we present a new scheme of direct mass measurements for short-lived RI beams in an isochronous storage ring with high mass precision (10^{-6}) and large m/q acceptance (10^{-2}). The scheme will work efficiently to measure the masses of unstable nuclei far from stability, particularly with extremely low intensity. The
method used to measure nuclear masses in an isochronous ring was originally developed at GSI Darmstadt, the so-called isochronous mass spectrometry (IMS) performed at ESR [4]. The details of the isochronous optics and the design of the storage ring at RIBF can be found elsewhere [5].

Principle of Mass Measurement

The principle is based on the proportionality between the charge-to-mass ratio ($\frac{q}{m}$) and the cyclotron frequency ($f_C$) in a magnetic field ($B$),

$$f_C = \frac{1}{2\pi m} \frac{q}{B}.$$  \hspace{1cm} (1)

In the case that the storage ring optics is adjusted to the isochronous mode ($B = B_0\gamma$) for a certain $m_0/q$ particle, one can determine the mass-to-charge ratio by measuring the revolution time ($T_0$) and the magnetic field ($B_0$), because the $\gamma$ factor is cancelled out,

$$T_0 = \frac{2\pi m_0}{q} \frac{1}{B} \gamma = \frac{2\pi m_0}{q} \frac{1}{B_0}.$$ \hspace{1cm} (2)

Here, $\gamma$ is a relativistic factor defined as $\gamma = 1/\sqrt{1 - \beta^2}$ and $\beta = v/c$. The relative differential of $m_0/q$ is given by

$$\frac{\delta(m_0/q)}{m_0/q} = \frac{\delta T_0}{T_0} + \frac{\delta B_0}{B_0}. \hspace{1cm} (3)$$

One can determine the mass value with a precision on the order of $10^{-6}$ by measuring $T_0$ and $B_0$ with a precision of $10^{-6}$.

For a non-isochronous particle with a slightly different mass-to-charge ratio, $m_1/q = m_0/q + \Delta(m_0/q)$, $\Delta(m_0/q) \sim 10^{-2}$, however, isochronism is no longer fulfilled, and the mass-to-charge ratio is given by

$$m_1 = \left(\frac{m_0}{q}\right) \frac{T_1}{T_0} \gamma_1 = \frac{m_0}{q} \frac{T_1}{T_0} \sqrt{1 - \beta_1^2} \left(1 - \frac{\beta_1^2}{2}\right), \hspace{1cm} (4)$$

where $T_1$ is the revolution time for a particle with $m_1/q$. The mass precision also depends on the precision of the velocity. The relative differential of $m_1/q$ is given as

$$\frac{\delta(m_1/q)}{m_1/q} = \frac{\delta(m_0/q)}{m_0/q} + \frac{\delta(T_1/T_0)}{T_1/T_0} + k \frac{\delta \beta_1}{\beta_1}. \hspace{1cm} (5)$$

The coefficient $k$ in the third term is an order of $10^{-2}$ for $\Delta(m_0/q) \sim 10^{-2}$. One can determine the mass value of a non-isochronous particle with a precision of $10^{-6}$ by measuring the velocity with a precision of $\delta \beta_1/\beta_1 \sim 10^{-4}$. The mass precision on the order of $10^{-6}$ will be achieved for all particles within a $m/q$ difference of $10^{-2}$. 

New Scheme of Mass Measurement

A new scheme consists of three experimental devices: 1) an in-flight fragment separator with a long injection line, 2) a fast pulsed kicker magnet, and 3) an isochronous storage ring. A schematic drawing of the conceptual configuration is shown in Fig. 1. As preliminary design values, we assume the following specifications: an RI beam energy of 200 MeV/u, an injection beam line of 180 m including the BigRIPS beam line, and a storage ring circumference of 60 m, which gives a revolution time of 350 ns/turn.

Rare RI beams are produced via projectile fragmentation or fission of uranium, in-flight separated through the BigRIPS fragment separator, and injected into the storage ring one by one [6]. The standard detector system installed in BigRIPS provides information concerning produced nuclei, such as $Z$, $A/q$, $v$, and beam emittance. After hundreds of revolutions in the ring, RI beams are kicked out of the ring to measure TOF stop signals and obtain further information on particle identification and beam emittance. Such information makes event-by-event mass corrections possible for any deterioration of the resolution induced by higher order aberration effects.

As described in the previous sections, one should measure both the revolution time and the velocity with a precision of $10^{-6}$ and $10^{-4}$, respectively. A long injection line of 180 m gives a 1 µs flight time for a beam of 200 MeV/u. Typical plastic scintillators, whose timing resolution is better than an order of 100 ps [7], are available to achieve such high precision for velocity measurements. Scintillation detectors can also be applied for revolution time measurements. A revolution of more than 300 turns provides a total time-of-flight of more than 0.1 ms in the ring, so that the precision of the revolution time is better than $10^{-6}$.

For individual injection, a fast timing response of the kicker magnet is essen-

Figure 1: Schematic drawing of the conceptual configuration of the mass measurement scheme at RIBF.
tial. The present fast electronics and kicker-magnet technology are still feasible for individual injection schemes. A plastic scintillator with phototubes provides a fast timing response for RI beams. The scintillation light response is fast (less than 1 ns) and the transit time in the scintillator is roughly 70% of the light. The electron transit time in the phototubes is estimated to be around 20 ns (depends slightly on the specification of phototubes). The delay time in the discriminator module is less than 20 ns. High frequency (HF) cables are available to transfer the trigger signal at almost the light velocity (96%) [8]. It takes 400 ns to transfer a signal in a HF cable of 100 m length. The injection system consists of a kicker magnet, a Tyratron and its driver module. The rise time of the magnetic field in the kicker is currently about 100 ns [9]. The response time of the Tyratron is typically 250 ns. The response time of the driver module of the Tyratron can be short (a few 10 ns) [10]. Finally, the kicker magnet can be excited within 900 ns in total after a RI beam hits the scintillator, which is faster than the time-of-flight of RI beams.

Summary

We present a new scheme for precision direct mass measurements of short-lived nuclei that are produced via projectile fragmentation or fission of high-energy uranium beam at RIKEN RIBF. The scheme is based on particle identification in the BigRIPS fragment separator and individual injection into an isochronous storage ring, which allows velocity corrections for non-isochronous particles in the mass evaluation procedure. The mass-to-charge ratios of stored nuclei are measured with the time-of-flight technique in the isochronous storage ring. An overall mass precision on the order of $\Delta m/m \sim 10^{-6}$ will be achieved.

References:
[8] Hitachi High frequency cable, Hitachi Co. Ltd.

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Introduction

The study of the evolution of the density distribution of protons and neutrons has been extensively addressed in the last 20 years as a fundamental tool to investigate the nuclear landscape. Indeed the measurement of matter and charge radii provide evidence for the occurrence of nuclear halos and neutron skins. While charged radii of short lived nuclei can be deduced in a model independent way using e. g. electron scattering or laser spectroscopy, the neutron radii determination is so far not straightforward. Experimentally, a variety of efforts have been undertaken to investigate the properties of the neutron-rich exotic nuclei, ranging from high-energy break-up reactions [2, 3] and elastic proton scattering [4, 5] to inelastic scattering and charge-exchange reactions [6]. Also, anti-protons have been used to probe the size of stable nuclei [7], whereas atomic capture has been exploited, but still all the collected data are not consistent among each other and partly model dependent. Most of the existing experimental data refer to stable and long-lived nuclei but the new SFRS facility at FAIR will enable us to extend the investigation to more exotic nuclei.

A novel method [1] is proposed to determine the charge and the matter radii of unstable and short lived nuclei using an pBar-A collider. The experiment makes use of the appropriately modified electron-ion collider Elise, to collide 30 MeV anti-protons with 740 AMeV ions. The total pBar-nucleon annihilation cross-section is measured detecting the loss of stored ions and the pBar-n, pBar-p cross-sections detecting the A-1 (Z-1 or N-1) residual nuclei after the annihilation, using the Schottcky method. Theoretical predictions show that the annihilation cross-section is proportional to the mean squared radius.

7 Expected Rates and Theoretical Predictions

Calculations have been carried out to estimate luminosities and reaction rates. Taking into account an intensity of 10^9 pBar and about 10^6 ions, whereas this last number accounts for the losses that occur between the SFRS and the NESR ring, a luminosity of 10^{24}/cm^2/s is reached for the ^{55}Ni nucleus. Such luminosities are feasible for nuclei with a half-life \( \tau \geq 1 \) s, due to the time needed to store and cool the ions. This limit in time translates in a minimal intensity of 10^7 ions.

Theoretical calculations predict a pBar-nucleon annihilation cross-section of about 1 barn for the ^{55}Ni nucleus at these energies [11], that translates in about 4.8 annihilation/sec. This corresponds to 0.72 Z-1 and 0.72 N-1 reactions/sec [12], where
these numbers already account for the fraction of A-1 nuclei lost after the annihilation. These numbers lead to a rate of 18000 count/h and if only the statistical error is considered in the radius calculation, a resolution of about 0.01 fm is obtained for the $\Delta r_{np}$.

It has been mentioned in the introduction that the radius can be extracted from the measured annihilation cross-section. In order to study this method the pBar absorption has been parametrized using an optical potential, where the real part is taken to be much smaller than the imaginary part. The cross-section has been calculated for the Ni chain to study its mass and energy dependence. Because of the strong absorption the annihilation cross-section gains strength only in the nuclear surface, in a crescent-like distribution with an average radius of about the average radius of the Wood-Saxon potential. Along the isotopic chain the pBar-p cross-section is slowly varying as a function of the mass number A, but the pBar-n cross-section reflects the rapid change of the neutron density with increasing neutron excess (see upper panel of figure 1). This implies that the measurement of the pBar-$\Lambda$ absorption can provide us with data on the existence and evolution of the neutron skin. The relation between the radius distribution and the absorption cross-section is visible in the bottom panel of figure 1 where the total cross-section is shown together with the mean square radius multiplied with an energy dependent constant $\alpha_0$. The ms-radii are in first order directly proportional to the measured absorption cross-section. Hence we can conclude that anti-proton annihilation at intermediate energies are an appropriate probe for nuclear sizes and shapes.

Another interesting aspect of this measurement concerns the energy dependency
of the cross-section. With increasing energy the magnitude of $\sigma_{abs}$ decreases but approaches an asymptotic value close to $T_{lab} = 400 \, \text{MeV}$. Since the absorption is happening predominantly on the nuclear surface, different energies allow to scan the tail of the wave functions. This energy scan is made possible by the features of the RESR ring that account for the energy setting of the ions. The pBar-nucleon annihilation is followed by pion emission, that can eventually interact with the A-1 nucleus. Only those events in which the pions have missed the nucleus lead to measurable A-1 nuclei in the NESR ring, hence the missing probability ($P_{\text{miss}}$) must be taken into account. It can also happen that the pBar annihilates with a deeply bound nucleon, leaving the A-1 nucleus excited. This nucleus can emit a nucleon turning into A-2 nucleus, this probability ($P_{\text{dh}}$) is also accounted for. Calculations have been carried out [12] to estimate these probabilities for some Ni and Sn isotopes, assuming an optical potential and that the nucleus can be seen as a semi-transparent disc. A relative momentum of $1 \, \text{GeV/c}$ between the pBar and the nucleon has been assumed. The value of $P_{\text{miss}}$ is proportional to the nucleus size, while $P_{\text{dh}}$ stays rather constant. The integrated probability has been estimated to be about 30% for the $^{58}$Ni nuclei and about 60% for the $^{132}$Sn nuclei.

One can see that the relative rate for the AIC reactions is fairly large in comparison with the atomic anti-proton case, even if the annihilation is rather peripheral [12].

8 Particle and Luminosity Measurement

The A-1 nuclei can be measured in the NESR ring exploiting the Schottcky noise frequency analysis [8]. Each of the nuclei passes through the pickups distributed along the NESR ring and via the Fast Fourier Transform technique a frequency spectrum is obtained. Since the velocities of all the nuclei are the same after the cooling in the NESR, the revolution frequencies in the ring reflect their mass-to-charge ratios. This method can be applied to ions with $A > 60$, since the momentum/charge acceptance of the NESR ring is about 1.75% in the longitudinal momentum deviation. For the detection of lighter nuclei silicon detectors can be placed in a pocket near the interaction region before the third NESR dipole, that would kick the fragment out of the ring acceptance. The good position and energy resolution of these detectors [9] allow to identify the $Z$ and the $p/q$ ratio of the nuclei. Another important aspect of the experiment is the measurement of the luminosity, that is later necessary to calculate absolute cross-sections. The time integrated luminosity $L_{dt}$ can be determined detecting the backwards (taking the ion direction as a reference) elastically scattered anti-protons. Calculations have been carried out to estimate the grazing angle for the Rutherford scattering for $^{132}$Sn and $^{56}$Ni. Assuming values of $3.2^\circ$ and $2.1^\circ$ respectively, a cylindric silicon detector with an angular coverage between $1.5^\circ$ and $4^\circ$ can enable the calibration.
Laura Fabbietti

9 Physics Program and Conclusions

The feasibility study of the AIC experiment has shown that it is an interesting tool to measure the evolution of the matter and charge radii instable and short-lived nuclei.

The experimental program will start with benchmarking measurements for stable nuclei, to establish the method and compare the results with those achieved using the X-Ray spectroscopy. The Sn isotopes constitute a good starting point for the benchmarking and in particular the odd isotopes can be investigated to interpret the pionic isotope shift observed in the deeply bound s-states [10]. Systematic studies of the isotopic and isotonic chains will follow with particular emphases on the odd-even staggering problem. Extended measurements of light nuclei (A ≈ 20 – 25) near to the drip-line are also foreseen in order to investigate the transition from the halo regime to the neutron skins in heavier nuclei. Last but not least the pBar-nucleon interaction can be investigated quantitatively in the framework of this project.

References


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Future Projects (Hardware)
Introduction

Antiproton physics, nuclear physics with rare isotope beams and atomic physics are major research fields at the proposed FAIR project [1]. The storage ring complex [2] will be vitally important for these research fields.

The storage ring complex consists of four different rings: the Collector Ring CR, the accumulator/decelerator ring RESR, the New Experimental Storage Ring NESR and the High Energy Storage Ring HESR which is designed by a consortium led by FZ Jülich [3].

The Collector Ring CR serves for fast stochastic precooling of antiprotons and rare isotopes. Additionally, it will be used for isochronous mass measurements of very short lived radioactive nuclei. For experiments with rare isotope beams the RESR serves as a decelerator ring. For antiproton physics the RESR acts in combination with the CR as an accumulator ring. The concept foresees the accumulation
of $7 \times 10^{10}$ antiprotons per hour, which is determined by the antiproton production rate and the cooling time in the CR.

The New Experimental Storage Ring NESR will be the main instrument for rare isotope and atomic physics with cooled beams. Additionally the NESR is used as a decelerator ring for antiprotons. After deceleration the beams are extracted to the low energy experiment area FLAIR \cite{4}.

The final layout of FAIR is shown in Figure 1. The present concept foresees a construction in stages. Stage one contains mainly the facilities for rare isotope physics, the new fragment separator Super-FRS, the CR and the NESR. Furthermore, civil construction is started on this stage. The intensity gain factor for rare isotopes, if compared to the existing GSI-facility, will be in the order of 100.

Stage two adds the synchrotron SIS100, the storage rings HESR and RESR and the proton linac. Hence, the antiproton physics program starts with stage two, while rare isotope intensity reaches its final value. Civil construction will be completed after stage two.

In stage three SIS300 and all experimental areas will be completed.

**Operation Schemes**

Due to the different requirements of each research field, operation schemes are different for rare isotope, antiproton and atomic physics experiments. Antiprotons are produced by an intense 29 GeV proton beam delivered by the SIS100. Up to $2.8 \times 10^{13}$ protons per cycle produce $1 \times 10^9$ antiprotons every 5 s at a special production target. The antiprotons are then separated and transported to the CR, where they are precooled at 3 GeV by a stochastic cooling system. Afterwards the antiprotons are transferred to the RESR. Accumulation of $7 \times 10^{10}$ antiprotons per hour is foreseen. The antiprotons are either reinjected to the SIS100 and accelerated for experiments with high energy antiprotons in the HESR or directly transferred to the NESR. The NESR can then be used to decelerate the beam to 30 MeV for experiments with low energy antiprotons. Present discussions to lower the primary proton energy and to modify the transfer to HESR will not affect the antiproton availability significantly.

Rare isotopes are produced by intense beams of heavy ions delivered by the SIS100. The typical scenario foresees a single 50 ns bunch of up to $1 \times 10^{12}$ $^{28+}$ ions at 1.5 GeV/u which is focused to the production target. The rare isotopes are separated in the SuperFRS and then injected into the CR at a fixed energy of 740 MeV/u. After precooling in the CR the beam is transferred to the RESR. For experiments with RI beams the RESR can serve as a decelerator ring. The RESR is capable of decelerating rare isotopes to variable energies down to 100 MeV/u within approximately 1 s. The NESR will be the final storage ring in the accelerator chain. Besides experiments using an internal target, the NESR offers the possibility to collide circulating bunches of ions with electron bunches counter-propagating in a small 500 MeV electron storage ring \cite{5}.
The Collector Ring CR

The Collector Ring CR has a circumference of 210 m. The ring is designed for three different tasks [6]: fast cooling of rare isotope beams (RIB), fast cooling of antiprotons (pbar) and isochronous mass measurements. Each of the three tasks requires a completely different setting of the ring optics with different beta- and dispersion functions. This leads to a variation of the acceptance of the CR. The main parameters of each mode are listed in Table 1.

Table 1: CR main parameters.

<table>
<thead>
<tr>
<th></th>
<th>RIB</th>
<th>pbar</th>
<th>isochron</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal tune</td>
<td>3.17</td>
<td>4.42</td>
<td>2.55</td>
</tr>
<tr>
<td>Vertical tune</td>
<td>3.18</td>
<td>4.24</td>
<td>3.17</td>
</tr>
<tr>
<td>Transition energy</td>
<td>2.9</td>
<td>3.54</td>
<td>1.84</td>
</tr>
<tr>
<td>Horizontal acceptance [mm mrad]</td>
<td>200</td>
<td>240</td>
<td>70</td>
</tr>
<tr>
<td>Vertical acceptance [mm mrad]</td>
<td>200</td>
<td>240</td>
<td>50</td>
</tr>
<tr>
<td>Momentum acceptance [%]</td>
<td>±1.5</td>
<td>±3</td>
<td>±0.7</td>
</tr>
</tbody>
</table>

Earlier lattice layouts favored a so-called split ring design. Although this design has advantages with respect to cooling efficiency, the present layout foresees two identical arcs. This type of layout offers a larger dynamic aperture and enables much simpler injection and extraction schemes.

Fast cooling of rare isotopes and antiprotons is accomplished via bunch rotation, adiabatic debunching and stochastic cooling. Since rare isotopes and antiprotons are injected at different energies and different velocities an adjustable stochastic cooling system is necessary [7]. Rare isotopes are injected at a fixed energy of 740 MeV/u with initial emittances of 200 mm mrad and a momentum spread of $\pm 1.5 \times 10^{-2}$. Final minimum emittances of 0.5 mm mrad and a final momentum spread of $\pm 5 \times 10^{-4}$.
are expected after a total cooling time of about 1 s. This corresponds to a cooling
time constant of 0.2 s.
Antiprotons are injected at an energy of 3 GeV. Minimum cooling time constants
of 1 s are envisaged. After a total cooling time of about 5 s the initial emittance of
240 mm mrad is reduced to 5 mm mrad. The momentum spread is reduced from
\( \pm 3 \times 10^{-2} \) to \( \pm 1 \times 10^{-3} \).
For isochronous mass measurements of very short-lived radioactive nuclei the CR is
equipped with one or two time-of-flight detectors.
Due to the required large aperture and its static operation, superconducting dipole
magnets are favorable for the CR. The dipole magnets are superferric magnets with
superconducting coils and warm iron, whereas the quadrupole magnets are normal
conducting. Crucial issues of the CR-design are the rf-cavities, which are used for
the bunch rotation process. A total amount of 400 kV rf voltage in the frequency
range from 1.2 MHz to 1.4 MHz is necessary for the bunch rotation process in the
case of rare isotopes. In the case of antiprotons the rf-voltage can be reduced to
150 kV.

The Accumulator/Decelerator Ring RESR

The RESR has a circumference of 245.5 m. It is sharing the building with the CR.
The tasks of the RESR should originally have been taken over by the NESR. But
the implementation of a stochastic cooling system into the NESR, which is necessary
for antiproton accumulation, without strong interference with the other functions,
is not possible. To keep the additional costs of the RESR low, it is foreseen to
to recycle as many parts as possible from the existing Experimental Storage Ring ESR
[8]. Some main components that are reused are the quadrupole magnets and beam
diagnosis elements. In order to minimize the design effort, the RESR uses the same
type of superferric dipole magnets as the NESR. The main RESR-parameters are
listed in Table 2. The layout of the RESR is shown in Figure 3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal tune</td>
<td>3.8</td>
</tr>
<tr>
<td>Vertical tune</td>
<td>3.3</td>
</tr>
<tr>
<td>Transition energy</td>
<td>3.62</td>
</tr>
<tr>
<td>Horizontal acceptance [mm mrad]</td>
<td>80</td>
</tr>
<tr>
<td>Vertical acceptance [mm mrad]</td>
<td>35</td>
</tr>
<tr>
<td>Momentum acceptance [%]</td>
<td>±1</td>
</tr>
<tr>
<td>Maximum dispersion [m]</td>
<td>8</td>
</tr>
</tbody>
</table>

The primary task of the RESR will be the efficient accumulation of antiprotons.
Accumulation of up to \( 10^{11} \) antiprotons within 0.5 - 2 hours is foreseen. This is
accomplished by adding batches of \( 10^8 \) antiprotons every 5 s at 3 GeV. The accumulation
scheme foresees longitudinal stacking in combination with stochastic cooling.
This could be either momentum stacking or a system using barrier buckets. Hence
the RESR will be equipped with two transverse cooling systems and up to three momentum cooling systems. The RESR lattice has to fulfill the requirements of the stochastic cooling system with regard to transition energy, beta functions, phase advance between pick-ups and kickers and dispersion to enable fast cooling and accumulation of the antiproton batches. A preliminary accumulation concept using momentum stacking already exists, while the feasibility of barrier bucket stacking in the RESR is still under investigation. Momentum stacking uses Palmer type momentum cooling in one of the dispersive regions of the ring. It foresees injecting beam from the CR to an inner orbit of the RESR. The beam then is moved by the rf-system to an outer orbit. Here stochastic cooling is applied to merge the injected beam with the already stored beam on the outer orbit.

Figure 3: Layout of the accumulator and decelerator ring RESR. The main task of the RESR is the accumulation of antiprotons.

The second task of the RESR will be the fast deceleration of rare isotopes to energies between 100 MeV/u and 500 MeV/u within 1 s. Therefore, an ramp rate of 1 T/s is required. The optical mode of the RESR remains unchanged during deceleration.

The New Experimental Storage Ring NESR

The New Experimental Storage Ring NESR has a circumference of 218.75 m. Main NESR parameters are listed in Table 3. The layout of the NESR is shown in Figure 4. The NESR is the main instrument for nuclear and atomic physics with stored stable and radioactive heavy ions [9]. It also serves an area for experiments with decelerated antiproton and RI beams. RI beams can be injected at energies between 100 MeV/u and 740 MeV/u. After cooling by the electron cooler ions are decelerated to their final energy. The lowest energy foreseen is 4 MeV/u. Antiprotons are injected at 3 GeV. Immediately after injection antiprotons are de-
Figure 4: Layout of the NESR. The NESR is an important tool for atomic and nuclear physics.

accelerated to 840 MeV. At this energy electron cooling is applied. Subsequent to cooling the antiprotons are decelerated to 30 MeV. Here the beam is cooled again and is finally extracted. Maximum ramping rate of the magnetic field for all deceleration processes is 1 T/s.

The NESR electron cooler has a maximum voltage of 450 kV. Some special features are included into the cooler design. The electron beam diameter can be adjusted. Furthermore, the generation of hollow electron beams is possible. To enable cooling immediately after deceleration of an ion or antiproton beam, the high voltage power supply is designed for fast ramping. Emittances for cooled rare isotope beams are between 0.1 mm mrad and 1 mm mrad depending on the particle number and on the beam energy. For a typical antiproton beam of $10^8$ antiprotons an emittance of 1 mm mrad at 840 MeV after cooling is expected. The momentum spread for both kinds of particles is in the order of $10^{-4}$. While the cooling time constant for highly charged heavy ions varies between 0.3 s and 0.5 s, the expected cooling time constant for antiprotons varies between 5 s and 25 s, depending on the initial beam parameters.

Table 3: NESR main parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horizontal tune</td>
<td>3.4</td>
</tr>
<tr>
<td>Vertical tune</td>
<td>3.2</td>
</tr>
<tr>
<td>Transition energy</td>
<td>5.74</td>
</tr>
<tr>
<td>Horizontal acceptance [mm mrad]</td>
<td>160</td>
</tr>
<tr>
<td>Vertical acceptance [mm mrad]</td>
<td>50</td>
</tr>
<tr>
<td>Momentum acceptance [%]</td>
<td>±1.5</td>
</tr>
<tr>
<td>Maximum dispersion [m]</td>
<td>7.24</td>
</tr>
</tbody>
</table>
Main experimental installations of the NESR are the internal target, an electron target and an electron-nucleus scattering facility employing a 500 MeV electron storage ring. The electron-nucleus scattering facility enables the determination of charge radii and charge distributions of radioactive nuclei circulating in the NESR. In order to achieve luminosities up to $10^{28}$ cm$^{-2}$s$^{-1}$, the circulating ion beam has to be bunched at a higher harmonic of the revolution frequency to form short bunches, which are matched to the frequency and length of the bunches in the electron ring. Therefore the NESR will be equipped with an rf-system for frequencies between 40 MHz and 80 MHz. The internal target of the NESR could either be a gas jet target as in the ESR [10] or a pellet target. It is used for atomic as well as for nuclear physics experiments. The installation of an additional electron target, which will be an electron cooler-like device, enables experiments with arbitrary relative velocities between ions and electrons. Various experiments will use the arcs of the NESR as a kind of spectrometer either for scattered ions or for reaction products. To obtain a high resolution, the lattice has to provide small beta functions and a large dispersion in the arcs. In the NESR arcs the horizontal beta function is below 7 m and the dispersion is 7.24 m. The resulting momentum resolution amounts to $2 \times 10^{-4}$ for a horizontal emittance of 0.1 mm mrad. This value is sufficient for most nuclear and atomic physics experiments.

To increase the intensity of short-lived rare isotope beams, the NESR allows the accumulation of RI beams. This is accomplished by the use of a barrier bucket accumulation system in combination with electron cooling.

Atomic and antiproton physics require fast and slow extraction of decelerated stored beams. The minimum energy for antiprotons will be 30 MeV whereas the minimum energy for ions will be 4 MeV/u. The NESR will enable two different kinds of slow extraction. Charge exchange extraction can be used for highly charged heavy ions. The extraction rate is adjusted either by the variation of the electron current of the electron cooler or the thickness of the internal target. Resonant extraction can be used for antiprotons as well as for heavy ions. In this case the extraction rate is controlled by variation of the sextupole field component or by the power of the noise excitation. Charge exchange and resonant methods will use the same extraction elements.

Outlook

The general layout of the storage ring facility presently fulfills the requirements of most physics experiments. Some conceptual work is left to be done. The layouts of the three rings are still not frozen. The lattice of the CR will be fixed by the end of 2005. The development of the stochastic cooling equipment is going on. It is planned to have a prototype tank including electrodes ready for measurements till end 2006. While the design of the superferric dipoles has already started, the bunch rotation cavity design for the CR will start beginning of 2006. One crucial point is the decision about the accumulation scheme in the RESR. This decision should be done in the course of 2005. Afterwards stochastic cooling design and - if necessary -
barrier bucket cavity design will start. The study on the NESR superferric dipoles started beginning 2005. Electron cooler design will start mid 2005. In addition to this work, further beam dynamics and equilibrium beam parameter calculations for all three rings have to be carried out.

References:

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Design of an isochronous storage ring and an injection line for mass measurements at the RIKEN RI beam factory


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Introduction

An isochronous storage ring and an injection line for mass measurements of rare RI beams will be constructed at the RIKEN RI beam factory. Measurements will be achieved with a relative uncertainty of about $10^{-6}$. The conceptual configuration was presented elsewhere [1]. In this paper more detailed designs of the isochronous storage ring and the injection line are presented.

Injection line

Since we need to measure the velocity of injection particles, a long injection line between the isochronous ring and the BigRIPS line is necessary. For the injection line, the TARN-II ring [2] will be recycled. TARN-II was a cooler storage ring for heavy ions. It was previously located at INS, Univ. of Tokyo. We will use its 24 dipole magnets. They are rectangle-type magnets. The bending angle of each magnet is fifteen degree.

Fig. 1 shows one of the designed plans of the injection line. In this design, the ring is constructed on the same basement as the BigRIPS line. There is a height difference of 3.5 m between the BigRIPS line and the ring. In order to cancel this difference, the injection line is twisted at points B and D. The isochronous ring is constructed under line AB.

From the view of the beam optics, the vertical and horizontal components are mixed at points of B and D. We therefore made a design to have double achromatic points at B and D. Fig. 2 shows the $(x/\delta)$ element of the transfer matrix and the beam radii. The $x$-axis lies in the horizontal plane. $\delta$ denotes the fractional momentum deviation. The element $(x/\delta)$ represents the momentum dispersion of the beam. At points B and D, a double achromatic condition is achieved. At points of C and E, the horizontal radius becomes longer.

We will use bending magnets of TARN-II at point of A and F7. We also designed the line to have a double achromatic condition at points A and F7.
Isochronous ring

Some parameters of the Isochronous ring are given in Table 1. The isochronous ring consists of sector magnets. The edges of the magnets are straight. In this case, we can achieve an isochronisity of $10^{-4}$. To achieve an isochronisity of less than $10^{-4}$, we should use trim coils and generate a harmonic field. Fig. 3 shows the harmonic field for a second-order correction.

We made a computer simulation code of the isochronous ring. The magnetic field was calculated with a hard edge approximation. Each magnetic sector was sliced into one thousand thin sectors. The trajectory in the magnetic field is circular. The magnetic field in each sector is uniform and equal to the value at the entrance. Fig. 4 shows an emittance study using the computer simulation code under the conditions of an isochronisity of $10^{-7}$ and a momentum acceptance of $\pm 1\%$. In these conditions, the emittance is about $0.9 \ \mu\text{mm rad}$.

A Monte Carlo simulation code of the isochronous storage ring and the injection line was made with the computer code MOCADI. [3] The condition of the magnetic field of the injection line was represented as a series of transfer matrices in the code. The limitation on the beam radii by the beam ducts was also incorporated. The paths of nuclei in the ring were calculated by a library function dynamically linked to MOCADI. Through this simulation, we will estimate the integrated performance of the injection line and the ring.

<table>
<thead>
<tr>
<th>Table 1: Some parameters of the Isochronous ring</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of sectors</strong></td>
</tr>
<tr>
<td><strong>Length between sectors</strong></td>
</tr>
<tr>
<td><strong>Circumference</strong></td>
</tr>
<tr>
<td><strong>Sector magnet</strong></td>
</tr>
<tr>
<td><strong>Center orbit radius</strong></td>
</tr>
<tr>
<td><strong>Maximum magnetic field</strong></td>
</tr>
<tr>
<td><strong>Tilting angle</strong></td>
</tr>
<tr>
<td><strong>Particle</strong></td>
</tr>
<tr>
<td><strong>Momentum</strong></td>
</tr>
<tr>
<td><strong>Momentum dispersion</strong></td>
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Figure 1: One of the designed plans of the injection line.

Figure 2: \((x/\delta)\) element of the transfer matrix of the injection line (top) and the beam radii (bottom).
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Figure 4: $x-x'$ plot in the conditions of an isochronisity of $10^{-7}$ and a momentum acceptance of $\pm 1\%$. 
The Isochronous Mode for Mass Measurements in the Planned CR Storage Ring

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Abstract. Short-lived exotic nuclides can be produced and separated in-flight with the planned fragment separator Super-FRS [1]. Their masses can be measured directly in the coupled isochronous storage ring (CR) [2]. The isochronous condition must be fulfilled not only in first order approximation but also in higher orders. The calculations of the isochronous mode of the CR, including higher orders of the isochronicity, were done and the results are presented. In order to enhance isochronous region to ions with larger deviation in mass-to-charge ratio, additional information is needed on the magnetic rigidity or the velocity. This can be obtained from a second time-of-flight detector placed inside the ring.

Introduction

The method of mass-measurements in the isochronous mode of a storage ring (Isochronous Mass Spectrometry) has been developed at the ESR (Experimental Storage Ring) at GSI [3], where exotic nuclei are produced and separated in-flight with the Fragment Separator (FRS) and injected into the ESR. The mass-to-charge ratio \( m/q \) of the stored ions circulating in the ring can be measured from the revolution time \( T \) and the velocity \( v \) of the ions.

\[
\frac{\Delta T}{T} = \frac{1}{\gamma_t^2} \frac{\Delta (m/q)}{(m/q)} + \left( \frac{\gamma_t^2}{\gamma_t^2 - 1} \right) \frac{\Delta v}{v},
\]

(1)

where \( \gamma \) is the relativistic Lorentz factor. The transition point \( \gamma_t \) is an ion-optical quantity of each storage ring. It is defined by the path of particles of different magnetic rigidity in the bending magnets due to the dispersion function \( D \),

\[
\gamma_t^{-2} = \frac{1}{C} \int \frac{D(s)}{\rho} \, ds
\]

(2)

where \( \rho \) is the radius of curvature of the reference orbit in the bending sections and \( s \) denotes the coordinate along the reference orbit in the ring. In the isochronous mode the velocity spread of stored ions of the same species is compensated by the corresponding change of the orbit. The path length \( C \) is determined by the magnetic rigidity. The isochronous condition is \( \gamma = \gamma_t \) and thus, the revolution time becomes velocity independent and can be used for \( m/q \) determination. The mass measurements can start immediately after injection into the ring, which allows to measure masses of exotic nuclei with lifetimes shorter than those, that can be investigated with Schottky Mass Spectrometry [4].
The Isochronous mode of the Collector Ring

In a real optical system we aim at large acceptance requiring large apertures of the magnets and the isochronicity has to be investigated for the full beam spread. The Collector Ring CR of the FAIR facility [14] is designed for fast stochastic cooling of rare isotope beams (RIB) and antiproton beams. Additionally, it will run in the isochronous mode as a time-of-flight (TOF) spectrometer for short-lived exotic nuclides ($T_{1/2} > 20\mu s$). They can be produced and separated in-flight in the Super-FRS fragment separator. The CR is symmetric with two arcs and two straight sections and designed for operation at a maximum magnetic rigidity of 13 Tm [2].

The exotic nuclei shall be injected at a velocity of $\gamma = 1.84$. To achieve the corresponding value of $\gamma_t$, one has to reduce it compared to the RIB mode ($\gamma_t = 2.9$), and to increase the dispersion function in both arcs (see Eq.2). This reduces the momentum acceptance to $\pm 0.5\%$. To fulfil this the maximum of the dispersion function must be not more than 30 m. The transverse acceptance is 100 mm mrad in both planes. The isochronous condition is reached by the special calculated quadrupole setting. The setting presented in this paper permits to get a shape of the dispersion function which allows to transmit the beam with momentum acceptance $\pm 0.5\%$ (see Fig.1). The calculation was done with the GICO [6] and MIRKO [7] codes. A detailed analysis of the dependence of the revolution time on the momentum spread of the stored particles in the CR was done with GICO. The results are shown in Fig.2. One can see that the isochronous condition is fulfilled in first order approximation, but the isochronicity curve still has a second order contribution. To correct isochronicity in second order we use sextupoles placed in the arcs of the ring. In the present layout of the CR there are six independent families of sextupoles. For isochronicity correction we do not use all of those sextupoles, but we have to apply all of them for the chromaticity correction [8]. In the right part of Fig.2 two curves describing isochronicity are shown. One can see that the

![Figure 1: The calculated beam envelope in x (upper part) and y (lower part) directions and the dispersion function (bright line) as a function of the path length in the CR. It is shown for a transverse emmitance of 100 mm mrad in both planes and a momentum deviation of $\pm 0.5\%$. The path length axis starts at the center of the straight section. The magnets apertures are indicated in the background.](image-url)
isochronicity curve with sextupole correction has only a very small third order contribution of $(\Delta T/T)_{\text{max}} = \pm 5.4 \cdot 10^{-7}$. It’s easy to correct the third order of the isochronicity with one octupole placed at a position of large dispersion. To preserve the symmetry of the ring it should be split into two halves placed at the maxima of dispersion in each half. So far, the calculations were done without the influence of the fringing fields and multipole components of the magnets. One has to care about the dependence of the revolution time on the transverse emittance. The storage ring has to be an achromatic system at least in first-order approximation and thus also the revolution time is independent of the transverse motion to first order [9]. But the contributions of second and higher orders are not zero. For example, the average spread in revolution times in vertical direction for a homogeneous distribution in the phase space is about $(\Delta T/T) \sim 2 \cdot 10^{-6}$.

Figure 2: Left: Revolution time as a function of momentum deviation in the standard RIB (black line) and the isochronous mode (grey line). In the isochronous mode the maximum time spread is $(\Delta T/T)_{\text{max}} = 1.7 \cdot 10^{-5}$ for a momentum spread of $\pm 0.5\%$. Right: The curves for the isochronous mode with (black line) and without (grey line) corrections.

**Velocity measurement in the CR**

During the revolutions in the ring the stored ions lose their energy in the foil of the TOF detector and thus change their magnetic rigidity ($B\rho$). It means that particles become non isochronous. For a fixed $B\rho$ acceptance the CR is also isochronous only for a small range of $m/q$ ratio. A large reduction of time resolution can occur when both values deviate from the reference values. This is illustrated in Fig.5 by an example from previous isochronous mass measurements in the ESR [10].

For evaluation of less isochronous ions we need additional information about their velocity or magnetic rigidity. The velocity measurement can be done with a second TOF detector placed in the straight section of the CR, where the CR is not isochronous. The distance between two TOF detectors is about 30 meters. The velocity accuracy which we can obtain is $\Delta v/v \sim 10^{-3}$ for one turn in the ring. For many turns this leads to an accuracy in magnetic rigidity of $\Delta B\rho/B\rho \sim 10^{-4}$ [11]. Knowing the complete curve as shown in Fig.3, one can evaluate the revolution time at exact isochronicity.
Conclusion

The isochronous mode of the CR was calculated, for a transverse emittance of 100 mm mrad in both planes and a momentum spread of ±0.5%. The ring is isochronous to first order at $\gamma_0$ equal 1.84. The chromaticity and the second order of the isochronicity were corrected with sextupole magnets. The third order of the isochronicity can be corrected with weak octupoles. The influence of the fringing fields and field inhomogeneities of the magnets has to be considered, but the present paper shows a strategy for systematic correction. In future, the problem of less isochronous ions with different mass-to-charge ratios can be overcome by a second TOF detector placed inside the ring, to measure the velocity in addition.

References

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Laser-Spectroscopy of the $2s^2S-2p^2P$ transitions of relativistic Li-like carbon ions at the ESR

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Introduction

The electronic structure of heavy few-electron systems, i.e., highly charged ions of high nuclear charge $Z$, provides unique insight into QED terms in the high field of the nucleus and properties of the nucleus itself. Though for atoms and light ions laser spectroscopy represents the method of choice for precision spectroscopy, the increase of the binding energies with nuclear charge prohibits the direct use of visible laser light. This drawback can be overcome with heavy ion storage rings like ESR where the ions are stored at an energy providing the Doppler-tuning to the resonance of interest and cooled providing low Doppler-broadening of the resonance.

Here, we present the first laser spectroscopic investigation of the ground state transitions and the $2S-2P$ fine-structure splitting of Li-like carbon ions (C IV), performed in parallel to a study on laser cooling of relativistic C$^{3+}$ ion beams at the ESR (GSI) [1, 2, 3]. The study represents a test experiment for laser cooling and spectroscopy of Li-like ions at the future facility FAIR [4].

Storage ring laser spectroscopy - the method

At an ion velocity of $\beta = v/c \approx 0.47$ the huge Doppler-shift $\omega_0 = \gamma (1 + \beta) \omega_{\text{lab}} \approx 1.66 \times \omega_{\text{lab}}$ is exploited for the excitation of the $2S-2P$ transition ($\lambda_0 \approx 155$ nm) with counterpropagating laser light of a frequency-doubled Ar-ion laser at $\lambda_{\text{lab}} \approx 257$ nm. Laser cooling [1], working on the same transition, relies on the resonant light pressure so that the excitation of the transition of interest can be identified by the detection of either the resonance fluorescence or the momentum change of the coasting ion beam.

The Ar-ion laser can – in principle – be locked to a calibrated iodine line ($\lambda_{\text{a3}} = 514.6734664$ nm) with a relative precision of better than $10^{-9}$ [5]. However, due to the Doppler-shift the less precise knowledge of the ion beam velocity limits the accuracy of the spectroscopy in the rest-frame to $\Delta \omega_0 / \omega_0 = (1 - \beta^2)^{-1} \Delta \beta = \beta^{-1} \Delta \gamma / \gamma$. In principle, the revolution frequency of a sufficiently cold ion beam can be deduced with comparative precision from Schottky-noise spectra. Yet, as the length...
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325

laser e−cool
−2400
zero e−current extr.
digitizing calib. f−error [Hz]
−10 10 200−20

Figure 1: Schottky-noise spectrum of an uncooled C\(^{3+}\) ion beam marking the revolution frequency corresponding to the resonance with the decelerating laser beam (solid line). The ion velocity at this frequency is measured aligning the electron cooled ion beam (dashed line) to the same revolution frequency. Absolute and statistical calibration errors (concerning the revolution frequency) are indicated as bars and explained in the text.

of the closed orbit depends on the individual setting of the storage ring lattice, usually known to \(3 \times 10^{-4}\) for the design orbit, this measurement does not translate into a value of the beam velocity with equivalent precision. At the ESR, where the beam can be electron-cooled, the determination of the acceleration voltage of the co-propagating electron beam \((U_e \sim 67 \text{kV})\) currently represents the method of choice for the determination of the ion velocity. This voltage is absolutely calibrated with a relative precision of \(U_{e \text{abs}}/U_e = 10^{-4}\) leading to a relative velocity uncertainty of only \(\Delta \beta/\beta \sim 4 \times 10^{-5}\). Moreover, the voltage stability is better than the accuracy of the calibration.

The spectroscopy measurement was performed in a way that, first, the position of the laser resonance was marked in the Schottky-spectrum for a coasting uncooled ion beam with a relative accuracy of \(5 \times 10^{-7}\) (solid curve in Fig. 1, a more precise evaluation of the laser resonance is possible simulating the influence of the light pressure, yet, not required here). The laser wavelength was stabilized to the low-wavelength side of the Doppler-broadened iodine-line at \(\lambda_{\text{laser, vac}} = 514.6729(3) \text{nm}\), the relative jitter was reduced to \(5 \times 10^{-9}\). For the determination of the ion velocity on resonance, electron cooling was activated and the laser beam taken out. The electron energy was tuned to match the original position of the laser-resonance marked in the Schottky-spectrum with a digitizing voltage resolution of \(\Delta U_{e \text{dig}}/U_e \sim 10^{-5}\) (dashed curve in Fig. 1). As the electron energy in the center of the electron beam, where the ion beam is positioned, is reduced by about 0.1% due to the space-charge of the electron beam, the best way of eliminating this dominant correction is to perform the above procedure for different electron currents and to extrapolate to zero current (Fig. 2) leading to a relative voltage precision of \(\Delta U_{e \text{zero}}/U_e \sim 5 \times 10^{-6}\).
Discussion and outlook

From the described determination of the Doppler-shift the following transition energies can be deduced (Tab. 1). For the ESR experiment the first error denotes the present calibration accuracy of the electron acceleration voltage and the second the statistical error owing to the extrapolation to zero electron current. Clearly, these errors dominate over any error arising from the laser interaction with the ions, leaving space for considerable improvements.

![Figure 2: Acceleration voltage of the electron cooler required to match the laser resonance as a function of the electron current, the error denoting the statistical error of the extrapolation to zero current, the absolute calibration having an accuracy of ±7 V.](image)

<table>
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<tr>
<th>Ref.</th>
<th>excitation energies</th>
<th>line structure splitting (2p²P)</th>
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<td></td>
<td>2s²S₁/₂−2p²P₁/₂</td>
<td>2s²S₁/₂−2p²P₃/₂</td>
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<tr>
<td>ESR (this work)</td>
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<td>64594.18(1.60)(0.08)</td>
</tr>
<tr>
<td>Exp. [6, 7]</td>
<td>64483.8(1.5)</td>
<td>64591.0(1.5)</td>
</tr>
<tr>
<td>Th. [8]</td>
<td>64483.7</td>
<td>64591.6</td>
</tr>
<tr>
<td>Th. [9]</td>
<td>64503.2</td>
<td>64610.3</td>
</tr>
<tr>
<td>Th. [11]</td>
<td>64485.4(1.1)</td>
<td>64592.3(2.2)</td>
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Table 1: Table comparing theoretical and experimental values of the ground-state excitation energies and the corresponding fine-structure splitting of the 2p²P levels of Li-like carbon ions C⁵⁺ (C IV). a for the line splitting only the relative drift of the electron acceleration voltage is of relevance (estimated to be on third of the absolute calibration error); b based on the evaluation of the C IV spectrum (here 10 lines) observed in conventional spectroscopy in beam-foil and tokamak experiments [7], c the error in the excitation energies is dominated by the error of the 2s²S state, not affecting the splitting of the 2p²P state; d 3rd order MPPT; e MCHF-BP calculation not including QED corrections, stated to amount to -7.67 cm⁻¹ for the 2s²S ground state [10]; f full 2nd order QED.

This first laser spectroscopic measurement of the 2²S−2²P transition energies reaches the same accuracy as set by actual theoretical work [11] and is consistent with state-of-the-art spectroscopic data [6, 7] on C IV. Though the present ESR data shows slightly higher values than reported in ref. [6, 7], it falls within the range set
by theory when QED corrections for the $2^3S$ term are included. The more precise measurement of the $2^3P$ fine-structure splitting can be better reproduced by theory omitting QED corrections.

With an improvement of the voltage calibration or measurements at different ion energies and laser wavelengths on the same transition, theory could be readily challenged for low Z ions. At the ESR the method could be extended up to $O^{5+}$ ions, while at the future FAIR synchrotron SIS 300, the full periodic system can be reached [1, 4]. Boosting the scattered photons into the X-ray regime at highly relativistic ion energies ($\gamma < 35$), the uncertainty stemming from the Doppler-term can be eliminated by the direct measurement of the energy of the scattered photon, allowing for unprecedented spectroscopic precision of few-electron systems in the high Z regime [4, 12].

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Diagnostics of spin–polarized heavy ion beams at storage rings

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During the recent years, relativistic collisions of highly–charged, heavy ions with atomic and electronic targets have been explored intensively at the GSI storage ring in Darmstadt. A large number of measurements have been carried out in order to explore, for instance, relativistic as well as quantum electrodynamic (QED) phenomena in energetic collisions of high–Z projectile ions with low–Z targets. Until now, however, most of the collision experiments have dealt with ion beams and target atoms (or free electrons) which are both spin–unpolarized. While, of course, such “spin–independent” measurements have brought a great deal of information on the structure and dynamics of heavy atomic systems, more details may be obtained from experiments with spin–polarized ions. Very recently, a number of such polarization experiments have been proposed for studying parity nonconservation phenomena in few–electron systems [1] or spin–dependent eects in electron capture processes [2].

Obviously, however, any practical realization of “spin–dependent” collision experiments will require the solution of two key problems: (i) how to produce beams of polarized heavy ions and (ii) how their polarization can be measured. The method for producing of polarized hydrogen–like heavy ions was recently discussed by Prozorov and co–workers [3]. In particular, it was proposed to apply the optical pumping of the hyperfine ground–state levels of hydrogen–like europium ion Eu$^{62+}$ with a nuclear spin $I = 5/2$ in order to obtain a predominant population of the state $|F = 2, M_F = 2\rangle$. Since the ion state $|F M_F\rangle$ results from the coupling of an electron in the (one–particle) state $|j_b \mu \rangle$ with the nuclear spin $\mathbf{F} = \mathbf{I} + \mathbf{j}_b$, a fully polarized $F = 2$ ground state may lead to a polarization of the nuclear spin of about $93\%$. However, as mentioned in [3], the measurement and, hence, the control of this polarization remained up to the present a unresolved problem.

Here, we suggest to utilize the radiative capture of a target electron into a bound state of the projectile ion as a “probe” process for measuring the spin–polarization of ion beam. As recently shown, for example, the linear polarization of the recombination x–ray photons is strongly affected by the spin–polarization of the target atoms [4]. Since, however, the electron and ion occur rather symmetrical in the collision process, a similar effect on the polarization of recombination light can therefore be expected if the projectile ions are themselves polarized. In order to investigate such polarization effects we calculated the linear polarization of the photons as emitted...
in the radiative capture of free electrons into the ground state of spin-polarized hydrogen-like heavy ions [5]. Most naturally, the polarization of the recombination photons is described in terms of the Stokes parameters, which are simply determined by the intensities of the light $I$, linearly polarized at the different angles with respect to the reaction plane [4, 5]. While the parameter $P_1 = (I_0 - I_90)/(I_0 + I_90)$ is obtained from intensities within and perpendicular to the reaction plane, the parameter $P_2$ follows a similar intensity ratio which is taken at $\chi = 45^\circ$ and $\chi = 135^\circ$, respectively.

As shown by the theoretical analysis [5, 6], the two Stokes parameters $P_1$ and $P_2$ behave in rather different ways with respect to the spin-polarization of (hydrogen-like) projectile ions. While the parameter $P_1$ does not depend on beam polarization and, hence, can not be used for polarization studies, the second Stokes parameter $P_2$ appears to be proportional to the degree of the beam polarization

$$P_2(\theta) \propto \lambda_F \cdot f(\theta). \quad (1)$$

In the Eq. (1), the beam polarization is defined by [3]:

$$\lambda_F = \sum_{M_F} n_{F,M_F} M_F/F \quad (2)$$

as the sum over the magnetic sublevels, where $n_{F,M_F}$ refers to the corresponding population. The Stokes parameter $P_2$ may serve, therefore, as a valuable tool for “measuring” the polarization properties of the heavy ion beams at storage rings.

Figure 1 displays the parameter $P_2$ as calculated, for example, for radiative capture of electrons into the ground $1s$ state of completely polarized ($\lambda_F = +1$) hydrogen-like europium ions with energies in the range $100$ MeV/u $\leq T_p \leq 700$ MeV/u. The effect of the ion polarization becomes particularly remarkable around a photon emission angle of $\theta = 18^\circ$, where the second Stokes parameter decreases from the $P_2 = 0.02$ for $T_p = 100$ MeV/u to almost $0.32$ for $T_p = 700$ MeV/u.

Figure 1: The Stokes parameter $P_2$ of the photons which are emitted in the electron capture into the $K$-shell of completely polarized hydrogen-like europium ions. Calculations are presented in the laboratory frame (i.e., rest frame of the electron target.)
In conclusion, the linear polarization of the emitted photons has been studied for the radiative capture of electrons into high-$Z$, hydrogen-like ions. For this capture process, emphasis was placed especially on the question of how the polarization of the emitted photons is affected by the spin-polarization of the projectile ions. It is shown that for hydrogen-like ions with nuclear spin $I > 1/2$, the spin-polarization of the ion beam gives rise to a linear polarization of the photons out of the reaction plane while, for the capture into unpolarized ions in contrast, the photon polarization is always either within or perpendicular to this plane. Moreover, the angle of this out-of-plane polarization of the photons is uniquely defined by the degree of polarization of the incoming ions. The measurement of the rotation angle may serve therefore as a tool for determining the polarization properties of the ion beam. Calculations on this polarization transfer have been carried out for the electron capture into the 1s ground state of (the initially hydrogen-like) Eu$^{62+}$ projectile ions, by using the independent particle approximation. Although such an approach, in which the initial and final two-electron states are described both by a single Slater determinant, seems to be justified for fast collisions [7], interelectronic (or correlation) effects may become important for decelerated ions. These effects may slightly modify the transition amplitudes for the capture of electron but keep the linear dependence (1) of the rotation angle on the polarization of the ion beam untouched.

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Diagnostics of Spin-Polarized Ion Beams by Hard X-Ray Polarimetry of Recombination Transition

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Particle and photon polarization phenomena occurring in the interaction of intense laser pulses with relativistic heavy-ion beams or in collisions of relativistic ions with matter have attracted increasing interest recently. Investigation of polarization features may provide a unique probe for our understanding of relativistic particle dynamics in the presence of extreme electro-magnetic fields. However, when dealing with highly-charged, heavy ions, experimental methods to measure the polarization of particles with high efficiency are scarce. Here, we discuss to exploit radiative recombination into the vacant K-shell of bare or H-like heavy ions which leads to x-ray emission in the regime far above 100 keV. The REC is known to provide a source of strongly linearly polarized photons. Very recently detailed theoretical investigations [1] predicted that this process may even reveal a possible spin polarization of the particles involved in the interaction (electrons or ions). Here, the spin polarization of the particles leads to a rotation of the photon polarization vector out of the scattering plane. Experimentally, this topic can be addressed with high efficiency by a new generation of solid state detectors capable to provide energy as well as position information for the detected photons [2, 3]. Polarization measurements can then be performed by exploiting the dependence of the differential Compton scattering cross-section on the linear polarization of the initial photon [4].

Radiative Recombination occurring in relativistic ion-atom collisions (also called Radiative Electron Capture, REC) is the time reversal of the photo ionization process assuming the validity of the impulse approximation [5]. This process is of considerable importance for plasma and astrophysical environments. Also its relevance for the operation of heavy ion accelerators and storage rings must be stressed. For bare and few-electron heavy ions and low-Z targets it is the most important projectile charge-exchange channel and the REC photons which govern almost entirely the projectile photon emission (compare Fig. 1) [6]. Consequently, absolute and differential radiative electron capture cross-sections have been studied in great detail. However, for high-Z ions with photon energies above 100 keV, it was demonstrated only recently that the (linear) polarization of the emitted photons can be measured by means of a new generation of segmented germanium detectors, which allow for
Figure 1: X-ray spectrum registered in coincidence with down-charged $^{91+}$ ions for 289 MeV/u $^{92+}$ interacting with a H$_2$ gas target. The spectrum (laboratory frame) was measured at an observation angle of 132°. The marked K-REC, L-REC, M-REC x-ray lines refer to radiative capture into the empty K-, L-, and M-shell of the projectile [6].

an energy as well as position resolution [3, 7]. A first series of polarization measurements were performed at GSI using these detectors [3, 4] and by applying the dependence of the angle-differential Compton scattering on the linear polarization of the incoming photons. As predicted theoretically [8, 9], a strong linear polarization of the K-REC photons is expected, which decreases in the forward direction as the energy of the projectiles is enlarged. For bare uranium ions at 400 MeV/u, for example, the photon polarization of the K-REC radiation has been analyzed at the jet-target of the storage ring ESR. For this purpose, a planar germanium pixel detector was used, mounted at an observation angle of 90° (compare Fig. 2). In the experiment, the photon polarization is obtained by recording events which occur simultaneously in two pixels of the detector. While one pixel is used to measure the Compton recoil electron ($E$), the other one records the scattered photon ($h\omega'$). A scatter plot of such coincident photon events is displayed in Fig. 3. The large number of events in the diagonal corresponds to events with a (constant) energy sum equal to the K-REC transition, i.e., $E_{K-REC} = E + h\omega'$. It is important to mention that, for our initial energies ($E_{K-REC} \approx 250$ keV), the condition $\Delta E < h\omega'$ is always fulfilled which allows us also to identify the segment where scattering takes place. The latter also explains the two maxima present in the 2D scatter plot. In Fig. 3b, we compare the coincident sum energy spectrum for scattering parallel ($I_p$) and perpendicular ($I_\perp$) to the reaction plane (defined by the ion beam and the propagation direction of the K-REC photon). As seen from this figure, the K-REC radiation appears strongly polarized within the scattering plane.

Experimentally, the polarization properties of the emitted photons are usually obtained from the Stokes parameter, i.e., the intensity ratios of the light measured under different angles with respect to the reaction plane. For example, the Stokes
parameter $P_1 = (I_{90} - I_{90'})/(I_{90} + I_{90'})$, is obtained from the intensities parallel and perpendicular to the scattering plane, while the parameter $P_2$ follows from a similar intensity ratio, taken at $\chi = 45^\circ$ and $\chi = 135^\circ$, respectively. The two parameters $P_1$ and $P_2$ together describe the (degree and direction of the) linear polarization in the plane perpendicular to the photon momentum whereas the third parameter $P_3$ denotes the degree of circular polarization.

In the theoretical treatment of electron capture, the Stokes parameters are closely related to the photon density matrix if no further information needs to be retained for the remaining ions apart from their level designation. For the capture of unpolarized electrons by bare ions, it was shown recently [10, 11], that only the Stokes parameter $P_1$ is non-zero (and positive for moderate projectile energies), while $P_2$ is identically zero (see also [9]). This implies that, for unpolarized electrons and ions, the polarization of the recombination photons will always be found within the reaction plane. For the capture of polarized electrons, in contrast, the Stokes parameter $P_2$ becomes non-zero, in particular at small forward angles $\theta_{RR}$, leaving $P_1$ unaffected in this case. For the photon polarization, however, any non-zero $P_2$ parameter results in a rotation of the polarization ellipse out of the reaction plane. Owing to the symmetry of the collision system, a similar result is found if the (unpolarized) electrons are captured by a polarized ion beam. Therefore, the rotation of the polarization ellipse may serve as a unique tool for measuring the polarization properties of ion beams [1], a result which has attracted a lot of recent interest.

Figure 2: Detector geometry at the internal jet-target of the ESR storage ring used for the measurement of the linear photon polarization for K-REC at 400 MeV/u $^{92+}$U→$^{79}$N$_2$ collisions by exploiting the Compton effect.) [3, 4].
Figure 3: a) Scatter plot (preliminary) for coincident Compton events as observed for 400 MeV/u $^{192+}$U to $^{2}$N$_2$ collisions at an observation angle of 90°. Here the K-REC photon energy amounts to 240 keV; b) A coincident sum energy spectrum (preliminary) for scattering parallel ($I_\parallel$) and perpendicular ($I_\perp$) to the reaction plane (defined by the ion beam and the propagation direction of the K-REC photon).

References


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Cooling Rate Estimates for Stochastic Precooling of Radioactive Ion Beams and Antiprotons for the CR Project

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Introduction

The main goal of the stochastic pre-cooling system at the CR is to provide fast cooling for secondary Rare Isotope Beams (RIBs) at 740 MeV/u or for antiproton beams at 3 GeV. Simulation calculations for momentum cooling and analytical calculations for transverse cooling have been performed to optimize system parameters for maximal cooling rate.

Collector Ring Cooling System

A short bunch (25 ns) of secondary particles (antiprotons or rare isotopes) is injected by a full aperture kicker into the CR. A strong rf voltage (\(<\ 40\) kV) is used for bunch rotation to decrease the momentum width. After adiabatic debunching the beam is cooled stochastically. Finally it is rebunched and extracted to the accumulator ring RESR. An efficient cooling system is needed due to the large initial 3D-emittance of the debunched beam and the ambitions cooling time requirements (see. Table 1).

<table>
<thead>
<tr>
<th>Cooling scenario</th>
<th>Beam parameters</th>
<th>RIBs</th>
<th>Antiprotons</th>
</tr>
</thead>
<tbody>
<tr>
<td>After injection</td>
<td>Transversal emittance ((\mu)m)</td>
<td>200</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>Momentum spread (%)</td>
<td>(\pm\ 1.75)</td>
<td>(\pm\ 3)</td>
</tr>
<tr>
<td>After debunching</td>
<td>Transversal emittance ((\mu)m)</td>
<td>200</td>
<td>240</td>
</tr>
<tr>
<td></td>
<td>Momentum spread (%)</td>
<td>(\pm\ 0.4)</td>
<td>(\pm\ 0.7)</td>
</tr>
<tr>
<td>After cooling</td>
<td>Transversal emittance ((\mu)m)</td>
<td>0.5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Momentum spread (%)</td>
<td>(\pm\ 0.05)</td>
<td>(\pm\ 0.1)</td>
</tr>
<tr>
<td>Total cooling time (s)</td>
<td></td>
<td>1</td>
<td>5</td>
</tr>
</tbody>
</table>

To perform efficient cooling the CR must meet the following requirements: 1) sufficient installation length for pick-up and kicker tanks; 2) location of the Palmer pick-up at high dispersion to provide a good momentum signal; 3) location of the other pick-ups and kickers at zero dispersion to prevent coupling between the longitudinal and horizontal subspaces; 4) the transition energy \(\gamma_t\) must be close enough to the relativistic Lorenz factor \(\gamma\) to minimize undesired mixing but not too close to \(\gamma\) to maximize the good mixing. In order to achieve a total cooling time of the order of 5 seconds for antiprotons and of 0.5 seconds for Rare Isotopes a band of 1-4 GHz is used. Figure 1 shows the present layout of the CR stochastic cooling
system. It consists of the following subsystems: a longitudinal notch filter cooling system (1-2 GHz) for antiprotons, a longitudinal Palmer cooling system (1-2 GHz) for rare isotopes, and two systems for horizontal and vertical cooling of each beam type (1-4 GHz).

![Diagram of stochastic cooling systems in the CR](image)

The success of stochastic cooling crucially depends on the impedance-bandwidth product of pick-up and kicker electrodes. The electrodes should be applicable both for rare isotopes and for antiproton beams, and because of the large initial emittances they should be plungeable. The new slot-line couplers [1] that have been designed at GSI, satisfy the requirement discussed above. The pick-up and kicker parameters of Table 2 are given under the estimation that both are reciprocal.

**Table 2: Preliminary parameters of CR Cooling System**

<table>
<thead>
<tr>
<th></th>
<th>L</th>
<th>V</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooling band [GHz]</td>
<td>1-2</td>
<td>1-2/2-4</td>
<td>1-2/2-4</td>
</tr>
<tr>
<td>Number of pick-up and kicker slots</td>
<td>48</td>
<td>64</td>
<td>64</td>
</tr>
<tr>
<td>Effective electrode length [mm]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Pick-up effective noise temperature [K]</td>
<td>80</td>
<td>80</td>
<td>80</td>
</tr>
<tr>
<td>Pick-up maximal impedance per slots [Ω]</td>
<td>25</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>Kicker maximal impedance per slots [Ω]</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

**Cooling System Optimization**

To optimize the system parameters for maximal cooling rate simulation calculations in the longitudinal phase space and analytical calculations in the transverse phase...
space were performed with the parameters of Table 2. The transverse cooling rate is approximately given by

\[
\frac{1}{\tau} = \frac{2W}{N} \left( 2Bg - g^2 (M + U) \right),
\]

(1)

where \( W \) is the cooling band, \( N \) is the number of particles, \( g \) is the system gain, \( U \) is the noise to signal ratio. The mixing factor \( M \) from kicker to pick-up (good mixing) and mixing factor \( B \) from pick-up to kicker (undesired mixing) can be written

\[
M \approx (|m_2 - m_1| \cdot \eta \cdot \delta p/p)^{-1}, \quad B \approx \cos \left( \tilde{m}\omega_{rec}\eta_{p-k} \frac{\delta p}{p} T_{p-k} \right).
\]

(2)

Here \( \eta \) is the frequency slip factor, \( m_1 \) and \( m_2 \) are the harmonic numbers at the lower and upper limits of the cooling band; \( \tilde{m} \) is the central harmonic number of the cooling band; \( \omega_{rec} \) is the revolution frequency of the reference particle, \( T_{p-k} \) is the nominal time of flight between pick-up and kicker. The local slip factor \( \eta_{p-k} \) is

\[
\eta_{p-k} = 1/\gamma_{p-k}^2 - 1/\gamma^2,
\]

where \( \gamma_{p-k} \) is the transition energy from pick-up to kicker and \( \gamma \) is the relativistic Lorenz factor.

For transverse cooling calculations the cooling rate formula (1) with time dependent mixing parameters has been used. In our calculation we have assumed that \( \Delta p/p \) changes linearly from 0.7% to 0.35% in 2 seconds. Different \( \gamma_i \) parameters between 3.47 and 3.67, which influence the mixing parameters, were tried (see Fig.2).

![Figure 2: Mixing parameters for different \( \gamma_i \).](image)

The \( \gamma_i \) parameter is optimized for 3.67. The according cooling times are shown in Fig. 3.

To investigate the longitudinal cooling process simulation calculations were performed using the Fokker-Planck equation [2]. The evolution of the momentum width for \( U^{92+} \) and for antiprotons is shown in Fig.4. To reach the required cooling time for antiprotons and for rare isotopes the average initial electrical power must be no less than 300 Watt.
Figure 3: Evolution of the emittance for different $\gamma_t$.

Figure 4: Evolution of the momentum width for different system gains (electrical powers) for $U^{92+}_{238}$ beam (left) and for antiprotons (right).

Conclusion

Simulations and analytical calculations of stochastic cooling at the CR to determine the system parameters such as undesired and good mixing, initial electrical power, and the lattice parameter $\gamma_t$ have been performed. The required total cooling time value of about 1 second for rare isotopes and of about 5 seconds for antiprotons can be reached using the parameters discussed above.

References


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Instrumentation
Storage Rings for Fixed Target Experiments

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Introduction

Storage rings, i.e. machines with a circular lattice that allow for the storage of charged particles at a constant energy play an important role in physics. The quest for high c.m. energies has led to the concept of electron or ion colliders where counter-rotating beams in a single or in two separate rings collide with each other. Early examples are the CERN Intersecting Storage Ring (ISR) and the SPS proton-antiproton collider which enabled the discovery of the intermediate vector bosons $Z^0$ and $W^\pm$. Using thin targets, i.e. targets which do not disturb the operation of the rings, parallel or dedicated experiments could be performed in one of the rings, yielding potentially new physics. For ion rings, this is limited to high energies where single-scattering losses are suppressed. Ion storage rings employed in parallel for internal target experiments are listed in Table 1.

<table>
<thead>
<tr>
<th>Storage ring</th>
<th>Max. energy</th>
<th>Beam</th>
<th>Experiment</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISR (CERN)</td>
<td>30 GeV</td>
<td>p</td>
<td>R704</td>
<td>H cluster target</td>
</tr>
<tr>
<td>SpS (CERN)</td>
<td>250 GeV</td>
<td>p/p</td>
<td>UA6</td>
<td>H cluster target</td>
</tr>
<tr>
<td>Fermilab Accum.</td>
<td>8 GeV</td>
<td>p</td>
<td>E760, E835</td>
<td>H cluster target</td>
</tr>
<tr>
<td>HERA-p</td>
<td>920 GeV</td>
<td>p</td>
<td>HERA-B</td>
<td>wire target</td>
</tr>
<tr>
<td>RHIC</td>
<td>250 GeV</td>
<td>p</td>
<td>H Jet-polarimeter</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: List of ion storage rings with internal target experiment.

The first is the experiment R704 at the CERN ISR on charmonium spectroscopy [1] employing a stored $\bar{p}$ beam and a hydrogen cluster target [2]. Also at CERN, the $pp$ collider SpS has been used in parallel by the UA6 experiment, designed to study the production of direct photons [3]. It consisted of an open magnetic spectrometer and a cluster target, interacting with the 250GeV $p$ or $p$ beam. Experiments E760/835 were again devoted to charmonium spectroscopy [4], which will be continued with higher precision at HESR/FAIR by PANDA [25]. The task of HERA-B was the observation of CP violation in the B-system. Ejectiles from a wire target in the halo of the 920GeV HERA proton beam were analyzed by an open spectrometer [6]. At RHIC, a H jet with known polarization is employed to calibrate the existing polarimeters [7].

The first dedicated ion storage ring was LEAR/CERN, the low energy antiproton ring, built as stretcher and for internal target experiments [8]. Its development was enabled by the CERN $\bar{p}$ source where economic use of the expensive $ps$ was mandatory. LEAR (1983–1996) had stochastic and electron cooling and ultraslow extraction. This innovative concept initiated several dedicated ion storage ring projects, the so-called *King LEAR’s Daughters* (D. Möhl), listed in Table 2.
Table 2: *King LEAR’s Daughters*. List of dedicated storage rings the construction of which was stimulated by LEAR (Ecool = electron cooling, Stcool = stochastic cooling).

<table>
<thead>
<tr>
<th>Period</th>
<th>Ring</th>
<th>Rigidity</th>
<th>Place</th>
<th>Cooling method</th>
<th>Special features</th>
</tr>
</thead>
<tbody>
<tr>
<td>86-02</td>
<td>IUCF cooler</td>
<td>3.6 Tm</td>
<td>Bloomington</td>
<td>Ecool</td>
<td>$\vec{p}$, d (long., vert.) PI\text{TEXT}</td>
</tr>
<tr>
<td>1989</td>
<td>TARN-II</td>
<td>5.8 Tm</td>
<td>Tokyo</td>
<td>Ecool</td>
<td>machine experiments</td>
</tr>
<tr>
<td>1989</td>
<td>TSR</td>
<td>1.3 Tm</td>
<td>Heidelberg</td>
<td>Ecool</td>
<td>Laser cooling of HI</td>
</tr>
<tr>
<td>88-05</td>
<td>CELSHUS</td>
<td>7.4 Tm</td>
<td>Uppsala</td>
<td>Ecool</td>
<td>WASA</td>
</tr>
<tr>
<td>1993</td>
<td>COSY</td>
<td>12 Tm</td>
<td>Jülich</td>
<td>Ecool, Stcool</td>
<td>$\vec{p}$ (vert.) EDDA ANKE</td>
</tr>
<tr>
<td>1990</td>
<td>ESR</td>
<td>10 Tm</td>
<td>Darmstadt</td>
<td>Ecool</td>
<td>Rare Isotopes mass. meas.</td>
</tr>
</tbody>
</table>

The IUCF cooler ring [9] was in operation for about 16 years, creating a wealth of new data in particular in the fields of polarization and machine physics. TARN-II [10] was built as test accumulator ring for the Japanese NUMATRON project and has been used extensively for machine studies. In 1989, the test storage ring TSR [11] has been put into operation at MPI Heidelberg. Its main goal was the storage of incompletely stripped ions for laser cooling and atomic physics experiments. Electron cooling is also available. The TSR has been used in 1992 for the FILTEX test, i.e. spin filtering of protons by a polarized hydrogen target. This experiment constitutes the first application of a polarized storage cell target [12] in an ion storage ring. The result [13] demonstrates that spin filtering of stored beams works which might be applied to polarize antiprotons.

In Table 3, electron rings with internal target experiments are listed. At the Budker Institute, Novosibirsk, the storage ring accelerator VEPP-3 has been operated with internal polarized D targets for form factor measurements since the mid 80’s [14]. Deep-inelastic scattering of polarized stored electrons has been proposed for LEP by the HELP collaboration, but has not been accepted. A similar proposal for the polarized HERA electron ring was realized by the HERMES collaboration. Spin-dependent structure functions of the nucleon are studied by using a polarized proton and neutron (D or $^3$He) target. At the MIT-Bates South Hall Ring (SHR) the BLAST experiment has successfully taken data on double-polarized e-D scattering at about 1GeV.

Electron Rings with Internal Target Experiments

Due to the interplay between radiative cooling and heating, stored electron beams have a small equilibrium emittance which is usually not affected by a thin gas target.
Therefore, in contrast to ion rings, no additional cooling system is required. In the following, the HERA electron ring and the SHR at MIT-Bates will be discussed.

**HERA-e**  This ring is part of the HERA ep collider and runs at 27.6GeV at half-integer spin tune of \( v_\perp = 62.5 \) with 20 to 50mA in current. The energy loss of about 100MeV per turn is compensated by a powerful rf system. The life time of the electron beam is about 10h. Electron polarization in excess of 50% is produced due to the Sokholov-Ternov effect in less than one hour and measured continuously by two independent Compton polarimeters [15, 16](see Figure 1). Pairs of spin rotators at three straight sections turn the spin longitudinal and back to vertical. In the east straight section, the HERMES experiment (Figure 3) is located which takes data on deep-inelastic scattering of electrons off a storage cell target which may be operated using polarized or high-density unpolarized gas; for an overview of the results see [17]. The polarized hydrogen and deuterium target is described in ref.[18]. In order to integrate a thin-walled storage tube with sensitive wall coating at a temperature of \( T = 100K \) into a machine with a strongly bunched electron beam of high intensity, several requirements had to be met:

- The cell is protected by means of a system of - partly moveable - tungsten collimators against direct and single-scattered synchrotron radiation;
- Conducting surfaces composed of thin-walled tubes are arranged up- and

<table>
<thead>
<tr>
<th>Ring</th>
<th>Energy</th>
<th>Beam</th>
<th>Experiment</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>VEPP-3 (BINP)</td>
<td>3GeV</td>
<td>e^-</td>
<td>DEUTERON</td>
<td>D storage cell</td>
</tr>
<tr>
<td>LEP-1 (CERN)</td>
<td>50GeV</td>
<td>e^-</td>
<td>HELP (proposal rejected)</td>
<td>H jet</td>
</tr>
<tr>
<td>HERA-e (DESY)</td>
<td>28GeV</td>
<td>e^+</td>
<td>HERMES</td>
<td>H, D, (^3)He storage cell</td>
</tr>
<tr>
<td>SHR (MIT-Bates)</td>
<td>1GeV</td>
<td>e^-</td>
<td>BLAST</td>
<td>D storage cell</td>
</tr>
</tbody>
</table>

Table 3: Electron Rings used for internal target experiments.

![Comparison of rise time curves](image)

Figure 1: Polarization rise detected by the transverse and longitudinal polarimeter.
downstream of the target cell for smooth variation of the cross section in order to avoid excitation of *Wake Fields* which would heat the target;

- A small admixture of water to the polarized gas helps to cover the cold storage tube with a thin layer of ice which has a beneficial effect on wall recombination of the polarized target atoms.

With these arrangements, the operation of neither the electron ring nor the target is significantly hindered. Resonant depolarization by harmonics of the bunch repetition frequency of \( f_B = 10.4 \text{MHz} \) is suppressed by a strong, uniform magnetic field of ‘non-resonant’ strength. Reliable operation within the HERA electron ring for the last ten years could be achieved \[18\].

**MIT-Bates South Hall Ring (SHR)** At MIT-Bates, polarized electron beams can be accelerated by a Linac and injected into the SHR at energies of up to 1.0GeV. By gradual stacking of electron pulses, a long-lived continuous polarized beam of over 200mA in current has been achieved \[19\]. The BLAST experiment is located in one of the straight sections of the racetrack-like SHR \[20\], consisting of a toroid spectrometer with a polarized deuterium gas target in the center. For stable longitudinal polarization at the target, a full Siberian Snake is located in the opposite straight section. No significant decay of beam polarization is visible within storage times of a couple of hours \[19\] (see Figure 3). The ring has been operated successfully for the BLAST experiment at a beam polarization of \( P = 0.6 \) or more until its shutdown in summer this year.
Dedicated Ion Rings

In the following, the ESR at GSI-Darmstadt, CELSIUS at Uppsala, COSY at Jülich (see Table 2) and the CSR-e/m rings at Lanzhou will be discussed briefly. Whereas the first three rings were built in the wake of the successful LEAR project, CSR belongs to a new generation of rings, which might be called King LEAR’s Grand-daughters (see Table 4).

**Experimental Storage Ring (ESR)**  The racetrack-like ESR is capable of accepting ions from the present GSI complex up to 10Tm in rigidity. An internal target station and an electron cooler are available, enabling a broad spectrum of experiments ranging from the study of Uranium one-electron states, the $\beta$ decay of highly-stripped ions, to the interaction of Laser fields with stored ions. Reactions of stored exotic ions with an internal gas target in reversed kinematics can also be studied, yielding information on nuclear structure of exotic nuclei. The EXL collaboration intends to continue these studies at FAIR [21]. A particularly successful application is Mass Measurement, based on Schottky spectra of stored ions. Two high-resolution modes are available: (i) with electron cooling in order to minimize the velocity spread, and (ii) operation near $\gamma$-transition for minimum frequency spread. A sample of results and an outlook to applications at FAIR were given at this meeting [22].

**CELSIUS**  The CELSIUS ring at TSL (Uppsala) is based on the magnets previously used in the CERN muon-(g-2) and the initial cooling experiments (ICE). Beams from the cyclotron can be stored in the 7.4Tm ring with four straights, two of them used for internal target experiments. A 300keV electron cooler provides a small beam size and compensates for heating by the targets. The Cluster target can be run with a variety of light and heavy gases. The Hydrogen Pellet target is used for the close-to-4π WASA detector. The CELSIUS ring is closed down in summer 2005 after 17 years of operation [23].
Erhard Steffens

**COSY** The cooler synchrotron COSY at FZ Jülich is a storage ring with a momentum range for protons and deuterons of 0.3 to 3.7 GeV/c [24]. Electron cooling at injection and stochastic cooling at final energies are provided. Polarized $H^-$ and $D^-$ beams are injected and accelerated to full energy by crossing about 15 spin resonances without significant polarization loss [25]. Intrinsic resonances, i.e. those which are connected to the vertical betatron tune, are crossed by means of fast quadrupole magnets (see Figure 4).

![Figure 4: A COSY fast quadrupole employed for tune jumping.](image)

A number of internal target experiments is performed at COSY, namely COSY-11 with cluster target, EDDA and ANKE with cluster and polarized hydrogen and deuterium gas target. In future the WASA detector with its pellet target will be installed at COSY in order to extend the study of exotic states to higher energies (see the various presentations about COSY experiments at this meeting). COSY is unique due to its stored polarized beams which will be exploited by the ANKE collaboration in its new spin program 'from COSY to FAIR’ [26].

**CSRm,e** The HIRFL facility at Lanzhou [27] comprises two storage ring accelerators (CSR) for highly charged heavy ions: the CSRm for accumulation and acceleration and the CSRe for internal target experiments. Injection into CSRm is accomplished directly from the K=450 ring cyclotron. Accelerated beams can be used to produce secondary beams on a production target which are then injected after separation as beams of rare isotopes into the CSRe for the study of nuclear structure of exotic nuclei. Both CSRm and CSRe have electron cooling with energies of 35 and 300 keV, resp. An internal target experiment similar to WASA is planned for CSRm, based on a 4π detector and a pellet target. Both rings have been constructed, and the commissioning is in progress.

**Outlook**

This overview has shown that the concept of electron and ion storage rings, combined with thin internal targets, was successfully applied within the last two decades. After a splendid harvest, most of these facilities have been shut down, like IUCF, AmPS, CELSIUS, Bates-SHR etc., are close to being shut down, like HERA, or are no longer used as internal target facility, like the SPS or LEAR. COSY with its program based on the WASA and ANKE detectors will continue for several more years. ESR at GSI will also run until the start of FAIR, but with low priority on internal target
experiments. The future relies on the experience gained at the past and present facilities and is summarized in Table 4, where some of the projects are listed which one might call King LEAR’s Granddaughters. The HIRFL facility with its ambitious extensions is already part of this future. Looking at the various opportunities to perform internal target experiments there is, after 2007, no electron ring left, with the possible exception of ELSA (Bonn). No internal target experiment has been accepted at LHC. The future seems to be at storage rings with heavy ions and/or secondary beams, i.e. rare isotopes or antiprotons.

<table>
<thead>
<tr>
<th>First Operation</th>
<th>Ring</th>
<th>Rigidity</th>
<th>Place</th>
<th>Cooling method</th>
<th>Special features</th>
</tr>
</thead>
<tbody>
<tr>
<td>2004</td>
<td>CSRm, CSRe a</td>
<td>10.6Tm</td>
<td>HIRFL</td>
<td>Ecool</td>
<td>HI, RI</td>
</tr>
<tr>
<td>2004</td>
<td>CSRe b</td>
<td>8.4Tm</td>
<td>Lanzhou</td>
<td>Ecool</td>
<td>HI</td>
</tr>
<tr>
<td>2013</td>
<td>Isochronous Ring/RIBF</td>
<td>50Tm</td>
<td>RIKEN</td>
<td>Ecool</td>
<td>RI mass meas.</td>
</tr>
<tr>
<td>2013</td>
<td>Isochronous Ring/RIBF</td>
<td>50Tm</td>
<td>Tokyo</td>
<td>Ecool</td>
<td>PANDA</td>
</tr>
<tr>
<td>2013</td>
<td>Isochronous Ring/RIBF</td>
<td>50Tm</td>
<td>FAIR</td>
<td>Ecool</td>
<td>PANDA</td>
</tr>
<tr>
<td>2013</td>
<td>Isochronous Ring/RIBF</td>
<td>50Tm</td>
<td>Darmstadt</td>
<td>Ecool</td>
<td>PANDA</td>
</tr>
</tbody>
</table>

Table 4: King LEAR’s Granddaughters. Future ion ring projects (HI = heavy ions, RI = rare isotopes).

The CSR rings of the HIRFL facility have already been discussed. The outlook is completed by a discussion of the future plans at RIKEN (Tokyo) and GSI (Darmstadt).

**Isochronous Ring/RIBF** As part of the rare ion beam facility RIBF (RIKEN, Tokyo) a ring has been proposed which is optimized for mass measurements [28]. Rare isotopes are injected by means of a separator which is complemented by a time-of-flight system which serves to suppress unwanted isotopes by three to four orders of magnitude, thus allowing for the detection of very faint beams. A target based on ions trapped by the space charge of an intense electron beam co-linear with the stored ion beam is proposed (SCRIT). RIBF is expected to start operation in 2006, whereas the mass measurement project has not been approved yet.

**GSI Extension: FAIR** The facility for antiproton and ion research (FAIR) [29] will be the future project of nuclear physics in Europe. The conceptual design report has been reviewed in 2002 in comparison with other large-scale projects with german participation. After the positive decision the project is now being prepared by an international consortium. The layout of FAIR is shown in Figure 5. The workhorse of the new facility is the SIS100 synchrotron with 100Tm bending power enabling the production of exotic beams like rare isotopes or antiprotons. A complex system of storage rings [30] is employed to cover a broad range of physics topics, ranging from atomic to nuclear and hadron physics, astrophysics and nuclear matter at extreme conditions. Hadron spectroscopy will be performed at the HESR antiproton storage ring by the PANDA experiment [25]. For high resolution, cooling with 4MeV electrons is required which is a challenging problem. Recently, the addition of an antiproton polarizer has been proposed by the PAX collaboration [26]. By means of an additional 3GeV ring, asymmetric pp collisions could be performed,
Figure 5: The layout of the FAIR facility, showing the existing GSI complex and its extension.

e.g. for the determination of transversity in the nucleon [32]. Detailed studies are required in order to demonstrate the feasibility of this ambitious proposal.

**Conclusions** Storage rings for ions and electrons have played an important role for nuclear and hadron physics experiments. Experiments with fixed target, i.e. thin gas targets, can provide superior energy resolution, detection of recoils and, in conjunction with a stored polarized beam, measurement of the spin correlation in the entrance channel. Blow-up of the stored beam can be compensated for by a cooling system, thus leading to long beam life times important for experiments with rare particles and/or low background. We are looking forward to the challenging applications of these powerful techniques at the new facilities under construction or in the design phase.

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COSY Ring


Institut für Kernphysik, Forschungszentrum Jülich, Germany

Abstract

In this paper the general layout of the COSY accelerator complex is presented, with special emphasis on the acceleration of polarized beams and beam cooling techniques.

Introduction

The COSY cooler synchrotron and storage ring provides polarized and unpolarized proton (deuteron) beams in the momentum range from 300 (600) MeV/c to 3.7 GeV/c for internal and external experiments [1, 2]. The COSY accelerator complex includes $H^-$ and $D^-$ sources and the cyclotron JULIC for pre-acceleration. The negative charged ions are injected via charge exchange into the COSY ring. The layout of the COSY facilities is shown in Fig. 1.
COSY's lattice has a racetrack design, consisting of two 180° arc sections connected by straight sections. The total length of the ring is 183.47 m. The straight sections can be tuned as telescopes with 1:1 imaging, giving a $2\pi$ betatron phase advance. The superperiodicity of the lattice can be adjusted to $P = 2$ or 6. Usually a $P=6$ optics is applied at injection and changed to $P=2$ during acceleration to avoid crossing the transition energy. The transverse working points are ranging from 3.55 to 3.7 in routine operation of COSY. To prepare high precision beams for internal and external experiments two different techniques for beam cooling are utilized: Electron cooling to increase phase space density at injection energy by means of stacking injection in combination with transverse feedback, and stochastic cooling to counteract beam heating of stored ions due to interaction with internal targets. Presently four internal experiments (ANKE, COSY 11, EDDA, PISA) are implemented. The installation of the WASA detector at an internal target area is in preparation. The beam is also delivered to three external experiment areas (Big Karl, JESSICA, TOF) utilizing slow extraction or kicker extraction [2, 3]. Due to limitations of the magnetic septum the maximum momentum for extracted beams is presently restricted to 3.4 GeV/c.

**Polarized Beams**

In a strong-focusing synchrotron like COSY two different types of first-order depolarizing resonances are excited, namely imperfection resonances caused by magnetic field errors and misalignments of the magnets, and intrinsic resonances excited by horizontal fields due to the vertical focusing. In case of protons five imperfection resonances are crossed in the momentum range of COSY, whenever the number of spin precessions per beam revolution is an integer ($\gamma G = k$, $k$: integer). The number of intrinsic resonances depends on the superperiodicity $P$ of the lattice, given by the number of identical periods in the accelerator. One obtains for the resonance condition with $2\pi$ betatron phase advance in the straight sections $\gamma G = k \cdot P \pm (Q_y - 2)$.

<table>
<thead>
<tr>
<th>$P$</th>
<th>$\gamma G$</th>
<th>Kin. Energy MeV</th>
<th>Momentum MeV/c</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>$2 + Q_y$</td>
<td>1997.1</td>
<td>2781.2</td>
</tr>
<tr>
<td>2</td>
<td>$2 + Q_y$</td>
<td>2201.8</td>
<td>2996.4</td>
</tr>
</tbody>
</table>

Table 1: Imperfection and intrinsic resonances for protons. Intrinsic resonances are listed for a vertical betatron tune of $Q_y = 3.61$ and different superperiodicities $P$. 
where \( k \) is an integer and \( Q_y \) the vertical betatron tune. The corresponding first-order depolarizing resonances for protons in the momentum range of COSY are listed in Table 1 [4]. However, due to symmetry-breaking installations in the COSY ring (e.g., ANKE spectrometer and electron-cooler magnets) the superperiod of the accelerator lattice in COSY is reduced to \( P = 1 \), leading to five additional intrinsic resonances in the energy range of COSY: 
\[
\gamma G = -1 + Q_y (992.4 \text{ MeV/c}), \quad 7 - Q_y (1505.3 \text{ MeV/c}), \quad 1 + Q_y (2222.0 \text{ MeV/c}), \quad 9 - Q_y (2659.4 \text{ MeV/c}), \quad 3 + Q_y (3328.6 \text{ MeV/c}).
\]

For deuterons the spin tune is about 25 times lower than for protons at the same energy and therefore depolarizing resonances are 25 times further apart from each other. No first-order depolarizing resonances are crossed for deuterons in the momentum range of COSY at an ordinary transversal betatron tune below 3.7. Since deuterons are spin-1 particles, they appear in three spin states \((1,0,-1)\) relative to an arbitrary quantization axis, compared to two spin states \((1,-1)\) of a spin-\( \frac{1}{2} \) particle like the proton. Three vector components and five components of a second-rank tensor are required to describe spin-1 polarization. The spin dynamics in circular accelerators of spin-1 particles has been discussed in [5]. The polarized source at COSY is designed to provide a sequence of vector and tensor polarized beams, to be selected by the user out of the variety of possible combinations.

**Polarized Beam Acceleration**

In recent years, vertically polarized proton beams have been routinely accelerated in COSY and delivered to internal as well as external experiments at different momenta with polarization above 80%. The main diagnostics tool to develop polarized beams in COSY is the EDDA detector [6], primarily designed to measure the pp-scattering excitation function during synchrotron acceleration. The polarization is determined by measuring the asymmetry of scattering between the circulating COSY beam and...
carbon or $CH_2$-fiber targets. Provisions to preserve polarization during acceleration are shown in the left plot of Fig. 2. The spin is flipped at the imperfection resonances $\gamma G = 2, 3, 4, 5$ and 6 using correction dipoles. To avoid polarization losses at intrinsic resonance tune jumps were applied. The measured polarization after the optimization for polarized beam is shown in the right plot of Fig. 2. Some polarization losses have been observed at the coupling resonance $\gamma G = 8 - Q_x$. By separating the two transversal tunes, the polarization losses could significantly be reduced. More than $10^{10}$ polarized protons have been stored at final momentum.

Deuteron polarization can be preserved without additional provisions up to top energy of COSY. Up to 70% polarization have been reached.

Spin Manipulation

Spin manipulation studies of vertical polarized protons, vector and tensor polarized deuterons, and investigations of higher-order resonances were carried out by the international SPIN@COSY collaboration [7]. A remarkably high measured proton spin-flip efficiency of $99.92 \pm 0.04\%$ was achieved by using a strong ferrite-core water-cooled RF dipole. For polarized deuterons a high spin-flip efficiency of $97 \pm 1\%$ was measured, and the dynamics of tensor polarization was studied in detail. The striking behavior of the spin-1 tensor polarization during spin-flips recently found at IUCF was confirmed. For higher-order spin resonance studies, a well-elaborated procedure to move betatron tunes during the COSY cycle was developed and applied. As expected, a total spin-flip was observed at a very strong first-order intrinsic spin resonance. Third-order spin resonances were measured to be much stronger than the second-order spin resonance for our conditions.

Cooled Beams

Electron Cooling

The COSY electron cooler is designed to produce up to 3 A electron beam at 100 keV. The electron cooler is shown in the photograph of Fig. 3. Main parameters of electron cooling at COSY are summarized in Table 2. Toroidal fields to the electron cooler section, beam in a solenoidal field usually operated at 0.08 T, an electron collector to recover its energy. The beam emittance of the circulating beam is typically reduced by one order of magnitude in all three dimensions of phase space. This takes many revolutions in the range of seconds at injection energy of COSY. In the right plot of Fig. 3 the $H^3$ counting rate and the beam current (BCT) is shown during stacking of cooled protons in COSY. The beam is injected every two seconds. The intensity of the stacked beam increases to an equilibrium of $5 \cdot 10^{10}$ protons after about 260 seconds. This intensity can only be reached, when a transverse feedback is applied [8], which suppresses coherent betatron oscillations. The applications for electron cooling at COSY are stacking injection of low intensity (polarized) beams, halo-suppression of extracted beams and performance and efficiency increase of kicker extraction [9, 10].
Figure 3: Electron cooler and stacking injection.

Table 2: Electron cooling parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron cooling</td>
<td>routinely used at injection energy</td>
</tr>
<tr>
<td>Electron energy</td>
<td>20 to 100 keV</td>
</tr>
<tr>
<td>max. Electron current</td>
<td>1 A at 20 keV, 3 A at 100 keV (routine operation with 200 mA at 24.5 kV)</td>
</tr>
<tr>
<td>Solenoid field</td>
<td>0.08 to 0.165 T</td>
</tr>
<tr>
<td></td>
<td>(applied up to 0.1 T, limited by toroidal closed orbit distortions)</td>
</tr>
<tr>
<td>Cooling section length</td>
<td>2 m</td>
</tr>
<tr>
<td>Electron beam diameter</td>
<td>2.54 cm</td>
</tr>
<tr>
<td>Diagnostic</td>
<td>$H^0$-profiles and $H^0$ count rate</td>
</tr>
<tr>
<td></td>
<td>two hor./vert. position pickups for electron and ion beam</td>
</tr>
<tr>
<td>Optics at cooler section</td>
<td>$\beta_x = 8$ m; $\beta_y = 16$ m; $D_x = -6$ m</td>
</tr>
</tbody>
</table>

**Stochastic cooling**

Photographs of the pickup and kicker system are shown in Fig. 4. The COSY stochastic cooling system operates in the frequency range from 1 to 3 GHz divided into two bands (1 - 1.8) GHz and (1.8 - 3) GHz. At present one of the two pickup/kicker systems is applied for horizontal cooling whereas the second system is split up for vertical and longitudinal cooling. Longitudinal cooling is realized by Notch-filter cooling utilizing the vertical cooling system in ‘sum mode’. The main parameters of the COSY cooling systems are compiled in Table 3. The stochastic cooling at COSY is mainly needed for luminosity preservation to counteract beam heating in present of cluster jet or atomic beam targets in COSY (see Fig. 5). Further information and references about stochastic cooling at COSY can be found in [11].
Instrumentation

Figure 4: Pickup (left) and kicker (right) of the stochastic cooler.

<table>
<thead>
<tr>
<th>Table 3: Stochastic cooling parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pickup</td>
</tr>
<tr>
<td>Kicker</td>
</tr>
<tr>
<td>Frequency range</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Ion velocities range</td>
</tr>
<tr>
<td>Installed RF power per plane</td>
</tr>
<tr>
<td>Longitudinal cooling</td>
</tr>
</tbody>
</table>

Beam Performance and Luminosity

The maximum number of particles accelerated in COSY is $1.5 \times 10^{11}$ for unpolarized beams and $1.2 \times 10^{10}$ for polarized beams up to now. The extraction efficiency utilizing slow extraction is routinely greater up to 80%, with extraction time in the range from tens of seconds up to half an hour. To get acceptable beam lifetimes for internal experiments, targets have either to be very thin or powerful beam cooling has to be applied (for further reading see [12]). Solid, cluster jet and atomic beam targets are internally used at COSY. After the installation of the WASA detector also a pellet target will be available. External targets are thicker by orders of magnitude, thus solid or liquid targets are applied at COSY. Typical effective target thicknesses, cycle descriptions and estimated luminosities at COSY are summarized in [13]. Internal and external peak luminosities for COSY are plotted in Fig. 6. The peak luminosity is ranging between $10^{26}$ and $10^{32}$ cm$^{-2}$s$^{-1}$, depending on the target thickness and number of circulating or extracted particles per second. In case of unpolarized beams average luminosities above $10^{32}$ cm$^{-2}$s$^{-1}$ can be reached for internal and external experiments at COSY. The average luminosity at COSY is typically one order of magnitude lower for polarized beams interacting with unpolarized targets, due the lower intensity of polarized beam delivered by the COSY injector system. Performing internal experiments with polarized beam and target (e.g. polarized atomic beam target with storage cell) an average luminosity of $10^{30}$ cm$^{-2}$s$^{-1}$ is possible.
Figure 5: Beam equilibrium with stochastic cooling and cluster jet target. Shown is the counting rate of an experimental setup with and without stochastic cooling. The COSY cycle was chosen to be one hour.

Figure 6: Peak luminosity of internal (area indicated right) and external (area indicated left) experiments for different effective target thickness at COSY. The luminosity is calculated for a typical range of circulating particles ($10^9$ to $10^{11}$) in COSY with a particle revolution frequency of 1 MHz. For external experiments an extraction time of 100 seconds is assumed.

Outlook

Machine experiments at COSY are planned to benchmark existing simulation code for cooled beams interacting with internal targets. These investigations are essential to verify and improve theoretical predictions with respect to design and layout of planned storage rings for the future GSI Facility for Antiproton and Ion Research (FAIR) [14]. In cooperation with the Budker Institute for Nuclear Physics in Novosibirsk a feasibility study for a 2MV electron cooler is in preparation [15]. Such a system would provide electron cooling up to top energy of COSY and could further increase to performance of COSY in terms of maximum luminosity and beam quality. Moreover it would open the possibility to gain experience in high-energy electron cooling also foreseen in the High-Energy Storage Ring (HESR) of the FAIR project.
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Polarized beams at storage rings

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Abstract

This paper reviews modern technics to accelerate polarized particles to high energy and to preserve their polarization in the storage rings. Possibilities of the beam polarization control are discussed for proton and electron machines.

Introduction

Spin is a quantum number of an internal angular momentum connected with a particle magnetic moment. This statement in its time could solved many discrepancies in the atom theory. Later its appeared, that the spin considerably contributes into particle interactions at high energies and put many puzzles to experimentalists and theorists. Due to this fact, there is increasing interest in the availability of spin-polarized beams at high energy and nuclear physics experiments.

It's good known that particles motion in modern accelerators is described with extremely high accuracy by the semi-classical approach. But for the spin, these is no quasi-classical limit when orbital quantum number are large. Even at highest energies, an electron, or a proton remains in eigen states “up” or “down” as particles with spin $\frac{1}{2}$ (in units of $\hbar$). The quantum operator for this spin is $\hat{S} = \frac{1}{2} \hat{\sigma}$, where $\hat{\sigma} = (\sigma_x, \sigma_y, \sigma_z) = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$ - Pauli matrixes.

Follow the Ehrenfest’s theorem we determine in the particle rest frame a classical vector of spin in any state $|\psi\rangle$ as a quantum average of spin operator $\hat{S} = \langle \psi | \hat{\sigma} | \psi \rangle$. This vector $\vec{S}$ precess in the rest frame around magnetic field $\vec{B}$ together with particle magnetic moment $\vec{\mu} = q \vec{S}$:

$$\frac{d\vec{S}}{d\tau} = \vec{\Omega} \times \vec{S}.$$  

Spin precession frequency $\vec{\Omega} = -(q_0 + q')\vec{B}$, where $q_0 = \frac{e}{m}$ and $q'$ are normal and anomalous parts of gyromagnetic ratio $q$. (We shall take later $c = \hbar = 1$).

A relativistic generalization of this spin motion equation to a laboratory frame have been done in different ways by many authors (see for example, [1]). The most easy-to-use for accelerators applications view can be presented in the next form:

$$\vec{S}' = \frac{d\vec{S}}{d\theta} = \vec{W}(\theta) \times \vec{S}$$  

with

$$\vec{W}(\theta) = -\frac{q_0}{\gamma} \left[ \left( 1 + \gamma a \right) \vec{B}_\perp + \left( 1 + a \right) \vec{B}_\parallel + \left( \frac{\gamma}{\gamma + a} + \gamma a \right) \vec{E} \times \vec{V} \right].$$
Here we decomposed the magnetic fields in two projections $B_\parallel$ and $B_\perp$ (along and perpendicular to particle velocity $\vec{V}$) and introduce so called magnetic anomaly of a particle $a = \frac{q}{q_0}$ and the generalized accelerator azimuth $\theta$ instead of time $t$.

The magnetic moment anomaly is a fundamental property of a particle on a level of their mass. By now, thanks to many measurements, magnetic anomalies of various particle are known with high accuracy. For example, for electron $a_e = 1.1596521859 \cdot 10^{-3} \pm 3.8 \cdot 10^{-12}$ and for proton: $a_p = 1.792847351 \pm 2.8 \cdot 10^{-8}$.

Before proceeding further we analyse some of the essential features of the above expressions:

- It’s important to note, that $s$ is expressed in the rest frame, whereas $E$ and $B$ are the fields in the laboratory frame.
- $q_0$ and $q'$ contribute differently to spin rotation by electric and magnetic fields (depending on parameter $\nu_0 = \gamma a$), whereas the particle revolution frequency is determined only by $q_0$:

$$\omega = -\frac{q_0}{\gamma} \left[ B_\perp + \frac{\gamma^2 - 1}{\gamma^2} \vec{E} \times \vec{V} \right]. \quad (2)$$

- At low energies a combinations of electric and magnetic fields are used to control spin orientation in polarized particles sources.
- In cases $\nu_0 = 1 \div 10$ combinations of longitudinal and transverse magnetic fields are applied to deliver the required beam polarization to an experiment area. For more higher energies ($\nu_0 > 10$) spin rotations by transverse magnetic fields are more effective

### Spin closed orbit

Let’s remind the approach, which is used for the orbital motion. Particle coordinates are given by the radius vector $\vec{R}(\theta) = \vec{R}_0(\theta) + \vec{r}$, where $\vec{R}_0(\theta)$ presents a periodical closed orbit. The vector $\vec{r} = x\vec{e}_x + z\vec{e}_z$ describes small deviation from CO - horizontal and vertical betatron oscillations with corresponding tunes $\nu_x$ and $\nu_z$.

Follow this approach we share the spin pression frequency in two parts:[2] $\frac{\vec{W}(\theta)}{\vec{W}_0(\theta)} + \vec{w}$. The periodical part $\frac{\vec{W}_0(\theta+2\pi)}{\vec{W}_0(\theta)}$ gives spin rotations by fields on the CO, whereas $\vec{w}$ is a small distortion ($|\vec{w}| \ll |\vec{W}_0|$) connected with momentum off particle oscillations. It’s evidently, the solution of the spin motion equation (1) at any azimuth $\theta$ with $\vec{W}(\theta) = \vec{W}_0(\theta)$ is a periodical unit vector $\vec{n}_0(\theta + 2\pi) = \vec{n}_0(\theta)$, which is the spin precession axis. A spin rotation around $\vec{n}_0(\theta)$ by an angle $\phi$ substitutes all spin rotations by arbitrary local fields along the CO. Similar to the betatron tunes we define the spin tune $\nu = \frac{\nu_0}{2\pi}$. Two other (perpendicular to $\vec{n}_0$) eigen solutions of the spin equation are complex vectors $\vec{n}$ and $\vec{n}^*$ rotating clockwise and contraclockwise around $\vec{n}_0$ with the spin tune: $\vec{n}(\theta + 2\pi) = \vec{n}(\theta) e^{-i\theta}$.

A precession axis for spin of momentum off particles is slightly differs from $\vec{n}_0$ and
can be found in the form \( \vec{n} = \sqrt{1 + |C|^2} \vec{n}_0 + Re(iC\vec{\eta}^*) \); \(|C| \ll 1\). Putting this \( \vec{n} \) into (1) we come in the linear approximation to the short-cut equation:

\[ C' = w_\perp = (\vec{w} \cdot \vec{\eta}^*) \]  \( \text{(3)} \)

**Ideal flat machine**

We proceed our consideration to an ideal flat mashie with an uniform vertical magnetic field \( K_z = \frac{\partial}{\partial \phi} \). In this case it’s clear, \( \vec{n}_0 \) coincides everywhere with the unit vector along the guiding field: \( \vec{n}_0 = \vec{e}_z \) and \( \vec{\eta} = (\vec{e}_x - i\vec{e}_y) e^{-i\omega_0 \phi} \), where \( \phi = \int_0^\phi K_z d\phi \). From (1) and (2) we see, that spin tune \( \nu = 1 + \nu_0 \). But in the accelerating frame \( (\vec{e}_x; \vec{e}_y; \vec{e}_z) \) after one particle turn spin rotates only by angle \( \phi = 2\pi \nu_0 = \gamma \alpha \).

This fact has a very important practical consequence. Since the values of magnet anomalies \( \alpha \) are known to great accuracy, one can deduce the \( \gamma \)-factor with high precision from spin tune measurement. A knowledge of the particle mass immediately gives an absolute beam energy calibration. An experimental technique for that is radio-frequency magnetic field applied in horizontal plane to kick the spin. On resonant frequency the kicks add up to a beam depolarization. This can generally be done with great accuracy. This energy calibration method was called resonant depolarization and by now it has been applied with success at many accelerators.[3]

**Spin resonances**

Focusing elements are unavoidable at any storage ring the same as the betatron oscillations. It’s appeared immediately as a distortion for the spin motion. A vertically deviated particle meets the radial component of the focusing magnetic fields. Using the particle motion equation this distortion can be described by \( w_\perp = t_0 z' = \nu g \). Putting that in (3) one finds, that \( \vec{n} \) oscillates around \( \vec{n}_0 \) with the betatron tunes \( \nu_0 \). In the resonance case \( \nu = \nu_k = k \pm \nu_z \) (so called “intrinsic resonances”) spin will rotates around the horizontal axis with a precession frequency \( w_k \), which is the resonance strength:

\[ |w_k| = |A_z| \frac{t_0}{2\pi} \int_{-\pi}^{\pi} g_\perp |f_z| e^{i(\nu \pm \nu_0) \phi} d\phi, \]

where we used the Floke form for the solution of \( z \) motion equation:

\( z = A_z f_z + \text{c.c.} \). One can see, that the strength of the intrinsic resonances enhances with the particle energy and the vertical oscillation amplitude. Calculations shown, when \( \nu_0 \approx 100 \) at any resonances \( k = mP \) (P is a machine periodicity) \(|w_k| \sim (0.1 \div 0.3) \cdot \omega_0 \) by \( A_z \approx 1 \text{mm} \) (see Fig.1).

Other spin distortions connect with vertical deviations of the CO caused by radial imperfection fields \( K_x = \frac{\partial}{\partial \phi} \). In this case putting into (3) the forced periodical part of the vertical motion \( Z_\perp \) we get strengths of imperfection resonances \( \nu = k \):

\[ |w_k| = \frac{t_0}{2\pi} \int_{-\pi}^{\pi} Z_\perp e^{-i\phi} d\phi = \frac{t_0}{2\pi} \int_{-\pi}^{\pi} K_x F_\perp(\phi) e^{-i\phi} d\phi, \]
where $\frac{d\theta}{dt} = \frac{d\theta}{d\tau} \theta$ is a spin response function, that reflects a sensitivity of $\bar{n}$-vector to vertical kicks. Most strong imperfection resonances have also $k = mP$ ($m$-integer). They increase with the energy faster than the intrinsics ($F_3 \sim \gamma$). But unlike to the intrinsic resonances one can adjust the vertical closed orbit to minimise $w_k$ up to level depending on his experimental technics.

![Intrinsic resonance strengths, protons in RHIC](image)

Figure 1: Intrinsic resonance strengths in a RHIC lattice, (normalized vertical emittance of $10\pi$ mm-mrad)

**Spin resonance crossing**

Since the spin tune is proportional to the energy spin resonance crossings are unavoidable while an acceleration. A gap between two imperfection resonances is equal to 440.652 MeV for electrons and 523.342 MeV for protons. The intrinsic resonances are located symmetrically around each imperfection resonance. So, the acceleration of polarized particles looks as very complicate issue.

In the simplest case of a separate resonance $\nu = \nu_k$ with a strength $w_k$ a final polarization $\zeta_F$ after one crossing with tune rate $\delta = \frac{d\nu}{dt}$ will be differs from the initial one: $\zeta_F = \zeta_0 \left(2e^{-\Psi} - 1\right)$, where $\Psi = \frac{\Psi w_k^2}{\nu^2}$ is a spin phase advance in the resonance zone (tune $\delta \sim w_k$).

When $\Psi \ll 1$ (fast crossing) polarization loss is small: $\delta \zeta \simeq \zeta_0 \Psi$. More interesting is opposite case: $\Psi \gg 1$. It leads to a spin flip ($\zeta_F \simeq -\zeta_0$) with an exponentially low depolarization: $|\delta \zeta| = 2\zeta_0 e^{-\Psi}$.

Both situations are widely used in accelerator practice. A suppression of the resonance strength (orbit corrections) or increasing tune rate (tune jump) lead to the fast crossing and vice versa an artificial resonance enhancement helps to safely reverse the polarization.

Let’s insert in the ideal flat machine at a part of the orbit $\theta = \theta_1$ a solenoid with the
longitudinal magnet field \( K_y = \frac{\phi}{4\pi} \), that rotates spin by an angle \( \phi = \frac{\phi}{4\pi} \int_{0}^{L} K_y d\theta \).

Exploring this simple model we shall give an easy-to-use way to find the spin tune and the \( \vec{n}_0 \)-axis. A general form of a unitary SU2 matrix of a vector rotation by an angle \( \phi \) around an unit vector \( \vec{n}_j \), can be presented as \( T_j = \cos \frac{\phi}{2} - i(\vec{n}_j \cdot \vec{\sigma}) \sin \frac{\phi}{2} \).

The one turn spin map will be product of the local matrixes \( T_j \); \( T = T_N \cdot T_{N-1} \cdot \ldots \cdot T_2 \cdot T_1 \), which has the same unitary form with \( \vec{n}_j = \vec{n}_0 \). Hence, one finds easy \( \cos(\pi \nu) = \frac{1}{2} \text{Tr}(T) \) and \( \vec{n}_0 = -\frac{\sin(\pi \nu)}{\text{Tr}(\vec{n}_j \cdot \vec{\sigma})} \text{Tr}(\vec{n}_j) \).

Practising to a machine with one solenoid we see that the solenoid shifts the spin tune \( \cos(\pi \nu) = \cos(\pi \nu_0) \cdot \cos \frac{\phi}{2} \) and a direction of the vector \( \vec{n}_0 \) is not vertical more and depends on the solenoid strength and spin tune.

If the solenoid is short \( \theta_1 \ll 1 \), we can take it as \( \delta \)-function like distortion and expand it in the series of resonances \( \nu = k \) with equal strengths \( |w_k| = \frac{1}{\pi} \).

So, it’s possible to provide the adiabatic resonance crossing by increasing the solenoidal field. This method was called a partial Siberian snake and is successfully used at many machines after its first test at VEPP-2M storage ring at 1976 year.[6]

The same adiabatic approach for an intrinsic resonance crossing can be realized by RF-dipole working near by the vertical tune. Under such condition the spin response function blows up \( F_3 \gg 1 \) and enhances the resonance harmonics in many times.

This method is successfully used on strongest intrinsic resonances at AGS.[7]

Siberian snakes

An interesting situation appears, when the rotation angle by the solenoid \( \phi = \pi \).

How it’s easy to see, the spin tune in this case is always equal to \( \frac{1}{2} \) independently on \( \nu_0 \). It means an exclusion totally the spin resonances while acceleration. Moreover, the vector \( \vec{n}_0 \) is longitudinal along the drift opposite to the snake insertion.[8]

Spin rotators with similar properties have been named “Siberian snakes”. They can be designed from combinations of longitudinal and transverse fields suitable for each specific case with one main requirement to be matched with machine lattice.

First test of the Siberian snake idea (solenoid at the IUCF proton storage ring) has shown full suppression imperfection resonances as well as intrinsic resonances.[9] To minimize machine optics and orbit distortions a snake transfer matrix have been done equal to the matrix of a drift \( L \) occupied by the insertion:

\[
M_x = \begin{pmatrix} 1 & L \\ 0 & 1 \end{pmatrix} ; \quad M_z = -M_x.
\]

Similar approach is proposed for future HESR storage ring (3.5 ÷ 15 GeV). Two pairs of solenoids and rotating quads together with the electron cooling solenoid will realize the optics of the 56 m straight. An angle of each quad rotation depending on fields strengths and beam energy can be design as a field superposition of two superconducting coils - regular quadrupole one and second rotated by 45 degree.

For more higher energy, as we noticed before, transverse fields is more effective for spin rotations. It turned out that helical magnetic field configuration is most convenient for these purposes, because it gives less orbit deviations in comparison with regular dipoles.

A scheme from four full twist helical magnets with mirror symmetry of the fields
polarity and helicity is able to rotate spin by 180° around arbitrary axis in the horizontal plane. Moreover the same magnet combination can work as a spin rotator from vertical direction to a position in the medium plane by any angle to the velocity. \[10\] Such scheme of Siberian snakes and spin rotators was realized at RHIC. Two snakes in each ring with the axis angles $\pm 45^\circ$ also provide the spin tune $\nu = \frac{1}{2}$ and opposite vertical polarization in the arcs. Four pairs of the spin rotators deliver the longitudinal polarization in collision points for detectors “STAR” and PHENIX”.

Recently at RHIC polarized protons in both ring were accelerated up to the top energy 200 GeV.

Figure 2: Schematic layout of BNL complex for polarized proton operations.

**Radiative polarization of electrons**

Electron radiates energy while accelerated. An intensity of this synchrotron radiation enhances $\sim \gamma^4$ and at high energy it determines all beam parameters. Due to quantum nature of this radiation the orbital motion get stochastic kicks. For their turn, the orbit jumps lead to fluctuations of the precession axis $\mathbf{n}(\theta)$ and to a spin diffusion - random changes of spin projections $S_n$. This effect spreads considerably the spin resonances, thus the acceleration of polarized electrons is possible only up to few GeV.

Fortunately aggravation of electron spin by radiative effects is more than compensated for by electron self-polarization due to small difference in probabilities of spin-flip quantum emission in states “spin up” and spin down”. A calculation of this effect in the homogeneous magnetic field \[11\] have shown, that an equilibrium degree of beam polarization $\zeta = \frac{3}{2\pi}$ $\simeq 0.924$ buildups with a characteristic time $\tau_p$, that can be written (in practical units) as $\tau_p(h) \approx \frac{R(h)}{(B/T)^2 [\text{EGGAV}]^2}$. It’s easy to estimate, that the radiative polarization is available at most of the electron-positron colliders and light source storage rings. It’s important to remark, that radiative polarization is unique method for obtaining of high energy polarized positrons.

However real fields at storage rings are far from homogeneous. More full study of the radiative polarization in real machine fields brings to the equilibrium polarization...
level $\zeta = \frac{q \gamma^2}{\alpha}$ and polarization time $\tau = \alpha$ with: [12]

$$\alpha_+ = \frac{5\sqrt{3}}{8} q_0^3 \gamma^2 \langle |\vec{B}|^3 \cdot (\vec{n}_0 - \vec{d}) \rangle_s; \quad \alpha_- = \frac{5\sqrt{3}}{8} q_0^3 \gamma^2 \langle |\vec{B}|^3 [1 - \frac{2}{9} (\vec{n}_0 \cdot \vec{V}) + \frac{11}{18} \vec{d}^2] \rangle_s, \quad (4)$$

where $\vec{b}$ is the unit vector along $\vec{B}$ and $\vec{d} = \gamma \frac{\partial \vec{n}}{\partial n}$ is a spin-orbit coupling vector, that shows a sensitivity of $\vec{n}$-axis to the orbital kicks by quantum emission. It’s clear, that a rate of the spin diffusion have to be $\sim d^2$.

An early observation of radiative polarization buildup in an $e^+e^-$ storage ring VEPP-2M is presented in the Fig.3.[13], from where it’s seen the asymptotic polarization ($\zeta \approx 0.92$) is near by the predicted value for the homogeneous field. However, with increasing of particle energy a depolarizing influence of the spin diffusion grows up ($|\vec{d}| \sim \gamma^2$) and one has to take specific measures to maximize an achievable degree of polarization. It appeared, that most effective method is “harmonic spin matching”. If the spin tune is far away from dangerous intrinsic resonances, it’s possible to compensate two nearest imperfection resonances by adjusting corresponding harmonics of the closed orbit and using data from a polarimeter as a feedback.

By now the radiative polarization have been observed and used at many storage rings in the energy range from 500 MeV (ACO, VEPP-2M) up to 50 GeV (LEP). As can be seen from the Fig.4 the polarization level dropped precipitously at high energies at LEP. It indicates a full overlapping of spin resonances due to the spin diffusion.

References

Figure 4: The maximum attained asymptotic polarization levels at different high energy $e^+e^-$ storage rings, with and without harmonic spin matching.


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Internal Targets for Storage Rings

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Introduction

Internal targets have become increasingly important in connection with the proliferation of storage rings and cooling methods for particle beams. Apart from the applied detector components for the registration and identification of reaction products at an internal beam storage ring experiment, the choice of the type of target and its properties strongly determines the quality of the recorded data and the physical aspects that can be investigated. Especially parameters like areal target density and target diameter at the interaction zone, gas load to the scattering chamber, possible degree of polarization and time structure of the target are of great importance.

Although there is a rich variety of different types of internal target devices such as (polarized) atomic beam targets, gaseous, liquid or solid state targets, there are currently huge efforts to optimize these types of targets and to develop new methods and techniques to meet the requirements for future internal beam experiments. Examples for current activities on the field of unpolarized target facilities will be presented.

Requirements on Internal Beam Targets

Target facilities for internal beam experiments have to fulfill several requirements in order to guarantee experimental data of highest quality. First of all a perfect internal target should provide the target material at the interaction zone without additional windows which have to be penetrated by the accelerator beam. Such windows would cause beam heating effects and would introduce background reactions due to scattering of beam particles or reaction ejectiles with the window material and, therefore, should be avoided if possible. To suppress such background reactions it is, of course, of great importance to provide target materials at the reaction zone of highest purity. Furthermore, the gas load of the target facility to the scattering chamber has to be as low as possible to avoid background from reactions with residual gas. The latter point might be of great importance in case of expensive accelerator beams like anti-protons beams.

The areal target density at the interaction point in the scattering chamber has to be high enough to obtain sufficient event rates of the reaction channel of interest. Dependent on the underlying production process, the capabilities of the detection system and beam heating effects in the target, areal target densities in the range between $10^{12}$ to $10^{16}$ atoms/cm$^2$ might be of interest. Of great importance here is the possibility to vary the absolute scale of the target beam intensity continuously.
within a short time period in order to adjust the counting rate to experimental conditions and to compensate for beam losses. Furthermore, a possibility to vary the target diameter at the interaction zone might be of interest to optimize a beam-target overlap or to define the interaction region without use of additional vertex detectors.

Ideally, the above mentioned target density at the interaction zone is continuous and homogeneous in space and time to avoid large time structure of the event rates, which might introduce problems with respect to data acquisition systems. Furthermore, the possibility to switch the target beam on or off within seconds allows for an injection, acceleration and preparation of the accelerator beam without influence of the target.

It is obvious that the above mentioned requirements can hardly be matched completely by a single type of internal target. Therefore, the “ideal” target type for a storage ring experiment is strongly dependent on the physics to be studied and the used hardware components for particle detection and data recording.

Cluster Jet Targets

In case of gas jet targets the target material is usually pressed through a special shaped nozzle. In order to provide an appropriate shaped target beam at the interaction zone, a set of molecular beam skimmers with certain diameters and shapes can be used. The most striking advantage of this type of target is the fact that in principle all gases can be used and that the areal target density in the scattering chamber can be varied easily over orders of magnitude just by changing operational parameters like the gas input pressure. However, due to the fact that gas jet beams rapidly diverge in a vacuum chamber, gas jet beams are typically used at low distances between nozzle and interaction zone. Furthermore, the target density is in the order of $10^{12}$ atoms/cm$^2$. To increase the density supersonic gas jet beams can be produced by using Laval-type shaped nozzles in combination with higher gas input pressures and low temperatures. By this an increase of the target density by approximately one order of magnitude can be achieved.

To obtain even higher target densities of $10^{14}$ atoms/cm$^2$ and above, one can make use of a possible condensation of gases leading to the formation of clusters. The required conditions of the gas before entering the nozzle and the properties of the nozzle itself are certainly directly connected to the gas which should be used. In case of hydrogen for example nozzle diameters of below $\sim 100$ μm, gas input pressures of several bars and temperatures below 40 K are necessary in order to obtain appropriate target beam densities. An important advantage of cluster jet beams compared to supersonic gas jet beams is the fact that the cluster jet beam, prepared by beam skimmers, travels through a ultra high vacuum chamber with an angular divergence which is only given by the geometry of the nozzle-skimmer system. Additional expansion of the cluster jet beam due to scattering with residual gas can be neglected due to the high mass of the clusters. According to this, cluster jet beams can be shot over several meters through a vacuum system and are, therefore, capable for $4\pi$ experiments with large distances between the target source and the interaction point.
The volume density distribution of a cluster jet beam differs significantly from the one of a conventional (supersonic) gas jet beam. In the latter case the target beam density distribution is typically given by a gaussian shape while in the case of a cluster jet beam homogeneous volume density distributions can be observed. This situation is demonstrated in figure 1. The figure on the left hand sides presents the areal target beam density at the interaction zone 65 cm behind the nozzle, measured at the cluster jet installation at Münster. The solid line corresponds to a calculation to the density distribution, assuming a homogeneous volume density. The perfect agreement with the experimental data confirms the assumption. This can also be seen in the right hand side figure where the volume density distribution is extracted from the previous figure. The importance of such a rectangular volume density distribution is the sharp boundary of the target beam and, therefore, the sharply defined interaction region. Due to these advantages, cluster jet beams are used with great success in internal beam experiments at storage rings. In table 1 typical working conditions and achieved areal target densities at the interaction region are presented for the case of hydrogen clusters. While the applied nozzle temperatures are similar, the gas input pressures vary significantly. This fact can be understood by the different nozzle diameters of the target installations. Due to the different nozzle diameters the presented target devices are obviously operated at different temperature/pressure combinations which directly concerns the cluster yields and, therefore, the cluster beam densities. The cluster jet target facilities from the CELSIUS ring at Uppsala and the one from the E835 experiment at Fermilab [2] were operated very successfully for many years and provided areal target densities in the range of $1-3 \times 10^{14}$ atoms/cm$^2$. In contrast to these installations, the two cluster jet target devices of the experiments ANKE and COSY-11, both located at COSY in Jülich, are equipped with much finer Laval-type nozzles and
Table 1: Comparison of operation parameters of different cluster jet target stations and areal target densities at the interaction region. The given parameters correspond to the production of hydrogen clusters.

<table>
<thead>
<tr>
<th></th>
<th>CELSIUS</th>
<th>FERMILAB E835</th>
<th>COSY-11 ANKE</th>
<th>Münster</th>
</tr>
</thead>
<tbody>
<tr>
<td>nozzle diameter</td>
<td>100 µm</td>
<td>37 µm</td>
<td>11-16 µm</td>
<td>16-28 µm</td>
</tr>
<tr>
<td>nozzle temperature</td>
<td>20-35 K</td>
<td>20-32 K</td>
<td>22-35 K</td>
<td>20-35 K</td>
</tr>
<tr>
<td>gas pressure</td>
<td>1.4 bar</td>
<td>&lt;10 bar</td>
<td>18 bar</td>
<td>&gt; 18 bar</td>
</tr>
<tr>
<td>distance from nozzle</td>
<td>0.32 m</td>
<td>0.26 m</td>
<td>0.65 m</td>
<td>2.1 m (!)</td>
</tr>
<tr>
<td>areal target density</td>
<td>$1.3 \times 10^{14}$</td>
<td>$3 \times 10^{14}$</td>
<td>$\geq 10^{14}$</td>
<td>$1.5 \times 10^{14}$</td>
</tr>
</tbody>
</table>

can thus use much higher gas input pressures. Due to this fact additional to the normal operation with the target material in a conventional gas phase these targets can be operated at temperature/pressure combinations where the gas is already in a supersaturated phase before passing the nozzle. Due to this the cluster process is strongly supported and even higher cluster yields can be achieved. This fact can be seen by the observed areal target density above $10^{14}$ atoms/cm$^2$ at distances from the nozzle twice as large as at the other installations. The effect of high cluster yields at such operational parameters can be seen from figure 2, obtained at the Münster cluster jet target installation and using a Laval-type nozzle with a diameter of 16 µm. Here the volume target density of a hydrogen cluster jet beam at a distance of ~2.1 m behind the nozzle is presented as function of the gas input pressure and the nozzle temperature. As expected low cluster beam densities are observed at high temperatures and low gas input pressures. Different to this a decrease of the temperature and/or an increase of the gas pressure leads to significantly higher cluster beam densities. The solid line of figure 2 represents the vapor pressure curve for hydrogen. Obviously, the target devices can be operated easily in a mode where the gas is already in a supersaturated state before passing the nozzle. The highest observed target beam densities where limited here just by the maximum accessible gas input pressure and the cooling power of our cryogenic nozzle generator.

Currently, at the cluster target device of the university of Münster further detailed studies on the production of highest hydrogen cluster beam densities are in progress. For this purpose modifications on the cluster source have been started to allow for measurements at higher gas input pressures and lower temperatures. Additionally, the available pumping speed at the nozzle chamber will be increased by a factor of three in order to handle the corresponding higher gas flows and to allow for the use of larger nozzles. It is expected that this will lead to target densities above the currently obtained areal target beam densities of above $10^{14}$ atoms/cm$^2$ at a distance of ~2.1 m. In addition, the former cluster target from the E835 experiment at Fermilab has
now been set up at a test field at the GSI in Darmstadt. In a combined research project studies on both targets have been started in order to develop high intense cluster jet targets for new internal beam experiments.

**Liquid Jet Targets**

A new and interesting approach to provide nuclear target beams at larger distances from the production point, i.e. several meters, is the production of superfluid helium beams. At the university of Frankfurt studies have been initiated in order to provide superfluid helium beams with micrometer diameters in combination with high vacuum conditions. The beams itself are produced by feeding thin cylindrical nozzles with diameters of ~2 μm with helium at low temperatures below 2 K [3]. Directly after the nozzle a continuous liquid helium beam is observed, which breaks up after 1 to 3 mm and forms droplets with diameters of two times the nozzle diameter. The distance of these droplets is reported to be similar to the droplet diameter. Without the use of skimmers the angular divergence of this beam is in the order of <0.5 mrad which corresponds to a target spread of below 2mm at a distance of 2 meters behind the nozzle. Therefore, such beam might be of great interest as nuclear target for future internal storage ring experiments.
Pellet Targets

An interesting method to use solid state materials as targets for internal beam experiments at storage rings is the approach to prepare a stream of frozen pellets which passes the scattering chamber. Such a target device was proposed for the first time by Sven Kullander in 1984 and build up in the following years at The Svedberg Laboratoy (TSL) in Uppsala [4]. From 1999 till 2005 this pellet target has been used at the CELSIUS storage ring in Uppsala successfully as the first and up to now only pellet target in particle production experiments. Here pellets of hydrogen and deuterium have been used for proton-proton and proton-deuteron scattering experiments.

The main idea to produce a pellet stream is to press liquid hydrogen at 14 K through a thin (20 μm) convergent glass nozzle at triple point conditions (72 mbar). The liquid hydrogen jet is broken up by a piezoelectric transducer leading to the formation of equidistant droplets of similar size. In a droplet formation chamber, which is kept at vacuum pressures below the triple point condition, the droplets start to freeze by evaporation and form finally the pellets which can then be injected into the vacuum system. In figure 3 a hydrogen pellet stream after this vacuum injection is presented [4], which can directly be shot over several meters through the scattering chamber as internal target beam. Therefore, pellet targets are well suited for 4π-experiments where high target densities and small, well-defined interaction zones are needed. Due to typical single pellet diameters of ~30 μm the areal density of a
single pellet is in the order of up to $10^{20}$ atoms/cm$^2$ for a central hit. However, due to the distance between the pellets ($\sim$mm) and the beam/target overlap, effective target densities in the order of $10^{15}$ to $10^{16}$ atoms/cm$^2$ are obtained. The divergence of the pellet stream in the scattering chamber of the Uppsala target is determined by a skimmer placed between nozzle and scattering chamber. Typically effective target beam diameters of 2-3 mm were used for the experiments. The Uppsala pellet target has now been dismounted from the CELSIUS rung and will be moved to the COSY storage ring at the FZ-Jülich for the planned WASA@COSY experiment.

Currently there are further efforts to developments pellet targets for storage ring experiments. Details on these activities have been presented during this conference by P. Fedorets [5] and Ö. Nordhage [6].

References


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Detectors for nuclear and hadron physics have usually to fulfill challenging demands. They have to cope with a high-rate of high-multiplicity interactions and to be resistant to a serious radiation dose. Particle identification for several types of secondaries, together with a high resolution in their momenta and vertex positions, have to be available to select interesting processes outside of a large background. The relevant aspects of this kind of detectors will be reviewed together with few significant examples of already realized experiments. Detectors of new generation, proposed or in preparation, will be discussed in details especially in relation of the high-energy program of the FAIR project for a large hadron facility in Europe.

The attention will be driven to original experiments aiming to measure polarized interactions. In particular, constraints imposed from double-polarization experiments on the design of fixed-target and collider detectors will be discussed. Spin is one of the less understood properties of the hadronic matter. Detectors sensitive to spin observables have to provide the same performances of the other experimental devices with additional constraints imposed by the polarization build-up and maintenance during the measurement.

Detectors for fixed target experiments

Few examples of fixed-target experiments will be reviewed in order of increasing complexity. The use of internal polarized gas target is now a mature technique to study polarized reactions. To identify the $e^+e^-$ signal out from the large particle flux is a goal common to several physics topics, which can be safely achieved by using almost hadron-blind Čerenkov detectors. The spectrometer magnet configuration has to be chosen not to spoil the Čerenkov detector or the polarized target performances.

The EDDA and ANKE detectors at FZJ. The Cooler–Synchrotron (COSY) at the Forschungszentrum, Jülich provides a proton (deuteron) beam of 1-2 GeV/c momentum. The EDDA experiment is designed to measure spin-correlations in elastic $pp$ scattering off a CH$_2$-fiber target or a polarized H-atomic gas target. The latter selects single hydrogen hyperfine states to be focused in the interaction region where the spin is aligned by a weak (10 mT) guiding field in either one of the 6 possible directions ($\pm x, \pm y, \pm z$). The EDDA spectrometer simply comprises of two cylindrical double layers of scintillator fibers (inner layer) and slabs (outer layer) which track the two particles outgoing the reaction without magnetic bending. The over-constrained elastic kinematics allows such an apparatus to provide all the required informations in a large interval (85 %) of the solid angle. In addition this device could be used to monitor the beam parameters [1]. The ANKE experiment measures heavy meson (kaon) production in nuclear media, deuteron wave function and few-body polarized reactions [2]. Solid strip and cluster gas targets were employed for
the unpolarized physics program. The ANKE spectrometer is a composite apparatus made by a dipole magnet and a multi-wire proportional chamber (MWPC) set. Separate tracking sections are employed for positive and negative charged, forward and backward ejectiles. Several telescopes with particle identification (PID) capability are installed to cover different solid angles. A silicon detector was designed to identify the spectator proton and get an effective neutron target from a deuteron one [3]. A polarized H,D target is currently being installed for the polarized physics program. The use of a polarized target puts additional constraints on the experimental set-up. Space has to be foreseen for the exhausting pump system. To not disturb the beam orbit with additional magnetic fields, the fringe field of the dipole magnet is used as guiding field for the target polarization. The fringe field provides only transverse polarization and is not strong enough to efficiently decouple nuclear and electronic spins so that only one hyperfine state is injected into the target.

The BLAST detector at MIT BATES Ring. The BATES Large Acceptance Spectrometer Toroid (BLAST) experiment measures then neutron and proton form factors and studies the spin structure of few-body nuclear ground states like the weakly-bound deuteron and the three body $^3$He system [4]. It employs a 1 GeV/c momentum beam of longitudinally polarized electrons that scatter off an internal polarized H, D and $^3$He gas target. The latter do not have any dilution from non-polarized species, are rapidly reversible and can be oriented with low magnetic fields. The spectrometer magnet consists of an eight-sector copper coil array producing a toroidal field which provides polar deflection for momentum measurement without affecting the target region by fringe fields. The detector is instrumented only into two opposing wedge-shaped sectors with scintillator detectors for time-of-flight measurement, Čerenkovcounters for particle identification, lead glass calorimeter, neutron counters and recoil detectors for complete reconstruction of the final state. The torus field, with almost negligible fringe fields, do not affect neither the holding field of the target, the beam polarization, nor the performance of the Čerenkovdetector. The magnet coils, being of warm copper, are quite massive and reduce the active solid angle. A strong effort was required to put into operation the polarized atomic beam source feeding the target cell through the large volume occupied by the torus magnet.

The CLAS detector at Jefferson Lab. The CLAS experiment measures the nucleon spin structure and electromagnetic interactions with nucleons and nuclei by scattering a polarized beam of 1-2 GeV/c momentum electron or gamma onto a frozen-spin H or D solid target. Although working with an extracted beam, the CLAS spectrometer is an interesting device since employs a design similar to the BLAST detector but maximizes the active area reaching almost 4π coverage. The torus magnet is based on six superconducting coils to minimize the material inside the tracking volume and it is shaped to match the integrated field to the average particle momenta, from 0.5 Tm for backward tracks up to 2 Tm in the forward direction. All the 6-fold sectors between the coils are instrumented. Feedthroughs, circuit boards and strut fixtures of the tracking drift-chambers are contained within the shadow of the torus coils [5]. Due to the toroidal field configuration, the charged particle trajectories lie approximately in planes of constant azimuth. To enhance the spatial resolution, each of the 6-fold sectors of the Čerenkovdetector is divided
Instrumentation

into 18 polar regions. In each region the light is focalized on the side to the two photomultiplier tubes located in the space obscured by the coils [6].

The E835 detector at Fermilab. The E835 experiment studies the charmonium spectroscopy and measures the proton time-like form factors by annihilating a 3 to 7 GeV/c antiproton beam on a Hydrogen gaseous jet-target. The typical final state is characterized by a single $e^+e^-$ pair of invariant mass equal to the center-of-mass energy. The over-constrained kinematics allows a simplified design of the E835 detector [7], which does not employ magnetic field like the EDDA detector. The particle trajectory is tracked by layers of scintillating fibers and straw tubes. The particle identification is based on a gas Čerenkov detector: the counter occupies a cylindrical shell around the beam line and is subdivided into two separate gas cells that cover the polar angle forward and backward regions, respectively. The cell are filled by gases of different refraction index (CO$_2$ in the forward and Freon-12 or Freon-13 in the backward cell) in order to best match the average particle momentum [8]. The lepton identification is complemented by measuring the energy loss in the tracking devices and the shower profile in the electromagnetic calorimeter, a barrel of lead-glass blocks. The best achievable stochastic term for the calorimeter energy resolution, close to 3 %, is degraded to almost 6 % due to the supporting steel partitions between blocks [9]. The $\pi/e$ rejection is high enough to allow measurements of reactions with less than 1 nb cross-section out of a total $\bar{p}p$ cross-section of the order of 70 mb.

The HADES experiment at GSI. The HADES experiment studies in medium hadron properties by measuring $e^+e^-$ pairs in relativistic nuclear collisions. It works with an extracted beam of ions with 1-2 GeV per nucleon hitting a thin target of high-A material (like Au). The detector comprises a ring imaging Čerenkov counter with total thickness lower than 1 % of radiation length to minimize background from photon conversions and multiple scattering. A MWPC with segmented CsI photocathode is used as photon detector to provide high granularity and deal with the extremely high multiplicity of charged tracks per event [10]. The low average momentum of the ejectiles, between 0.1 and 1 GeV/c, put stringent limitations to the material budget for tracking: the MWPC of the spectrometer are all external to the compact Čerenkov detector and filled by He gas. A superconducting torus magnet has to be used, like the previous detectors, not to spoil the Čerenkov detector performances [11].

The CERES experiment at CERN. The CERES experiment at CERN tests the conjectured transition form ordinary hadronic matter to quark-gluon plasma: it compares $e^+e^-$ pair production in ultra-relativistic 450 GeV p-Be, p-Au and in 200 GeV/nucleon S-Au collisions at central rapidities [12]. The CERES detector is a not conventional example, based on two concentric azimuthally symmetric ring-imaging Čerenkov detectors that provide particle identification plus a rough tracking system. The Čerenkov threshold ($\gamma = 32$) is high enough to substantially suppress signals from the large number of hadrons produced in the collision. A superconducting double solenoid between the two detectors provides an azimuthal deflection for momentum determination. The magnetic field in the region of the inner RICH radiator is compensated nearly zero using asymmetry in the currents of the coils, thus preserving the information of the original direction of the particles. A set of
correction coils shapes the field in the second RICH radiator such that it points back to the target, ensuring straight trajectories and therefore sharp ring images. The Čerenkov photons are registered in two multi-wire chambers operated with He with photo-sensitive TMAE as gas additive [13]. A radial-drift silicon detector closely behind the target, providing high-resolution vertex and tracking, is used to veto early photon-conversion and Dalitz decays, which are the only significant source of background. Such a device was able to reach a signal over back-ground ratio of 1:4, in S-Au collisions and in the region of low dilepton invariant-masses, from 200 MeV/c² to beyond 1 GeV/c², where the combinatorial background is maximum.

**The HERMES detector at DESY.** The HERMES experiment was designed to investigate the internal spin structure of nucleons and nuclei by deep-inelastic scattering of 27.5 GeV/c momentum polarized positrons and electrons by polarized gaseous targets (e.g. hydrogen, deuterium and helium-3) internal to the HERA-e storage ring. The positrons (electrons) circulating in the ring become transversely polarized by the emission of spin-flip synchrotron radiation [14]. A longitudinal beam polarization is generated at HERMES by the use of a pair of spin rotators before and after the experiment. The HERMES detector [15] is a forward spectrometer with a dipole magnet providing a field integral of 1.3 Tm. The forward geometry allows the insertion of shielding plates to decouple the target and spectrometer fields. In this way, either a longitudinal or a vertical holding fields could be employed in the target for helicity and transverse-spin studies, respectively [16]. An additional horizontal iron plate shields the HERA beam lines from the dipole field, thus dividing the spectrometer into two identical halves with a ±40 mrad blind central sector. In each detector-half, tracking is accomplished by drift chamber planes and particle identification is provided by a likelihood method based on the collected signals of four subsystems: a ring-imaging Čerenkov detector (RICH), a lead-glass calorimeter, a transition-radiation detector, and a preshower hodoscope. For positrons in the momentum range of 2.5 to 27 GeV/c, the identification efficiency exceeds 98% and the hadron contamination is less than 0.5%. The RICH detector is primary design for hadron identification in semi-inclusive and exclusive reactions. There the same array of photo-multipliers collect the light emitted by particles passing through two contiguous radiators, a wall of silica aerogel tiles and a volume of C₄F₁₀ gas [17].

The use of two radiators with different refraction indexes allows efficient hadron identification in an extended range of momenta, from 2 up to 15 GeV/c.

**Detectors for colliders**

Few detector examples will be reported, working from middle to high energy regime, before discussing the case of a polarized collider. The collider detectors generally employ solenoid fields since they offer a large volume free for tracking and with smooth variation of the field strength. For such a field the bending is proportional to the transverse momentum and is therefore minimum for the most-energetic particles scattered in the forward region. Moreover it has large fringe fields outside the fiducial volume and it requires special care to cope with transverse spin polarization.

**The KLOE detector at LNF.** The KLOE experiment is designed to measure CP and CPT violation parameters in the decays of neutral kaons. It works at
the Frascati e+e- collider, DAΦNE, which operates at a center of mass energy of 1020 MeV, the mass of the Φ-meson. The KLOE detector is embedded inside a superconducting coil which produces a solenoid field of 0.6 T. To track the π⁺π⁻ decays, a drift-chamber has to be used large enough to contain the mean decay length of K_L mesons (3.4 m). As a consequence, the electromagnetic calorimeter has outsize dimensions, with an internal diameter of 4 m and a length exceeding 3 m. It has to identify the 2π⁰ decays in the photon energy range from 300 MeV down to 20 MeV and to reconstruct the decay path with a precision of few millimeters. The adopted solution is a matrix of scintillating fibers embedded in a structure made of grooved 0.5 mm thick lead foils [18]. The fibers are grouped into 4 x 4 cm² elements and at both calorimeter ends via light guides coupled with photomultipliers. With this solution a ~ 1.5 cm radiation length is achieved with a 13 % unconventionally large sampling fraction, resulting in a stochastic term small as much as 5.4 % for the energy resolution. The decay path can be obtained from a measurement of the time-of-flight of photons from π⁰ decays, exploiting the excellent time resolution of the order of 56 ps/√E(GeV). Such a calorimeter could hardly cope with high particle rates (i.e. at larger center-of-mass energies) since it provides 1D views of the signals.

The BABAR detector at SLAC. The BABAR experiment studies the CP-violation in the decays of neutral B mesons. The experiment works at the PEP-II e⁺e⁻ collider and determines the time interval between the two B-meson decays in each ™(4S) → BB event. The collider is asymmetric, with beam energies of 9 upon 3 GeV, to exploit the displacement in the decay vertexes due to the relativistic boost of the ejectiles. The detector is asymmetric as well, and built in order to keep the read-out electronics as much as possible outside the active detector volume. In order to reconstruct the B decay vertex with the required 80 μm resolution a five-layers barrel of double-sided silicon strip detectors is used [19]. The read-out chips are placed in the forward and backward supporting structures outside the active area of the detector. The signals from the strips are brought to the readout electronics using fanout circuits consisting in conductive traces on a thin flexible insulator. Particle identification (PID) is needed both to reconstruct one of the two B mesons in an exclusive decay mode, and to tag the beauty content of the second recoiling B meson. In order to minimize the CsI calorimeter cost, the PID system must be thin in both radiation length and physical dimension. To match these requirements a detector working with internally-reflected Čerenkovlight (D IRC) is used for the first time [20]. It is made by 144 bars of high quality quartz placed close together to form a cylinder around the central tracking region between the drift chambers and the CsI calorimeter. Once generated by the passing particle, the Čerenkovlight is transported through successive total internal reflections to the ends of the radiator bars. The photons exit the bar when they reach the backward end of the tracking volume, and the Čerenkovimage is then allowed to expand in purified water, with a refractive index approximately matching the one of the bar, and is detected by a two-dimensional array of photo-multipliers. This device has been proven to be a powerful tool for hadron identification with limited material budget but can hardly be applied to electron PID since the particle path inside the radiator is too short to allow the use of small refraction indexes.
The CMS detector at CERN. The CMS experiment is designed for the Higgs and supersymmetric particles investigation at the proton-proton Large Hadron Collider (LHC) working at 14 TeV center-of-mass energies and at luminosities up to $10^{34}$ cm$^{-2}$s$^{-1}$. Such a challenging detector has to operate at un-precedent high-rates and high-radiation doses and required extensive studies to improve the performances of each of the detector systems employed. The silicon vertex detector is divided into pixels to reduce the occupancy and simplify the pattern recognition [21]. The read-out chips have to be installed in the backward side of the active silicon layer, at a price to increase the material thickness in the particle path. The electromagnetic calorimeter is made by a large number of PbWO$_4$ crystals, 50 cm long ($\sim$ 25 radiation lengths) to contain electromagnetic showers up to 4 TeV and with a small $2 \times 2$ cm$^2$ section to enhance spatial resolution [21]. Among the available scintillating media, PbWO$_4$ has short radiation length and small Molière radius leading to a compact device, a short scintillating decay constant and a good radiation hardness demonstrated on full length crystals doped with niobium. The drawback of low light yield is effectively overcome by the use of relatively large area Si avalanche photocathodes, able to provide gain in the presence of the 4 T solenoid magnetic field. The big effort devoted to improve the PbWO$_4$ performances in radiation damage and light yield made this material one of the most promising tools for future experiments, although its use in large devices is discouraged by the high-cost of the scintillating material.

The PHENIX detector at BNL. The Relativistic Heavy ion Collider accelerates nuclear beams from proton to gold with momenta ranging from 25 up to 250 GeV/c. The PHENIX experiment studies the quark-gluon plasma in ultra-relativistic ion collisions and the nucleon spin-structure in proton-antiproton polarized reactions. The PHENIX detector [22] measures $e^+e^-$ pair production in ion collisions and the parity violating asymmetry in $W \rightarrow e\nu_e$ production in polarized $\bar{p}p$ reactions. A large RICH detector is employed for electron identification, where spherical mirrors focus the Čerenkov light onto two arrays of photomultipliers located on either side of the entrance window [23]. Ethane is used as light radiator gas to match the high-momentum of the ejectiles ($\gamma \sim 30$) and to limit the total thickness of the detector to below 2 % of radiation length. In conjunction with the lead-scintillator calorimeter it provides a $\pi/e$ rejection power greater than $10^6$. The use of a Čerenkov detector and polarized beams put additional constraints to the spectrometer magnet design, likewise the internal target detectors already described above. The un-conventional solution is a couple of Helmotz coils with counter-acting currents in order to compensate close to zero the field along the beam line. Moreover the detector is only instrumented into two left-and-right halves, leaving a volume on top and bottom free for a massive iron yoke driving the field lines outside the region where the RICH is operated [24].

Detectors at FAIR - HESR

The Facility for Ions and Antiprotons Research (FAIR) at Darmstadt is a large-scale project for a future European laboratory where hadronic matter could be studied in all its forms (from heavy nuclear systems to nucleon structure functions, from
Instrumentation

The High Energy Storage Ring was initially designed to store high-quality antiproton beam up to 15 GeV/c, with momentum spread down to $dp/p \sim 10^{-5}$ and luminosity up to $10^{32}$ cm$^{-2}$s$^{-1}$, to serve PANDA fixed-target experiment [25]. Recently a new proposal was submitted to convert HESR in a synchrotron to allow the study of proton-antiproton polarized reactions in both fixed-target and collider mode [26].

**The PANDA detector at FAIR.** The PANDA collaboration propose to study several questions of hadron and nuclear physics in interactions of antiprotons with nucleons and nuclei, using a multi-purpose detector. The physics topics cover charmonium spectroscopy, charm meson production in nuclear media, gluonic excitations and hypernuclei. The proposed PANDA detector is a state-of-the-art detector with internal gaseous cluster (or jet) unpolarized target surrounded by both a central solenoid and a forward dipole spectrometers. It comprises a vertex silicon pixel detector and a PbWO$_4$ scintillating crystal calorimeter like CMS, a set of tracking straw tubes like E835 and a DIRC detector for hadron identification like BABAR. Such a detector is hardly suitable for a polarized physics program. The 2 T solenoid field is not compatible with a polarized internal target. A transverse beam polarization can only be maintained by compensating the strong spin precession in both the solenoid and in the forward dipole fields.

**The PAX detector at FAIR.** Polarized antiprotons, by spin filtering with an internal polarized gas target, provide access to a wealth of single- and double-spin observables. This includes a first direct measurement of the transversity distribution of the valence quarks in the proton, a test of the predicted opposite sign of the Sivers-function, related to the quark distribution inside a transversely polarized nucleon, in Drell-Yan (DY) as compared to semi-inclusive DIS, and a first measurement of the moduli and the relative phase of the time-like electric and magnetic form factors $G_{E,M}$ of the proton. Still open questions in polarized and unpolarized $pp$ elastic scattering can be addressed as well. The PAX collaboration has developed a viable experimental set-up which can be realized at FAIR [26]. The PAX detector concept is well-suited to provide Drell-Yan $e^+e^-$ pair detection, out of the overwhelming ($\sim 10^7$ times larger) background from hadronic $pp$ reactions. In addition, such a detector is able to efficiently detect secondaries in two body reactions, like rare annihilations into $e^+e^-$ pair and elastic scattering events, where the over-constrained kinematic simplifies the event reconstruction and reduces the particle identification requirements. The apparatus is optimized to detect electron pairs since several mature techniques exist to efficiently identify electrons without an adverse effect on the momentum resolution in the energy range accessible at HESR, from 0.5 to 10 GeV. To works with muons is a more challenging alternative as demonstrated by TOPAZ [27]. The detector has a large angle acceptance, the transverse spin effects being maxima at large transverse momenta. The magnet has a torus configuration to not affect the transverse spin orientation of the beam and the operation of the Čerenkov detector. It also does not conflict with the holding field of the internal polarized target foreseen for the low-energy physics program. The spectrometer concept [26] comprises a compact silicon vertex detector close to the interaction point like BABAR, plus a conventional set of drift-chambers external to the torus magnet like CLAS/HADES. The lepton identification is accomplished
by a Čerenkov detector like CLAS/E835, inserted into the free space of the tracking arm of the drift chambers. A lead-glass homogeneous device like E835/PHENIX or a scintillating fiber-lead sampling solution like KLOE can be envisaged for the large electromagnetic calorimeter thanks to the not stringent requirements on the energy resolution and radiation hardness.

References


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The Polarized Internal Gas Target of ANKE at COSY

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Abstract.

For future few-nucleon interaction studies with polarized beams and targets at COSY-Jülich, a polarized internal storage-cell gas target has been developed and for the first time installed at the magnet spectrometer ANKE in June 2005. Laboratory studies of prototype cells with the polarized hydrogen beam from the atomic beam source and with use of the Lamb-Shift polarimeter have been performed. A sufficient ratio of the signal from the polarized atoms to that from unpolarized background was achieved. The COSY-beam properties at the ANKE-target position have been studied with diaphragms and with a prototype of a storage cell, fed by unpolarized gas. The obtained results are presented.

Introduction

In the foreseeable future COSY will be the only storage ring for polarized proton and deuteron beams. Combined with the polarized internal target (PIT) \cite{1}, being installed at ANKE, double polarized experiments can be performed like those on the proton-induced deuteron breakup \cite{2}. The gas-storage cell of the PIT will be fed by the beam of polarized H or D from the atomic beam source (ABS). The nuclear polarization of the target gas will be measured with the Lamb-shift polarimeter (LSP) \cite{3,4} by extracting a gas sample from the cell tube. In order to optimize the COSY-beam intensity and to minimize the interaction between the beam and the target-cell wall, the operation parameters of COSY have to be studied. Such measurements have been started with the use of different diaphragms and a first prototype of a storage cell. They have to be continued in the commissioning phase of the PIT, which has been installed at the ANKE-target position for the first time in June 2005.
The atomic beam source

The intensity of the $^1$H beam is up to $8 \times 10^{16}$ atoms/s for two hyperfine states and the achieved polarization is $p = -0.96 \pm 0.005$. The beam width is about $\sigma = 2.85 \pm 0.42$ mm. Details of the ABS have been reported elsewhere, e.g. Ref. [5]. Here, only details of the layout are listed that concern the ABS as a component of the PIT, when it is installed at the ANKE-target position:

1. To follow the lateral movement of the central analyzing dipole magnet D2 in the ANKE setup, the ABS and the target chamber are mounted in a bridge between the beam-bending magnet D1 and D2 (Fig. 1).

2. The layout of the PIT installation at ANKE is based on the request to exchange the PIT against the cluster or foil targets, also used at ANKE, within a single maintenance week.

3. The forces by the stray field of the D2 magnet to ABS components like the turbomolecular and cryogenic pumps, the pressure gauges, and the rf transition units have eventually to be reduced by appropriate shielding.

The Lamb-shift polarimeter

The LSP allows one to measure the nuclear polarization of the $^1$H or $^2$D beam from the ABS within a few seconds with a precision of 0.5% [3]. Originally, the LSP was mainly used to determine the polarization of the ABS beam and, e.g., for tuning the rf transition units. In the meantime, laboratory studies have demonstrated that it is possible to measure the polarization of a sample of atoms effusing from a storage cell into the LSP. The strong background by atoms from H$_2$, recombined in the ionizer, could be strongly reduced by the installation of a nonevaporable getter pump around the ionizing volume [4]. After a number of additional modifications like installation of a new beam chopper, the sensitivity studies have to be continued in the new geometry at the ANKE-target chamber, shown in Fig. 1.

PIT at ANKE

In early 2005, the ABS and the LSP were transferred from the laboratory to a position within the COSY hall outside the accelerator tunnel. There, the ABS was mounted in the new bridge. All the supply units like the compressors for the cryogenic pumps and the electronic racks were mounted on a common platform for transfer to the ANKE-target place. In June 2005, the ABS and the platform were positioned there for the first time. The right-hand side of Fig. 1 shows the ABS in the COSY tunnel, connected to the target chamber below it. A careful look to the right-hand part of Fig. 1 lets one perceive the left-hand end of the support bridge, lying on the yoke of magnet D1, a part of the bridge below the diaphragm pumps, and the linear translator, mounted on the top of the D2 yoke (at the right hand side), to which the bridge is connected. The LSP was added later as shown in its position at the target chamber in the left-hand part of Fig. 1.
Storage cell tests

As a first step to study and to optimize the COSY beam intensity and its lateral dimensions at the ANKE-target position, the beam diameter was measured with a diaphragm, suspended in a horizontally and vertically moveable frame (Fig.2). The initial intensity of the stored COSY-beam at injection and after acceleration to 1.2 GeV was measured as function of the diaphragm position. By cutting the beam from its horizontal and vertical edges, the beam dimensions at injection were determined as $36_{\text{hor}} \times 16_{\text{ver}}$ mm. After acceleration they shrank to $9_{\text{hor}} \times 12_{\text{ver}}$ mm.
When the accelerated beam was heated by the beam of the ANKE-cluster target, with a thickness of about $10^{14}$ at/cm$^2$ similar to that expected for the gas of the PIT, the beam profile became circular with a diameter of 15-16 mm. Finally, a beam of initially $1.28 \times 10^{10}$ polarized deuterons could be stored, circulating through a cell of $30_{hor} \times 20_{ver}$ mm cross section, a length of 220 mm, and fed by unpolarized molecular hydrogen-gas flow producing the expected gas thickness of the PIT.

**Discussion**

For the measurements, performed until now, neither stochastic nor electron cooling were used. Stacking injection combined with electron cooling may be an option to minimize the beam diameter at maximum intensity. These features have to be investigated. With cell tubes of reduced $20 \times 20$ mm cross section and about 350 mm length, luminosities up to $10^{30}$ cm$^{-2}$ s$^{-1}$ are thought feasible.

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Observation and measurement of hydrogen and nitrogen frozen droplets (pellets) at the Moscow-Jülich Pellet Target

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Targets of frozen micro spheres ("pellets") have been proposed for high luminosity experiments \((L > 10^{32} \text{ 1/cm}^2\text{s})\) at internal accelerator beams. Pioneering work on pellet targets has been made at Uppsala, Sweden [1].

A pellet target with a different cooling concept has been developed at the Institut für Kernphysik (IKP) of the Forschungszentrum Jülich (FZJ) by a group from the Institute for Theoretical and Experimental Physics (ITEP), Moscow and the Moscow Power and Engineering Institute (MPEI) [2]. In this construction the liquid nitrogen and the cold helium gas are used for cooling, which provides the possibility for the liquefaction and pellet production from different gases, e.g. \(\text{H}_2\), \(\text{D}_2\), \(\text{N}_2\), \(\text{Ar}\), \(\text{Kr}\) and \(\text{Xe}\).

The layout of the target is shown in Fig. 1 (left). Target consists of the target cryostat (Fig. 1 (right)) and the dumping system. There are two baths with liquid \(\text{N}_2\) and liquid \(\text{He}\) in the upper part of the target cryostat. The cooling is realized in three steps. In the first, hydrogen (for example) is flowing through the liquid nitrogen bath and cooled down to \(\sim 100\, \text{K}\). The cold evaporated \(\text{He}\) gas is used for cooling in the second stage, the heat-exchanger, where hydrogen is cooled down to \(22\, \text{K}\). Finally, the hydrogen is liquefied in the condenser with cold He gas.

After condensation, the liquid hydrogen flows through a nozzle, mounted on the outlet of the condenser, into the triple point chamber (TPC), where conditions close to the triple point for the particular target material \((T_{\text{tr}}=14\, \text{K}, p_{\text{tr}}\sim 100\, \text{mbar} \text{ for hydrogen})\) are maintained.

The diameter of the liquid jet in the TPC can be as small as \(\sim 10\, \mu\text{m}\), depending on the nozzle diameter. Inside the TPC the jet is broken into mono-sized droplets with diameters down to \(\sim 20\, \mu\text{m}\) by a sonic generator with resonant frequency \(3\, \text{kHz}\). The generator is mounted coaxially on the outer surface of the nozzle. Passing the sluice between TPC and first vacuum chamber the droplets freeze due to surface evaporation and a continuous flow of frozen pellets with diameters down to \(\sim 20\, \mu\text{m}\) is generated. Finally, the pellets pass through two vacuum chambers in order to decrease the pressure from 100 mbar (TPC) down to \(10^{-7}\text{--}10^{-8}\, \text{mbar}\) (scattering chamber). In the last step, pellets enter the dumping system, where they are collected and evaporated.

The diagnostic system is based on CCD cameras, which provide the possibility for detection and measurement of individual pellets. A special software for the cameras has been developed for observation and measurement of the jet and droplet

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parameters and for tuning the coaxiality of the nozzle and sluice. The information from the CCD cameras is written to disk for subsequent analyses. Figure 2 presents photos in the triple point chamber: a jet of liquid $\text{H}_2$ in the upper part of the chamber (left) and splitting of the $\text{H}_2$ jet into droplets in the bottom of the chamber (right). For these tests a steel nozzle with diameter 38 $\mu$m has been used, corresponding to a droplet diameter of 70 $\mu$m. Figure 3 shows $\text{N}_2$ (left) and $\text{H}_2$ (right) frozen pellets at the sluice outlet into the first vacuum chamber. Due to the high velocity of the pellets ($\sim$60–70 m/s) and the sensitive time of the CCD ($\sim$5 $\mu$s) the pellets are seen as short tracks with lengths proportional to their velocities. The pellet diameters are 30 $\mu$m, which corresponds to a nozzle diameter of 18 $\mu$m. Systematic tests showed that the size and frequency stability of the pellets is not worse than 10%.

Two different nozzle types are used in the target: stainless steel nozzles and the glass nozzles glued into the brass housing. During 2004 several tests for stable pellet production with different nozzle diameters have been performed. The results are presented in Table 1.

<table>
<thead>
<tr>
<th>Nozzle type</th>
<th>Nozzle diameter</th>
<th>Target material</th>
<th>Pellet diameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>25 $\mu$m</td>
<td>$\text{H}_2$</td>
<td>50 $\mu$m</td>
</tr>
<tr>
<td></td>
<td>38 $\mu$m</td>
<td>$\text{H}_2$</td>
<td>70 $\mu$m</td>
</tr>
<tr>
<td></td>
<td>38 $\mu$m</td>
<td>$\text{N}_2$</td>
<td>70 $\mu$m</td>
</tr>
<tr>
<td>Glass</td>
<td>10 $\mu$m</td>
<td>$\text{H}_2$</td>
<td>&lt; 20 $\mu$m</td>
</tr>
<tr>
<td></td>
<td>18 $\mu$m</td>
<td>$\text{H}_2$</td>
<td>30 $\mu$m</td>
</tr>
<tr>
<td></td>
<td>18 $\mu$m</td>
<td>$\text{N}_2$</td>
<td>30 $\mu$m</td>
</tr>
<tr>
<td></td>
<td>40 $\mu$m</td>
<td>$\text{H}_2$</td>
<td>70 $\mu$m</td>
</tr>
</tbody>
</table>

Table 1: Target parameters for which the stable pellet production in the first vacuum chamber has been observed.
During the last test in the spring 2005, after systematic investigation of the nozzle/sluice adjustment, for the first time the frozen hydrogen pellets (nozzle 15 µm, pellets 25 µm) were observed in the scattering chamber (Fig. 4) which has a distance of ~ 100 cm from the TPC.

Main achievements and the current status of the pellet target:
- stable H\textsubscript{2} and N\textsubscript{2} jet production in the triple point chamber (TPC)
- splitting of H\textsubscript{2} and N\textsubscript{2} jets into mono-sized droplets inside the TPC
- frozen H\textsubscript{2} and N\textsubscript{2} droplets (pellets) in the first vacuum chamber
- observation of H\textsubscript{2} pellets in the scattering chamber
- minimal pellet size less than 20 µm (with 10 µm nozzle)
- target can operate over long times (> several hours) and maintain stable parameters (pressure and temperature)

Main advantages of the target design:
- cooling with cold He gas provides the possibility to tune the regimes of jet generation for different gases: H\textsubscript{2}, D\textsubscript{2}, N\textsubscript{2}, Ar, Kr and Xe
- using the cold He gas for cooling supplies vibrationless conditions for jet production and subsequent splitting into the mono-sized droplets
- diagnostic system based on CCD cameras allows one to investigate the parameters (size and velocity) of individual droplets and pellets

Future plans:
- installation at internal target place of COSY
- Systematic study of beam-target interactions (important for PANDA)
Figure 3: $\text{N}_2$ (left) and $\text{H}_2$ (right) frozen pellets at the sluice outlet in the first vacuum chamber.

References


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Figure 4: Photo of a pellet in the scattering chamber.
A high-density pellet target for antiproton physics with PANDA

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Abstract
The PANDA experiment at the future FAIR facility is designed for a luminosity of \(2 \times 10^{32}\) cm\(^{-2}\)s\(^{-1}\). With a limited number of antiprotons stored in HESR this results in a required effective target thickness of \(4.5 \times 10^{15}\) atoms/cm\(^2\), which could be fulfilled by using frozen micro-spheres (pellets) of hydrogen. We will discuss the recent achievements and plans in terms of experimental and theoretical understanding of pellet properties such as pellet rate, pellet position detection, and vacuum conditions in the interaction region.

Introduction
The PANDA experiment has a broad physics program covering e.g. charmonium spectroscopy, gluonic excitations, and properties of charmed mesons in nuclei [1].

Very rare decays together with a limited number of antiprotons put high demands on the target and its thickness. With \(N_p = 1 \times 10^{11}\) stored antiprotons, a momentum range \(1.5 \sim 15\) GeV/c (\(\beta = 0.848 \sim 0.998\)), a HESR circumference \(\Omega = 574\) m, and a design luminosity \(\mathcal{L} = 2 \times 10^{32}\) cm\(^{-2}\)s\(^{-1}\), the required target thickness is

\[
\rho_{\text{req}} = \frac{\mathcal{L}}{N_p \, \Omega \, \Delta \nu} = 4.5 \times 10^{15}\ \text{atoms/cm}^2.
\]

In order to have almost \(4\pi\) coverage for the PANDA detector, any bulky equipment for the target generation needs to be placed outside of the detector, some \(\gtrsim 2\) m away from the interaction point. Furthermore, for pp annihilations a pure hydrogen target is needed. Currently, a target system providing frozen micro-spheres (pellets) are the only proven working solution, which could fulfill these requirements. Such a target has been used for many years at the WASA experiment at The Svedberg Laboratory (TSL) in Uppsala, Sweden.

Target thickness and pellets
The operation principal of the WASA pellet target can be found elsewhere [2-4], and in this paper we only briefly repeat the most important steps.

First, hydrogen gas is cooled to liquid, which is pressed through a nozzle. The resulting liquid jet breaks up into droplets due to an acoustical excitation of the nozzle and the droplets are subsequently injected to vacuum via a capillary. The droplets freeze to (solid) pellets either in the capillary or within some centimeters afterward [4]. The vacuum injection is a crucial step, mainly due to the induced
angular spread, observed to have a FWHM of about 1.0 mm at a distance 0.7 m. At this position a skimmer is used to collimate the pellet beam, such that what gets through: i) cannot hit the narrow target pipe of inner diameter 5 mm close to the interaction point, and ii) is very close to homogenously distributed. Finally, the typical pellet rate at the interaction point is $5 \times 10^3 / s$.

It is important to note that the full-width pellet spread at the interaction point, $S_{ip}$, is defined only by geometry: the skimmer location and diameter. The present skimmer at the WASA pellet target has a diameter of 0.59 mm implying $S_{ip}^{geom} = 2.0$ mm which is in good agreement with the experimental value $S_{ip}^{exp} = 2.1$ mm obtained from tilting the pellet generator meanwhile observing the pressure at the same level as the interaction point [5]. The skimmer geometry also affects the pellet rate within $S_{ip}$.

Pellets are discrete and locally very thick, $p_{loc} = 87.1$ kg/m$^3$ [6], a pellet diameter of $D \sim 30 \mu m$, and an effective length of a sphere, $2D/3$. The antiproton beam will, however, cover a much larger area than the local area-projection of a single pellet. Thus the effective target thickness needs another area to be associated with. The antiproton beam area ($A_b$) should be adjusted such that on average (at least) one pellet is always in the beam. Hence, we can define the minimal associated target area for pellets as

$$A_t \equiv S_{ip} \cdot \langle \ell \rangle,$$

where $\langle \ell \rangle$ is the average inter-pellet distance. This means that the maximum luminosity is obtained if $A_b$ and $A_t$ are matched, and thus the antiproton beam needs to be non-symmetric with (full) width $\sim S_{ip}$ and height $\sim \langle \ell \rangle$. Furthermore, this matching is a prerequisite to enable an (almost) constant event rate for the data acquisition system.

Using the molar hydrogen mass $M$ and Avogadro’s constant $N_A$, the number of protons in a pellet can be written as $2p_V V N_A / M$. These protons spread out over $A_t$ sets the effective target density to

$$p_t^{eff} = p_{loc}^{A_p} A_p = p_{loc}^{V A_t}$$

where $A_p$ is the projected pellet area. Fig. 1 shows some combinations of values for different pellet parameters, all providing the required target thickness of $4.5 \times 10^{15}$ atoms/cm$^2$.

It is still under investigation, but so far simulations indicate that in the foreseen operating regime of effective target thickness the antiproton beam will, on a qualitative level, be heated in the same way, independent on whether the target is homogenously distributed (gas, cluster-jet) or discrete (pellets) [7].

**Research and Development**

As explained above, the aim for an (almost) constant event rate demands the inter-pellet distance and vertical antiproton-beam size to be matched. Other constraints come from the requirement to have a small beta function at the target, which minimizes emittance growth due to multiple small-angle scattering, and that the electron
Prjan Nordhage

Figure 1: (Left) The pellet rates needed for various parameters to achieve the required target thickness of $4.5 \times 10^{15}$ atoms/cm$^2$. (Right) The corresponding inter-pellet distance which should be met by the beam (full) height to give maximum luminosity.

cooler works more efficient on an already cooled antiproton beam (at a section with large beta value). Consequently, a smaller inter-pellet distance is favorable. This implies that the pellets should have a higher rate but in order not to exceed the required effective target thickness (and thereby cause additional beam heating) they must also be of a smaller size (see Fig. 1). To define the R&D-goals for a pellet target, all these aspects must be taken into account.

In theory, the pellet size could be reduced by: i) decreased nozzle outlet, ii) increased transducer frequency, and iii) decreased driving pressure of the hydrogen gas. In practice, however, one can not choose freely among the different parameters but one is restricted to find a combination that results in a pellet concentration (at the skimmer) that corresponds to a proper pellet rate. To increase the pellet rate further, we consider two measures: i) improved survival ratio of the droplets/pellets during the vacuum injection, and ii) decreased angular spread. An idea to realize the first measure is to have the micro-spheres frozen already in the droplet formation chamber (see details in Ref. [4]). The second measure is build on the behavior of the gas flow through the vacuum injection capillary. After its exit, the gas velocity has a transverse component which might be responsible for the pellet spread. By further optimizing the capillary geometry, and especially its exit, this transverse velocity of the gas could hopefully be reduced and thereby also the angular pellet spread.

The location to do the R&D work of the pellet parameters is at the pellet test-station (PTS) at TSL in Uppsala. The PTS is an external apparatus which is used without interference with the WASA pellet target.

As a first PTS project, we have studied and reported on the vacuum condition in a pellet-pipe configuration close to what is proposed for PANDA. The vacuum measurements agree with the calculations [8], performed by VAKLOOP [9]. Another finding was that the installation of a second skimmer together with a pump (between the two skimmers) significantly decreased the pressure throughout the whole system. The conclusion was that if only one skimmer is used, a non-negligible fraction of the total number of pellets will pass the skimmer but under a deflection originating
from the collision with the skimmer edge. These pellets could continue all the way down to the interaction point, but bouncing back and forth against the pellet-pipe wall. Due to the geometry of the pipe system such pellets are most likely not to end up in the pellet dump. Instead they will evaporate at other places in the system, which would also deteriorate the vacuum at the interaction point. Calculations show that this might be a big effect [10], such that the installation of a second skimmer could be an effective way to improve the vacuum situation for any pellet target, e.g. WASA at COSY.

The next PTS project will be to develop a combined pellet counter and online profile/tracking system by utilizing a 96 kHz-readout linescan camera. Consequently, the goal is to exploit the discrete nature of pellets and provide a localized target and thereby a well-defined vertex. This could as well be achieved from the data acquisition system by reconstructing the vertex for some of the several hundred events that occur in each pellet.

Implementation into the PANDA-detector

The outer diameter of the WASA detector is about 3.3 m, and the corresponding diameter for PANDA is 3.7 m. Thus, since a pellet target system fits in WASA, it will also fit in PANDA.

Using the previously mentioned vacuum calculations, we can predict the pressure distribution (originating from pellet outgassing only) for PANDA/HESR. Assuming a pellet speed of 70 m/s and $S_p = 1.5$ mm, we see in Fig. 2 the pressure for two pellet sizes (and rates), both adding up to the required target thickness of $4.5 \times 10^{15}$ atoms/cm$^2$. To quantify the result, we define the ratio 'background due to gas to signal from pellet' as

$$\frac{B_{\text{gas}}}{S_{\text{pellet}}} = \int \rho_{\text{gas}}(z) \, dz \, A_p \, \frac{1}{4 \rho_p} \frac{h}{A_P} \langle N_p \rangle,$$

where $\langle N_p \rangle$ is the average number of pellets in the beam. With $\langle N_p \rangle = 1$ for both cases (thus different antiproton beam areas), we get $B_{\text{gas}}/S_{\text{pellet}}$ to 4.8% and 3.2% for the pellet sizes 20 $\mu$m and 30 $\mu$m, respectively.

![Figure 2: Predicted pressure in the interaction region of PANDA.](image)
Conclusion and Outlook

To reach the design luminosity in PANDA, a pellet target is a very promising option due to the high target thickness it can provide. The concept of the existing WASA pellet target almost suits as it is—and we know how to improve it further. In the pellet test-station, the vacuum condition has been experimentally measured and agrees with the calculations. The pellet test-station is going to be used for further tests, e.g. in the development of a pellet-tracking system that is an approach to a detector-independent vertex determination.

Acknowledgements

The authors wish to thank Z.-K. Li for his contributions to the pellet target developments as well as V. Ziemann for valuable discussions. One of us (O.N.) acknowledges the financial support from GSI, in Darmstadt, Germany, and also the travel grant from The Royal Physiographic Society in Lund, Sweden.

References:

[8] Ref. [1], section 4.1.5.

Contact e-mail: orjan.nordhage@tsl.uu.se
Triggering at storage rings

A. Kulikov

JINR, Dubna, Russia

General requirements to a trigger system in any experiment include i) strong rejection of background in order to match the event flux with rate capability of the data acquisition system (DAQ), ii) efficient detection of the events of interest and iii) low dead time.

Usually there are also requested i) the possibility of parallel running of different triggers which allows to accumulate the data not only for the central physics process but for other processes, too, and for the setup calibration; ii) flexibility to modify the on-line selection criteria.

A common approach to reach these goals consists in use of multilevel trigger architecture and pipelined data flow.

In fact, there is no large difference between the trigger/DAQ systems at storage rings and other accelerators. In both cases the trigger complexity is defined by the signal to background ratio, requested background rejection, luminosity and event multiplicity. Some difference may come from time structure of the beam: at storage rings a long duty cycle results in almost permanent flow of data while at cycling accelerators rather long intervals between the beam deliveries are available. For example, at CERN PS the beam spills of 400–500 ms duration are separated by not less than 1 s intervals which permit to postpone some software operations till the beam spill end. This difference is usually taken into account in the DAQ architecture.

Multilevel trigger systems in large and medium scale experiments in many cases consist of hardware and software stages. A rather fast first level trigger is a hardware subsystem which includes dedicated processors with implemented selection algorithms. Trigger technology is based on use of integrated circuits FPGA (Field Programmable Gate Array), ASIC (Application Specific Integrated Circuit), PLD (Programmable Logic Device) and RAM (Random Access Memory) used for LUT (Look-Up Tables) and some versions of these devices. FPGA circuits are completely reprogrammable and hence provide very flexible logic. On the contrary, ASIC have fixed implemented logic and cannot be reprogrammed but they are faster and cheaper, so are preferable for doing some standard operations.

Due to limitation of the maximum allowed latency of the first level trigger, the selection algorithms at this stage are usually not very complicated. Not all detectors are used at Level 1 trigger and not full granularity is exploited.

Complete (or almost complete) information from the detectors is used at higher level software trigger which analyzes the data selected at Level 1. At the software stage more precise tracking is done, matching of data from different detectors is verified, particle momenta are obtained, invariant mass is calculated and so on, leading to almost final process identification. For fast performing of these operations a computer farm is a proper choice.

In order to reduce a dead time, the pipeline memories are used to store raw data until the Level 1 trigger decision is issued. Depending on the Level 1 result, the data
of a given event are either sent to higher level trigger for further analysis or cleared. The trigger logic itself can be arranged as a pipeline (e.g. like the neutral particle trigger in NA48 [1] at CERN) where at each pipeline step some logic operation is fulfilled. With every pipeline clock the analysis of a new event can start that at sufficiently high clock frequency results in dead time free trigger operation.

Let us look how the trigger systems are arranged in some of recently running experiments. In HERA-B, the fixed target experiment using the 920 GeV proton beam of HERA $ep$ collider, the trigger system [2] consists of several stages, Fig. 1.

<table>
<thead>
<tr>
<th>Stage</th>
<th>Interaction Rate</th>
<th>Latency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pretrigger</td>
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<td></td>
</tr>
<tr>
<td>First level trigger</td>
<td>3 MHz</td>
<td>10 $\mu$s</td>
</tr>
<tr>
<td>Second level trigger</td>
<td>20 kHz</td>
<td>4 ms</td>
</tr>
<tr>
<td>Reconstruction</td>
<td>1 MHz</td>
<td>4 s</td>
</tr>
</tbody>
</table>

![Figure 1: Trigger of the HERA-B experiment.](image)

Pretrigger basing on information from electromagnetic calorimeter and muon detectors defines the Regions of Interest (RoI) for further track search. An almost twice reduced data flux is analyzed at the Level 1 stage where tracks are found using only part of tracking stations with a maximum latency of about 10 $\mu$s. After Level 1 the event rate decreases to 20 kHz and the selected events are analyzed by the software Level 2 trigger. Here a full tracking is done with use of drift times and all tracking stations in drift chambers and Si strip detectors and the vertices are found. The output event flux of 100 Hz is further analyzed by the final trigger stage, where full event reconstruction is made, data are written to tape and all operations for monitoring and calibration are fulfilled. The reconstruction stage is implemented here not for event rate reduction (which is small enough) but permits to log the events which are well analyzed already.

BaBar [3], the experiment at PEP-II $e^+e^-$ asymmetric collider, exploits a similar trigger scheme, Fig. 2, where event selection at Level 1 provided by FPGA based processors is followed by the software trigger stage with full reconstruction of the events.

Recently the PAX experiment has been proposed [4] for FAIR at GSI to study spin physics with use of a polarized antiproton beam. The experiment will include two phases, starting with 3.5 GeV/c polarized/unpolarized antiprotons impinging on a polarized fixed target then being followed by the asymmetric 15x3.5 (GeV/c)$^2$ $pp$ collider phase with both $\bar{p}$ and $p$ polarized.

The main physics issue consisting in measurement of transversity distributions via detection of Drell-Yan processes is accompanied by other topics of comparable significance.
significance. Hence, the trigger system of PAX has to provide selection of all needed processes at the condition of high hadron background (the cross section of Drell-Yan processes is about $10^{-7}$ of the $p\bar{p}$ cross section). The expected interaction rate is up to few MHz, therefore the on-line background suppression of $>10^3$ is required.

Conceptual design of the PAX detector is shown in Fig. 3. In the current preliminary configuration it includes silicon strip detectors, drift chambers, scintillation hodoscopes, drift chambers and electromagnetic calorimeter. All these detectors can be used for trigger selection.

Though the detailed simulations yet has to be done, some general remarks about the trigger architecture can be done. It is proposed to build a two-level trigger system as illustrated in Fig. 4. Raw data from all the detectors feed the pipeline and from some of them are sent to the Level 1 logic. Here the electron/hadron separation is provided with Cherenkov counters, local and total energy deposits in the calorimeter are identified, multiplicity information is taken into account. Events selected at the first level are further analyzed by the next, second trigger level. At Level 2 track segments in Si detectors and in drift chambers are found and then linked, matching of tracks with EM calorimeter hits is checked, momentum...
reconstruction and invariant mass calculation can be done. If the Level 1 latency allows, search for the track segments could be done at the first level trigger. Tracking detectors in PAX are out of magnetic field, hence the track segment search algorithm could be not very complicated.

Figure 4: Probable trigger architecture in PAX.

The above scheme is only the first draft and is a subject for discussion as far as more data are obtained from simulations.

References:


Contact e-mail: kulikov@nusun.jinr.ru
APPENDICES
Appendix A

Scientific Program

Sunday, 22 May

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tbody>
<tr>
<td>16:00 – 17:00</td>
<td>Registration (Gustav-Stresemann-Institute, Bonn)</td>
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<tr>
<td>17:00 – 19:00</td>
<td>Reception</td>
</tr>
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Monday, 23 May (Plenary session: 09:00 – 18:00)
(I: Invited talk, C: Contributed talk)

**Chairperson: F. Rathmann**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tr>
<td>09:00</td>
<td>Welcome address (H. Ströher – FZJ) – 10’</td>
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<tr>
<td></td>
<td>I  Antiproton physics (P. Dalpiaz – Ferrara) – 40’</td>
</tr>
<tr>
<td></td>
<td>I  Spin structure of nucleon (W. Vogelsang – BNL) – 40’</td>
</tr>
<tr>
<td>10:30</td>
<td>COFFEE</td>
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<tr>
<td>11:00</td>
<td>I  PANDA (O. Hartmann – LNF INFN) – 30’</td>
</tr>
<tr>
<td></td>
<td>I  PAX (P. Lenisa – Ferrara) – 30’</td>
</tr>
<tr>
<td></td>
<td>I  FLAIR (E. Widmann – Vienna) – 30’</td>
</tr>
<tr>
<td>12:30</td>
<td>LUNCH</td>
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**Chairperson: E. Steffens**

<table>
<thead>
<tr>
<th>Time</th>
<th>Event</th>
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<tr>
<td>14:00</td>
<td>I  HERA physics (M. Klein – DESY) – 45’</td>
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<tr>
<td></td>
<td>C  Results on DVCS at HERMES (H. Marukyan – Yerevan) – 15’</td>
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<td></td>
<td>C  Transversity from SSA (O. Shevchenko – JINR) – 15’</td>
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<td>C  Transversity via SSA in PAX (A. Nagaytsev – JINR) – 15’</td>
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<td></td>
<td>I  EDM experiments in storage rings (Y. Semertzidis – BNL) – 30’</td>
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<td>16:00</td>
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<tr>
<td>16:30</td>
<td>I  From LEAR to LEIR (M. Chanel – CERN) – 30’</td>
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<td></td>
<td>C  ATRAP experiment (W. Oelert – FZJ) – 15’</td>
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<tr>
<td></td>
<td>I  FAIR-storage rings (P. Beller – GSI) – 30’</td>
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<tr>
<td></td>
<td>C  The antiproton ion collider at FAIR (L. Fabbietti – TU Munich) – 15’</td>
</tr>
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</table>

* For the full title of the talk see the contribution
## Scientific Program

### Chairperson: H.O. Meyer

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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<tr>
<td>09:00</td>
<td>I Hadron physics with hadronic probes (V. Metag – Gießen) – 45’</td>
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<tr>
<td>09:00</td>
<td>I Nuclear physics: status, questions (W. Gelletly – Surrey) – 45’</td>
</tr>
<tr>
<td>10:30</td>
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<tr>
<td>11:00</td>
<td>I CELSIUS experiments (H. Calen – Uppsala) – 30’</td>
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<tr>
<td>11:00</td>
<td>I COSY ring (A. Lehrach – FZJ) – 20’</td>
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<tr>
<td>11:00</td>
<td>I Spin physics inside the COSY ring (A. Kacharava – Erlangen) – 20’</td>
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<td>11:00</td>
<td>I COSY external experiments (A. Gillitzer – FZJ) – 20’</td>
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<tr>
<td>14:00</td>
<td>I Recent achiev. in mass measurement (Yu. Novikov – GSI) – 30’</td>
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### Parallel sessions (14:30 – 18:00)

#### Hadron physics

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<td>C Φ production in pp (M. Hartmann – FZJ) – 15’</td>
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<td>14:30</td>
<td>C Φ production in pn (Y. Maeda – FZJ) – 15’</td>
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<td>14:30</td>
<td>C ω production in pp (S. Barsov – FZJ) – 15’</td>
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<tr>
<td>14:30</td>
<td>C η, η’ production in NN at COSY–11 (J. Przerwa – Cracow) – 15’</td>
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<tr>
<td>14:30</td>
<td>C Two-pion production (M. Bashkanov – Tübingen) – 15’</td>
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<td>14:30</td>
<td>C Strangeness production in pp (P. Winter – FZJ) – 15’</td>
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<td>16:00</td>
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<td>16:30</td>
<td>C Strangeness production in pd (Yu. Valdau – FZJ) – 15’</td>
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<tr>
<td>16:30</td>
<td>C (2N) clusters in K⁺ production (M. Nekipelov – FZJ) – 15’</td>
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<tr>
<td>16:30</td>
<td>C HBT method of ppη system (P. Klaja – Cracow) – 15’</td>
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<td>16:30</td>
<td>C pd–He3 η/η’ reaction at COSY–11 (H. Adam – Münster) – 15’</td>
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<tr>
<td>16:30</td>
<td>C Inverse kinematics studies (Yu. Murin – Uppsala) – 15’</td>
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<td>16:30</td>
<td>C Pion production in S–matrix appr. (V. Malafaia – Lisbon) – 15’</td>
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#### Nuclear and Accelerator physics

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<td>14:30</td>
<td>C Isotope shifts by DR (C. Brandau – GSI) – 15’</td>
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<td>C Mass and half–life at FRS–ESR (Yu. Litvinov – GSI) – 15’</td>
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<td>C Mass measurements in RIKEN (T. Yamaguchi – Saitama) – 15’</td>
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<td>C Isochronous storage ring (M. Yamaguchi – Tsukuba) – 15’</td>
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<td>14:30</td>
<td>C EXL –experiment at FAIR (P. Egelhof – GSI) – 15’</td>
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<td>C Isochronous mode for CR ring (S. Litvinov – GSI) – 15’</td>
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<td>C Polarized heavy ion beams (A. Surzhykov – Kassel) – 15’</td>
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<td>C Laser cooling at ESR (FAIR) (M. Bussmann – Munich) – 15’</td>
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<td>C Diagnostics of spin–pol. IB (S. Tashenov – GSI) – 15’</td>
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<td>C Stochastic precooling for CR (I. Nesmiyan – GSI) – 15’</td>
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## Wednesday, 25 May (Plenary session: 09:00 – 16:00)

**Chairperson:** E. Stephenson  

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<tr>
<td>09:00</td>
<td>I</td>
<td>C. Bloise</td>
<td>DAPHNE: status, perspectives</td>
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<td></td>
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<td>W.L. Zhan</td>
<td>Lanzhou facility</td>
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<tr>
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<td></td>
<td>M. Yosoi</td>
<td>SPring-8 laser–backscattering facility</td>
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<tr>
<td>11:00</td>
<td>C</td>
<td>Yu. Orlov</td>
<td>EDM search</td>
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<td>C</td>
<td>C.J.G. Onderwater</td>
<td>Polarimeter for deuteron EDM</td>
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<tr>
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<td>C</td>
<td>V.G. Baryshevsky</td>
<td>EDM of deuterons in a storage ring</td>
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<tr>
<td></td>
<td>C</td>
<td>L. Benussi</td>
<td>Hypernuclear physics with FINUDA</td>
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<td>C</td>
<td>J. Marton</td>
<td>Kaonic atoms at DEAR/SIDDHARTA</td>
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<td></td>
<td>C</td>
<td>L. Kondratyuk</td>
<td>K–light nucleus interaction</td>
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<td>C</td>
<td>R. Engels</td>
<td>PIT target at ANKE–COSY</td>
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<td>C</td>
<td>P. Fedorets</td>
<td>Moscow–Jülich pellet target</td>
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<td>C</td>
<td>Ö. Nordhage</td>
<td>Pellet target for PANDA</td>
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<td>C</td>
<td>A. Kulikov</td>
<td>Triggering at storage rings</td>
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## Thursday, 26 May (Plenary session: 09:00 – 13:00)

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<td>09:00</td>
<td>I</td>
<td>H. O. Meyer</td>
<td>Instrumentation at storage rings</td>
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<td></td>
<td>I</td>
<td>Th. Stöhlker</td>
<td>Atomic physics: SPARC</td>
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<tr>
<td>11:00</td>
<td>I</td>
<td>A. Khoukaz</td>
<td>Targets at storage rings</td>
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<tr>
<td></td>
<td>I</td>
<td>Yu. Shatunov</td>
<td>Beams of storage rings</td>
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<td></td>
<td>I</td>
<td>M. Contalbrigo</td>
<td>Detectors at storage rings</td>
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<td></td>
<td>I</td>
<td>U.–G. Meißner</td>
<td>Outlook: Challenges in hadron and nuclear physics</td>
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<tr>
<td>13:15</td>
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# Appendix B

## List of Participants

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<th>Name</th>
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<th>Institution</th>
<th>Country</th>
</tr>
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<td>Adam</td>
<td>Universität Münster</td>
<td>Germany</td>
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<td>Aslanyan</td>
<td>Petros</td>
<td>JINR Dubna</td>
<td>Russia</td>
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