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Spin physics at COSY and beyond

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Abstract. Hadron physics aims at a fundamental understanding of all particles and their interactions that are subject to the strong force. Experiments using hadronic probes bear the potential to shed light on open questions that address the structure of hadrons and their interaction, as well as the symmetries of nature. The COoler SYnchrotron COSY at the Forschungszentrum Jülich accelerates protons and deuterons with momenta up to 3.7 GeV/c. In combination with internal polarized Hydrogen and Deuterium targets, the availability of electron and stochastically cooled polarized proton and deuteron beams allows for precision measurements. This report highlights selected recent results from the ongoing spin physics programs at the COSY facility. Spin physics projects reaching into the future, such as the quest for polarized antiprotons, the search for permanent electric dipole moments of protons and deuterons, and a test of time reversal invariance using COSY, are presented as well.

1. Introduction

The COSY facility at Forschungszentrum Jülich (Germany) comprises sources for unpolarized and polarized beams, an injector cyclotron (JULIC) and the storage and cooler ring with a circumference of about 184 m [1]. It stores, accelerates and cools beams of protons and deuterons, which may be polarized, and provides them at internal target stations or extracts them for use at external targets and detectors. With a maximum beam momentum of 3.7 GeV/c, it is well suited for a wide range of hadron physics with hadronic probes in fact it can be considered the hadron spin physics machine because of its possibilities to produce, accelerate, manipulate and use polarized beams and targets [2].

The paper is structured as follows. First, we discuss ongoing investigations by the ANKE collaboration at COSY to determine spin-dependent neutron-proton elastic amplitude (section 2), and near threshold pion production studies which are relevant for chiral perturbation theory (χ PT) (section 3). The quest for polarized antiprotons, pursued by the PAX collaboration, is outlined in section 4. Some additional aspects on what longitudinally polarized proton beams at COSY might contribute physics wise are given in section 5. The physics case for electric dipole moment (EDM) searches of protons, deuterons, and other light nuclei, as outlined in section 6, is truly spectacular. While these searches are extremely challenging experimentally, they bear the potential for a bright future of spin physics, in particular at Jülich. The observation of a time-reversal invariance violation in nuclear reactions as one of the most fundamental symmetries in nature, will be revisited at COSY in the future (section 7).

2. Spin-dependent neutron-proton elastic amplitude studies

A good understanding of the Nucleon-Nucleon (NN) interaction still remains one of the most important goals of nuclear and hadronic physics. Apart from their intrinsic importance for the study of nuclear forces, NN data are necessary ingredients in the modelling of meson production and other nuclear reactions at intermediate energies. It goes without saying therefore that any facility that could make significant contributions to this important database should do so.

The ANKE collaboration has embarked on a systematic program to measure the differential cross section, analyzing powers, and spin correlation coefficients of the $\vec{d}\vec{p} \rightarrow \{pp\}_s n$ deuteron charge-exchange breakup reaction. The aim is to deduce the energy dependence of the spin-dependent np elastic amplitudes. By selecting the two final protons with low excitation energy, typically $E_{pp} < 3$ MeV, the emerging diproton is dominantly in the 1S_0 state.

In impulse approximation the deuteron charge-exchange reaction can be considered as an $np \rightarrow pn$ scattering with a spectator proton. The spin dependence of the np charge-exchange amplitude in the cm system can be displayed in terms of five scalar amplitudes as:

$$\begin{aligned} f_{np} = & \alpha(q) + i\gamma(q)(\vec{\sigma}_1 + \vec{\sigma}_2) \cdot \vec{n} + \beta(q)(\vec{\sigma}_1 \cdot \vec{n})(\vec{\sigma}_2 \cdot \vec{n}) \\ & + \delta(q)(\vec{\sigma}_1 \cdot \vec{m})(\vec{\sigma}_2 \cdot \vec{m}) + \varepsilon(q)(\vec{\sigma}_1 \cdot \vec{l})(\vec{\sigma}_2 \cdot \vec{l}), \end{aligned}$$

where α is the spin-independent amplitude between the initial neutron and final proton, γ is a spin-orbit contribution, and β , δ , and ε are spin-spin terms. In the 1S_0 limit of the impulse approximation, the $\vec{d}\vec{p} \rightarrow \{pp\}_s n$ observables are directly related to the np spin-dependent amplitudes through:

$$\begin{aligned} \frac{d^4\sigma}{dt d^3k} &= \frac{1}{3} I \left\{ S^-(k, \frac{1}{2}q) \right\}^2, \\ I &= |\beta|^2 + |\gamma|^2 + |\varepsilon|^2 + |\delta|^2 R^2, \\ I A_y^d &= 0, \quad I A_y^p = -2\Im(\beta^* \gamma), \\ I A_{xx} &= |\beta|^2 + |\gamma|^2 + |\varepsilon|^2 - 2|\delta|^2 R^2, \\ I A_{yy} &= |\delta|^2 R^2 + |\varepsilon|^2 - 2|\beta|^2 - 2|\gamma|^2, \\ I C_{y,y} &= -2\Re(\varepsilon^* \delta) R, \quad I C_{x,x} = -2\Re(\varepsilon^* \beta), \end{aligned}$$

where $R = \left\{ S^+(k, \frac{1}{2}q) / S^-(k, \frac{1}{2}q) \right\}^2$ and S^\pm are form factors that can be evaluated using low energy NN information. Here \vec{k} is the pp relative momentum in the diproton and \vec{q} the momentum transfer between the deuteron and diproton.

Although corrections due to final p - and higher pp waves have to be taken into account in the detailed analysis, it is clear that in the low E_{pp} limit a measurement of the differential cross section, A_{xx} , and A_{yy} would allow the extraction of $|\beta(q)|^2 + |\gamma(q)|^2$, $|\delta(q)|^2$, and $|\varepsilon(q)|^2$ over a range of values of q .

For the above to be the realistic objectives, the methodology has to be checked in energy regions where the np amplitudes are reasonably well known. An extended paper [3] has recently been published with this in mind. The new ANKE results for the deuteron Cartesian tensor analyzing powers A_{xx} and A_{yy} at three beam energies are shown in figure 1 as functions of the momentum transfer. The agreement between the experimental data and the impulse approximation predictions, obtained using the reliable SAID np amplitudes as input at $T_n = 600, 800$, and 900 MeV, is very encouraging. This success provides a motivation for repeating these measurements at higher energies where the np input is far less certain.

The maximum deuteron energy available at COSY is $T_d \approx 2.3$ GeV (1.15 GeV per nucleon) and the ANKE results for A_{xx} and A_{yy} near this energy are shown in figure 2a. The neutron-proton amplitudes are here not as well known and the deviations of the data from the predicted

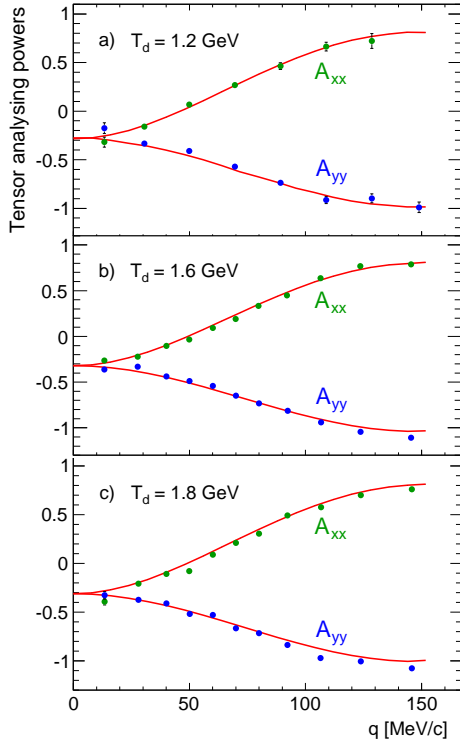


Figure 1. Preliminary results of the Cartesian tensor analyzing powers A_{xx} (green dots) and A_{yy} (blue dots) of the $dp \rightarrow \{pp\}_s n$ reaction at beam energies of $T_d = 1.2, 1.6$, and 1.8 GeV for low diproton excitation energy, $E_{pp} < 3$ MeV. The solid red curves are results of an impulse approximation calculation, where the input np amplitudes were taken from the SAID program at the appropriate energies.

curves strongly suggest that there are deficiencies in the SAID values of the np amplitudes in this region.

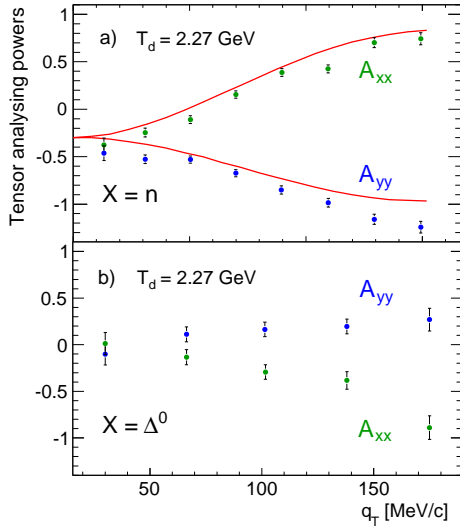


Figure 2. Preliminary results of the Cartesian tensor analyzing powers for the $dp \rightarrow \{pp\}_s X$ reaction at $T_d = 2.27$ GeV: with a neutron (a) or Δ^0 isobar (b) in the final state. In the Δ case the variable used is the transverse momentum transfer q_T . The red solid lines for the neutron are the results of an impulse approximation calculation.

The deficiencies of the SAID input np amplitudes at 1.135 GeV can be shown more explicitly by forming the following combinations of the observables:

$$\begin{aligned} (1 - A_{yy})/(1 + A_{xx} + A_{yy}) &\approx (|\beta|^2 + |\gamma|^2)/|\varepsilon|^2, \\ (1 - A_{xx})/(1 + A_{xx} + A_{yy}) &\approx |\delta|^2/|\varepsilon|^2, \\ (1 - A_{xx})/(1 - A_{yy}) &\approx |\delta|^2/(|\beta|^2 + |\gamma|^2). \end{aligned}$$

The variation of these quantities with q are presented in figure 3 for the 1.2 and 2.27 GeV data. Whereas at the lower energy all the ratios are well described by the model, at the higher it is seen that it is only $|\delta|^2/(|\beta|^2 + |\gamma|^2)$ which is well understood. It seems that the SAID program currently overestimates the values of $|\varepsilon|$ at small q . This will become clearer when absolute values of the cross sections are extracted at 2.27 GeV.

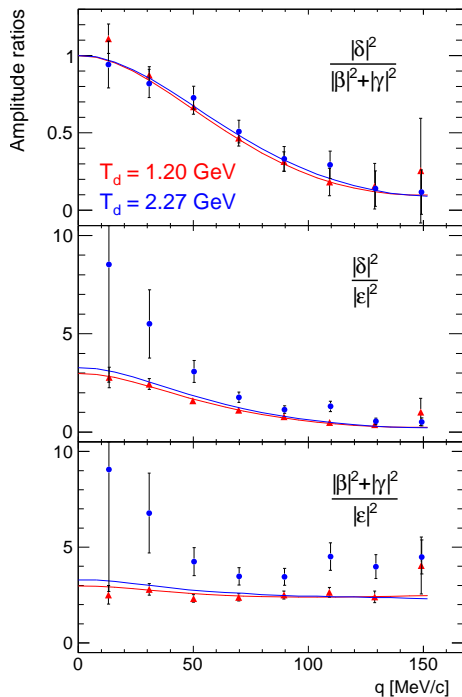


Figure 3. Preliminary results of the measured observable ratios as functions of q for two different beam energies. Solid lines are impulse approximation predictions.

The final goal is to go to even higher energies by using a polarized proton beam (available up to 3 GeV at COSY) incident on the ANKE polarized deuterium storage cell target [4], $\vec{p}\vec{d} \rightarrow \{pp\}_s n$. This could be very fruitful because so little is known about the spin dependence of the np charge exchange reaction much above 1 GeV.

In order to determine the relative phases of the spin-spin amplitudes $(\beta, \delta, \epsilon)$, it is necessary to determine the spin correlation parameters $C_{x,x}$ and $C_{y,y}$. A large amount of data was successfully obtained from the first double-polarized neutron-proton scattering experiment at ANKE. The preliminary results for the vector-vector spin correlation coefficients in the $\vec{d}\vec{p} \rightarrow \{pp\}_s n$ reaction at $T_d = 1.2$ GeV are shown in Fig 4, where they are seen to be in satisfactory agreement with impulse approximation predictions. The analysis of the higher energy data is in progress.

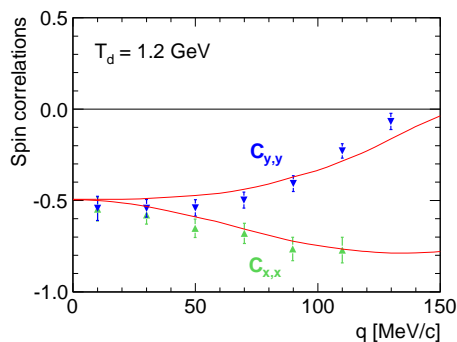


Figure 4. Preliminary results of the vector spin-correlation coefficients in $\vec{d}\vec{p} \rightarrow \{pp\}_s n$ reaction at $T_d = 1.2$ GeV. The red curves are the predictions of the impulse approximation calculation.

It was shown at Saclay that at $T_d = 2$ GeV the $\Delta(1232)$ isobar can be excited in the

$\vec{d}p \rightarrow \{pp\}_s \Delta^0$ reaction and substantial tensor analyzing powers were measured. In impulse approximation, these are also sensitive to a spin-transfer from the neutron to the proton in $np \rightarrow p\Delta^0$. The Δ^0 is seen clearly also in the ANKE charge-exchange breakup data at 1.6, 1.8, and 2.27 GeV. The values of A_{xx} and A_{yy} deduced at 2.27 GeV and shown in figure 2b are very different to those measured for the 'normal' deuteron breakup with even changes of the signs. ANKE will therefore also provide useful information on the spin structure of the Δ excitation in neutron-proton collisions.

3. Near threshold pion production in diproton reactions at ANKE

With the advent of chiral perturbation theory (χ PT), the low-energy effective field theory of QCD, accurate calculations have become possible for hadronic reactions. The approach has been also extended to describe pion production in nucleon-nucleon collisions [5, 6]. Prior to the ongoing investigations at ANKE, a data set in double-polarized near-threshold pion production has been produced at IUCF(see e.g., [7, 8]). This process is of special importance because of several reasons:

- being the first inelastic channel of the NN interaction, it contains information about the NN inelasticity that is needed to extend NN models above the pion production threshold;
- it provides nontrivial tests of χ PT in the regime with large momentum transfer [9];
- it allows one to quantify the pattern of charge symmetry breaking by studying the forward-backward asymmetry of the differential cross section in $pn \rightarrow d\pi^0$ [10];
- the pion production mechanism in $NN \rightarrow NN\pi$ near threshold is closely connected to the physics behind the other low-energy hadronic reactions as demanded by chiral symmetry.

Let us focus on the last issue in more detail. The general idea of chiral effective field theory is based on a clean separation of hadronic scales around the chiral limit. According to the scheme, all long-ranged operators related to the small (dynamical) scale, such as one-pion exchange, pion loops etc., are explicitly included in the evaluation of the transition amplitude whereas all short-ranged mechanisms are parametrized by local contact operators. Specifically, the short range physics of p -wave pion production in $NN \rightarrow NN\pi$ (when the pion is produced in a p -wave with respect to the beam) is absorbed in the local $4N\pi$ contact term, the strength of which – the low energy constant (LEC) d – is unknown and may be extracted from the experimental data as will be discussed below. This LEC is very important in the few body sector since it also contributes to the three-nucleon force (see, e.g., [11]), to electroweak processes such as $pp \rightarrow de^+\nu$, triton β decay and muon absorption on deuterium $\mu^-d \rightarrow nn\nu_\mu$, as well as to reactions involving photons $\pi d \rightarrow \gamma NN$ and $\gamma d \rightarrow nn\pi^+$. Thus, it is of high importance to identify what is needed to allow for a reliable extraction of this LEC from $NN \rightarrow NN\pi$. Since the LEC accompanies the p -wave pion while the nucleons are still in s -waves, the effort should be focused on measuring the observables that would allow one to extract the corresponding p -wave amplitudes from the data.

Of especial interest are thus the processes $pp \rightarrow \{pp\}_s \pi^0$ and $pn \rightarrow \{pp\}_s \pi^-$, with the formation of a 1S_0 proton pair (diproton) in the final state. The measurements of $d\sigma/d\Omega$, A_y and the spin-correlation coefficients $A_{x,x}$ and $A_{x,z}$ for both reactions will permit an amplitude analysis that is necessary to single out the relevant p -wave amplitudes from the rest.

The ANKE spectrometer is particularly well suited for the study of reactions with a final diproton. The excellent resolution in the excitation energy of the proton pair, $\sigma_{E_{pp}} < 0.5$ MeV, allows one to select the range of low $E_{pp} < 3$ MeV. This ensures the dominance of the 1S_0 state of the final proton pair. Single and double polarization experiments can be conducted through the use of the polarized COSY beams and the ANKE polarized internal storage cell target [4].

As a first step in the program, measurements with a polarized proton beam incident on unpolarized hydrogen and deuterium cluster targets were performed at ANKE in 2009 at a beam energy of $T_p = 353$ MeV.

Figure 5 shows the results obtained for the $\vec{p}p \rightarrow \{pp\}_s \pi^0$ reaction. Since A_y must be antisymmetric about 90° , the acceptance is effectively complete. If one considers only pion waves with $l \leq 2$, a non-zero value of the analyzing power in this process must arise from the interference between the s and d waves. The strong signal observed here shows immediately the importance of this interference.

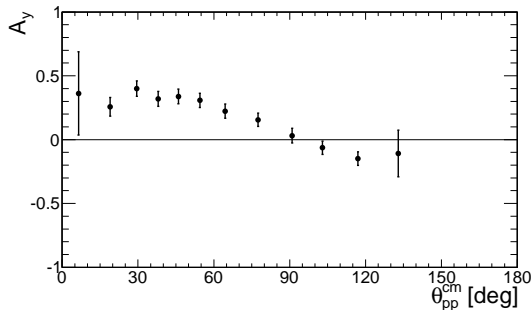


Figure 5. Preliminary results for the analyzing power A_y of the $pp \rightarrow \{pp\}_s \pi^0$ reaction at $T_p = 353$ MeV.

The results for the $\vec{p}n \rightarrow \{pp\}_s \pi^-$ reaction are presented in Figs. 6 and 7. The ANKE data are shown together with the results from TRIUMF [12] and compared to the prediction of the IKP theory group [13]. The value of the LEC $d = 3$ is favoured, though it must be stressed that the pion d -waves have not yet been included in the calculations.

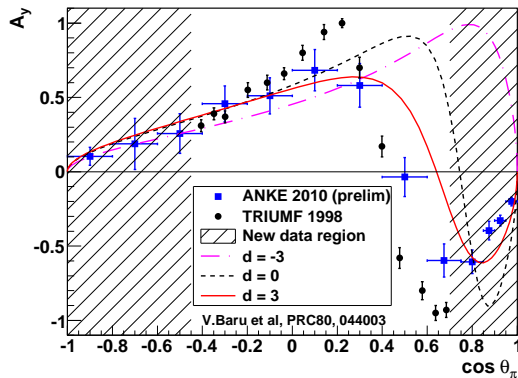


Figure 6. Preliminary results for the analyzing power A_y in the $\vec{p}n \rightarrow \{pp\}_s \pi^-$ reaction at $T_n=353$ MeV (blue squares). Also shown are the results of χ PT calculation for $d = 3$ (red solid line), $d = 0$ (black dashed line), and $d = -3$ (magenta dot-dashed line). The data from TRIUMF [12] are shown as black circles.

The results were obtained with a 40 MeV wide range of effective beam energy in the free pn -scattering, *i.e.*, $T_{\text{free}} = 353 \pm 20$ MeV. The $E_{pp} < 3$ MeV cut was imposed on the data but, to facilitate the comparison with previous results, the cross section has been recalculated for the $E_{pp} < 1.5$ MeV cut used at TRIUMF. This was done using the Migdal-Watson approximation for the final state interaction in the 1S_0 proton pair. The main advantage of the ANKE measurement is the extended angular range compared to the pre-existing data.

The transitions involving the $4N\pi$ contact interaction correspond to the p -wave pion production in the $np \rightarrow \{pp\}_s \pi^-$ reaction. The initial nucleons in this case appear in the partial waves that are coupled: $^3S_1 \rightarrow ^1S_0 p$ and $^3D_1 \rightarrow ^1S_0 p$. Due to the coupled channel effect the contact term contributes to both partial waves which may provide a more rich dependence of the observables on the LEC d . Note, that a linear combination of these p -wave amplitudes may be fixed by the only measurement of $\xi = (1 - A_{xx}) \cdot d\sigma/d\Omega$ for $np \rightarrow \{pp\}_s \pi^-$ under the

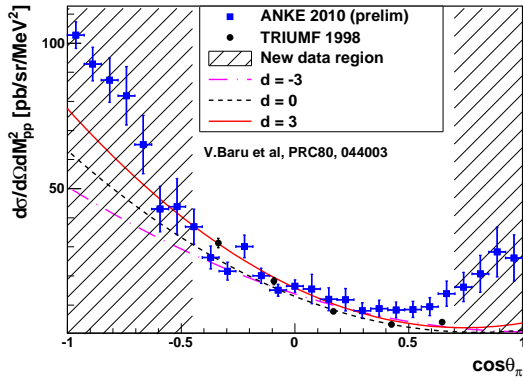


Figure 7. ANKE preliminary results for the cross section of the $\vec{p}\vec{n} \rightarrow \{pp\}_s \pi^-$ reaction at $T_n=353$ MeV in the $E_{pp} < 1.5$ MeV range. The data from TRIUMF [12] are shown as black circles. The conventions are the same as those used in the caption to figure 6.

assumption that the interference of pion p - and d -waves is small. This linear combination could be compared directly to the χ PT calculation. Thus, the double polarization experiment for the measurement of A_{xx} and A_{yy} , scheduled for 2011, will greatly improve our knowledge of the LEC d .

The χ PT predictions for A_{xx} and ξ are shown in figures 8 and 9 for several values of the LEC d . If one considers only s, p and d partial waves, then $\xi \propto \sin^2 \vartheta_\pi$. Thus, only the scale parameter proportional to the linear combination of the p -wave amplitudes, has to be extracted from the measurement of the angular dependence. The experiment will provide the most systematics-free way to fix the value of the LEC d [14].

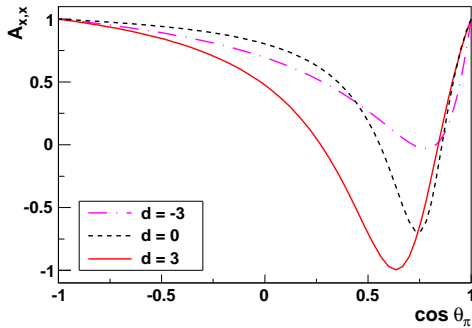


Figure 8. Spin correlation coefficient A_{xx} of the $\vec{p}\vec{n} \rightarrow \{pp\}_s \pi^-$ reaction at $T_p = 353$ MeV. The curves present calculations for different values of the LEC d .

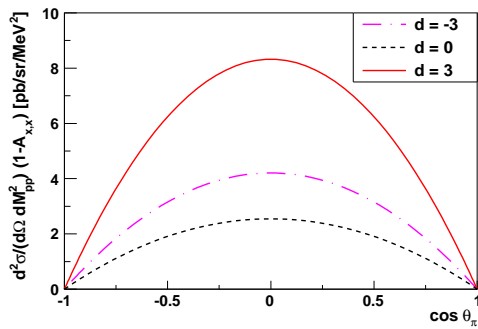


Figure 9. Prediction for $(1 - A_{xx}) \cdot d\sigma/(d\Omega dM_{pp}^2)$ of the $\vec{p}\vec{n} \rightarrow \{pp\}_s \pi^-$ reaction at $T_p = 353$ MeV. The curves present calculations for different values of the LEC d .

At the same time, the magnitudes of the p -wave amplitudes individually and their relative phases should be deduced from a combined analysis of these results with our cross section

and analyzing power data for $pp \rightarrow \{pp\}_s \pi^0$ and $np \rightarrow \{pp\}_s \pi^-$, which have already been taken [14, 15]. Two determinations of the LEC d will therefore be possible.

4. The quest for polarized antiprotons

The physics potential for QCD experiments with high-energy polarized antiprotons is enormous but until now many experiments have been impossible because of the lack of a high-luminosity beam. This situation could change with the advent of a stored beam of polarized antiprotons and the realization of a double-polarized, high-luminosity antiproton-proton collider. The collaboration for Polarized Antiproton Experiments (PAX) has formulated the physics program that would be possible with such a facility [16]. Following studies with proton beams, PAX is now in the process of preparing the experimental equipment for the first measurements with polarized antiproton beams at CERN's Antiproton Decelerator (AD) [17], which is currently the world's only antiproton storage facility.

The experimental approach adopted by the PAX collaboration to produce a beam of polarized antiprotons is based on spin filtering, a technique that exploits the spin dependence of the strong interaction. The total cross-section depends on the relative orientation of the spins of the colliding particles, i.e., $\sigma(\uparrow\uparrow) \neq \sigma(\uparrow\downarrow)$. The method was shown to work in the 1990s with protons in a 23 MeV beam stored in the Heidelberg Test Storage Ring, which passed through a polarized hydrogen gas target [18, 19].

The original idea of PAX to use polarized electrons to produce a polarized beam of antiprotons [20] has meanwhile been discarded. This suggestion triggered further theoretical work on the subject, which led to a suggestion by a group from Mainz [21, 22] to use co-moving electrons (or positrons) at slightly different velocities than the orbiting protons (or antiprotons) as a means to polarize the stored beam. The cross section for $e\bar{p}$ spin-flip predicted by the Mainz group in a *numerical* calculation is as large as about $2 \cdot 10^{13}$ barn, if the relative velocities between proton (antiproton) and electron (positron) are adjusted to $v/c \approx 0.002$. At the same time, *analytical* predictions for the same quantity by a group from Novosibirsk [23] range well below a mbarn. Thus prior to the experiment, the two theoretical estimates differed by about 16 orders of magnitude. It should be also emphasized, that the practical use of the $\vec{e}p$ or $e^+\bar{p}$ processes to polarize a stored beam of antiprotons is excluded if the spin-flip cross sections are smaller than about 10^7 barn. Our recent COSY experiment, carried out to resolve these conflicting calculations, showed that the measured cross sections are too small for making spin flip a viable tool in polarizing a stored beam [24].

In contrast to the proton-proton system, the experimental basis for predicting the build-up of polarization in a stored antiproton beam by spin filtering is practically nonexistent. It is therefore a high priority to perform a series of dedicated spin-filtering experiments using stored antiprotons together with a polarized target, which the PAX collaboration is aiming to undertake at the AD ring at CERN [17].

The AD is a unique facility at which stored antiprotons in the appropriate energy range are available with characteristics that meet the requirements for the first antiproton polarization build-up studies. In 2009, the European Research Council awarded an Advanced Grant to the Jülich group to pursue these studies at the AD. Once an experimental proton-antiproton data base is available, work can begin to design a dedicated polarized antiproton ring.

The Jülich theory group has made predictions for the spin-dependent cross-sections for the expected build-up of polarization in an antiproton beam. In addition, a group from the Budker Institute for Nuclear Physics, Novosibirsk, has recently generated estimates on the basis of a Nijmegen proton-antiproton potential. These indicate that antiproton beam polarizations of 0.15–0.20 (spin filtering with transverse target orientation) and 0.35–0.40 (longitudinal) might be expected [25].

For efficient commissioning of the equipment required for the measurements at the AD, the

PAX collaboration is preparing polarization build-up studies using stored protons at the Cooler Synchrotron (COSY) at Jülich. Because the spin-dependence of the proton-proton interaction is well known at energies where electron cooling is available at COSY (up to 130 MeV), details of the polarization build-up process can also be studied.

The polarized internal target, consisting of an atomic beam source and a Breit-Rabi type target polarimeter, has been successfully operated with an openable storage cell [26]. Such an openable cell constitutes an important development for the investigations with stored antiprotons at the AD [27]. The storage-cell technique works beautifully with the target polarization unaffected by the opening and closing of the storage cell. This constitutes a major milestone because for the first time, both high polarization and density have been achieved with an openable storage cell. While this is crucial for investigations of the spin-dependence of the proton-antiproton interaction at the AD, many other experiments employing internal storage-cell targets can also benefit from this development. In addition, an efficient experimental method has recently been developed to determine the machine acceptance and the acceptance angles at the location of the target [28].

The quadrupole magnets for the low- β insertion of PAX at COSY were installed during the summer shutdown in 2009. During a beam time in early 2010, the β -functions at the location of the PAX quadrupoles were measured for the non-zero dispersion setting, by varying the magnet currents. The calculated and measured values at the location of the quadrupoles match nicely. The model calculations suggest that β -functions of β_x around 0.38 m and β_y around 0.36 m were reached. The measured beam lifetimes at COSY did not depend on whether the low- β section was powered on or not.

In the second half of 2010, the PAX collaboration has performed machine studies at COSY to obtain a better insight into the actual limitations of the beam lifetime. First spin-filtering measurements at COSY with transversely polarized protons could be carried out in the fall of 2011. Making use of the COSY spin flipper, capable to reverse the polarization after filtering without loss, systematic errors can be minimized [29].

The installation at the AD will consist of a set of additional quadrupole magnets, the internal target and a detection system surrounding the openable storage cell. The PAX proposal for the AD [17] is currently awaiting approval. It would be advantageous if the six additional quadrupole magnets could be installed without modification of the current AD lattice (i.e., while the central AD quadrupole magnet in that section remains in place). Subsequent machine studies to commission the low- β section would ensure that the proposed experimental set-up for the spin-filtering studies is compatible with the other physics pursued at the AD. Once satisfactory operation of the equipment has been achieved, the first measurements of the polarization build-up in proton-antiproton scattering will be possible. A Siberian snake needs to be installed at a later stage, and the AD electron cooler should be upgraded to provide electron-cooled antiproton beams with an energy of up to 500 MeV.

5. Physics with longitudinally polarized protons

The physics case for longitudinally polarized protons is closely linked to the aspects outlined in sections 2, 3, and 4. By means of a Siberian snake, the spin closed orbit at the location of the polarized target can be aligned along the direction of motion of the stored particles.

The required field strengths that can be obtained with a solenoid together for the various experimental investigations are listed in table 1. The concept is based on a fast ramping device that provides a field integral of 4.7 Tm, which can be either installed opposite the ANKE target location at the PAX interaction point. Installation of the snake at the ANKE target location allows one to provide longitudinal beam polarization in the straight section of COSY opposite the snake.

Table 1. Required field integrals for the Siberian snake in the proposed experiments.

Purpose/Measurement	$\int B_z \cdot dl$ (Tm)
Determination of A_{xz} in $\vec{p}\vec{n} \rightarrow \{pp\}_s\pi^-$ at ANKE requires at $T_p = 353$ MeV	3.329
PAX at COSY requires at $T_p = 140$ MeV	1.994
PAX at AD requires at $T_p = 500$ MeV	4.090
$\vec{p}\vec{d}$ breakup studies in the range of $T_p = 30 - 50$ MeV require up to	1.165
$ \vec{p} = p_z$ at the maximum possible proton beam energy of $T_p = 2880$ MeV in COSY requires	13.887

5.1. Pion production and chiral effective field theories

Besides what has been discussed in section 3, on the practical side, the $pp \rightarrow \{pp\}_s\pi^0$ or $np \rightarrow \{pp\}_s\pi^-$ reactions have the big advantage for COSY that both the pion and diproton have spin-zero, which means that the only spin degrees of freedom are connected with the initial state. There are therefore no non-trivial spin-transfer observables, so that re-scattering experiments are not required.

In general, for both π^0 and π^- production there are four types of experiments that are possible. These are the unpolarized differential cross section $(d\sigma/d\Omega)_0$, the beam or target analyzing power A_y , the in-plane spin-correlation A_{xx} , and the mixed correlation parameter A_{xz} . Knowing these one can determine the magnitudes and relative phase of the two invariant amplitudes as functions of the pion production angle for the pp and pn experiments. Using a Siberian snake, the spin correlation parameter A_{xz} can be determined using a longitudinally polarized beam (p_z) and the transversely polarized deuterium storage cell target at ANKE (q_y) [4].

5.2. Polarized antiprotons

Exploiting the spin-filtering techniques to provide a beam of polarized antiprotons requires measurements of the total spin-dependent cross sections σ_1 and σ_2 at the AD of CERN. While σ_1 can be readily determined at the AD using a transversely polarized target, the determination of σ_2 requires in addition the installation of a Siberian snake in the AD straight section opposite the target. Commissioning of such a snake at COSY is therefore a necessary step for the antiproton spin filtering studies with longitudinal polarization at the AD.

5.3. Deuteron breakup

The physics objective is to test the predictive power of the chiral perturbation theory in the three nucleon continuum. To that end, a proposal has been submitted recently to the COSY PAC [30]. In particular the effects of current schemes for three nucleon forces can be investigated that recently were implemented at third order in the calculations. The experimental data and the theoretical predictions for reactions with three nucleons at low and intermediate energies are today at variance. The data will provide an independent determination of certain low energy constants vital to chiral effective field theory. New experimental data on spin observables at these energies will no doubt offer constraints to further our understanding of the hadronic interaction in the few-nucleon system.

We propose to measure the spin dependence of the pd breakup at 30 and 49 MeV proton beam energy, in an energy range where previous measurements are rather limited or non-existent. The experiment will be carried out at the planned PAX interaction point in the COSY ring. In the first phase of the experiment, we will focus on the analyzing powers and the spin correlation parameters at 30 MeV proton beam energy. In a second phase, we intend to

measure the observables at 49 MeV. The last stage will be coordinated with the development of a Siberian snake for longitudinal beam polarization. The proposed experimental setup allows one to utilize all orientations of target polarization (q_x , q_y , and q_z). Together with a Siberian snake installed at the ANKE location in COSY, the stable orientation of the beam polarization p_z along the longitudinal axis becomes possible, and that will facilitate measuring the so-called axial observables, which are forbidden by parity in elastic scattering and possess a certain sensitivity to three-nucleon forces (3NF). Two previous experiments that were initiated to test this argument were done at 9 and 135 MeV. At the lower energy, the nucleon longitudinal analyzing power, A_z , turned out to be consistent with zero [31, 32]. At the higher energy the axial observables measured were sizeable but the message concerning the effect on including current 3NF was mixed [33]. A further test of the theoretical argument would be a comparison of predictions by the chiral perturbation theory to experimental data taken at an intermediate energy.

5.4. Machine physics aspects

Machine physics studies with a Siberian snake would address the acceleration of polarized beams in medium and high-energy circular accelerator. Numerous spin resonances have to be overcome without losing the beam polarization. Depolarization mechanisms caused by snake resonances (higher-order spin resonances) could be studied in detail. These studies could be performed during ramping up the snake field or by changing the working point of COSY with fixed snake field.

A full snake at highest COSY energies requires a Siberian snake with $\int B_z \cdot dl = 13.887$ Tm, which could be employed for the measurement of spin correlation parameters in $\vec{p}\vec{n}$ elastic scattering up to a proton beam energy of $T_p = 2880$ MeV using the ANKE polarized deuterium gas target and the system of silicon tracking telescopes to identify the spectator protons [2].

6. Search for electric dipole moments of protons, deuterons, and ^3He at COSY

Although extremely successful in many aspects, the Standard Model (SM) of particle physics is not capable to explain the apparent matter-antimatter asymmetry of our universe, and thus fails to explain the basis for our existence, for it has way too little CP -violation. There are two strategies to hunt for physics beyond the Standard Model: one option is to explore higher energies, as presently done, *e.g.*, at the LHC. The other alternative is to employ novel methods which offer very high precision and sensitivity. Permanent electric dipole moments violate both time reversal and parity invariance, and are therefore CP -violating. Searches for permanent electric dipole moments of protons, deuterons and heavier nuclei provide highest sensitivity for the exploration of physics beyond the SM, thus possess an enormous physics potential. The reach in energy scale for finding new physics beyond the Standard Model is estimated to range up to 1000 TeV, way beyond that of the LHC [34]. In turn, these searches require a long-term engagement (> 10 yr).

It is essential to perform electric dipole moment (EDM) measurements on different targets with similar sensitivity in order to unfold the underlying physics and to explain the baryogenesis. While neutron EDM experiments are pursued at many different locations worldwide (essentially, wherever neutrons are available), no such measurements are conducted yet for proton and other light nuclei. However, since a measurement on the proton has the potential to reach an order of magnitude higher precision than corresponding neutron EDM experiments, the proton EDM is a must-do. It should be noted that EDM measurements of proton, deuteron, and ^3He could be performed in one-and-the same unique machine.

EDM searches of charged fundamental particles have hitherto been impossible, because of the absence of the required new class of storage rings. In addition, these searches apply to charged hadrons which constitutes a novelty in its own. The method is based on the spin precession of a

particle due to its magnetic and electric dipole moments in external electromagnetic fields, while circulating in a storage ring. Freezing the horizontal spin motion, *i.e.*, forcing the particles' spin to always point along the direction of motion, cancels the $(g - 2)$ precession. During a typical spin coherence time (SCT) of about 1000 s, the build-up of a vertical polarization component in the beam indicates the signal for a finite EDM of the orbiting particles [35].

COSY has a history of highly successful operation of cooled polarized beams and targets – in fact, COSY is a unique facility for spin physics with hadronic probes on a world-wide scale. Many foreign groups have exploited its capabilities, *e.g.*, the Spin-at-COSY (see *e.g.*, [36]) and the dEDM collaboration [37]. Over the years, the accelerator group and the two experimental institutes have acquired in-depth experience in polarized beam/target manipulation and polarimetry. The IKP-COSY environment, including the theoretical group is thus ideally suited for a major (medium-sized) project involving spin and storage rings as it will be required for the search for permanent EDMs of charged fundamental particles (*e.g.*, protons, deuterons, and other light nuclei).

The question of whether particles possess permanent electric dipole moments has a long-standing history, starting from the proposal by Ramsey and Purcell to search for a neutron EDM as a signature for parity (P) and time-reversal (T or CP) violation, which, over the last 50 years or so, resulted in ever decreasing upper limits. We are planning to search for EDMs of the proton and other charged particles in a storage ring with a statistical sensitivity of $\approx 2.5 \times 10^{-29}$ e·cm per year, pushing the limits even further and with the potential of an actual particle-EDM discovery.

The proposed new method employs radial electric fields (and magnetic fields) to steer the particle beam in the ring, magnetic or electric quadrupole magnets to form a strong focusing lattice (*e.g.*, FODO), and internal polarimeters to probe the particle spin state as a function of storage time. An RF-cavity and sextupole magnets will be used to prolong the SCT of the beam. For protons, it requires building a storage ring with a highly uniform radial E-field with strength of ≈ 17 MV/m between stainless steel plates about 2 cm apart. The bending radius will be ≈ 25 m and including the straight sections it will have a physical radius of ≈ 30 m. The so-called magic momentum of $0.7 \text{ GeV}/c$ (232 MeV), is the one, where the $(g - 2)$ precession frequency is zero (see table 2).

The spins of vertically polarized protons injected into the EDM ring can be rotated into the horizontal plane by turning on a solenoidal magnetic field in a straight section of the EDM ring and turning it off at the appropriate time. The EDM signature shows up through the development of a transverse component of the particle spin.

Table 2. Parameters for the transverse electric and magnetic fields required to freeze the spin in an EDM storage ring of radius $r = 30$ m.

Particle	p (GeV/ c)	E (MV/m)	B (T)
Proton	0.701	16.8	0
Deuteron	1.000	-4.03	0.16
^3He	1.285	17.0	-0.051

In table 3, we give current and anticipated EDM bounds and sensitivities for nucleons, atoms, and the deuteron. The last column provides a rough measure of their probing power relative to the neutron (d_n). At this level, it will be an order of magnitude more sensitive than the currently planned neutron EDM experiments at SNS (Oak Ridge), ILL (Grenoble-France), and PSI (Villigen, Switzerland) [38].

Table 3. Current EDM limits in units of [e·cm], and long-term goals for the neutron, ^{199}Hg , ^{129}Xe , proton, and deuteron are given here. Neutron equivalent values indicate the EDM value for the neutron to provide the same physics reach as the indicated system.

Particle	Current Limit	Goal	d_n equiv.	reference
Neutron	$< 1.6 \times 10^{-26}$	$\approx 10^{-28}$	10^{-28}	[39]
^{199}Hg	$< 3.1 \times 10^{-29}$	10^{-29}	10^{-26}	[40]
^{129}Xe	$< 6.0 \times 10^{-27}$	$\approx 10^{-30} - 10^{-33}$	$\approx 10^{-26} - 10^{-29}$	[41]
Proton	$< 7.9 \times 10^{-25}$	$\approx 10^{-29}$	10^{-29}	[40]
Deuteron		$\approx 10^{-29}$	$3 \times 10^{-29} - 5 \times 10^{-31}$	

6.1. A pilot experiment at COSY

All EDM searches for nuclear EDMs that have been carried out up to now, have used nuclei that are part of an electrically neutral atomic or molecular system. The current best limit for a proton EDM $|d_p| < 7.9 \times 10^{-25} \text{ e cm}$ is obtained using ^{199}Hg , with a relative uncertainty of $\approx 30\%$ [40].

Direct measurements of nuclear EDMs of proton or deuteron aiming at sensitivities of 10^{-29} e cm (see table 3) require a special new type of storage ring which incorporates electrostatic deflectors, which constitutes a major investment. A first *direct* measurement of an upper limit for the proton EDM using a normal magnetic storage ring like COSY, however, seems feasible, and the concept of such a measurement is outlined below.

Making use of a Siberian snake in COSY yields a stable longitudinal spin close orbit in a target section opposite the snake (see figure 10, top panel). Using two RF E-field systems in front and behind the snake (middle and bottom panels) allow one to provide a certain degree of depolarization in the beam due to the torque $\vec{d} \times \vec{E}$, where d denotes the proton electric dipole moment. When the RF E-field is reversed in polarity turn by turn, this torque produces a small mismatch between the two stable spin axes, hence the beam depolarizes. While the angle is exceedingly small ($\alpha \approx 10^{-7} \text{ rad}$, see figure 10, bottom panel), the number of turns n in the machine can be made very large ($n \approx 5 \cdot 10^{10}$). The sensitivity of this approach is rather limited to values of $d \approx 10^{-17} - 10^{-18} \text{ e cm}$, but a measurement would nevertheless constitute a first *direct* measurement of an upper limit for the proton EDM.

7. Time reversal invariance test at COSY

Time-reversal symmetry is one of the most fundamental symmetries in nature. CP-violation phenomena, which can be regarded as equivalent of T-violation on the basis of the CPT theorem, have been observed in K^0 and B systems. In the standard model (SM) CP violation appears as a complex phase parameter in the Cabibo-Kobayashi-Maskawa (CKM) matrix. Currently all observed CP phenomena appear to be consistent with the SM. However, as mentioned before, the standard model CP violation is by orders of magnitude too small to account for the apparent asymmetry between matter and anti-matter in the universe.

Several measurements using different techniques for time-reversal invariance are reported in the literature, most prominently the search for permanent EDMs (see section 6). The current upper limit on time-reversal parity conserving non-invariance of 1.2×10^{-5} was obtained by measurements of the total cross sections using a polarized neutron beam and Holmium target [42]. However, the interpretation of measurements at a fundamental level is difficult due to the use of nuclear targets.

The theoretical interpretation of measurements with a polarized proton beam and deuterium target would be much cleaner. A status report about an earlier preparatory experiment carried out at COSY is given in [43]. It was proposed to use COSY as an accelerator, ideal zero degree

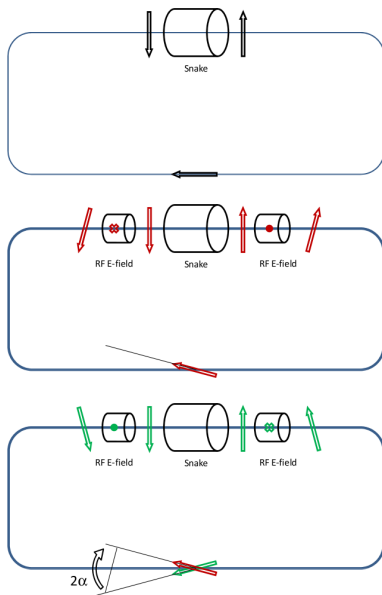


Figure 10. Concept of a proton EDM measurement using a Siberian snake in COSY. Top panel: Using the snake, the spin closed orbit is aligned along the direction of motion of the proton beam in the straight section opposite the snake. Middle panel: For odd turns in the machine, an electric RF E-field perpendicular to the ring plane in front and behind the snake rotates the stable spin axis by a small angle α away from the longitudinal direction. Bottom panel: For even turns in the machine where the RF E-field is reversed, the spin closed orbit is then rotated by an angle 2α , leading after n turns to a depolarization of the beam, $P(n) = P_0 \cdot \cos(2\alpha)^n$.

spectrometer, and detector. The test beam time (in October 2006) has shown that the accuracy of the standard beam-current transformer (BCT) is not sufficient to reach necessary precision of 10^{-6} in a time-reversal non-invariance test.

Nowadays a much higher quality of the polarized beam can be obtained using the new PAX facility. Recently, a new BCT, using low temperature superconducting quantum interference devices, has been developed and tested for GSI Darmstadt, which allows to improve BCT resolution by an order of magnitude [44]. Thus, the effects of the breaking of time-reversal invariance can be searched for simultaneously in measurements of total cross sections using the beam-current transformer, and studies of differential observables using the PAX detection system, as outlined in sections 4 and 5.3. It should be noted, that the main source of background below the pion threshold for these studies comes from the pd breakup. For a time-reversal invariance test at COSY, the use of longitudinal polarization (see section 5) may be helpful.

8. Summary

COSY is the only facility worldwide which provides polarized beams of protons and deuterons in the intermediate energy range for internal and external experiments. Together with existing and new detection systems, it constitutes an indispensable facility for studies of hadron physics with hadronic probes. Its importance is further strengthened by the need to perform preparatory tests for the upcoming FAIR project at GSI. The search for EDMs of protons, deuterons, and other light nuclei presents both an exceptional opportunity for world-class physics and a tremendous challenge for experiment and theory.

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