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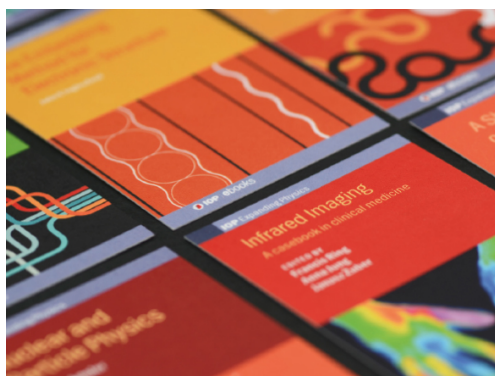
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Recent results from the deuteron charge–exchange on hydrogen programme at ANKE/COSY

David Mchedlishvili^{1,2} and David Chiladze^{1,2} for the ANKE collaboration

¹ Institut für Kernphysik, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

² High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia

E-mail: d.mchedlishvili@fz-juelich.de, d.chiladze@fz-juelich.de

Abstract. A good understanding of the Nucleon–Nucleon interaction (NN) 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. Experiments at COSY, using a polarised deuteron beam and/or target, can lead to significant improvements in the np database by studying the quasi-free reaction on the neutron in the deuteron - $dp \rightarrow \{pp\}n$. At low excitation energies of the final pp system, typically $E_{pp} < 3$ MeV, the spin observables are directly related to the spin-dependent parts of the neutron–proton charge–exchange amplitudes. Measurement of the deuteron–proton spin–correlations allows one also to fix the relative phases of these amplitudes in addition to their overall magnitudes. Recent results of this study at ANKE/COSY are presented, including preliminary data on $dp \rightarrow \{pp\}\Delta^0$.

1. Introduction

An understanding of the NN interaction is fundamental to the whole of nuclear and hadronic physics. One of the principal tools used in this study is phase-shift analyses (PSA), which requires precise experimental data as input [1]. The database on proton–proton elastic scattering is enormous and the wealth of spin-dependent quantities measured has allowed the extraction of NN phase shifts in the isospin $I = 1$ channel up to a beam energy of at least 2 GeV [1]. The situation is far less advanced for the isoscalar channel, where the much poorer neutron–proton data only permit the $I = 0$ phase shifts to be evaluated up to at most 1.3 GeV, but with significant ambiguities above about 800 MeV [1]. More good data on neutron–proton scattering are clearly needed.

It was emphasised many years ago that quasi-free (p, n) or (n, p) reactions on the deuteron can act, in suitable kinematic regions, as a spin filter that selects the spin-dependent contribution to the np elastic cross section [2]. The comparison of this reaction with free backward elastic scattering on a nucleon target might allow a direct reconstruction of the np backward amplitudes [3].

The ANKE collaboration has embarked on a systematic programme to measure the differential cross section, analysing 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 [4]:

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

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:

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

where $R = \{S^+(k, \frac{1}{2}q)/S^-(k, \frac{1}{2}q)\}^2$ 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 . In order to fix the relative phases of the spin-spin amplitudes ($\beta, \delta, \varepsilon$) it is necessary to determine also the spin-correlation parameters $C_{x,x}$ and $C_{y,y}$.

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 [5] has recently been published with this in mind.

2. The experimental setup

The experiments were carried out at the COoler SYnchrotron (COSY) of the Forschungszentrum Jülich. This machine is capable of accelerating and storing polarised and unpolarised proton and deuteron beams with momenta up to 3.7 GeV/c. The forward part (FD) of the ANKE magnetic spectrometer [6], shown in Fig. 1, is used for the deuteron charge-exchange reaction studies. The FD consists of multiwire chambers for track reconstruction and three layers of a scintillation hodoscope that permit time-of-flight and energy-loss determinations [7]. A polarised deuteron beam together with the hydrogen cluster target were used during the experiment. Particles from the different reactions were tracked in the FD detector. Figure 2 shows the experimental acceptance of ANKE for single particles at $T_d = 1.17$ GeV in terms of the laboratory production angle in the horizontal plane and the magnetic rigidity. The kinematical curves for various nuclear reactions are also illustrated. Among the observed reactions, there are two that are of main interest, *viz.* deuteron charge-exchange $dp \rightarrow \{pp\}n$ and the quasi-free $dp \rightarrow p_{sp}d\pi^0$ reaction with a fast spectator proton, p_{sp} . The latter is used to measure the polarisation of the deuteron beam and also to determine the luminosity. In both cases, two particles are detected in the FD detector. In the subsequent data analysis the $p_{sp}p$ pairs are distinguished from $p_{sp}d$ by comparing the measured and calculated time-of-flight differences between these particles. Building missing-mass distributions for these reactions allows one to identify the unobserved third particle.

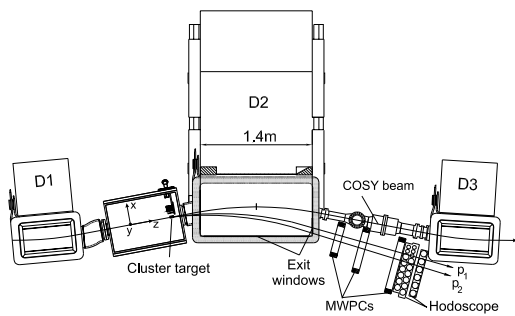


Figure 1. The ANKE experimental set-up showing the positions of the three dipole magnets D1, D2, and D3. The Forward Detector (FD) consists of three MWPCs and a hodoscope composed of three layers of scintillation counters.

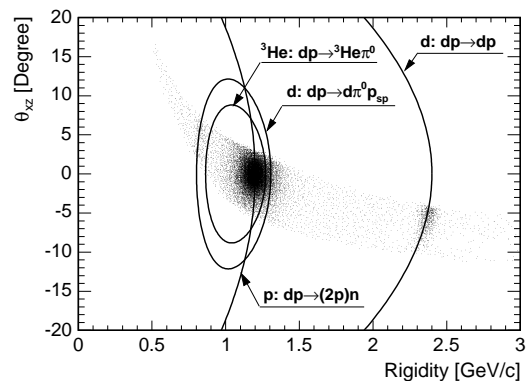


Figure 2. The ANKE experimental acceptance for four nuclear reactions of interest at a deuteron momentum of $P_d=2400$ MeV/c.

3. The proof-of-principle experiment at $T_d = 1.17$ GeV

The first experiment in the deuteron charge-exchange programme at ANKE was carried out at a deuteron beam energy of $T_d = 1170$ MeV (585 MeV per nucleon). The main goal of this run was to check the methodology to be used in np charge-exchange studies. The results shown in Fig. 3 [8] are compared with the predictions of the impulse approximation program [9] using as input the neutron-proton amplitudes taken from the SAID analysis [10].

The precision of these data is such that one can derive ratios of the magnitudes of amplitudes that are comparable in statistical accuracy with those that are in the current database [10]. Thus, at $T_n = 585$ MeV per nucleon, we find

$$\begin{aligned} |\beta(0)|/|\varepsilon(0)|^{\text{ANKE}} &= 1.86 \pm 0.15, \\ |\beta(0)|/|\varepsilon(0)|^{\text{SAID}} &= 1.79 \pm 0.27. \end{aligned}$$

It seems therefore that, in cases where the amplitudes are well known, one can get reliable results.

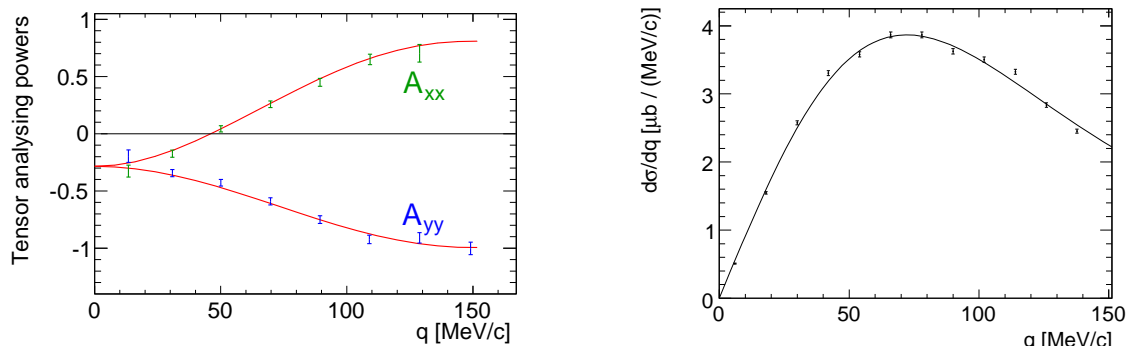


Figure 3. Tensor analysing powers (left) and unpolarised differential cross section (right) of the $dp \rightarrow \{pp\}n$ reaction for excitation energies $E_{pp} < 3$ MeV [5, 8] compared with impulse approximation predictions [9].

In order to extract full information about the neutron–proton amplitudes, and not merely their ratios, one has to measure absolute cross sections as well as analysing powers. By evaluating the luminosity from the quasi-free $np \rightarrow d\pi^0$ reaction, the shadowing effect in the deuteron (where one nucleon hides behind the other) largely cancels out between the $dp \rightarrow \{pp\}n$ and $dp \rightarrow p_{\text{sp}}d\pi^0$ reactions. Combining these data leads to the charge–exchange cross sections shown in Fig. 3. The agreement with the calculation of the unpolarised cross section in impulse approximation [9] is very encouraging.

4. $dp \rightarrow \{pp\}n$ reaction studies at higher energies

4.1. Recent experiments with polarised deuteron beams at ANKE

Two experiments have been carried out at ANKE in recent years using the polarised deuteron beam at $T_d = 1.2, 1.6, 1.8$ (in 2005) and $1.2, 2.27$ GeV (in 2006).

The first step when studying the charge–exchange reaction at higher energies is to establish the polarimetry standards using the scattering asymmetries in a suitable nuclear reaction with known analysing powers. Polarisation calibration standards described in the previous study [11] are few and exist only at discrete energies. It is therefore of great practical importance to be able extend such applications to arbitrary energies where standards are not yet available. If one avoids depolarising resonances in the machine, the beam polarisation can be conserved when ramping the beam energy up or down [12]. Since there are no deuteron depolarising resonances in the COSY energy region, this makes things easier. In order to verify this polarisation export technique with a circulating deuteron beam at COSY, the scheme illustrated diagrammatically in Fig. 4 was implemented.

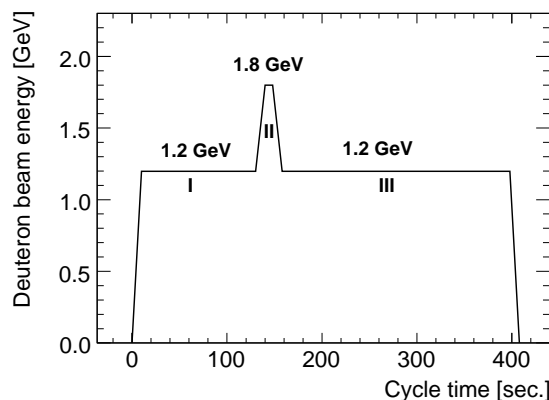


Figure 4. Schematic diagram illustrating the three different flat-top regions used in a single COSY cycle. The identity of the deuteron polarisation measured in regions I and III means that the 1.2 GeV polarisation could be exported to 1.8 GeV.

Using the dp -elastic reaction, which is sensitive to both vector and tensor polarisations of the beam, we have measured the polarisations in regions I and III of Fig. 4. The results are presented in Table 1 in terms of the observed asymmetries β . Given that, within the small error bars, $\beta_{y/yy}^I = \beta_{y/yy}^{III}$, no significant depolarisation can have taken place.

The polarisation export technique is a useful tool for the polarisation experiments at any available energy at COSY. The data on $T_d = 1.6$ GeV, 1.8 GeV and 2.27 GeV energy were taken using a COSY super-cycle that included the $T_d = 1.2$ GeV flat top during both (2005, 2006) beam times.

The polarised deuterium ion source at COSY is capable of providing beams with different spin configuration, *i.e.*, with different vector and tensor polarisations. It uses radio frequency

Flat top	β_y	β_{yy}
I	-0.213 ± 0.005	0.057 ± 0.003
III	-0.216 ± 0.006	0.059 ± 0.003

Table 1. Results of the asymmetry measurements for regions I and III of Fig. 4. β_y and β_{yy} represent the asymmetries for the vector and tensor components of the polarisation, respectively

transition units (RFTs) together with quadrupole magnets and exchanges the occupation numbers of the different hyperfine states in the deuterium. In order to minimise systematic errors, several configurations of the ion source were used. Hence, the beam polarisation had to be determined separately for each state. In order to achieve this, the relative luminosities C_n of each state with respect to the unpolarised mode has to be established so that one can then use:

$$N_{\text{pol}}/N_0 = C_n \left[1 + \frac{1}{4} P_{zz} [A_{xx}(q)(1 - \cos 2\phi) + A_{yy}(q)(1 + \cos 2\phi)] \right] \quad (1)$$

where N_{pol} and N_0 are the polarised and unpolarised numbers of counts, respectively.

4.2. The count calibration

The standard method to normalise the counts, as used in the first experiment [5], is based on the Beam Current Transformer (BCT) signal provided by the COSY accelerator. The BCT signal is proportional to the COSY beam intensity and allows one to determine the relative luminosities (C_n) with a percent accuracy since the orbit in the ring should be identical for the different polarisation modes.

A technical problem in the BCT readout occurred during the 2006 beam time and this only became obvious at the analysis stage. The accuracy of the BCT data was worse than 10%, which was largely insufficient for the analysing power studies, and an alternative was required. Quasi-free $dp \rightarrow p_{\text{sp}} d\pi^0$ counts at $\vartheta = 0^\circ$ do not depend on the beam polarisation. The accuracy achieved when using this reaction depends mainly on the angular precision of the ANKE forward detector. The technique works well at low energy ($T_d = 1.2$ GeV), but the counting rate falls with energy so that at $T_d = 2.27$ GeV the statistics are almost one order less.

A much more robust method is provided by the $dp \rightarrow p_{\text{sp}} X$ reaction. The number of single-track events is enormous (a few hundred million events in the 2006 beam time data) for all beam energies. Although the rates could in principle depend on the tensor polarisation of the deuteron beam, no such dependence was found up to proton spectator momenta of 60 MeV/c. In order to be cautious, we used a 40 MeV/c cut on the spectator momentum. The new results are mainly in good agreement with the old ones (determined using the $dp \rightarrow p_{\text{sp}} d\pi^0$ reaction) except for a few modes (Table 2).

During the 2005 beam time the BCT signal was reliable and this gave us the possibility of comparing the two methods of count calibration, when good agreement was found. However, the new method benefits from the enormous statistics and, furthermore, provides information directly about the luminosity.

4.3. Deuteron beam polarimetry

The following reactions were used in our analysis in order to determine the polarisation of the deuteron beam at $T_d = 1.2$ GeV, where the analysing powers are well known: quasi-free $np \rightarrow d\pi^0$ for the vector component (P_z) and $dp \rightarrow \{pp\}n$ for the tensor component. In the case of the $np \rightarrow d\pi^0$ reaction, the ratio of the polarised to unpolarised counts has the form:

$$N_{\text{pol}}/N_0 = C_n (1 + P_z A_y(\vartheta) \cos \phi) , \quad (2)$$

Pol. mode	BCT	$np \rightarrow d\pi^0$	$dp \rightarrow p_{sp}X$
1	1.000 ± 0.000	1.000 ± 0.000	1.0000 ± 0.0000
2	0.511 ± 0.006	0.650 ± 0.132	0.5116 ± 0.0003
3	0.471 ± 0.005	0.454 ± 0.109	0.4735 ± 0.0003
4	0.485 ± 0.005	0.312 ± 0.116	0.4832 ± 0.0003
5	0.438 ± 0.005	0.340 ± 0.112	0.4379 ± 0.0003
6	0.394 ± 0.004	0.608 ± 0.107	0.3895 ± 0.0002
7	0.438 ± 0.005	0.578 ± 0.105	0.4358 ± 0.0003
8	0.427 ± 0.005	0.410 ± 0.117	0.4270 ± 0.0003

Table 2. The normalisation coefficients obtained using different calibration methods for the 2005 beam time data at $T_d = 1.6$ GeV for eight different polarisation modes.

where ϑ is the deuteron CM angle.

Experimental counts were divided into several bins of ϑ in the range 0° to 40° and the $\cos \varphi$ distributions filled for each bin and each polarisation state. The ratios of these distributions to the unpolarised state were fitted using Eq.(2). The mean analysing power A_y in each bin was taken from the SAID database for $pp \rightarrow d\pi^+$ reaction which, due to isospin invariance, is the same as for $np \rightarrow d\pi^0$. The beam polarisation in each state was taken as the average over the ϑ bins.

The determination of the tensor polarisation (P_{zz}) of the beam is done using charge-exchange events that were divided into several bins of momentum transfer in the range 0 to 160 MeV/c. The $\cos 2\varphi$ distributions were filled for each bin and polarisation mode. The ratios to the unpolarised state were fitted using:

$$N_{\text{pol}}/N_0 = C_n \left(1 + \frac{1}{4} P_{zz} [A_{xx}(q) (1 - \cos 2\phi) + A_{yy}(q) (1 + \cos 2\phi)] \right) \quad (3)$$

where the theoretical predictions for A_{xx} and A_{yy} were used at mean q values in each bin. These predictions at $T_d = 1.17$ GeV were checked experimentally at ANKE in the earlier studies [8]. The beam polarisation in each state was taken as the weighted average over the momentum transfer.

The polarisations reported in Tables 3 and 4 are different for each mode. During the 2006 beam time the values of P_z and P_{zz} approached $\approx 70\%$ and $\approx 55\%$ of the ideal values, respectively. But, in the 2005 beam time, a higher value of $P_{zz} \approx 85\%$ of ideal was found, while the vector polarisation values were similar to those of 2006. To ensure an understanding of these two results, a simulation of the whole system of the COSY deuterium ion source was done. For this the efficiencies were simulated for each radio frequency transition unit and also for each of the quadrupole magnets. As a result we could obtain high values for the tensor polarisation with reasonable efficiencies for the separate parts of polarised source, as well as for the whole system.

4.4. The tensor analysing powers

The new ANKE results for the deuteron Cartesian tensor analysing powers A_{xx} and A_{yy} at three beam energies are shown in Fig. 5 as functions of the momentum transfer. The agreement between the experimental data and the impulse approximation predictions obtained using the

Polarisation	Ideal values		P_z	P_{zz}
mode	P_z	P_{zz}	$(np \rightarrow d\pi^0)$	$(dp \rightarrow \{pp\}n)$
1	0	0	—	—
2	$-\frac{2}{3}$	0	-0.272 ± 0.102	-0.002 ± 0.022
3	$+\frac{1}{3}$	-1	0.374 ± 0.116	-0.559 ± 0.023
4	$-\frac{1}{3}$	+1	-0.196 ± 0.104	0.464 ± 0.020
5	0	+1	0.179 ± 0.118	0.604 ± 0.020
6	-1	+1	-0.445 ± 0.101	0.496 ± 0.020
7	+1	+1	0.678 ± 0.128	0.394 ± 0.021
8	0	-2	-0.088 ± 0.109	-0.231 ± 0.023

Table 3. Ideal and measured values of the beam polarisation during the 2006 beam time. Measurements were done for eight different configurations of the polarised deuterium ion source at $T_d = 1.2$ GeV.

Polarisation	Ideal values		P_z	P_{zz}
mode	P_z	P_{zz}	$(np \rightarrow d\pi^0)$	$(dp \rightarrow \{pp\}n)$
1	0	0	—	—
2	$+\frac{1}{3}$	+1	0.26 ± 0.06	0.82 ± 0.03
3	$-\frac{2}{3}$	0	-0.52 ± 0.05	0.15 ± 0.04
4	$+\frac{1}{3}$	-1	0.14 ± 0.06	-0.73 ± 0.04
5	0	+1	-0.05 ± 0.05	0.85 ± 0.03
6	0	-2	0.08 ± 0.06	-0.78 ± 0.04
7	-1	+1	-0.51 ± 0.05	0.01 ± 0.03
8	+1	+1	0.35 ± 0.06	0.84 ± 0.03

Table 4. Polarimetry results for the 2005 beam time, analogous to those in Table 3.

reliable SAID np amplitudes as input at $T_n = 600, 800, \text{ and } 900$ 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 the same picture in the bottom panel. The neutron-proton amplitudes are here not as well known and the deviations of the data from the predicted curves strongly suggest that there are deficiencies in the SAID values of the np amplitudes in this region.

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:

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

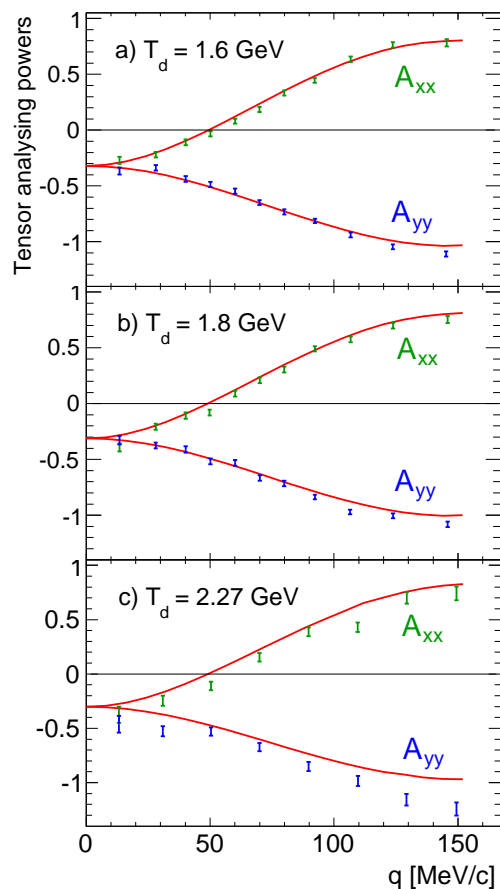


Figure 5. Cartesian tensor analysing powers A_{xx} (green dots) and A_{yy} (blue dots) of the $dp \rightarrow \{pp\}_s n$ reaction at beam energies of $T_d = 1.6, 1.8$, and 2.27 GeV for low diproton excitation energy, $E_{pp} < 3$ MeV. The curves result from an impulse approximation calculation, where the input np amplitudes were taken from the SAID program at the appropriate energies.

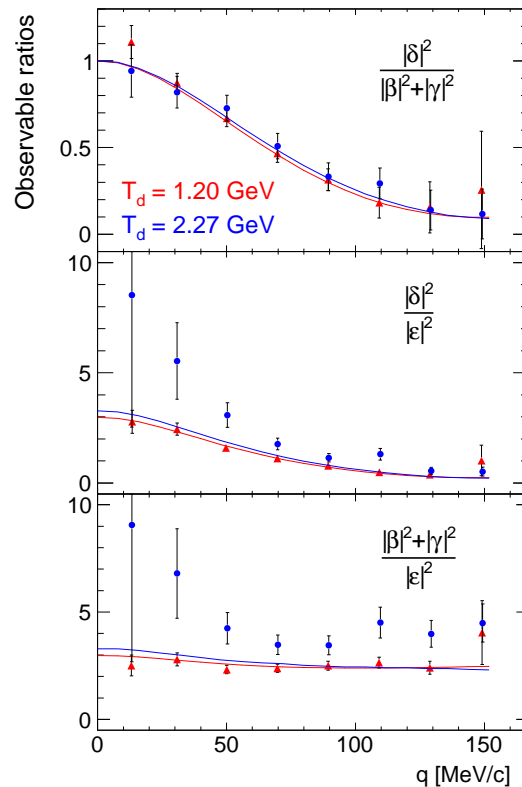


Figure 6. Measured observable ratios as functions of q for two different beam energies. Solid lines are impulse approximation predictions.

The variation of these quantities with q are presented in Fig. 6 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 $|\epsilon|$ at small q . This will become clearer when absolute values of the cross sections are extracted at 2.27 GeV.

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

5. Experiment with polarised beam and target

5.1. Beam and target polarimetry

In order to determine the relative phases of the spin–spin amplitudes (β, δ, ϵ) 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–polarised neutron–proton scattering experiment at ANKE during 2009 [13].

Three different combinations of vector and tensor polarised deuterons, *viz.* ($P_z = 0, P_{zz} = 0$), ($P_z = -1, P_{zz} = +1$), and ($P_z = -2/3, P_{zz} = 0$), were injected in consecutive cycles into the COSY ring to interact with a polarised hydrogen cell target, which was fed by a polarised Atomic Beam Source (ABS). A cell with dimensions $20 \times 15 \times 370 \text{ mm}^3$ was used in order to increase target density up to 10^{13} cm^{-2} . To ensure that the COSY beam passed successfully through the cell, a dedicated beam development was required. Stacking injection with electron cooling was implemented with hundreds of injections per cycle. The polarisation of the target was flipped from +1 state (spin “up”) to -1 (spin “down”) every 5 seconds throughout the whole cycle. To simplify the asymmetry evaluation in such a complicated scenario, separate runs with the same beam cycles but with an unpolarised hydrogen target were also recorded.

The cell introduced additional complications in the analysis. The scattering on the cell walls produces additional background that would dilute the analysing power signal. Ideally one could record data with an empty cell and use them for background subtraction, but it would take several weeks to collect sufficient statistics. Therefore Nitrogen gas (from UGSS), which has very similar properties to cell walls, was injected into the cell to simulate the shape of the background (Fig 7).

The second major complication was due to the spread of the interaction points along the cell. Direct vertex reconstruction was therefore required for each event in order to extract the correct scattering angle. Since the polarisation signal is proportional to the polar angle, the correct angular information is crucial for any kind of polarisation analysis. Vertex reconstruction was performed by extrapolating the two–track events to the scattering point, using the time–of–flight information taken from the forward scintillator hodoscope (Fig 8).

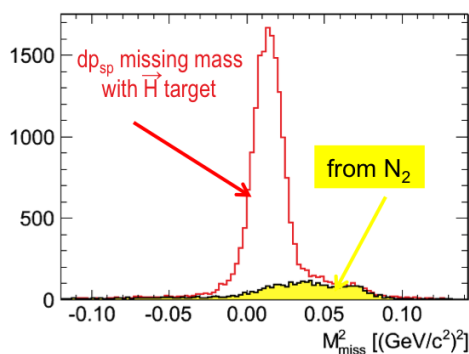


Figure 7. Example of the background subtraction procedure for the dp two–track events.

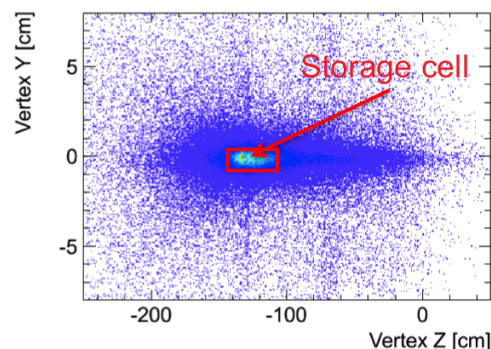


Figure 8. Vertex reconstruction on YZ plane using the dp events and timing information from the scintillator counters.

Target polarimetry was done using the $d\vec{p} \rightarrow d\pi^0 p_{sp}$ events with only unpolarised states of the deuteron beam. If the proton acts as a spectator, this can be considered as quasi-free $np \rightarrow d\pi^0$, for which the analysing power is very well known. For an unpolarised deuteron beam and polarised hydrogen target, the asymmetry ratio between polarised and unpolarised yields

can be expressed as a function of θ and ϕ as:

$$\epsilon^{\uparrow(\downarrow)}(\theta, \phi) = \frac{N^{\uparrow(\downarrow)}}{N^0}(\theta, \phi) = 1 + Q_y^{\uparrow(\downarrow)} A_y(\theta) \cos \phi, \quad (4)$$

though in practice only data with $|\cos \phi| > 0.8$ were used.

After background subtraction and vertex reconstruction, data was binned in π^0 cm angles and asymmetries for both “spin-up” and “spin-down” states were produced according to Eq. (4). To ensure the correct asymmetry determinations, all three yields were normalised on the $dp \rightarrow p_{\text{sp}} X$ count rates for momenta $p_{\text{sp}} < 40$ MeV/c. After evaluating the asymmetry for each $\theta_{\pi^0}^{\text{cm}}$ bin (Fig. 9), the polarisations of the target were determined using the analysing power from the SAID database. This gave $Q_y^{\downarrow} = -0.761 \pm 0.020$ and $Q_y^{\uparrow} = 0.662 \pm 0.013$.

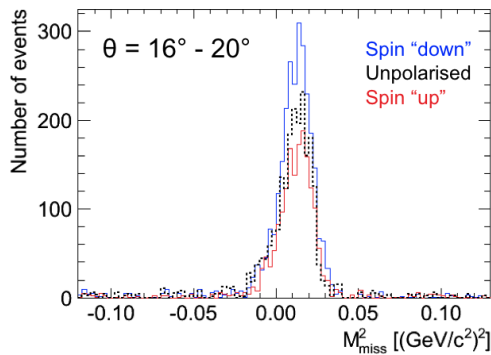


Figure 9. Normalised missing-mass distribution for one of the $\theta_{\pi^0}^{\text{cm}}$ bins after background subtraction and vertex reconstruction.

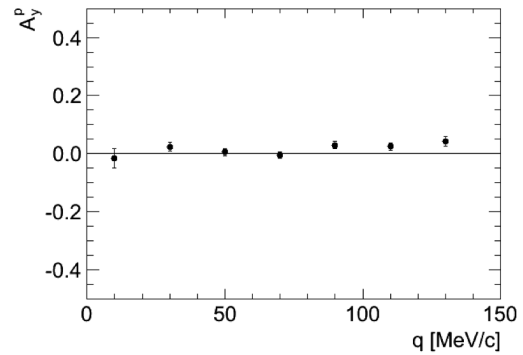


Figure 10. Proton analysing power A_y^p for the $dp \rightarrow ppn$ reaction for $E_{pp} < 3$ MeV.

The polarisation of the beam was determined with the same procedures as before and the final results were $P_z = 65\%$ and $P_{zz} = 40\%$ of the ideal expectations.

5.2. The spin-correlation coefficients

After successfully establishing the beam and target polarisations, it is then possible to study the spin-correlation coefficients $C_{x,x}$ and $C_{y,y}$ of the $d\bar{p} \rightarrow \{pp\}n$ reaction as a function of q . For this purpose it is best to use beam polarisation states with only vector polarisation. This then leads to the following dependence for the ratio of the polarised to the unpolarised yields [14]:

$$\frac{N^{\text{pol}}}{N^0} = 1 + Q_y A_y^p(\theta) \cos \phi + \frac{3}{2} P_z A_y^d(\theta) \cos \phi + \dots + \frac{3}{4} P_z Q_y [(1 + \cos 2\phi) C_{y,y} + (1 - \cos 2\phi) C_{x,x}] + \dots \quad (5)$$

Fortunately A_y^d vanishes in impulse approximation [4] and, by analysing only polarised target yields for an unpolarised beam, we could obtain the A_y^p dependence on q presented in Fig. 10. The small values shown there further simplify the determination of $C_{x,x}$ and $C_{y,y}$. The background subtraction was carried out in the same way as for the $dp \rightarrow d\pi^0 p_{\text{sp}}$ events using the Nitrogen data (Fig. 11). After binning the normalised counts in q intervals, the $\cos 2\phi$ dependence allows us to extract $C_{x,x}$ and $C_{y,y}$ spin-correlation coefficients separately. The data with $E_{pp} < 3$ MeV are compared with theoretical predictions in Fig. 12. The good agreement with our experimental points shows that the two relative phases between the spin-spin amplitudes are well predicted by the SAID program and indicates that the spin-correlation coefficients will provide useful amplitude information at higher energies.

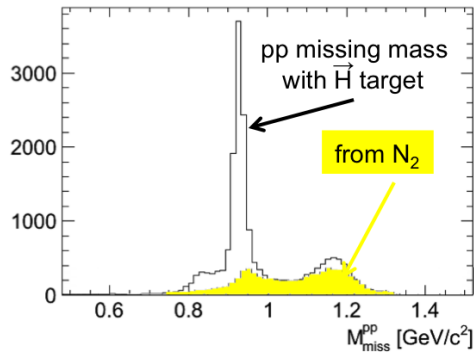


Figure 11. Example of the background subtraction procedure for dp two-track events.

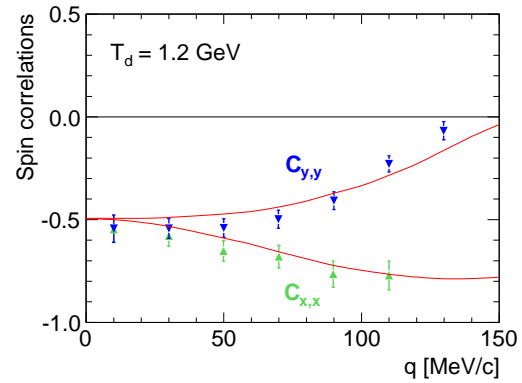


Figure 12. Vector spin-correlation coefficients in the $\vec{d}\vec{p} \rightarrow \{pp\}_s n$ reaction at $T_d = 1.2$ GeV. The curves are impulse approximation predictions.

6. The $dp \rightarrow \{pp\}\Delta^0$ reaction

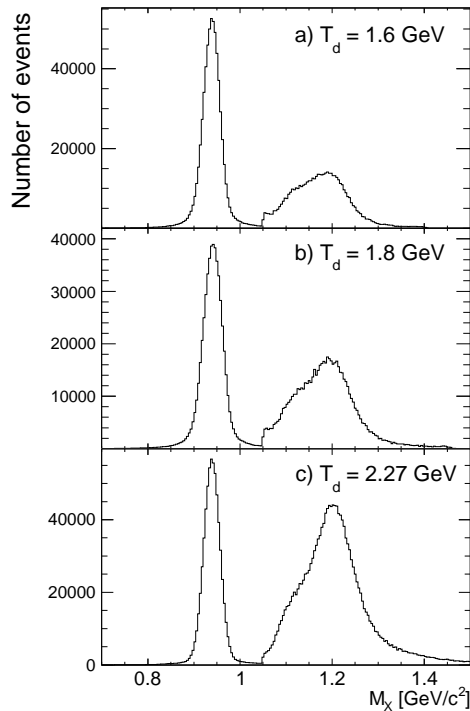


Figure 13. The missing-mass M_x distribution for the reaction $dp \rightarrow \{pp\}_s X$ at three deuteron beam energies. In addition to the neutron peak, one sees clear evidence for the excitation of the Δ^0 isobar.

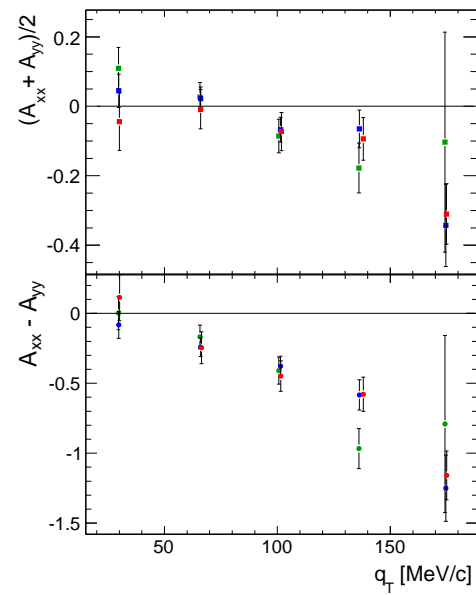


Figure 14. The q dependence of the mean (squares) and difference (circles) values of the tensor analysing powers for the $dp \rightarrow \{pp\}_s \Delta^0$ reaction. Green corresponds to 1.6 GeV results, blue to 1.8 GeV and red to 2.27 GeV.

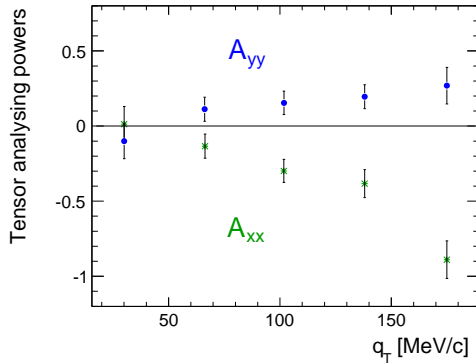


Figure 15. The tensor analysing powers for the $dp \rightarrow \{pp\}_s \Delta^0$ reaction at 2.27 GeV.

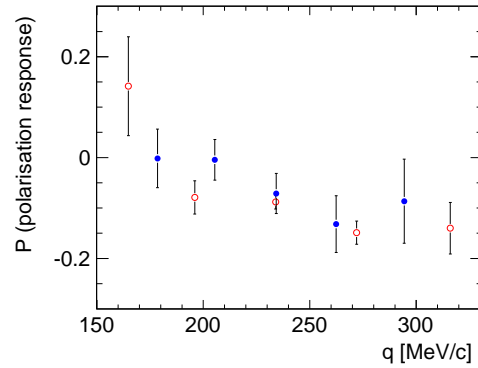


Figure 16. The comparison of the ANKE results at $T_d = 2.27$ GeV (blue points) with results produced at Saclay at $T_d = 2.0$ GeV (red circles). Results are shown in terms of full momentum transfer.

It was demonstrated many years ago at Saclay that at $T_d = 2.0$ GeV the $\Delta(1232)$ isobar can be excited in the charge-exchange reaction $\vec{d}p \rightarrow \{pp\}\Delta^0$ and substantial tensor analysing powers were measured [15]. In impulse approximation, these are also sensitive to a spin-transfer from the neutron to the proton in $np \rightarrow p\Delta^0$, which is very hard to measure directly.

Analysing the data from the 2005 and 2006 beam times for all three higher energies, we also see a clear peak in the Δ^0 mass region of the missing-mass spectra shown in Fig. 13 (note: for clarity of presentation this region is scaled by factor of 8). We have carried out a preliminary investigation of the Δ region with the intention to compare the results with those for the neutron case. The same analysis was used to obtain the tensor analysing powers of the $dp \rightarrow \{pp\}\Delta^0$ process. One major difference from the neutron channel is that the momentum transfer to the Δ has a significant longitudinal component due to the ΔN mass difference. Hence the data are presented in terms rather of the transverse momentum transfer q_T instead.

The results at $T_d = 2.27$ GeV are shown in Fig. 15. Things become a little clearer if we plot the averages of and the differences between the A_{xx} and A_{yy} as functions of q_T on the same plots for the three different energies. Figure 14 shows that these quantities actually vary little with beam energy. If we compare the results for the Δ and neutron channels, we can easily notice the differences in absolute values of the tensor analysing powers, as well as the difference in their signs. A theoretical model is still needed to explain the detailed behavior of Δ^0 production.

It is important to note that at Saclay only a linear combination of A_{xx} and A_{yy} , which they called the “Polarisation response” could be extracted. The comparison of the ANKE results for this quantity with those from Saclay is shown on Fig. 16. Taking into account the error bars and the difference in beam energy, it seems that these two experiments are consistent with each other.

It is therefore clear that ANKE will provide useful information also on the spin structure of Δ excitation in neutron-proton collisions. This field will expand tremendously when the beam and target are interchanged and ANKE measures $pd \rightarrow \{pp\}\Delta$ with both slow protons in the Silicon Tracking Telescope system (STT) [16] and the products of the $\Delta^0 \rightarrow p\pi^-$ decay in the ANKE magnetic spectrometer.

7. Summary and outlook

- ANKE/COSY can contribute to the small angle np charge-exchange database up to 1.15 GeV with a polarised deuteron beam and up to 3 GeV with a polarised deuterium target.
- Theoretical work is needed to evaluate deuteron corrections to $dp \rightarrow \{pp\}n$.
- ANKE can provide experimental data on the production of the $\Delta(1232)$ in deuteron charge-exchange reactions. These may allow us to explore as yet unknown aspects of the nucleon-nucleon interaction. The Δ production will also be studied in the near future in the $pd \rightarrow \{pp\}\Delta$ channel.
- It can contribute to the pp elastic database for $5^\circ < \theta_{cm} < 30^\circ$ up to the maximum beam energy of ≈ 3 GeV [17].

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