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Neutron–Proton Scattering Experiments at ANKE–COSY

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Abstract. The nucleon–nucleon interaction (NN) is fundamental for the whole of nuclear physics and hence to the composition of matter as we know it. It has been demonstrated that stored, polarised beams and polarised internal targets are experimental tools of choice to probe spin effects in NN–scattering experiments. While the EDDA experiment has dramatically improved the proton–proton date base, information on spin observables in neutron–proton scattering is very incomplete above 800 MeV, resulting in large uncertainties in isoscalar np phase shifts. Experiments at COSY, using a polarised deuteron beam or target, can lead to significant improvements in the situation through the study of quasi–free reactions on the neutron in the deuteron. Such a measurements has already been started at ANKE by using polarised deuterons on an unpolarised target to study the $dp \to \{pp\}n$ deuteron charge–exchange reaction and the full program with a polarised storage cell target just has been conducted. At low excitation energies of the final pp system, the spin observables are directly related to the spin–dependent parts of the neutron–proton charge–exchange amplitudes. Our measurement of the deuteron–proton spin correlations will allow us to determine the relative phases of these amplitudes in addition to their overall magnitudes.

1 Introduction

An understanding of the NN interaction is fundamental to the whole of nuclear and hadronic physics. 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 ambiguity above about 800 MeV [1]. The data on which such an analysis is based come from many facilities and it is incumbent on a laboratory that can make a significant contribution to the communal effort to do so.

It has recently been argued that, even without measuring triple–spin observables, a direct amplitude reconstruction of the neutron–proton backward scattering amplitudes might be possible with few ambiguities provided that experiments on the deuteron are included [2]. This work studied in detail the ratio of the forward charge–exchange cross section of a neutron on a deuterium target to that on a hydrogen target,

$$R_{np}(0) = \frac{\mathrm{d}\sigma(nd \to pnn)/\mathrm{d}t}{\mathrm{d}\sigma(np \to pn)/\mathrm{d}t}, \qquad (1)$$

where t is the four–momentum transfer between the initial neutron and final proton.

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Due to the Pauli principle, when the two final neutrons are in a relative S–wave their spins must be antiparallel and the system is in the ${}^1S_0$ state. Under such circumstances the $nd \to p\{nn\}$ reaction involves a spin flip from the $S = 1$ of the deuteron to the $S = 0$ of the dineutron and hence is dependent on the np spin-isospin-flip amplitudes. If the data are summed over all excitation energies of the nn system, then the Dean closure sum rule allows one to deduce from R_{np} the fraction of spin–dependence in the pn charge–exchange amplitudes [3]. Such measurements have now been carried out up to 2 GeV [4].

However, Bugg and Wilkin [5] have shown that much more information on the np charge–exchange amplitudes can be extracted by using a polarised deuteron beam or target and studying the charge–symmetric $\vec{d}\,p \to \{pp\}n$ reaction. To achieve the full benefit, the excitation energy E_{pp} in the final pp system must be kept low. Experiments from a few hundred MeV up to 2 GeV [6,7] have generally borne out the theoretical predictions and have therefore given hope that such experiments might provide valuable data on the amplitudes in the small momentum transfer region.

The ANKE collaboration is embarking on a systematic programme to measure the differential cross section and analysing powers of the $\vec{d}\,p \to \{pp\}n$ reaction up to the maximum energy of the COSY accelerator of 1.15 GeV per nucleon, with the aim of deducing information on the np amplitudes [8]. Higher energies per nucleon will be achieved through the use of a deuterium target. Spin correlations will also be studied with a polarised beam and target [9]. However, for these to be valid objectives, the methodology has to be checked in a region where the *np* amplitudes are reasonably well known.

The first evaluation of the analysing powers and differential cross sections of the $\vec{d}\,p \to \{pp\}n$ reaction at $T_d = 1170$ MeV has been reported in Refs. [10,11]. Since both the cross section and two tensor analysing powers at 585 MeV per nucleon largely agree with theoretical predictions based upon reliable neutron–proton phase–shift analysis, this gives us confidence that the methods used here can be extended to higher energies where much less is known about the *np* elastic amplitudes. The possibilities of such work will be discussed in this contribution.

2 The SAID database and phase shift analysis

2.1 The $pp \to pp$ database

Apart from their intrinsic importance for the study of nuclear forces, nucleon–nucleon data are also necessary ingredients in the description of meson production and other nuclear reactions at intermediate energies. It is incumbent on any facility that can make a significant and new contribution to this important database of knowledge to do so. Let just discuss the cross section situation in some detail.

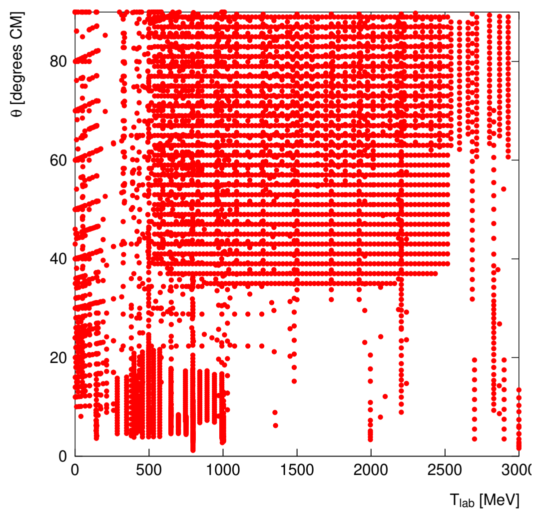

Fig. 1. Abundance plot of the *pp* elastic differential cross section $d\sigma/d\Omega$ (left) extracted from the SAID [1] and NN-online [13] databases. The points show the positions in energy and centre-of-mass angle of existing measurements. It is important to note that in the energy range of $0.5 < T_p < 2.5$ GeV the plot is largely dominated by the very precise COSY–EDDA data [14] but that these only cover the range in scattering angle $\approx 35^\circ < \theta_{cm} < 90^\circ$.

A full *pp* phase shift analysis requires data on cross sections, analysing powers, spin correlation, and transfer parameters. The scatter plot of Fig. 1 shows the energies and c.m. angles where there are experimental data on the elastic differential cross section [12,13]. The cross section is, symmetric about $\theta_{cm} = 90^\circ$, which accounts for showing only data below this angle. The vast bulk of the data above 500 MeV were obtained by the COSY–EDDA collaboration [14], but these were limited to c.m. scattering angles above about 35°. This scatter plot also shows that there is a lack of good data even for the differential cross section at small angles for beam energies above 1 GeV. This is mainly due to the design of the EDDA detector, which requires a significant minimum momentum transfer to the recoil proton in order that both protons can be detected [14]. It is therefore clear that new high quality small angle *pp* elastic scattering data are required.

Most nucleon–nucleon phase shift and amplitude analysis in the GeV range is carried out by the SAID collaboration [12]. When the group was asked what impact a measurement of the differential cross section in the range say $5^\circ < \theta_{cm} < 30^\circ$ at say 2.4 GeV with a precision of 5% would have on the phase shifts, the answer was effectively NONE [15]. SAID already predicts those results with a 2% uncertainty – despite there being no experimental information available in this region. How can we understand this apparent contradiction?

Professor Rentmeester [Nijmegen NN-online] explains the situation as follows [16]. For a single–energy proton–proton phase shift analysis, only the lower partial wave phase shifts are free parameters. For the higher waves, fixed values are chosen from the one–pion exchange (OPE) model, assuming that: (i) The OPE is “known” (its strength as well as the basic mechanism), and (ii) In the wave where one starts using just the OPE, the non–OPE contribution cannot be determined with statistical significance.

The second point could be tested if new data at small angles, where currently no data exist, enable the determination of a new phase shift in an analysis. The 2% predicted uncertainty is very dependent on the parametrisation and the set of data that are used to determine the free parameters. If pseudo–data are generated with the predicted angular shape as the source, such input would only provide a confirmation of the prediction. The values for the phase shifts would stay the same; only their uncertainties might change, depending on the uncertainties assumed for the pseudo–data. Hence, if one can produce good data in a region where there is none, they are always potentially useful.

To contribute usefully to the *pp* database, the cross sections must be measured absolutely in, say, mb/sr. EDDA had a relative monitor (measuring electron pairs from the target) which was normalised to data taken in an external experiment at low energy. How does one measure directly the luminosity for internal experiments at a storage ring without relying on a comparison with a measurement with an extracted beam ?

The ANKE collaboration and the COSY machine crew have jointly developed an independent and very accurate method for determining absolutely the luminosity in an experiment at an internal target position of COSY. The technique relies on measuring the energy losses due to the electromagnetic interactions of the beam as it repeatedly passes through the target by studying the Schottky spectrum [17].

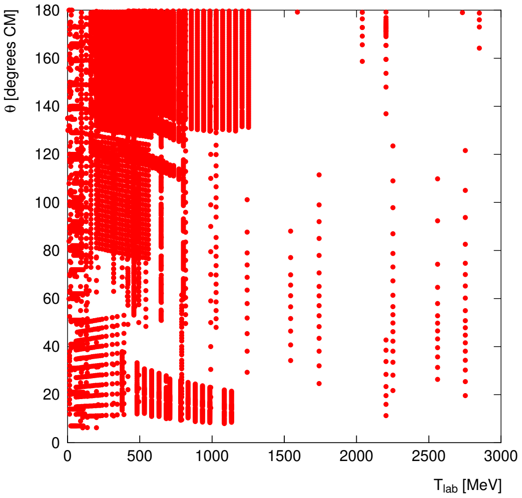

Fig. 2. Abundance plot of neutron–proton elastic scattering evaluated from Ref. [13].

The aim of the proposed experiment at ANKE [18] is to use this powerful tool in the measurement of the differential cross section and the proton analysing power of proton–proton elastic scattering in the energy range from 1.6 to 2.8 GeV for centre-of-mass angles $10° < \theta_{cm} < 30°$.

2.2 Neutron–proton elastic scattering database

Dick Arndt has stressed that there is a *Gross misconception within the community that neutron–proton amplitudes are known up to a couple of GeV. The np data above 800 MeV is a DESERT for experimentalists* [19]. The *np* scatter plot of differential cross sections shown in Fig. 2 is much emptier than that for proton–proton of Fig. 1. There has been no equivalent of EDDA that could revolutionise the neutron–proton database.

At COSY we have no neutron beam and so we must use a deuteron beam or a deuterium target and this raises the usual questions regarding deuteron corrections. Nevertheless, a large programme of spin physics involving the deuteron is planned [8].

3 Deuteron charge exchange

By neutron–proton charge exchange we merely mean near–backward *np* elastic scattering where the final proton is going close to the direction of the initial neutron. The *np* charge–exchange amplitudes measure directly the differences between small angle *pp* and *np* elastic amplitudes and hence the differences between amplitudes with isospin $I = 1$ and $I = 0$.

Charge exchange can be studied at COSY with a deuteron beam of up to ≈ 1.1 GeV/A and with a deuterium target up to ≈ 2.8 GeV/A [8]. Of especial interest is the region of small excitation energies E_{pp} in the final *pp* system since, as it was stressed in introduction, the Pauli principle then demands that the protons should have opposite spin projections so that they lie in the $^1S_0$ state. Hence in the $dp \to \{pp\}_S n$ reaction there is a spin–flip from the $^3S_1$, $^3D_1$ of the deuteron to $^1S_0$ of the diproton. The data are therefore sensitive to spin–flip, isospin–flip transitions, as indicated pictorially in Fig. 3.

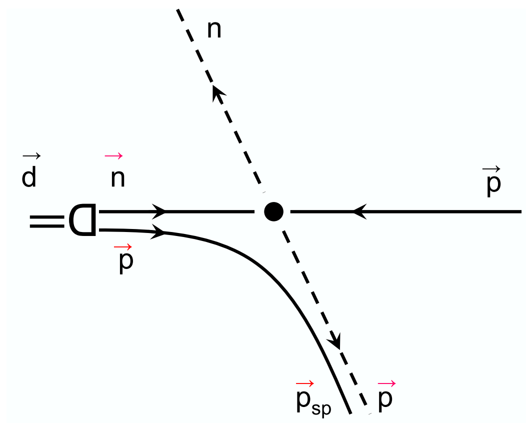

Fig. 3. Symbolic depiction of deuteron charge exchange on the proton.

The reaction can have a polarisation dependence that can be linked to that in neutron–proton charge–exchange. Supposed the deuteron is polarised with spin projection $M = +1$ along the beam direction. If we neglect the deuteron *D*-state, this means that both the proton and neutron inside the target are polarised with $m = +\frac{1}{2}$. In the final state one of the two protons must have polarisation $m = -\frac{1}{2}$. This means that the data are then sensitive to the $np \to pn$ spin transfer between the initial neutron to the final proton.

The above hand–waving ideas are put on a more quantitative foundation within the impulse approximation model of Fig. 4 [5]. This will lead to a deuteron charge–exchange amplitude that is proportional to that for $np \to pn$ times a form factor that depends upon the overlap of the initial deuteron with the *pp* scattering wave function. In addition to all the spin complications, one has to be careful to include all relevant partial waves in the description of the *pp* scattering state.

In impulse (single–scattering) approximation, the deuteron charge–exchange amplitude is of the form

$$\mathcal{M} = \langle \mathbf{k}, m_3, m_4, m_2 \left| f_{12} e^{i\mathbf{q}\cdot\mathbf{r}} \right| d, M, m_1 \rangle. \qquad (2)$$

Here f_{12} is the *pn* elastic charge–exchange amplitude between the incident proton (of spin projection m_1) to the final neutron (of spin projection m_2) at momentum transfer $\mathbf{q}$ where, to a very good approximation, $q^2 = -t$. The relative momentum between the two protons is denoted by $\mathbf{k}$ so that $E_{pp} = k^2/m$.

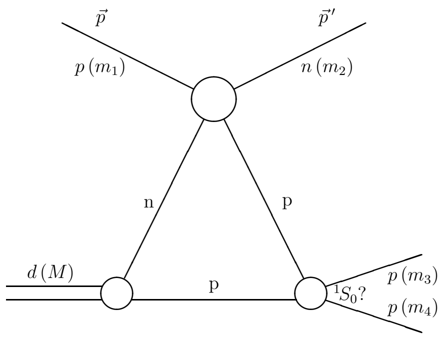

Fig. 4. Impulse approximation diagram for the $dp \to \{pp\}n$ reaction.

The most general form of the np amplitude is

$$\begin{aligned} f_{np} &= \alpha + i\gamma(\sigma_n + \sigma_p) + \beta(\sigma_n \cdot \hat{n})(\sigma_p \cdot \hat{n}) \\ &+\delta(\sigma_n \cdot \hat{m})(\sigma_p \cdot \hat{m}) + \varepsilon(\sigma_n \cdot \hat{\ell})(\sigma_p \cdot \hat{\ell}), \end{aligned} \quad (3)$$

where the unit basis vectors are defined in terms of the initial and final c.m. momenta by

$$\hat{n} = \frac{\mathbf{p} \times \mathbf{p}'}{|\mathbf{p} \times \mathbf{p}'|}, \ \ \hat{m} = \frac{\mathbf{p}' - \mathbf{p}}{|\mathbf{p}' - \mathbf{p}|}, \ \ \hat{\ell} = \frac{\mathbf{p}' + \mathbf{p}}{|\mathbf{p}' + \mathbf{p}|} \cdot \quad (4)$$

It is convenient to use a normalisation that is frame–independent where

$$\left(\frac{d\sigma}{dt}\right)_{np\to pn} = |\alpha|^2 + |\beta|^2 + 2|\gamma|^2 + |\delta|^2 + |\varepsilon|^2 . \quad (5)$$

As a first approximation, consider deuteron charge exchange data with $E_{pp} < 3$ MeV where it is reasonable to assume $^1S_0$ dominance. There are then two form factors that arise from the integral over the Fermi momenta:

$$\begin{aligned} S^+(k, \tfrac{1}{2}q) &= \langle\psi_k^{(-)}|j_0(\tfrac{1}{2}qr)|u\rangle + \sqrt{2}\langle\psi_k^{(-)}|j_2(\tfrac{1}{2}qr)|w\rangle , \\ S^-(k, \tfrac{1}{2}q) &= \langle\psi_k^{(-)}|j_0(\tfrac{1}{2}qr)|u\rangle - \langle\psi_k^{(-)}|j_2(\tfrac{1}{2}qr)|w\rangle/\sqrt{2}, \end{aligned} \quad (6)$$

where $u(r)$ and $w(r)$ are the S- and D-state components of the deuteron wave function and $\psi_k^{(-)}(r)$ is the pp ($^1S_0$) scattering wave function.

Denote the ratio of the transition form factors by

$$R = S^+(k, \tfrac{1}{2}q)\Big/S^-(k, \tfrac{1}{2}q) \quad (7)$$

and the sum of the modulus–squares of the spin–flip amplitudes by

$$I = |\beta|^2 + |\gamma|^2 + |\varepsilon|^2 + |\delta|^2 R^2. \quad (8)$$

Impulse approximation applied to $dp \to (pp)_{^1S_0}n$ then leads to the following predictions for the differential cross section, deuteron and proton analysing powers (A), and spin–spin correlation parameters (C) [5,20,21]:

$$\begin{aligned} \frac{d^4\sigma}{dtd^3k} &= \tfrac{1}{3}I\left\{S^-(k, \tfrac{1}{2}q)\right\}^2 , \\ I A_y^d &= 0 , \\ I A_y^p &= -2\Im(\beta^*\gamma) , \\ I A_{xx} &= |\beta|^2 + |\gamma|^2 + |\varepsilon|^2 - 2|\delta|^2R^2 , \\ I A_{yy} &= |\delta|^2R^2 + |\varepsilon|^2 - 2|\beta|^2 - 2|\gamma|^2 , \\ I C_{y,y} &= -2\Re(\varepsilon^*\delta)R, \\ I C_{x,x} &= -2\Re(\varepsilon^*\beta) \\ I C_{yy,y} &= -2A_y^p. \end{aligned} \quad (9)$$

At COSY–ANKE we do not have yet (!) longitudinally polarised targets or beams. Therefore, in terms of the proton polarisation Q (target) and deuteron vector and tensor polarisations P_z and P_{zz} (COSY beam), the observables are given by [22]:

$$\begin{aligned} \sigma/\sigma_0 = 1 &+ \left(QA_y^p + \tfrac{3}{2}P_zA_y^d\right)\cos\phi \\ &+\tfrac{1}{4}P_{zz}\left[(A_{yy} + A_{xx}) + (A_{yy} - A_{xx})\cos 2\phi\right] \\ &+\tfrac{3}{4}P_zQ\left[(C_{y,y} + C_{x,x}) + (C_{y,y} - C_{x,x})\cos 2\phi\right] \\ &+\tfrac{1}{4}P_{zz}Q\Big[(\tfrac{1}{2}C_{xx,y} + \tfrac{1}{2}C_{yy,y} + C_{xy,x})\cos\phi \\ &+(\tfrac{1}{2}C_{xx,y} - \tfrac{1}{2}C_{yy,y} + C_{xy,x})\cos 3\phi\Big] . \end{aligned} \quad (10)$$

Here ϕ is the azimuthal angle with respect to the COSY ring. Note that the $(A_{yy} + A_{xx})$ term has no ϕ dependence and so its value cannot be determined from looking at the angular variation.

4 The experimental facility

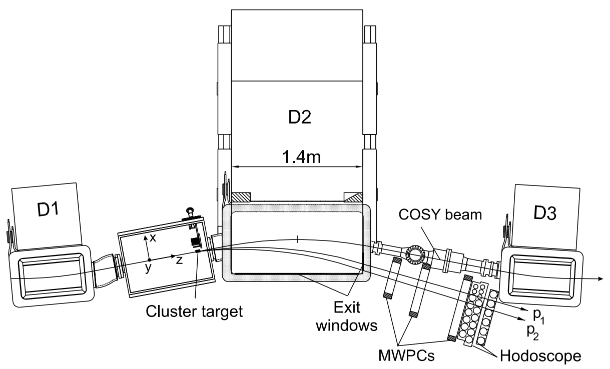

Fig. 5. Top view of the ANKE experimental set-up, showing the positions of the three dipole magnets D1, D2, and D3. The hydrogen cluster-jet injects target material vertically downwards. The Forward Detector (FD) consists of three MWPCs and a hodoscope composed of three layers of scintillation counters.

The COSY COoler SYnchrotron of the Forschungszentrum Jülich is capable of accelerating and storing protons and deuterons with momenta up to 3.7 GeV/c [23]. The ANKE magnetic spectrometer of Fig. 5 used for the charge–exchange reaction study is located at an internal target position that forms a chicane in the storage ring. Although ANKE contains several detection possibilities [24], only those of the Forward Detector (FD) system were used to measure the two fast protons from the $dp \to \{pp\}n$ charge exchange [10], as well as the products associated with the calibration reactions. 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 [25]. The measurements were carried out using a polarised deuteron beam and a hydrogen cluster–jet target [26]. The main trigger used in the experiment consisted of a coincidence of different layers in the hodoscope of the FD. Figure 6 shows the experimental acceptance of ANKE for single particles at $T_d = 1170$ MeV in terms of the laboratory production angle in the horizontal plane and the magnetic rigidity. The kinematical loci for various nuclear reactions are also illustrated. In addition to the protons from the deuteron charge exchange $dp \to \{pp\}n$, of particular interest are the deuterons produced in the quasi–free $dp \to p_{\rm sp} d\pi^0$ reaction with a fast spectator proton, $p_{\rm sp}$. It is important to note that these spectators, as well as those from the deuteron breakup, $dp \to p_{\rm sp}pn$, have essentially identical kinematics to those of the charge–exchange protons. As a consequence, the $(d, 2p)$ reaction can only be distinguished from other processes yielding a proton spectator by carrying out coincidence measurements. Deuterons elastically scattered at small angles are well separated from the other particles in Fig. 6.

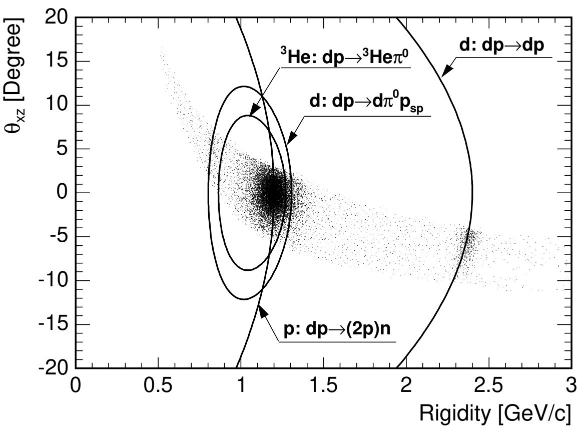

Fig. 6. ANKE experimental acceptance for four nuclear reactions of interest at a deuteron momentum of $p_d = 2400$ MeV/c.

5 Deuteron Polarimetry at ANKE

The polarised deuteron source at COSY provides different combinations of vector and tensor polarisations as well as an unpolarised beam. The EDDA detector is now only used as a proton and deuteron polarimeter and this is only possible at energies where there are calibration standards. The analysing powers for $dp \to dp$ have been well measured at $T_d = 270$ MeV. The EDDA measurements at this energy showed that $P_z \approx 0.74\, P_z^{ideal}$ and $P_{zz} \approx 0.59\, P_{zz}^{ideal}$, where the P^{ideal} are the *ideal* values of the polarisation.

Now, due to their small anomalous magnetic moment, deuterons tend not to depolarise during acceleration – but this has to be checked! It can be seen from the plot of the particle angle versus its momentum in Fig. 6 that it is possible to measure at least four nuclear reactions simultaneously at ANKE, *viz.* $dp \to ^3\mathrm{He}\,\pi^0$, dp elastic scattering, $dp \to (pp)n$, and quasi–free $dp \to d\pi^0$ with a spectator proton [27].

After acceleration to $T_d = 1170$ MeV, the $dp \to p_{sp} d\pi^0$ reaction was measured at $T_n = 585$ MeV/nucleon. Here the p_{sp} = "spectator" proton that is supposed not to take an active part in the reaction. Only events were selected where the spectator (Fermi) momentum in the deuteron rest frame was very small, in which case the vector polarisation of the deuteron was the same as that of the neutron. This therefore allows one to measure quasi–free $np \to d\pi^0$ analysing power as well as its cross section. By charge independence, the neutron analysing power in $np \to d\pi^0$ should be identical to that of the the proton in $pp \to d\pi^+$, for which there are extensive data [12]. The results shown in Fig. 7 are consistent with no depolarisation of the deuteron beam between 270 and 1170 MeV.

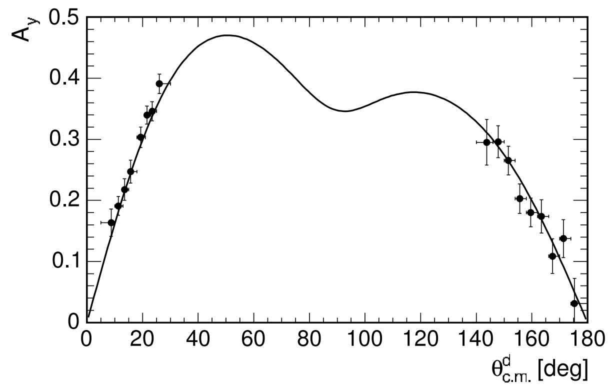

Fig. 7. Analysing power of the $np \to d\pi^0$ reaction measured at ANKE compared to the curve of values of A_y in $pp \to d\pi^+$, as extracted from the SAID database [12].

Elastic deuteron–proton scattering events can be picked out very easily just by looking at the momentum spectrum of a single particle measured in ANKE. This gives rise to the narrow peak at a momentum just a bit lower than that of the beam (2400 MeV/c) in Fig. 8. Since this is a logarithmic scale, the background is very small, as can be seen in the Gaussian fit on a linear scale in the right panel of the figure. The even bigger but wider peak for $p \approx 1200$ MeV/c correspond to protons that arise from the break–up of deuterons which have twice the momentum on average.

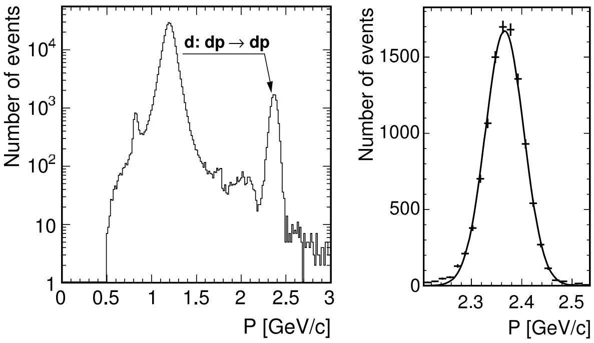

Fig. 8. Left: Single–track momentum spectrum for the dp data at 1170 MeV on a logarithmic scale. Right: Fit result of the elastic peak region with a Gaussian function on a linear scale.

Using just the deuteron identification from the peak in Fig. 8 it was possible to extract values of both the tensor and vector analysing powers of elastic deuteron–proton scattering assuming that the COSY beam polarisations were as given by the EDDA polarimeter. In this way results were found that were compatible with those published at neighbouring energies from Argonne [28] and Saclay [29], as demonstrated in Fig. 9.

The other calibration reaction that can be studied is that of $dp \to {}^3\mathrm{He}\,\pi^0$. Since this is a two-body reaction it shows up as an isolated angle in a plot of ^{3}He angle *versus* momentum. Using the EDDA values of the deuteron polarisations, the results achieved for the forward analysing power was

$$\begin{aligned} A_{yy}^{ANKE}(\theta = 0^\circ) &= 0.461 \pm 0.030 \\ A_{yy}^{SATURNE}(\theta = 0^\circ) &= 0.458 \pm 0.014. \end{aligned} \tag{11}$$

The ANKE data were in complete agreement with those from Saclay [30], where the reaction was only measured in the forward direction.

In summary therefore, the agreement with other data on the three calibration reactions show that, to within a few percent, deuterons do not depolarise inside COSY and so we can now look at the deuteron charge exchange, which is the main goal of the programme.

6 The $dp \to \{pp\}n$ reaction

The results for the tensor analysing powers (A_{ii}) of the $\vec{d}\,p \to \{pp\}n$ reaction at $T_d = 1170$ MeV are shown in Fig. 10 [10]. These are compared with the predictions of the impulse approximation program [20] using as input neutron–proton amplitudes taken from the SAID analysis [12].

The first thing to notice is that, as the excitation energy E_{pp} increases, the analysing powers are reduced a bit. This is because the amount of spin–triplet P-waves in the pp system increases with E_{pp} and, in impulse approximation,

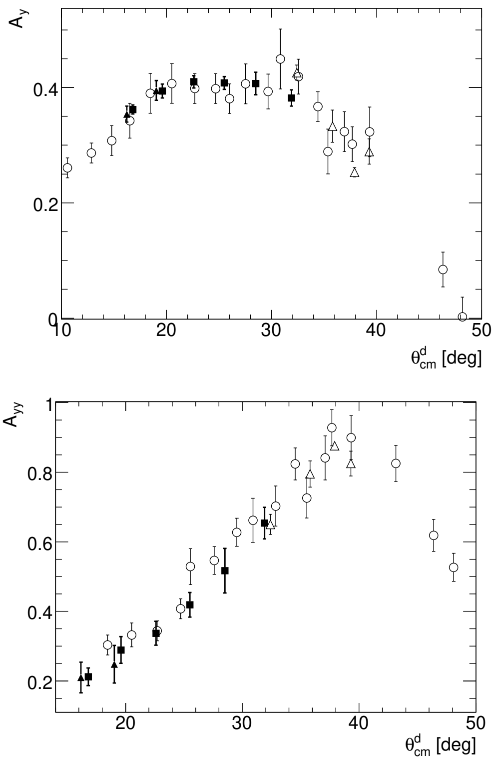

Fig. 9. Vector (upper panel) and tensor analysing powers (lower panel) for elastic deuteron–proton scattering at small forward angles. The ANKE data at 1170 MeV [27] (solid squares) were obtained using information solely from the forward detector system. These data are compared to the results from Argonne at 1194 MeV [28] (open circles) and SATURNE at 1198 MeV [29] (open triangles).

spin–triplet pp waves introduce tensor analysing powers of the opposite sign [5]. This effect can, to some extent, be countered by looking also at the angle between the momentum transfer $\mathbf{q}$ and the pp relative momentum $\mathbf{k}$. When these two vectors are perpendicular, $\mathbf{k}\cdot\mathbf{q} = 0$, spin-triplet final states cannot be excited and so the signal then remains large. This is illustrated in the figure by considering separately the intervals $|\cos\theta| \lessgtr 0.5$. The predicted curves include all final pp partial waves but these are taken as plane waves for angular momenta above $L = 2$ [20].

The precision of these data is such that one can derive ratios of amplitudes that are comparable in statistical accuracy with those that are in the current databases [12]. Thus, at 585 MeV per nucleon, we find

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

Where the amplitudes are well known one gets reliable results.

One obvious question is: what causes the sharp angular dependence that is seen in Fig. 10? If we neglect the deuteron D-state and contamination from P and higher pp waves, all the q dependence must come from the neutron–

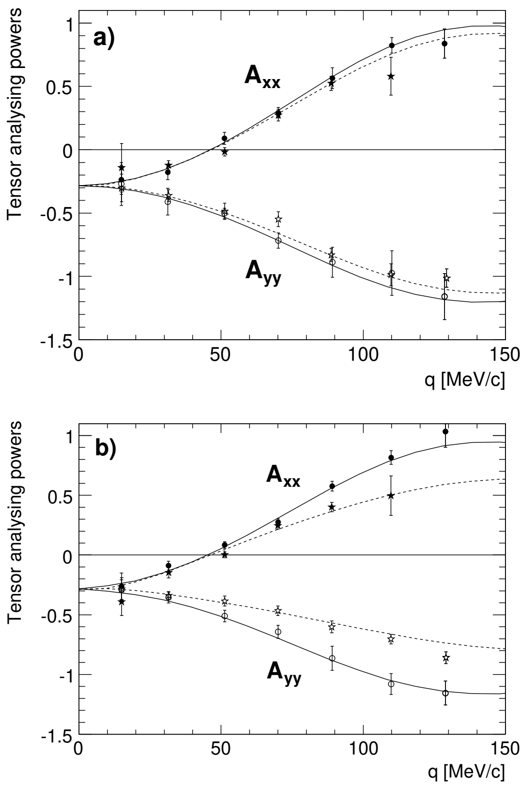

Fig. 10. Cartesian tensor analysing powers A_{yy} (open symbols) and A_{xx} (closed) of the $\mathbf{d}p \to (pp)n$ reaction for a) $0.1 < E_{pp} < 1$ MeV, and b) $1 < E_{pp} < 3$ MeV. The circles correspond to events where $|\cos\theta_{qk}| < 0.5$ whereas the stars denote $|\cos\theta_{qk}| > 0.5$. The solid and broken curves, which involve respectively the same angular selection, follow from the impulse approximation program of Ref. [20], for which the 585 MeV input amplitudes were taken from Ref. [12].

proton charge–exchange amplitudes, which leads to:

$$A_{xx} = \frac{|\beta|^2 + |\gamma|^2 + |\varepsilon|^2 - 2|\delta|^2}{|\beta|^2 + |\gamma|^2 + |\varepsilon|^2 + |\delta|^2},$$
$$A_{yy} = \frac{|\delta|^2 + |\varepsilon|^2 - 2|\beta|^2 - 2|\gamma|^2}{|\beta|^2 + |\gamma|^2 + |\varepsilon|^2 + |\delta|^2}. \quad (12)$$

At $q = 0$ we have $\beta(0) = \delta(0)$ and $\gamma(0) = 0$ and, consequently, $A_{xx} = A_{yy}$ in the forward direction. This is, of course, a general result because in the forward direction we have no way of distinguishing between the x and y directions.

Of greater interest is the fact that the one-pion-exchange amplitude only contributes directly to the δ amplitude. If just to take an undistorted amplitude, then we would find that it went something like:

$$f_{np} \approx \frac{(\sigma_1 \cdot \mathbf{q})(\sigma_2 \cdot \mathbf{q})}{(\mu^2 + q^2)}, \quad (13)$$

where μ is the pion mass. This would vanish in the forward direction and definitely not be acceptable. If, on the other hand, one merely damps the np S-wave one ends up with the model, where the δ amplitude has the form:

$$\delta(q) \approx \delta(0)\,\frac{\mu^2 - q^2}{\mu^2 + q^2}, \quad (14)$$

which is a good approximation to much data.

Notice that, according to Eq.14 the δ amplitude should vanish around $q \approx \mu$. Equation (12) then shows that A_{xx} should approach its maximum value of +1 for $q \approx 140$ MeV/c, which it does in Fig. 10. On the other hand, since it is known that $|\beta| > |\varepsilon|$, it follows that A_{yy} should become large and negative when the momentum transfer is close to the pion mass.

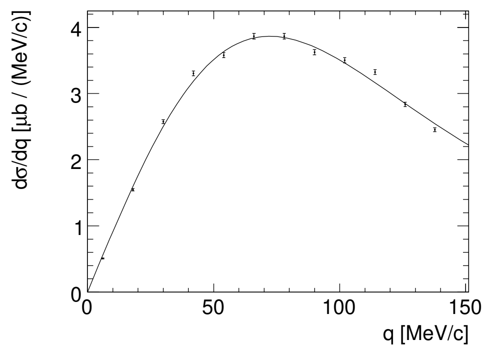

Fig. 11. Unpolarised differential cross section for the $dp \to \{pp\}n$ reaction for $E_{pp} < 3$ MeV [11] compared with the impulse approximation predictions [20].

In order to show that one can extract information about neutron–proton amplitudes and not merely ratios, one has to describe absolute cross sections as well as the analysing powers. By evaluating the luminosity from the quasi–free $np \to d\pi^0$ reaction, the shadow effect in the deuteron (where one nucleon hides behind the other) largely cancels out between the $dp \to \{pp\}n$ and $dp \to p_{sp}d\pi^0$ and this leads to the charge exchange cross section results shown in Fig. 11 for $E_{pp} < 3$ MeV [11]. The agreement with the calculation of the unpolarised cross section in impulse approximation [20] is very encouraging.

Data at $T_d = 2.27$ GeV ($T_n \approx 1.15$ GeV) are currently being analysed and the first *preliminary* results are shown in Fig. 12. Here the neutron–proton amplitudes are not well known and the deviations from the curves predicted on the basis of the current SAID analysis [12] strongly suggest that these data can contribute to the establishment of reliable np amplitudes. The absolute normalisation will be achieved here on the basis of the fast spectator protons since the $pn \to d\pi^0$ cross section is too low at high energies. This work is in progress.

While these proceedings were being prepared the ANKE collaboration has taken the data for the first measurement of spin correlations in the $\vec{d}\vec{p} \to \{pp\}n$ reaction [31]. This was much harder than the earlier experiments because it has conducted with a long polarised gas

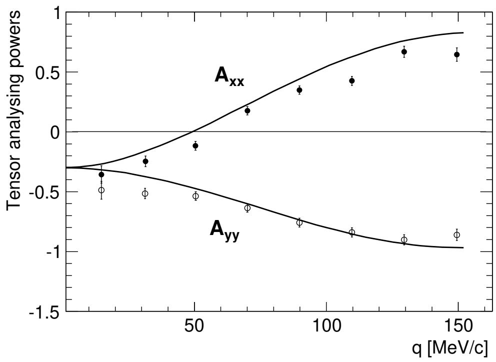

Fig. 12. Cartesian tensor analysing powers A_{yy} (open symbols) and A_{xx} (closed) of the $dp \to (pp)n$ reaction at beam energy of $T_d = 2.27$ GeV for $0 < E_{pp} < 3$ MeV. The The solid curves are the results of the impulse approximation program [20], for which the 1150 MeV input amplitudes were taken from Ref. [12].

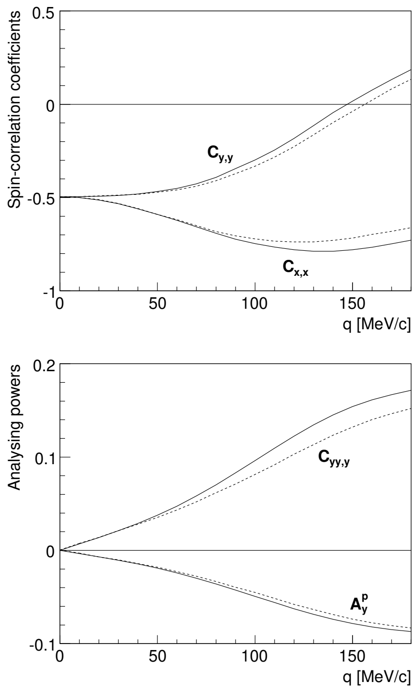

Fig. 13. Predicted vector spin–correlation coefficients (upper panel) and the proton analysing power, as well as the tensor spin–correlation coefficient (lower panel), in the deuteron charge–exchange reaction at 585 MeV/nucleon for cuts in excitation energy of $E_{pp} < 1$ MeV (solid line) and $E_{pp} < 3$ MeV (dashed line) [20].

cell target where the density is low and the vertex is far less well determined. As can be seen from Eq. 10, $C_{y,y}$ is proportional to an interference between the ε and δ amplitudes. As a consequence one can expect much structure in these observables and the impulse approximation predictions at 585 MeV per nucleon for all the observables that are currently measurable at ANKE are shown in Fig. 13.

7 Why stop at the neutron?

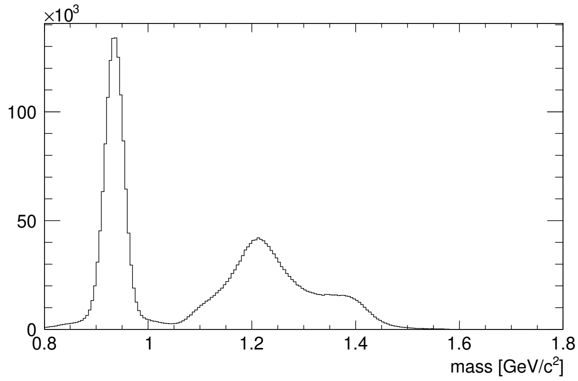

Fig. 14. Numbers of events from the unpolarised $dp \to \{pp\}_S X$ at $T_d = 2.27$ GeV as a function of the missing mass m_X. In addition to the neutron peak, one sees clear evidence for the excitation of the Δ^0 isobar.

It was already shown at Saclay many years ago that at $T_d = 2$ GeV one can also excite the $\Delta(1232)$ isobar in the charge–exchange reaction $\vec{d}\,p \to \{pp\}\Delta^0$ and substantial tensor analysing powers were measured [32]. In impulse approximation, these are also sensitive to a spin–transfer from the neutron to the proton in $np \to p\Delta^0$, which is very hard to measure directly. The Saclay spectrometer SPESIV had a very small acceptance and the experiments are now being repeated at ANKE. It is far too early to quote results but it is seen from Fig. 14 that the $\Delta(1232)$ is seen very clearly in the raw data.

Hence it seems that ANKE will also provide useful information 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 $pd \to \{pp\}\Delta$ with both slow protons in the Silicon Tracking Telescope system (STT) [33] and the products of the $\Delta^0 \to p\pi^-$ in the ANKE magnetic spectrometer.

8 Summary and outlook

- COSY–ANKE can contribute to the pp elastic database for $5° < \theta_{cm} < 30°$ up to the maximum beam energy of ≈ 3 GeV.
- It can contribute to the small angle np charge–exchange database up to 1.1 GeV with a polarised deuteron beam and 3 GeV with a polarised deuterium target.
- Theoretical work is needed to evaluate deuteron corrections to $dp \to \{pp\}n$.
- A lot of data will be taken on small angle np elastic scattering through the measurement of the $dp \to \{pn\}p$ reaction. The deuteron corrections are much larger here and significant theoretical work is going to be needed to disentangle them.
- Production of the $\Delta(1232)$ will also be studied in nearest future in $pd \to \{pp\}\Delta$ channel as well.

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