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Study of the $p\vec{d} \to n\{pp\}_s$ charge-exchange reaction using a polarised deuterium target

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ABSTRACT

The vector and tensor analysing powers, A_y and A_{yy}, of the $p\vec{d} \to n\{pp\}_s$ charge-exchange reaction have been measured at a beam energy of 600 MeV at the COSY-ANKE facility by using an unpolarised proton beam incident on an internal storage cell target filled with polarised deuterium gas. The low energy recoiling protons were measured in a pair of silicon tracking telescopes placed on either side of the target. Putting a cut of 3 MeV on the diproton excitation energy ensured that the two protons were dominantly in the $^1S_0$ state, here denoted by $\{pp\}_s$. The polarisation of the deuterium gas was established through measurements in parallel of proton–deuteron elastic scattering. By analysing events where both protons entered the same telescope, the charge-exchange reaction was measured for momentum transfers $q \geq 160$ MeV/c. These data provide a good continuation of the earlier results at $q \leq 140$ MeV/c obtained with a polarised deuteron beam. They are also consistent with impulse approximation predictions with little sign evident for any modifications due to multiple scatterings. These successful results confirm that the ANKE deuteron charge-exchange programme can be extended to much higher energies with a polarised deuterium target than can be achieved with a polarised deuteron beam.

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It was pointed out several years ago that the charge exchange of polarised deuterons on hydrogen, $\vec{d}p \to \{pp\}_s n$, can furnish useful information on the spin dependence of elastic neutron–proton amplitudes near the backward centre-of-mass direction provided that the final proton pair $\{pp\}_s$ is detected at very low excitation energy E_{pp} [1]. In this limit the diproton is dominantly in the $^1S_0$ state and so there is then a spin–isospin flip from the $(S, T) = (1, 0)$ of the deuteron to the $(0, 1)$ of the diproton. At small momentum transfers between the deuteron and diproton, the deuteron charge-exchange amplitudes can be interpreted in impulse approximation in terms of *np* amplitudes times form factors that reflect the overlap of the deuteron bound-state and the diproton scattering-state wave functions [1].

Following pioneering experiments at Saclay [2,3], the most detailed studies of the $\vec{d}p \to \{pp\}_s n$ reaction were undertaken by the ANKE Collaboration at deuteron energies of $T_d = 1.2$, 1.6, 1.8, and 2.27 GeV, i.e., at energies per nucleon of $T_N = 600$, 800, 900, and 1135 MeV [4,5]. At the three lower energies the predictions [6] of the impulse approximation model describe the data very well on the basis of *np* input taken from the SAID SP07 partial wave solution [7]. Deviations were, however, noted in the 2.27 GeV data [5] that were ascribed to an overestimate of the strength of the *np* spin-longitudinal amplitude at 1135 MeV.

The major constraint on the ANKE programme is the maximum deuteron energy of 2.3 GeV available at the COSY accelerator [8]. To continue the studies at COSY to higher energies, where there is great uncertainty in the neutron–proton amplitudes, the experiments have to be carried out in inverse kinematics, with a proton beam incident on a polarised deuterium target. The study of the charge exchange at low momentum transfers would then require the measurement of two low energy protons recoiling from the target [9]. In order to show that this is a viable approach, the method has first to be tested in a region where there is little ambiguity in the neutron–proton amplitudes. We therefore report here on the first measurement of the $p\vec{d} \to n\{pp\}_s$ charge-exchange at 600 MeV that extends the earlier deuteron beam data out to larger values of the momentum transfer q.

The experiment was carried out using the ANKE magnetic spectrometer [10] situated inside the storage ring of the COoler SYnchrotron (COSY) [11] of the Forschungszentrum Jülich. The whole target facility consists of three major components: the atomic beam source (ABS) [12], the storage cell (SC) [13], and the Lamb-shift polarimeter (LSP) [14].

The ABS is capable of providing deuterium beams with different combinations of vector (Q_y) and tensor (Q_{yy}) polarisations. Four different modes were used in the current experiment with ideal polarisations of $(Q_y, Q_{yy}) = (+1, +1)$, $(-1, +1)$, $(0, -2)$ and $(0, +1)$, where the quantisation axis y is taken to be the upward normal to the plane of the COSY ring. The atomic beams from the ABS are introduced into the storage cell placed inside the ANKE vacuum chamber via a feeding tube and diffuse along the cell that is illustrated in Fig. 1. The Lamb-shift polarimeter, which measures the polarisation of the atomic beam from the ABS, is used for tuning the settings of the ABS before the experiments.

The polarised deuterium gas cell was rather similar to that used in the previous ANKE experiment with polarised hydrogen [5]. The cell was made of 25 μm thick aluminium foil (99.95% Al) with the inner walls coated with Teflon in order to minimise the depolarisation of the deuterium atoms. The cell had dimensions $20 \times 15 \times 390$ mm^3 [13]. Such a cell increases the target thickness by about two orders of magnitude compared to using the ABS jet directly as a target and, as a result, an average luminosity of $L \approx 5\text{–}7 \times 10^{28}$ cm^{-2} s^{-1} was obtained over the ten days of data taking.

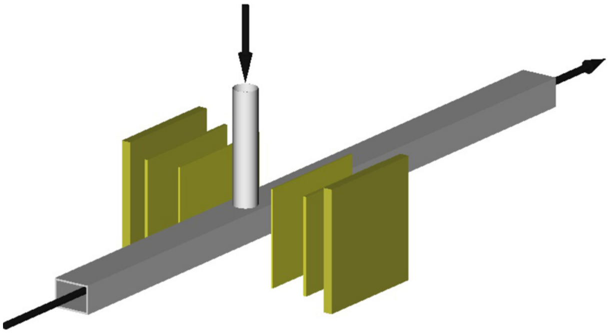

Fig. 1. Schematic view of the ANKE target area showing the positions of the polarised deuterium cell target and its feeding tube and the two Silicon Tracking Telescopes (STT). The COSY beam direction is indicated by the long horizontal arrow.

Though several nuclear reactions can be measured by detecting fast particles that pass through the ANKE magnetic analyser, both the polarimetry and the measurement of the charge-exchange reaction were achieved by detecting only slow particles that emerge from the target cell using a pair of Silicon Tracking Telescopes (STT) [15].

The two STT, each consisting of three double-sided silicon strip layers of 70 μm, 300 μm and 5 mm thickness, were placed symmetrically inside the vacuum chamber, to the left and right of the cell, as shown in Fig. 1. The distances of the sensitive layers away from the target axis were 2.8 cm, 4.8 cm, and 6.1 cm so that maximum angular range that could be covered by an STT with such a cell is roughly $30^\circ < \theta_{\text{lab}} < 150^\circ$. In the case of normal incidence, in order to pass through the three layers, the recoiling protons or deuterons must have energies of at least 2.5 MeV, 6 MeV, and 30 MeV, respectively. For stopping particles the particle identification is unambiguous. Therefore, for elastic or quasi-elastic events, if the recoiling particle is stopped in one of the STT layers, the polar angle is restricted to almost normal incidence. Under such circumstances the effective cell length is comparable to the STT size (around 7 cm). Although the gas from the rest of the cell does not contribute to the counting rate, the long cell helps to increase the target density in the effective region. For proton–deuteron elastic scattering, which is the main polarimetry reaction used for this study, greater precision in the angle of the recoiling deuteron is achieved by deducing it from the energy measured in the telescope rather than from a direct angular measurement.

The experiment was conducted using the pairs of polarisation modes that are defined in Table 1. The ABS was configured in such a way as to provide identical polarised gas densities for the pairs of modes $(1, 2)$ and $(3, 4)$. The target was switched every 10 seconds, first between polarisation modes 1 and 2 and later between 3 and 4. Since the beam was stable on such a short time scale, this procedure ensured equal luminosities for each member of the pair.

Due to the loss of polarisation of the atoms in the target through collisions with the cell walls or through the recombination into molecules, the polarisation of the deuterium in the cell is smaller than that of the atoms coming from the ABS and may also vary along the length of the cell. The values of the target polarisations have therefore to be established under the actual conditions of the experiment and, for this purpose, elastic proton–deuteron scattering was measured, with the recoiling deuteron being detected in the STT. This has the advantage that the relatively small effective cell region is almost identical for the charge-exchange and polarimetry reactions so that the data are primarily sensitive to the average polarisation over this region. Nevertheless, it is very im-

Table 1

The ideal and measured vector and tensor polarisations of the target given in terms of average polarisations, $\langle Q \rangle = (Q_{1(3)} + Q_{2(4)})/2$, and the polarisation differences, $\Delta Q = Q_{1(3)} - Q_{2(4)}$, between the members of the two pairs of polarised modes used in the ANKE experiment. The systematic uncertainties, arising from the analysing powers of the proton–deuteron elastic reaction, are listed separately. It is important to note that the effective target thicknesses are identical in the $(1,2)$ modes, as they are also in the $(3,4)$ modes.

Polarisation	Modes 1, 2			Modes 3, 4		
	Ideal	Measured	Sys. err.	Ideal	Measured	Sys. err.
ΔQ_y	$+2$	1.46 ± 0.01	0.03	0	-0.07 ± 0.01	0.01
$\langle Q_y \rangle$	0	-0.03 ± 0.01	0.01	0	-0.02 ± 0.02	0.01
ΔQ_{yy}	0	0.17 ± 0.02	0.01	-3	-1.68 ± 0.02	0.14
$\langle Q_{yy} \rangle$	$+1$	0.88 ± 0.03	0.11	$-\frac{1}{2}$	-0.13 ± 0.06	0.03

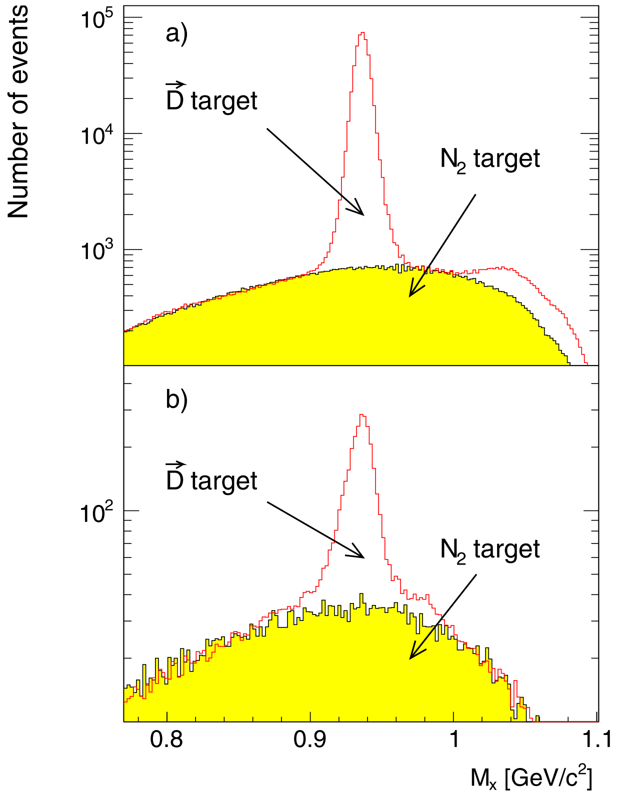

Fig. 2. The missing-mass M_X spectra of the $p\vec{d} \to dX$ (a) and $p\vec{d} \to ppX$ (b) reaction measured in the STT for 600 MeV protons incident on the polarised cell target. In both cases the shape of the background was simulated by filling the cell with unpolarised nitrogen gas.

portant to be sure that the reaction had taken place on the target gas rather than on the aluminium walls. To provide a rapid simulation of this background, the cell was later filled with unpolarised nitrogen gas. As shown in Fig. 2, this gives a very good description of the background away from the missing-mass peaks that are associated with the unobserved proton coming from the deuterium target. In the pd elastic scattering case the background is in any case very low; there is no difficulty at all in identifying elastic events because of the strong link between the angle and the energy deposited in the STT.

The cross section for elastic proton–deuteron scattering is very high near the forward direction but drops fast with momentum transfer q. However, q is very well determined in the STT. There are measurements of both the vector A_y and tensor A_{xx} and A_{yy} analysing powers of the $\vec{d}p \to dp$ reaction with polarised deuteron beams at neighbouring energies to our 600 MeV per nucleon. The data from Argonne at $T_d = 1194$ MeV [16], from SATURNE at $T_d = 1198$ MeV [17,18], and from ANKE at $T_d = 1170$ MeV [19] show large and well-measured analysing powers.

For a two-body reaction, such as $p\vec{d}$ elastic scattering, or a more general process, such as $p\vec{d} \to n\{pp\}_s$, where one does not consider the internal variables of the diproton, the number of particles N scattered at polar angle θ and azimuthal angle ϕ is given by

$$N(\theta,\phi) = N^0(\theta)\left\{1 + \frac{3}{2}Q_y A_y^d(\theta)\cos\phi + \frac{1}{4}Q_{yy}\big[A_{yy}(\theta)(1+\cos 2\phi) + A_{xx}(\theta)(1-\cos 2\phi)\big]\right\}, \tag{1}$$

where ϕ is measured from the horizontal plane of the COSY accelerator. Here N^0 is the corresponding number obtained with an unpolarised target.

The STT [15], which have limited azimuthal acceptance, are placed in the same horizontal plane as the target cell and, under these conditions, only accept events close to $\phi = 0°$ and $180°$. As a consequence, the present measurements are primarily sensitive to the values of A_y and A_{yy} for any reaction. During the experiment the working conditions for the STT were such that the difference between the total efficiencies for different polarised modes in a pair is expected to be very small. This was experimentally verified using background events that were free from polarisation effects. Such events were collected from the vicinity of the missing-mass peak corresponding to the elastic pd scattering of Fig. 2a. By evaluating the ratio of the counts for two members of a polarisation pair, which is directly the product of relative efficiency times the relative luminosity between the two modes, it was shown that the relative efficiency is unity within 1.5%. We note here again that the luminosities are the same for each of the polarisation modes in a given pair of Table 1.

Using the data from the left and right STT, the ratios of the difference to the sum of counts were evaluated for each pair of polarised modes. We describe here the procedure used for modes $(1,2)$; modes $(3,4)$ were treated in a similar fashion. The $(1,2)$ ratios correspond to:

$$\frac{N_1 - N_2}{N_1 + N_2} = \frac{\Delta V + \Delta T}{2(1 + \langle V \rangle + \langle T \rangle)}, \tag{2}$$

where N_1 and N_2 are the number of counts in modes 1 and 2. In terms of polarisation observables,

$$\begin{aligned}
\Delta V &= \frac{3}{2}\Delta Q_y A_y^d(\theta)\cos\phi,\\
\langle V \rangle &= \frac{3}{2}\langle Q_y \rangle A_y^d(\theta)\cos\phi,\\
\Delta T &= \frac{1}{4}\Delta Q_{yy}\big[A_{yy}(\theta)(1+\cos 2\phi) + A_{xx}(\theta)(1-\cos 2\phi)\big],\\
\langle T \rangle &= \frac{1}{4}\langle Q_{yy} \rangle\big[A_{yy}(\theta)(1+\cos 2\phi) + A_{xx}(\theta)(1-\cos 2\phi)\big],
\end{aligned} \tag{3}$$

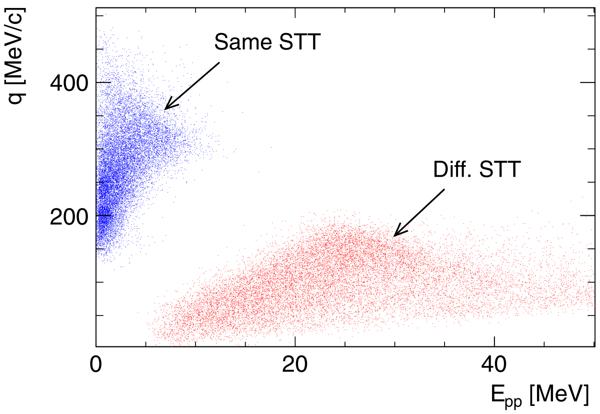

Fig. 3. The three-momentum transfer q versus the pp excitation energy E_{pp} for the $p\vec{d} \to ppX$ events at $T_p = 600$ MeV that fall within $\pm 3\sigma$ of the neutron peak. The data are shown separately for cases where the two protons enter the same (blue) or different (red) STT. The current construction of the STT means that there can be no events where q and E_{pp} are simultaneously small. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

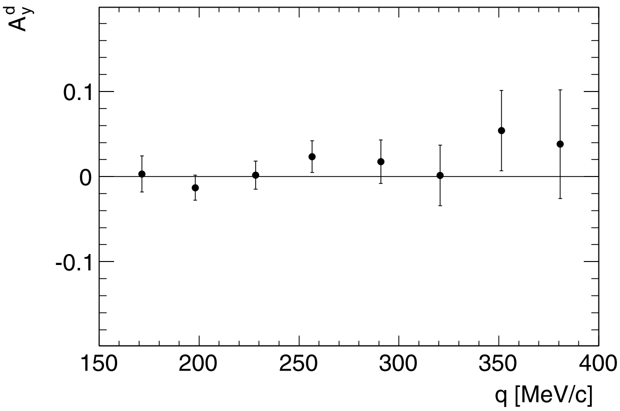

Fig. 4. Deuteron vector analysing power A_y^d of the $p\vec{d} \to n\{pp\}_s$ reaction with an $E_{pp} < 3$ MeV cut. Impulse approximation predictions [6] based upon the SP07 solution for the neutron–proton elastic scattering amplitudes [7] were used to correct for tensor analysing power effects.

where $\Delta Q = Q_1 - Q_2$ and $\langle Q \rangle = (Q_1 + Q_2)/2$ are, respectively, the difference and the average polarisations for the $(1,2)$ pair. The two-dimensional (θ, ϕ) maps were built from these ratios for pd elastic scattering, which were then fitted simultaneously in both variables in order to determine all four polarisation values entering in Eq. (3).

The vector (A_y) and tensor (A_{xx}, A_{yy}) analysing powers used in the polarimetry were taken as weighted averages of the measurements already mentioned [16–19] that were carried out at very close energies per nucleon. Since Eq. (1) shows that the polarised cross section is significantly less sensitive to the tensor than the vector term, Q_{yy} is less well determined than Q_y. The statistical errors presented in Table 1 clearly illustrate this behaviour. Moreover, the systematic uncertainties, arising from the determination of the input analysing powers, are significantly larger for the tensor polarisations. Estimates for these uncertainties are also given in Table 1.

When measuring the $\vec{d}p \to \{pp\}_s n$ reaction with a polarised deuteron beam by detecting the two fast protons in the ANKE forward detector, it was possible to investigate regions where the momentum transfer q between the deuteron and the diproton and the diproton energy E_{pp} were both small [5]. This is no longer the case in inverse kinematics when the two slow protons are measured in the STT. This is due to the requirement that the protons pass through the first silicon layer of the detector. They then have energies above 2.5 MeV, i.e., momenta above about 70 MeV/c. This means that, if the two protons are measured in different STT, then q can be small but $E_{pp} \gtrsim 6$ MeV because the protons are going in opposite directions. On the other hand, if the two protons are measured in the same STT, then E_{pp} can be small but the momentum transfer has a lower limit of $q \gtrsim 2 \times 70$ MeV/c. There is therefore a significant hole in the acceptance, which is demonstrated by the data shown in Fig. 3. This is in complete contrast to the deuteron beam data, where the region where $E_{pp} < 3$ MeV and $0 < q < 140$ MeV/c is routinely accessed [5].

In this letter we report only on results obtained at low E_{pp} for events where the two protons entered the same STT. These data provide a natural continuation from the small q region studied in the deuteron beam measurements [5]. Having detected two protons in one STT the missing mass of the $p\vec{d} \to ppX$ reaction is constructed and an example of this is shown in Fig. 2b. For this three-body final state the measurement errors are larger than for pd elastic scattering and the background from the cell walls can be more problematic. However, the shape of this background is simulated very well by the contribution from the nitrogen gas filling that is also shown. Similar background subtractions were made for all four polarisation modes of Table 1, where the nitrogen normalisation was fixed from fitting outside the peak region.

Data were taken by flipping the target polarisations between modes $(1,2)$ or between $(3,4)$. Since ΔQ_y is largest for the $(1,2)$ pair, this combination provides the best measurement of the deuteron vector analysing power A_y^d in the charge-exchange reaction. Using Eq. (3) for the deuteron charge-exchange reaction, the values of A_y^d were obtained by evaluating the differences between the ratios for left and right STT. This reduces any tensor analysing power signal but, in addition, corrections for any small residual effects were made using impulse approximation predictions [6]. As shown in Fig. 4, for the standard cut of $E_{pp} < 3$ MeV it was found that $A_y^d = 0$ within error bars, with an average over all momentum transfers of $\langle A_y^d \rangle = 0.005 \pm 0.008$. This agrees with theoretical predictions [1] and experimental results at lower momentum transfers [4,5].

The best determination of the tensor analysing power A_{yy} is found by comparing the rates in modes $(3,4)$, which have the same luminosities but tensor polarisations of opposite sign. Using Eq. (2), the values of A_{yy} were obtained separately from the left and right STT data. The two experimental asymmetries, which showed good agreement within error bars, were averaged to produce the final A_{yy} values. The results with the standard E_{pp} cut are shown in Fig. 5, where they are compared with ANKE data at lower momentum transfers [4] and also with impulse approximation predictions [6]. With the $E_{pp} < 3$ MeV cut it is believed that the ${}^1S_0$ state dominates at small q, but P and higher waves become more important as q increases. A tighter cut on E_{pp} would, in principle, be possible since the E_{pp} resolution is around 0.3 MeV for $E_{pp} < 1$ MeV and below 1 MeV for higher E_{pp}. However the count rate drops rapidly with a lower E_{pp} cut and the currently available data might not help in the identification of any possible dilution of A_{yy} by the higher partial waves.

The new A_{yy} results shown in Fig. 5 are very large below about 200 MeV/c but join quite smoothly onto the lower momentum transfer data obtained with the polarised deuteron beam [4]. Furthermore the data seem to be essentially consistent with impulse approximation predictions [6]. However, at such large values of q one has to question to what extent the single scattering of impulse approximation is still quantitatively valid. Formulae have been derived that incorporate the effects of double scattering but only for the ${}^1S_0$ final state [1]. Such terms have little effect for momen-

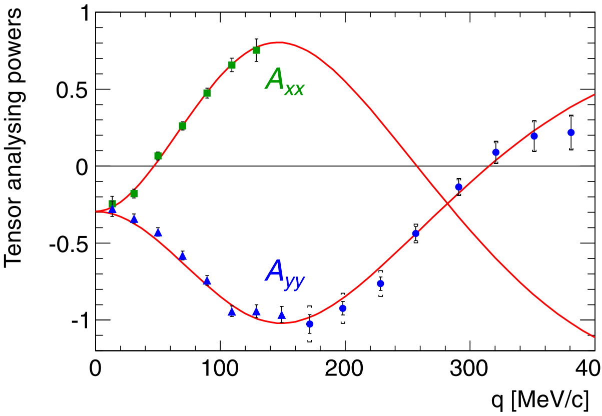

Fig. 5. Tensor analysing powers A_{xx} (green squares) and A_{yy} (blue triangles) of the $\vec{d}p \to \{pp\}_s n$ reaction with $E_{pp} < 3$ MeV from the earlier deuteron beam measurements at 600 MeV/nucleon [4]. These data were restricted to the region $q < 160$ MeV/c. The current A_{yy} results (blue dots), which provide data in the region $q > 160$ MeV/c, were obtained in inverse kinematics using a 600 MeV unpolarised proton beam incident on a polarised deuterium target. The extended error bars indicated by ⊔ and ⊓, which are important in the STT data below 250 MeV/c, include the effects arising from the uncertainties in the target polarisations. The curves are impulse approximation predictions [6] based upon the SP07 solution for the neutron–proton elastic scattering amplitudes [7].

tum transfers below 140 MeV/c where A_{yy} has its minimum but double scattering in the $^1S_0$ limit tends to push the momentum transfer for which A_{yy} crosses zero down by about 20 MeV/c. On the other hand, double scattering will be far less important for P and higher waves in the pp system and so the 20 MeV/c shift must be considered as very much an upper limit. More detailed calculations are in progress.

Data taken with two separate STT have necessarily large E_{pp}, which will generally reduce the analysing power signal through the excitation of higher partial waves [6]. Unfortunately, the data so far obtained have very limited statistics and could not usefully determine the tensor analysing power at high E_{pp}.

Having shown that a polarised deuterium cell can be successfully used for charge-exchange studies in an energy region where the neutron–proton amplitudes are well understood, measurements at higher energies are scheduled for the near future. These will also include studies with polarised proton beams in order to determine spin-correlation coefficients. Another attractive possibility is to measure in coincidence fast protons or pions in the ANKE magnetic spectrometer. These would allow one to study in details the $\{pp\}_s\Delta^0(1232)$ final state, where the decay $\Delta^0(1232) \to \pi^- p$ defines the alignment of the isobar [8].

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