First measurements of spin correlations in the $\vec{n}\vec{p} \to d\pi^0$ reaction

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Abstract

The transverse spin correlations $A_{x,x}$ and $A_{y,y}$ in the $\vec{n}\vec{p} \to d\pi^0$ reaction have been measured for the first time in quasi-free kinematics at the COSY-ANKE facility using a polarised deuteron beam incident on a polarised hydrogen cell target. The results obtained for neutron energies close to 353 MeV and 600 MeV are in good agreement with the partial wave analysis of data on the isospin-related $pp \to d\pi^+$ reaction, though the present results cover also the small-angle region, which was largely absent from these data.

Key words: Pion production, Spin correlations
PACS: 13.75.-n, 14.40.Be, 25.40.Qa

It follows from isospin invariance that the cross section for $np \to d\pi^0$ should be half of that for $pp \to d\pi^+$ but all the spin observables should be identical for the two reactions. However, there have been relatively few measurements of the neutron-induced cross section [1,2] and even less is known about the spin dependence.

In contrast, the $pp \to d\pi^+$ reaction has long provided a test bed for countless phenomenological models of pion production at intermediate energies, some of which are summarised in Refs. [3,4]. In more recent years the reaction has also been frequently discussed within the framework of chiral perturbation theory [5]. The available data set is very large, with measurements of the cross section, analysing powers, spin correlations and spin transfers in both the direct and inverse channel and these have allowed partial wave analyses to be attempted for proton beam energies $T_p < 1.3$ GeV [6].

There have been several measurements of the longitudinal $A_{z,z}$ and the transverse spin correlation $A_{y,y}$ in the $\vec{p}\vec{p} \to d\pi^+$ reaction, sometimes leading to inconsistent results [6], but meaningful data on $A_{x,x}$ are much rarer [7]. If one keeps only the dominant S-wave $\Delta(1232)N$ intermediate state then $A_{x,x} = A_{y,y} = A_{z,z} = -1$ in the forward direction and so it is not surprising that the measured values of these observables are strongly negative at intermediate energies. The combination $A_{x,x} + A_{y,y} - A_{z,z} + 1$ must vanish when the pion c.m. polar angle $\theta_\pi = 0°$ or $90°$ and deviations from this at arbitrary angles only arise from pion d or higher waves. As a consequence, quite generally $A_{x,x}$ can never be positive in the forward direction [8].

In a free two-body or quasi-two-body reaction, such as $np \to d\pi^0$ or $np \to \{pp\}_s\pi^-$, we take the beam direc-

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Preprint submitted to Elsevier   Received: 10 July 2013/ Revised version:

tion to lie along the z-axis and the momentum of the produced pion in the c.m. to be $\boldsymbol{p}_\pi = (p_\pi^x, p_\pi^y, p_\pi^z) = p_\pi(\sin\theta_\pi\cos\phi_\pi, \sin\theta_\pi\sin\phi_\pi, \cos\theta_\pi)$. If the target Q and beam P polarisations are in the y direction then the dependence of the differential cross section on the pion azimuthal angle φ_π is given by

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega}\right)_0 \left[1 + (PA_y^P + QA_y^Q)\cos\varphi_\pi \right. \\ \left. + PQ\left(A_{y,y}\cos^2\varphi_\pi + A_{x,x}\sin^2\varphi_\pi\right)\right]. \quad (1)$$

The unpolarised c.m. differential cross section $(d\sigma/d\Omega)_0$ and the beam A_y^P and target A_y^Q analysing powers, as well as the spin-correlation parameters $A_{x,x}$ and $A_{y,y}$, are all functions of θ_π.

However, for a quasi-free reaction induced by an incident deuteron, the neutron direction is not precisely aligned along that of the beam due to the Fermi motion in the deuteron. This introduces an incident angle that can be several degrees in the laboratory system. In order to correct for this effect, the three-momentum of the incident neutron is reconstructed on an event-by-event basis. Nevertheless, any small P_z and Q_z components arising in such a quasi-free measurement are neglected.

A second effect of the Fermi motion, especially its longitudinal component, is that in a quasi-free reaction the c.m. energy $\sqrt{s}$ is not unambiguously fixed by the incident beam energy. Although in our case the effective beam energy $T_{\rm neutron} = [s-(m_p+m_n)^2]/2m_p$ is constructed for every event, the limited statistics and the finite resolution mean that data must be grouped over a relatively wide energy range.

Two experiments were carried out at the COoler SYnchrotron (COSY) at the Forschungszentrum Jülich using the ANKE magnetic spectrometer [9], which is sited at an internal target position of the accelerator. Though the purposes of the measurements were different, the apparatus and analysis techniques were quite similar. The first used transversally polarised 726 MeV deuterons to investigate the spin-correlation in the $\vec{n}\vec{p} \to \{pp\}_s\pi^-$ reaction in the vicinity of $T_{\rm neutron} \sim 353$ MeV, where the diproton $\{pp\}_s$ is dominantly in the $^1S_0$ state [10]. The second used 1,200 MeV deuterons to study the $\vec{d}\vec{p} \to \{pp\}_s n$ reaction at around 600 MeV per nucleon, as a precursor for measuring np charge-exchange amplitudes at higher energies [11].

The apparatus was described in great detail in the two publications [10,11] and only the salient points are discussed here. The spectrometer consists of two dipole magnets D1 and D3, which deflect the circulating deuteron beam from and back to the nominal orbit, respectively. The main dipole D2 is used to analyse the momenta of charged particles produced in a nuclear reaction. Only the ANKE Forward Detector (FD) [12,13] was needed to study the $np \to d\pi^0$ reaction in both of these experiments.

A measurement of a spin correlation requires both a polarised beam and target. Although a polarised target could be provided directly in the form of a jet from the polarised Atomic Beam Source (ABS) [14], much higher densities can be achieved if this is used to feed a storage cell. Cells of dimensions $x \times y \times z = 19 \times 15 \times 390\ \mathrm{mm}^3$ (at 726 MeV) and $20 \times 15 \times 370\ \mathrm{mm}^3$ (at 1,200 MeV) were constructed from 25 μm Teflon-coated aluminium. Here z is measured along the beam direction with x and y referring to the horizontal and vertical transverse directions, respectively.

Having registered two fast charged particles in the forward detector, deuteron-proton pairs were isolated by comparing the difference between their arrival times in the FD with that predicted from the reconstructed three-momenta of the particles. At 726 MeV this was confirmed by the energy loss in the forward hodoscope. In order to enhance the quasi-free nature of the reaction, only events where the kinetic energy of the detected proton in the rest frame of the incident deuteron was below 6 MeV were retained. In this case it is expected that this is a *spectator* proton, $p_{\rm spec}$, that only influences the reaction through the kinematics. The distributions in the proton momenta, which are shown explicitly in Refs. [10,11], are consistent with this interpretation.

After putting a cut on the spectator momentum, the $dp \to dp_{\rm spec}\pi^0$ reaction was finally identified from the missing-mass peak in the $dp \to dp_{\rm spec}X$ data, which is illustrated for the two energies in Fig. 1. The vertex position is clearly less well determined when using a long cell rather than a point target and there can also be contamination arising from the beam halo striking the cell walls. The shape of this missing-mass background was simulated by filling the cell with nitrogen gas. This was then fitted outside the peak region and subtracted to reveal the π^0 signal.

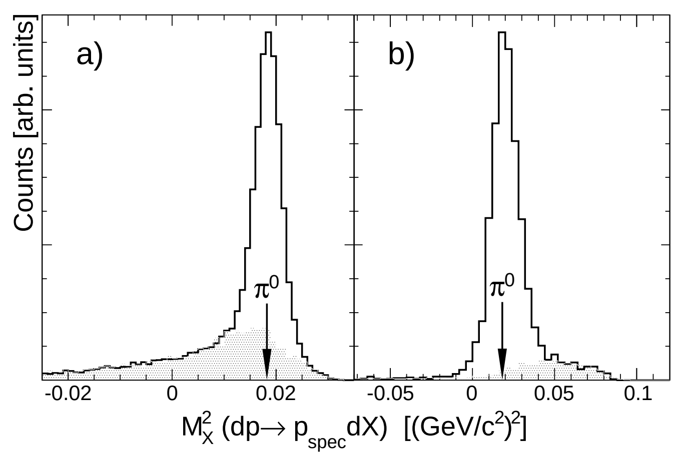

Fig. 1. Comparison of the $(d, dp_{\rm spec})$ missing-mass-squared distributions when using a polarised hydrogen target (solid lines) or filling the cell with nitrogen gas (shaded area). a) $T_d = 726$ MeV, b) $T_d = 1,200$ MeV.

The distributions in effective neutron beam energy for all the $dp \to p_{\rm spec}dX$ events that fall within the $\pm 2.5\sigma$ of the π^0 peaks in Fig. 1 are shown in Fig. 2. In the data analysis the wings of the distributions were cut and only data in the regions $333 < T_{\rm neutron} < 373$ MeV and $500 < T_{\rm neutron} < 700$ MeV were retained. In the first case the average neutron energy varied between 351 MeV and 357 MeV, being lowest for $\theta_\pi \approx 90^\circ$. The smaller angular range at the higher energy resulted in much smaller deviations from the overall average value of 600 MeV.

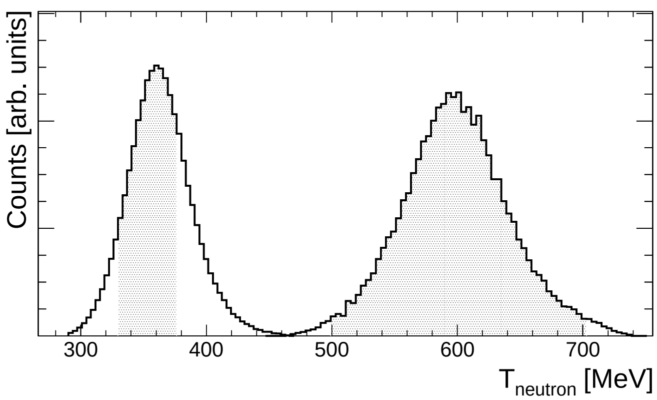

Fig. 2. Effective neutron beam energies for the quasi-free $np \to dX$ reaction obtained with a 6 MeV spectator energy cut for those events that fall within the $\pm 2.5\sigma$ of the π^0 peaks in Fig. 1. The results from the two experiments are shown on the same plot and data within the shaded areas were retained in the analysis. These correspond to $333 < T_{\text{neutron}} < 373$ MeV and $500 < T_{\text{neutron}} < 700$ MeV for the two beam energies.

The analysing power in the $np \to d\pi^0$ reaction [6] can be used to estimate the average polarisation Q of the hydrogen in the target cell. In the 600 MeV experiment an unpolarised deuteron beam was part of the three-polarisation-mode cycle [11] but only a small fraction of the data were taken with unpolarised hydrogen in the cell. Using an extended data set we find $Q^\uparrow = 0.59 \pm 0.07$ and $Q^\downarrow = -0.79 \pm 0.10$ [11], though it must be stressed that the uncertainty in $Q^\uparrow - Q^\downarrow$, which does not depend on the unpolarised target data, is much less than those of the individual modes. The analogous figures at 353 MeV are $Q_\uparrow = 0.59 \pm 0.07$ and $Q_\downarrow = -0.70 \pm 0.11$ [10]. The consistency of these results suggests that the polarisation of the gas in the target cell fed by the ABS is reproducible, though one cannot rely on this when determining the spin-correlation in a reaction.

The beam polarisations were also estimated using the asymmetry observed in the $dp \to p_{\text{spec}} d\pi^0$ reaction. However, it should be noted that the selection of the polarisation modes for the deuteron beam was influenced by the purposes of the principal experiments in the two cases. At 353 MeV, two modes with nominal deuteron vector polarisations of $\pm\frac{2}{3}$ were chosen with zero deuteron tensor polarisation. The measured neutron polarisations in the deuteron beam were $P_\uparrow = 0.55 \pm 0.08$ and $P_\downarrow = -0.45 \pm 0.08$ [10].

In order to avoid complications arising from tensor polarisation components of the deuteron beam, only the unpolarised and the nominal $(P_y, P_{yy}) = (-\frac{2}{3}, 0)$ modes were taken into account at 600 MeV and the latter gave rise to a neutron polarisation that was measured to be $P_\downarrow = -0.51 \pm 0.05$ [11].

The values obtained for the average of the product of the beam and target polarisations using the above data do not have sufficient precision to provide the best measurements of a spin correlation. Though both the beam and target polarisations seemed stable to better than 10%, we must also guard against the possibility that these vary with time in different ways so that the average of the product might differ from the product of the averages. In both experiments one can use other reactions that are directly sensitive to the average of PQ, where $Q \equiv |Q_\uparrow - Q_\downarrow|/2$, and similarly for P.

By imposing the condition on the $\vec{n}\,\vec{p} \to \{pp\}_s\pi^-$ measurement that $A_{y,y} = 1$ at 353 MeV, an average $PQ = 0.373 \pm 0.015$ was obtained [10]. At 600 MeV per nucleon the theoretical predictions [15] for the transverse spin correlation at small momentum transfers in the $\vec{d}p \to \{pp\}_s n$ reaction yielded $PQ = 0.372 \pm 0.010$. The error bar here includes the uncertainty in the correction coming from the difference between $|Q_\uparrow|$ and $|Q_\downarrow|$ but it does not reflect the uncertainty in the reaction model nor in the neutron-proton charge-exchange amplitudes [16] used in the estimations. By looking at the quality of the predictions of other charge-exchange observables at this energy [11], it is estimated these contribute to a systematic uncertainty in the value of PQ of up to 10%.

The procedures for extracting the values of the spin correlations are very similar to those used to obtain $A_{x,x}$ and $A_{y,y}$ for the quasi-free $\vec{n}\vec{p} \to \{pp\}_s\pi^-$ reaction at 353 MeV [10] or $\vec{d}\vec{p} \to \{pp\}_s n$ at 600 MeV per nucleon [11]. In both cases the φ_π dependence of Eq. (1) has to be fitted in order to extract $A_{x,x}$ and $A_{y,y}$ separately. At 600 MeV per nucleon, the limited ANKE angular acceptance, especially in the vertical direction, means that only the near-forward or backward regions were covered and this problems becomes more severe for $A_{x,x}$. The results in this case, shown in Fig. 3, are in reasonable agreement with the predictions of the SAID $pp \to d\pi^+$ partial wave analysis [6] averaged over the neutron energy distribution shown in Fig. 2 [1]. In addition to the statistical errors, which include those arising from the background subtraction, the systematic uncertainties are shown by shaded bands. The effects considered, which can vary significantly in importance between 353 and 600 MeV, include uncertainties in the relative luminosities, in the polarisation product PQ, in the influence of the longitudinal polarisations arising from the Fermi motion, and that of the finite range in T_{neutron}. These have been compounded quadratically. In contrast, no significant effects resulted from any differences between the up and down polarisations nor from the resolution or binning.

It should be noted that there are no measurements at all of $A_{x,x}$ for $\vec{p}\vec{p} \to d\pi^+$ in the vicinity of 600 MeV and those for $A_{y,y}$ are generally at larger angles [7,17], as shown in Fig. 3b. The large negative values obtained in the forward direction are to be expected because at 600 MeV there is sufficient energy to produce a $\Delta(1232)$ plus a nucleon at

[1] Due to the nearly linear energy behaviour, the energy averaging is actually of little importance here provided that the predictions are made at the mean beam energy of 600 MeV.

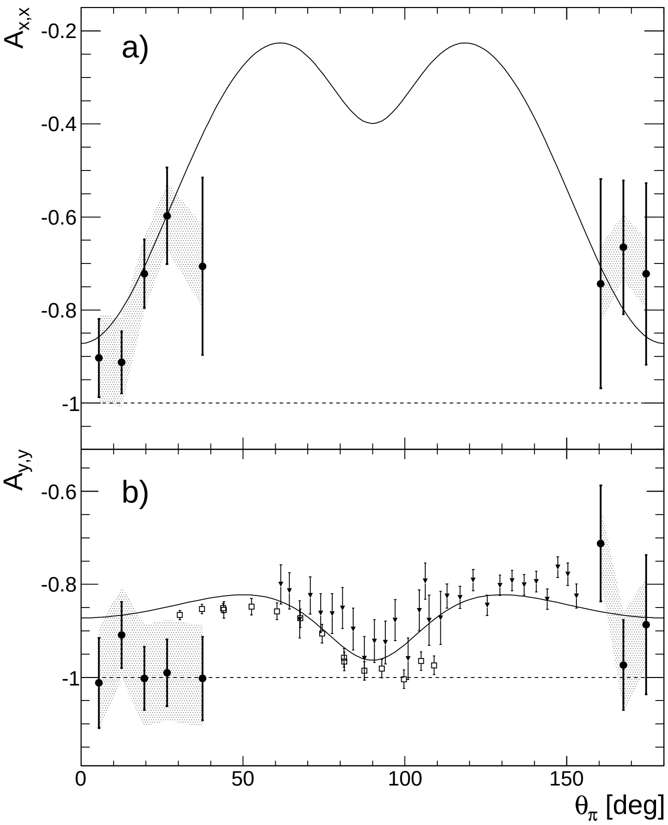

Fig. 3. The values of a) $A_{x,x}$ and b) $A_{y,y}$ measured in the $\vec{n}\vec{p} \to d\pi^0$ at energies around 600 MeV as a function of the pion polar angle θ_π in the c.m. frame. Statistical uncertainties are shown with error bars; systematic uncertainties are illustrated with shaded bands. The results are compared with the SAID predictions [6], which have been weighted with the measured energy distribution. Also shown are the PSI $\vec{p}\vec{p} \to d\pi^+$ results at 578 MeV (closed triangles) [7] and those of LAMPF at 593 MeV (open squares) [17]. The systematic uncertainties in these cases are between 5% and 10%.

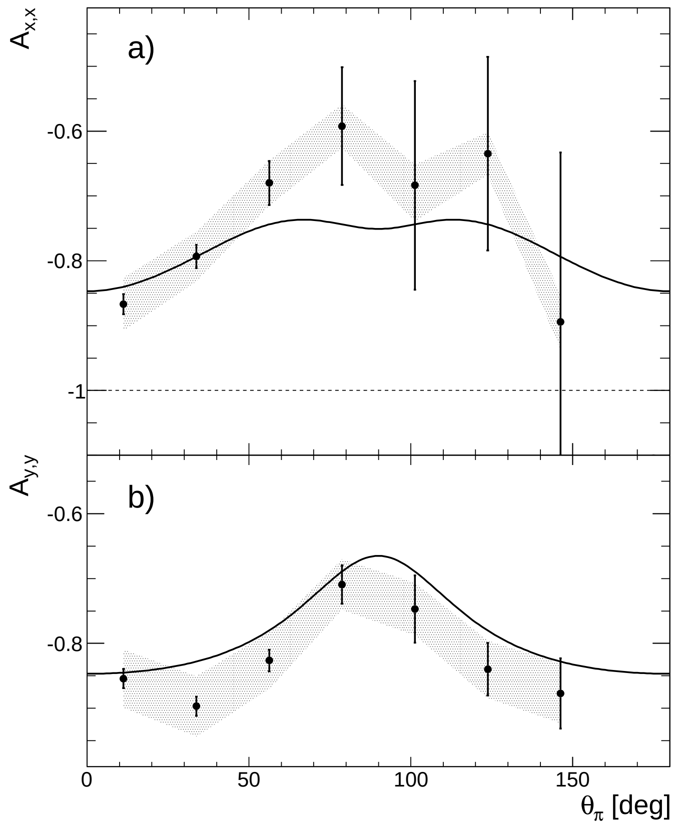

Fig. 4. Data obtained around 353 MeV, with the same conventions as in Fig. 3. Statistical uncertainties are shown with error bars; systematic uncertainties are illustrated with shaded bands. Published data with very large error bars [18] are not displayed.

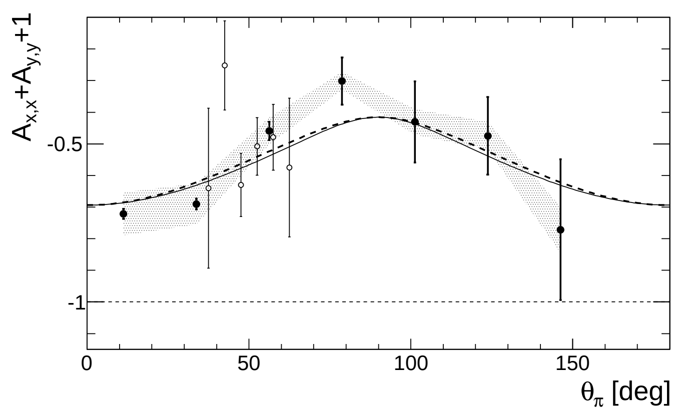

Fig. 5. The combination $1 + A_{x,x} + A_{y,y}$ measured in the $\vec{n}\vec{p} \to d\pi^0$ reaction at 353 MeV as a function of θ_π compared with the SAID $\vec{p}\vec{p} \to d\pi^+$ predictions (dashed curve) [6]. Statistical uncertainties are shown with error bars; systematic uncertainties are illustrated with shaded bands. Also presented are IUCF data for $A_{z,z}$ taken at 350 MeV for the $\vec{p}\vec{p} \to d\pi^+$ reaction (open circles) [18] and the SAID prediction for this observable (solid curve).

rest in the c.m. frame and such an intermediate state would lead to $A_{x,x} = -1$ at $\theta_\pi = 0°$.

The situation is qualitatively different for the 353 MeV data shown in Fig. 4 for there ANKE covers far more of the angular distribution. It is also very different in that at such a low energy s-wave pion production plays a more important role. The larger statistics allows a tighter cut to be placed on T_{neutron} and our measurements of both observables are well described by the current SAID partial wave solution [6]. However, the existing data for $A_{x,x}$ and $A_{y,y}$ for the $\vec{p}\vec{p} \to d\pi^+$ reaction at low energy have error bars as large as the signal [18] and thus provide little constraint on the partial wave solution.

The measurements of the $\vec{p}\vec{p} \to d\pi^+$ longitudinal spin correlation $A_{z,z}$ at 350 MeV are more precise [18] and we compare these in Fig.5 with the values that we have obtained for $1 + A_{x,x} + A_{y,y}$ for the $\vec{n}\vec{p} \to d\pi^0$ reaction at 353 MeV. These two quantities coincide exactly at $\theta_\pi = 0°$ and 90° and they will be equal more generally if one neglects pion d-waves, which should be a good approximation at these low energies. The agreement with both these data and the predictions of the SAID partial wave analysis is very reasonable.

We have presented here measurements of the $A_{x,x}$ and $A_{y,y}$ spin correlation coefficients for the $\vec{n}\vec{p} \to d\pi^0$ reaction at two energies, one close to threshold where the s-wave pion production is important and the other in a region where p-wave production is dominant, being largely driven by the S-wave $\Delta(1232)N$ intermediate state. All our data are consistent with the current SAID solution for $pp \to d\pi^+$, though our measurements cover the small angle region that is largely absent from existing $\vec{p}\vec{p} \to d\pi^+$ data. No sign is found for any breaking of isospin invariance.

The forward direction is in a region that is well suited for measurements with ANKE and there is a particularly simple interpretation of the results there. The value of $A_{x,x}$ at $\theta_\pi = 0^\circ$ determines unambiguously the ratio of the production of odd pion partial waves from an initial spin-singlet NN system to that for even partial waves that come from spin-triplet initial states.

We are grateful to other members of the ANKE Collaboration for their help with the experiment and to the COSY crew for providing such good working conditions. This work has been supported by the COSY FFE, the Shota Rustaveli National Science Foundation, the Heisenberg-Landau programme, and the European Union Seventh Framework Programme under grant agreement n°283286.

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