



## Coherent pion production in proton–deuteron collisions



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### ABSTRACT

Values of the proton analysing power in the  $pd \rightarrow {}^3\text{He}\pi^0/{}^3\text{H}\pi^+$  reactions at 350–360 MeV per nucleon were obtained by using a polarised proton beam incident on a deuterium cluster-jet target and with a polarised deuteron beam incident on a target cell filled with polarised hydrogen. These results have a much larger angular coverage than existing data. First measurements are also presented of the deuteron vector analysing power and the deuteron–proton spin correlations. Data were also obtained on the deuteron–proton spin correlation and proton analysing power at small angles at 600 MeV per nucleon, though the angular coverage at this energy was much more restricted even when using a deuteron beam. By combining the extrapolated values of the spin correlations to the forward or backward directions with published measurements of the deuteron tensor analysing powers, the relative phases between the two non-vanishing amplitudes were evaluated.

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The simplest coherent pion production reaction, where all the final nucleons are bound in a nucleus, is  $pp \rightarrow d\pi^+$  and the associated literature is very extensive and the database enormous [1]. However, because of the identical nature of the two initial protons, odd and even pion waves do not interfere in the differential cross

section which, as a consequence, is symmetric around  $90^\circ$  in the centre-of-mass (c.m.) frame. The first more general coherent pion production reaction is  $pd \rightarrow {}^3\text{He}\pi^0$ , where striking effects arising from the interference between  $s$  and  $p$  partial waves are observed in the differential cross section even very near threshold [2,3].

Since there is only one isospin amplitude, the cross section for  $pd \rightarrow {}^3\text{H}\pi^+$  should be twice that for  $pd \rightarrow {}^3\text{He}\pi^0$  but all the polarisation observables should be identical for the two reactions. On the other hand, the  $\frac{1}{2}^+1^+ \rightarrow \frac{1}{2}^+0^-$  spin structure leads to six

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independent amplitudes, all of which are functions of the pion production angle. There are therefore a very wide range of possible experiments, which have been discussed in detail by Uzikov [4]. The observables that are accessible at the COSY accelerator involve the polarisations of the incident particles and measurements have been made of the proton and deuteron vector analysing powers and the proton–deuteron vector spin correlations.

Measurements of the differential cross section and proton analysing power for  $\bar{p}d \rightarrow {}^3\text{He}\pi^0$  were undertaken at TRIUMF at 350 MeV [5], though the acceptance of their spectrometer was very limited near the forward and backward directions. The cross section data show a steep but rather featureless drop from the forward (small c.m. angle  $\theta_\pi^{\text{cm}}$  between the proton and the pion) to the backward directions and this was confirmed by later measurements by the GEM collaboration [6,7]. Much more structure is, however, seen in the distribution of the corresponding analysing power [5]. In addition to improving significantly the angular coverage of these TRIUMF data, we show for the first time data on the deuteron–proton vector spin correlations and the deuteron vector analysing power. It is hoped that these new observables will stimulate further theoretical work.

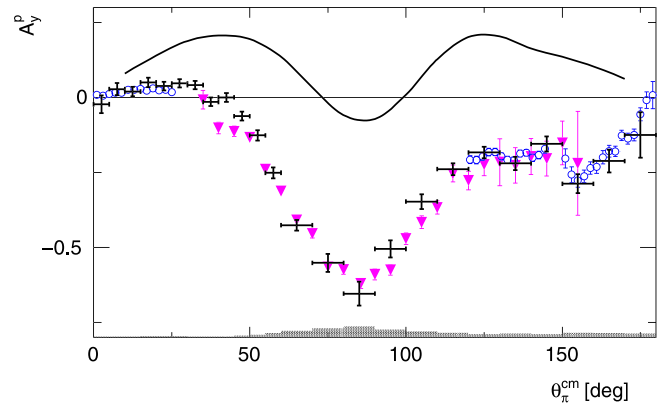
The data that we report here came as by-products of measurements of quasi-free pion production in proton–neutron collisions using a deuterium target [8] and deuteron beam [9] in the region of 353–363 MeV per nucleon and also deuteron charge exchange at 600 MeV per nucleon [10]. The experimental conditions, including the crucial determination of the beam and target polarisations, were already described in these publications so that we can here be relatively brief.

The experiments were carried out at the ANKE spectrometer facility [11], which is installed inside the COSY cooler synchrotron storage ring of the Forschungszentrum-Jülich. The proton analysing power was first studied by using a polarised 353 MeV proton beam incident on a deuterium cluster-jet target [12]. The polarisation of the circulating proton beam,  $|p| = 0.66 \pm 0.06$ , was reversed in direction every six minutes.

The triton or  ${}^3\text{He}$  from the  $pd \rightarrow {}^3\text{H}\pi^+ / {}^3\text{He}\pi^0$  reaction was registered in the ANKE Forward Detector (FD). The FD comprises a set of multiwire proportional and drift chambers and a two-plane scintillation hodoscope [13]. The data were collected with a dedicated trigger for high energy losses in one of the counters of the first hodoscope plane.  ${}^3\text{He}$  and tritons were then selected using the calibrated energy loss in the hodoscope and the particle momentum, which was reconstructed from the MWPC information. All  ${}^3\text{He}$  and low energy tritons, which fly backwards in c.m. frame, stopped in the first plane of the hodoscope. However, the fast (forward-going) tritons reached the second plane and in this case the time of flight between the planes was used as an additional criterion for the particle identification. The pion was finally identified through the missing mass in the reaction.

Since 353 MeV is far above the threshold for the  $pd \rightarrow {}^3\text{H}\pi^+ / {}^3\text{He}\pi^0$  reactions, there is no acceptance in ANKE for events in the central region of c.m. angles. Nevertheless the angular coverage was maximised by combining the spin-dependent data associated with fast  ${}^3\text{He}$  and both fast and slow  ${}^3\text{H}$ .

Isospin invariance requires that the ANKE results for the proton analysing power should be identical for  ${}^3\text{H}$  and  ${}^3\text{He}$  detection and these data are compared with the TRIUMF values [5] in terms of the c.m. angle  $\theta_\pi^{\text{cm}}$  between the initial proton and final pion. Though the data sets are consistent, the ANKE results define the behaviour for small and large  $\theta_\pi^{\text{cm}}$  more clearly and with much higher statistics. Despite the smooth behaviour of the differential cross sections with angle, the rich structure in  $A_y^p$  indicates that many partial waves with different phases contribute actively at this



**Fig. 1.** TRIUMF data on the proton analysing power  $A_y^p$  in the  $\bar{p}d \rightarrow {}^3\text{He}\pi^0$  reaction at 350 MeV [5] (magenta triangles) are compared to ANKE results at 353 MeV (blue open circles) obtained by detecting fast  ${}^3\text{He}$  ( $\theta_\pi^{\text{cm}} \gtrsim 150^\circ$ ) and  ${}^3\text{H}$  ( $120^\circ \lesssim \theta_\pi^{\text{cm}} \lesssim 145^\circ$ ), and slow  ${}^3\text{H}$  ( $\theta_\pi^{\text{cm}} \lesssim 25^\circ$ ). We do not include here the 9% systematic error that is mainly associated with uncertainties in the COSY beam polarisation. Also shown are the ANKE values at 363 MeV per nucleon deduced from measurements with a deuteron beam incident on a long cell filled with polarised hydrogen gas (black crosses). The shaded area indicates the systematic uncertainties in the deuteron beam measurements. There is no evidence for any violation of isospin invariance, which requires that the analysing powers measured with  ${}^3\text{He}$  and  ${}^3\text{H}$  detection should be identical. The curve corresponds to the predictions by Falk in a cluster-model approach [14,15]. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

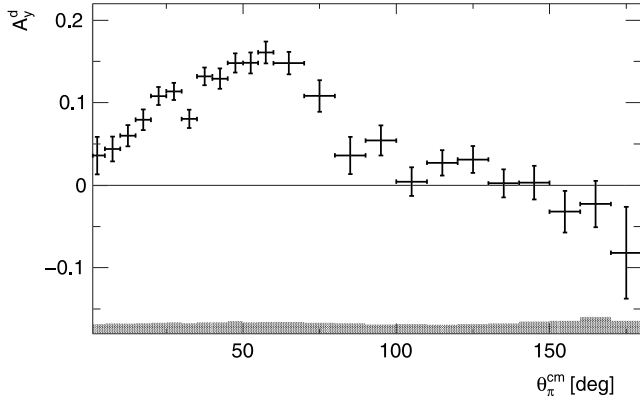
energy. The general behaviour of  $A_y^p$  is also confirmed by ANKE measurements with a polarised hydrogen cell, to which we now turn.

In the experiment with the deuteron beam at an energy of 726 MeV, the forward boost coming from the higher beam momentum means that all the  ${}^3\text{He}$  and  ${}^3\text{H}$  reached the second layer of the FD and so the timing information associated with hits in the first and second layers of this detector is even more critical. The forward boost also increases significantly the angular acceptance. Only vector polarisation modes of the deuteron source were used and these had ideal values of  $p_\uparrow = \frac{2}{3}$  and  $p_\downarrow = -\frac{2}{3}$  in the  $y$  direction.<sup>1</sup> However, such high figures are never achieved in practice and the measured values had magnitude  $|p| = 0.50 \pm 0.05$ , with the tensor polarisation being below 2% for both modes. The target was a 39 cm long Teflon-coated aluminum storage cell fed from an atomic beam source. The orientation of the hydrogen spin was reversed every five seconds and the mean target polarisation was determined from the  $\bar{p}\bar{n} \rightarrow d\pi^0$  calibration reaction to be  $|q| = 0.69 \pm 0.04$  [9].

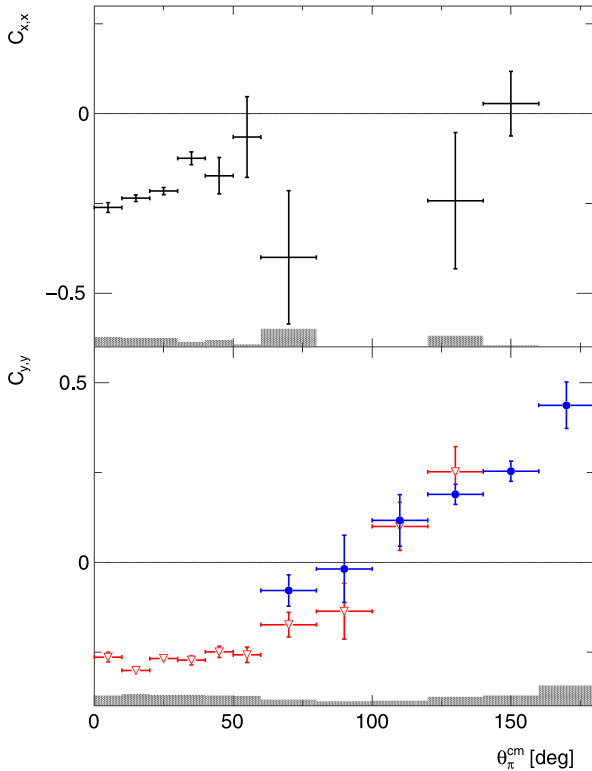
The experimental conditions are clearly not as clean for the storage cell compared to the cluster-jet target. There is a background from events arising from the aluminium walls and the target is far from being point-like. Nevertheless, having both beam and target polarised it is possible to extract proton and deuteron analysing powers as well as the spin correlations. The values obtained for  $A_y^p$  from the deuteron beam experiment, which are also shown in Fig. 1, also cover the central region of angles. Though the statistics are limited and the angular bins wider, the resulting data are completely consistent with both the TRIUMF and the ANKE cluster-jet data taken in  $pd$  kinematics.

Since the tensor polarisation of the deuteron beam is vanishingly small, the deuteron vector analysing power  $A_y^d$  can also be extracted from the data by looking at the dependence of the count-

<sup>1</sup> We are here using the notation where  $\hat{z}$  lies along the beam direction,  $\hat{y}$  represents the upward normal to the plane of the COSY ring, and the other transverse direction  $\hat{x}$  lies along  $\hat{y} \times \hat{z}$ .



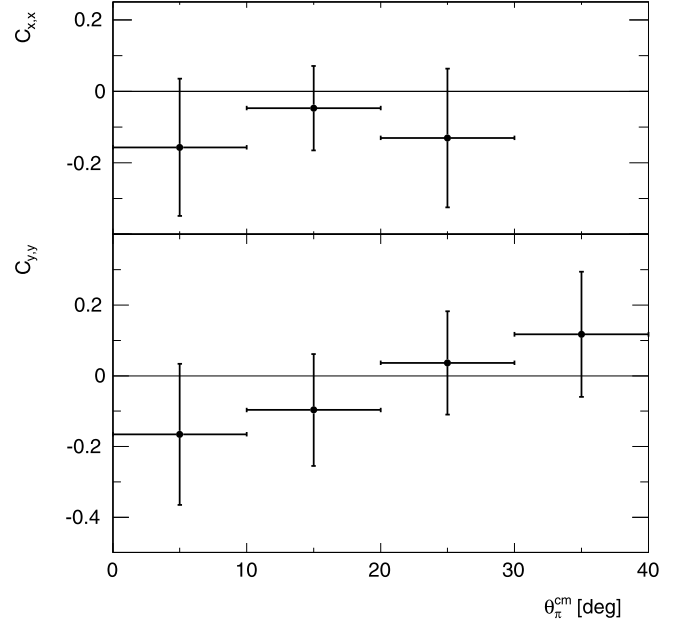
**Fig. 2.** Deuteron vector analysing power  $A_y^d$  measured in the  $\vec{d}p \rightarrow {}^3\text{He}\pi^0/{}^3\text{H}\pi^+$  reactions at 726 MeV. The data are presented in terms of the c.m. angle between the proton and pion. The shaded area indicates the systematic uncertainties in the measurement.



**Fig. 3.** Transverse spin correlation coefficients  $C_{x,x}$  and  $C_{y,y}$  in the  $\vec{d}p \rightarrow {}^3\text{He}\pi^0$  and  $\vec{d}p \rightarrow {}^3\text{H}\pi^+$  reactions at 363 MeV per nucleon. In the  $C_{y,y}$  case the (red) inverted triangles were obtained through  ${}^3\text{He}$  detection and the (blue) circles through  ${}^3\text{H}$  detection. The shaded area indicates the systematic uncertainties in the measurement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

ing rates on the vector polarisation of the beam. The results obtained from the combined  $\vec{d}p \rightarrow {}^3\text{He}\pi^0/{}^3\text{H}\pi^+$  data are shown in Fig. 2. The error bars here are somewhat larger than those for the corresponding  $A_y^p$  data of Fig. 1 due to the choice of the beam polarisation modes. It is perhaps significant that the abrupt change in  $A_y^d$  occurs at  $\theta_\pi^{\text{cm}} \approx 80^\circ$ , which is close to the deep minimum in  $A_y^p$ .

The acceptance in the COSY experiments is limited by the size of the vertical gap in the ANKE analysing magnet, which results in the  $C_{y,y}$  coefficient being measured over a much wider angular range than  $C_{x,x}$ . The consequences of this are illustrated in Fig. 3



**Fig. 4.** Transverse spin correlation coefficients  $C_{y,y}$  and  $C_{x,x}$  measured in the  $\vec{d}p \rightarrow {}^3\text{He}\pi^0$  reaction at 600 MeV per nucleon. The systematic errors are below 0.03.

where, by considering both  ${}^3\text{He}\pi^0$  and  ${}^3\text{H}\pi^+$  detection, values of  $C_{y,y}$  could be obtained over the whole angular range at 726 MeV, whereas the  $C_{x,x}$  measurements were only possible for small angles close to the forward and backward directions. It should be noted here that  $C_{y,y}$  changes sign around  $90^\circ$ .

The main difference between the double-polarisation measurements at 726 and 1200 MeV was the choice of the beam polarisation modes. In the latter case, in addition to an unpolarised mode, these included a pure vector polarised mode with ideal values of  $(p_z, p_{zz}) = (-\frac{2}{3}, 0)$ . This experiment was carried out over two separate beam times, with the measured values of the beam polarisations being  $p_z = -0.53 \pm 0.05$  and  $p_z = -0.62 \pm 0.08$ , and average target polarisations of  $|q| = 0.66 \pm 0.03$  and  $|q| = 0.78 \pm 0.03$ .

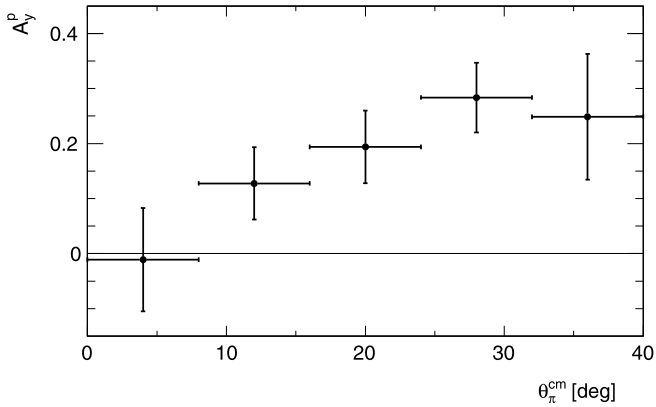
At 600 MeV per nucleon it is no longer feasible to make a clean selection of tritons by their energy loss in the scintillation hodoscope of the FD. As a consequence, only data on the  $\vec{d}p \rightarrow {}^3\text{He}\pi^0$  reaction are shown at this higher energy and this limits severely the angular range covered in the experiment. The  $C_{x,x}$  and  $C_{y,y}$  coefficients measured at small angles are presented in Fig. 4, though the error bars are much more significant than at 363 MeV per nucleon.

The uncertainties in the corresponding deuteron vector analysing powers are very large and these data are not shown. However, values of the proton analysing powers could be extracted for small angles by exploiting the polarisation of the hydrogen in the target and these data are presented in Fig. 5. These results for  $\theta_\pi^{\text{cm}} < 40^\circ$  are significantly larger than those of the lower energy data shown in Fig. 1.

In the forward and backward directions the number of independent amplitudes reduces from six to two and these may be written as [16]

$$F(dp \rightarrow {}^3\text{He}\pi^0) = \bar{u}_\tau \mathbf{p} \cdot (A\boldsymbol{\epsilon} + iB\boldsymbol{\epsilon} \times \boldsymbol{\sigma}) u_p. \quad (1)$$

Here  $\boldsymbol{\epsilon}$  is the deuteron polarisation vector,  $\mathbf{p}$  the proton c.m. momentum, and  $u_p$  and  $u_\tau$  are the initial and final fermion spinors. Apart from one discrete ambiguity, all the possible experimental information is contained in the initial-state spin observables:



**Fig. 5.** The proton analysing power  $A_y^p$  for the  $d\bar{p} \rightarrow {}^3\text{He}\pi^0$  reaction at 600 MeV per nucleon extracted from data obtained with a polarised hydrogen target. Systematic uncertainties, which were dominated by those in the target polarisation, were below 5%.

$$\begin{aligned} \frac{d\sigma}{d\Omega} &= \frac{kp}{3} (|A|^2 + 2|B|^2), \\ T_{20} &= \sqrt{2} \frac{|B|^2 - |A|^2}{|A|^2 + 2|B|^2}, \\ C_{y,y} = C_{x,x} &= -\frac{2\text{Re}(A^*B)}{|A|^2 + 2|B|^2}, \end{aligned} \quad (2)$$

where  $k$  is the pion c.m. momentum. The forms of these equations are identical for  $\theta_\pi^{\text{cm}} = 0^\circ$  and  $180^\circ$  though, of course, the amplitudes  $A$  and  $B$  are different in the two cases.

The deuteron tensor analysing power  $T_{20}$  was measured in the forward/backward directions at Saclay [17] and the values interpolated at 726 MeV are  $T_{20}(0^\circ) = -1.01 \pm 0.01$  and  $T_{20}(180^\circ) = -1.10 \pm 0.06$ . However, it is easily shown from Eq. (2) that the corresponding spin correlation in the forward or backward direction is bounded by

$$(C_{y,y})^2 \leq \frac{4}{9} \left[ 1 - T_{20}/\sqrt{2} - (T_{20})^2 \right], \quad (3)$$

from which one sees quite generally that  $|C_{y,y}| \leq 1/\sqrt{2}$ .

Using the forward value of  $T_{20}$  measured at Saclay, Eq. (3) shows that  $|C_{y,y}(0^\circ)| \leq 0.56 \pm 0.01$  to be compared to the value  $-0.27 \pm 0.03$  deduced from extrapolating the combined data of Fig. 3 to the forward direction. The error bars are larger in the backward direction where one finds from the data of Fig. 3 that  $C_{y,y}(180^\circ) = +0.46 \pm 0.04$  compared to the upper bound from Eq. (3) of  $0.50 \pm 0.04$ .<sup>2</sup>

The change in sign of  $C_{y,y}$  between the backward and forward directions is significant. If the phase angle is defined by  $\phi = \arg(B/A)$  then, in the forward direction,  $\cos\phi = 0.49 \pm 0.05$  whereas in the backward direction  $\cos\phi = -0.90 \pm 0.10$ .<sup>3</sup> The change in sign of  $\text{Re}(A^*B)$  could be due to structure in either amplitude. The Saclay data indicate that this is likely to be caused by the  $B$  amplitude because  $B(180^\circ)$  seems to have a zero in the vicinity of  $T_d = 650$  MeV [17].

The deuteron tensor analysing power bound of Eq. (3) provides little real constraint at 1.2 GeV. Using the Saclay value of  $T_{20}(0^\circ) = -0.66 \pm 0.02$  one finds that  $|C_{y,y}(0^\circ)| < 0.68 \pm 0.01$  to be compared with the extrapolated value of Fig. 4,  $C_{y,y}(0^\circ) =$

$-0.10 \pm 0.08$ . These mean that in the forward direction the  $A$  and  $B$  amplitudes at 600 MeV per nucleon are almost completely out of phase, with  $\cos\phi = 0.14 \pm 0.12$ .

The simplest phenomenological model used to describe the  $pd \rightarrow {}^3\text{He}\pi^0$  reaction is the cluster approach, first proposed by Ruderman [18]. It is here assumed that the  $pn \rightarrow d\pi^0$  reaction takes place on the neutron in the target deuteron and that the deuteron produced is captured by the spectator proton to generate the observed  ${}^3\text{He}$ . Due to the mass differences, there are ambiguities in the implementation of the kinematics in any such model. The prescription employed by Falk [19] assumes that the c.m. momentum of the pion is the same in the  $pd \rightarrow {}^3\text{He}\pi^0$  and  $pn \rightarrow d\pi^0$  reactions. Though this model can describe the data taken very near threshold [3], its predictions for the proton analysing power at 363 MeV in Fig. 1 are not encouraging [19]. The model should work best at small  $\theta_\pi^{\text{cm}}$  and the sign of  $A_y^p$  is correct there but the magnitude is much too large. The predicted dip around  $90^\circ$  is seen in the data but the large angle prediction is even wrong in sign as well as magnitude. The proton analysing power depends sensitively upon the relative phases of amplitudes, which might be changed by secondary effects. "It is clear that the model is lacking in one or more aspects; one of these might well be the neglect of the  $\{pp\}$  singlet contribution" [15].

In their implementation of the cluster model, Germond and Wilkin attempted to include singlet contributions from the  $pp \rightarrow \{pp\}\pi^0$  in addition to the dominant  $pn \rightarrow d\pi^0$  [16]. They employed a slightly different kinematic prescription to Falk, where the pion momenta in the  $\pi^0 {}^3\text{He} \rightarrow pd$  and  $\pi^0 d \rightarrow pn$  were assumed to be identical in the laboratory frame. However, they only carried out the calculations in the forward/backward directions and so no estimates could be made of  $A_y^p$  or  $A_y^d$  and, moreover, no predictions were made of the spin-correlation parameter. Furthermore, the signs of the  $D$ -wave contributions have also been questioned [20].

It was shown that the inclusion of the spin-singlet terms was crucial for the predictions of both the cross section and the deuteron tensor analysing power. Reasonable values could then be obtained in the backward direction up to  $T_d \approx 700$  MeV, though the range of validity is somewhat larger in the forward direction. Since the input that generates the  $A$  and  $B$  amplitudes are essentially independent their relative phase  $\phi$  must depend upon the details of the model. However, the change in the phase of  $B$  between the forward and backward directions seems to be of more general interest.

In summary, we have measured the proton analysing power in the  $pd \rightarrow {}^3\text{He}\pi^0$  and  $pd \rightarrow {}^3\text{H}\pi^+$  reactions with a polarised proton beam incident on a deuterium cluster-jet target and, in inverse kinematics, with a polarised deuteron beam incident on a target cell filled with polarised hydrogen. These results, obtained at 350–360 MeV per nucleon, led to values of the proton analysing power that were consistent with the TRIUMF measurements though with much larger angular coverage. This was facilitated by invoking isospin invariance, which requires that all analysing powers and other spin observables should be identical for  ${}^3\text{He}$  and  ${}^3\text{H}$  detection.

Of even greater importance for the theoretical modeling are the first ever measurements of the deuteron vector analysing power and the deuteron–proton vector spin correlations. These were obtained at 363 MeV per nucleon but small angle spin correlations and proton analysing powers were also extracted at 600 MeV per nucleon from data taken with a target cell filled with polarised hydrogen. The combination of Saclay  $T_{20}$  and COSY  $C_{y,y}$  data shows that the two non-vanishing amplitudes are almost completely out of phase in the forward direction at 600 MeV per nucleon. How-

<sup>2</sup> All the error bars in the extrapolated values of  $C_{y,y}$  or the phase angle  $\phi$  include the systematic uncertainties.

<sup>3</sup> There remains a discrete ambiguity corresponding to the sign of  $\sin\phi$ .

ever, in the 350–360 MeV per nucleon region, there is a large overlap in phase in both the forward and backward directions, though the relative phase  $\phi$  changes significantly between these two extremes.

We are grateful to the COSY crew for providing such good working conditions, especially of the polarised beams. We thank W.R. Falk for correspondence and for providing numerical values of the  $A_y^p$  predictions used in Fig. 1. This work has been partially supported by the COSY FFE programme and the Shota Rustaveli National Science Foundation.

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