

Excitation of the $\Delta(1232)$ isobar in deuteron charge exchange on hydrogen at 1.6, 1.8, and 2.3 GeV

D. Mchedlishvili^{a,b}, S. Barsov^c, J. Carbonell^d, D. Chiladze^{a,b}, S. Dymov^{e,f}, A. Dzyuba^c, R. Engels^b, R. Gebel^b, V. Glagolev^g, K. Grigoryev^{b,c}, P. Goslawski^h, M. Hartmann^b, O. Imambekov^e, A. Kacharava^{b,*}, V. Kamedzhiev^b, I. Keshelashvili^{a,i}, A. Khoukaz^h, V. Komarov^e, P. Kulesa^j, A. Kulikov^e, A. Lehrach^b, N. Lomidze^a, B. Lorentz^b, G. Macharashvili^{a,e}, R. Maier^b, S. Merzliakov^{b,e}, M. Mielke^h, M. Mikirtychyants^{b,c}, S. Mikirtychyants^{b,c}, M. Nioradze^a, H. Ohm^b, M. Papenbrock^h, D. Prasuhn^b, F. Rathmann^b, V. Serdyuk^b, H. Seyfarth^b, H.J. Stein^b, E. Steffens^f, H. Stockhorst^b, H. Ströher^b, M. Tabidze^a, S. Trusov^k, Yu. Uzikov^{e,l}, Yu. Valdau^{b,c}, C. Wilkin^m

^a High Energy Physics Institute, Tbilisi State University, GE-0186 Tbilisi, Georgia

^b Institut für Kernphysik and Jülich Centre for Hadron Physics, Forschungszentrum Jülich, D-52425 Jülich, Germany

^c High Energy Physics Department, Petersburg Nuclear Physics Institute, RU-188350 Gatchina, Russia

^d Institut de Physique Nucléaire, Université Paris-Sud, IN2P3-CNRS, F-91406 Orsay Cedex, France

^e Laboratory of Nuclear Problems, JINR, RU-141980 Dubna, Russia

^f Physikalisches Institut II, Universität Erlangen-Nürnberg, D-91058 Erlangen, Germany

^g Laboratory of High Energies, JINR, RU-141980 Dubna, Russia

^h Institut für Kernphysik, Universität Münster, D-48149 Münster, Germany

ⁱ Department of Physics, University of Basel, Klingelbergstrasse 82, CH-4056 Basel, Switzerland

^j H. Niewodniczański Institute of Nuclear Physics PAN, PL-31342 Kraków, Poland

^k Institut für Kern- und Hadronenphysik, Forschungszentrum Rossendorf, D-01314 Dresden, Germany

^l Department of Physics, M.V. Lomonosov Moscow State University, RU-119991 Moscow, Russia

^m Physics and Astronomy Department, UCL, Gower Street, London WC1E 6BT, UK

ARTICLE INFO

Article history:

Received 23 May 2013

Received in revised form 6 August 2013

Accepted 6 August 2013

Available online 14 August 2013

Editor: D.F. Geesaman

Keywords:

Deuteron charge exchange

Pion production

Polarisation effects

ABSTRACT

The charge-exchange break-up of polarised deuterons $\vec{d}p \rightarrow \{pp\}_s n$, where the final $\{pp\}_s$ diproton system has a very low excitation energy and hence is mainly in the 1S_0 state, is a powerful tool to probe the spin-flip terms in the proton–neutron charge-exchange scattering. Recent measurements with the ANKE spectrometer at the COSY storage ring at 1.6, 1.8, and 2.27 GeV have extended these studies into the pion-production regime in order to investigate the mechanism for the excitation of the $\Delta(1232)$ isobar in the $\vec{d}p \rightarrow \{pp\}_s X$ reaction. Values of the differential cross section and two deuteron tensor analysing powers, A_{xx} and A_{yy} , have been extracted as functions of the momentum transfer to the diproton or the invariant mass M_X of the unobserved system X . The unpolarised cross section in the high M_X region is well described in a model that includes only direct excitation of the Δ isobar through undistorted one pion exchange. However, the cross section is grossly underestimated for low M_X , even when Δ excitation in the projectile deuteron is included in the calculation. Furthermore, direct Δ production through one pion exchange only reproduces the angular dependence of the difference between the two tensor analysing powers.

© 2013 Elsevier B.V. All rights reserved.

It was pointed out many years ago that quasi-free (p, n) or (n, p) reactions on the deuteron can, in suitable kinematic regions, act as a spin filter that selects the spin-dependent contribution to the neutron–proton elastic charge-exchange cross section [1]. The comparison of this reaction with free backward elastic scattering

on a nucleon target provides information on the neutron–proton backward elastic scattering amplitudes. This field has been comprehensively surveyed in Ref. [2].

Theory suggests that even more detailed information on the np charge-exchange amplitudes could be obtained by measuring the charge-exchange break-up of tensor polarised deuterons, $\vec{d}p \rightarrow \{pp\}_s X$ [3]. By selecting two final protons with low excitation energy, typically $E_{pp} < 3$ MeV, the emerging diproton is dominantly

* Corresponding author.

E-mail address: a.kacharava@fz-juelich.de (A. Kacharava).

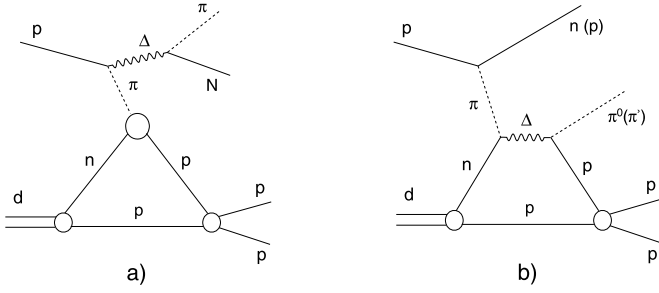


Fig. 1. The one-pion-exchange contribution to $\Delta(1232)$ production in the deuteron charge-exchange break-up reaction. (a) The direct (D) term. (b) The exchange (E) term.

in the 1S_0 state. The reaction then involves a spin flip from the initial spin triplet of the deuteron to the spin singlet of the S -wave diproton. In the well-studied neutron case, $X = n$, the amplitude in impulse approximation is proportional to that in $np \rightarrow pn$, times a form factor that reflects the overlap of the initial deuteron and final diproton wave functions. This approach describes quantitatively a range of measurements of the differential cross section, tensor and vector analysing powers, and spin correlation coefficients in the $dp \rightarrow \{pp\}_s n$ reaction provided that the contamination of P - and higher partial waves in the final pp system is taken into account [4].

The ANKE-COSY Collaboration has carried out a series of experiments to deduce the energy dependence of the spin-dependent np elastic amplitudes by identifying the neutron channel in the $dp \rightarrow \{pp\}_s n$ reaction [5]. However, the same experimental data clearly show the possibility of extending these studies into the pion-production regime in order to investigate the excitation of the $\Delta(1232)$ isobar.

It was first demonstrated at SATURNE that the $\Delta(1232)$ can indeed be produced in the $\bar{d}p \rightarrow \{pp\}_s \Delta^0$ charge-exchange reaction at a deuteron beam energy $T_d = 2.0$ GeV [6–8]. In analogy to the final neutron case, it is expected that the highly inelastic deuteron charge-exchange measurements correspond to a spin transfer from the initial neutron to final proton in the $\bar{n}p \rightarrow \bar{p} \Delta^0$ process with a spectator proton. This would give valuable information on the spin structure in the excitation of the Δ isobar.

Unlike the case of nucleon–nucleon elastic scattering, however, there is no reliable amplitude analysis of the data on $\Delta(1232)$ production in the $NN \rightarrow N\Delta$ reaction. The one-pion-exchange (OPE) model is quite successful in describing the unpolarised cross section of the $pp \rightarrow \Delta^{++}n$ reaction as shown, for example, in Ref. [9]. The model contains direct (D) and exchange (E) terms which, when applied to the $dp \rightarrow \{pp\}_s N\pi$ reaction, correspond to the diagrams in Figs. 1(a) and (b), respectively. It should be noted that in impulse approximation the direct diagram contains the same triangle loop as in the $dp \rightarrow \{pp\}_s n$ reaction, i.e., the same $d \rightarrow \{pp\}_s$ form factors.

Measurements have been carried out at the COoler SYnchrotron (COSY) [10] of the Forschungszentrum Jülich using transversely polarised deuteron beams with energies $T_d = 1.2, 1.6, 1.8$, and 2.27 GeV incident on an unpolarised hydrogen cluster-jet target [11]. Several configurations of the deuterium polarised ion source were used. In order to carry out beam polarimetry measurements, COSY was programmed to provide beam first at 1.2 GeV, where the analysing powers for several reactions are precisely known [12]. Without additional injection, the deuterons were then accelerated to one of the higher energies. Since there are no depolarising resonances for deuterons in the COSY energy range, the beam polarisations should be identical at 1.2 GeV and

the higher energy. This was checked at the 4% level by repeating the measurement of the analysing powers after deceleration [13].

Two of the reactions observed are important for the present discussion, namely the deuteron charge-exchange $dp \rightarrow \{pp\}_s X$ and the quasi-free $dp \rightarrow p_{\text{spec}} d\pi^0$, where the spectator proton, p_{spec} , has a momentum about half that of the beam. After recording two charged particles, proton–proton and deuteron–proton pairs were subsequently separated using the differences between the arrival times of the two particles at the detector. Once the two charged particles have been recognised, the missing-mass distributions allow the reactions to be identified. A detailed description of the procedure for distinguishing different reactions, as well as the description of the ANKE magnetic spectrometer [14], can be found in Refs. [5,13]

In addition to displaying a well-separated neutron peak, the experimental $dp \rightarrow \{pp\}_s X$ missing-mass spectra also show a lot of strength at higher M_X that must be associated with pion production. The analysis of these data for both the differential cross section and deuteron tensor analysing powers is similar to that for $\bar{d}p \rightarrow \{pp\}_s n$, whose results have already been reported in some detail [5]. Greater emphasis in this Letter will therefore be given to the results rather than the procedures.

Values of the absolute luminosity are required in order to extract normalised cross sections. In this experiment these were obtained by measuring simultaneously the quasi-free $np \rightarrow d\pi^0$ reaction. The cross section for producing this final state is smaller than that for $pp \rightarrow d\pi^+$ by an isospin factor of two. There are extensive measurements of the latter reaction and these have been included in the amplitude analysis of the SAID group [15]. An additional advantage of using quasi-free pion production for normalisation is that the effect of the shadowing in the deuteron largely cancels out between the $dp \rightarrow \{pp\}_s X$ and $dp \rightarrow p_{\text{spec}} d\pi^0$ reactions, where p_{spec} is a spectator proton. Furthermore, in both cases two fast hadrons have to be detected so that there is less influence from any acceptance uncertainties.

The count rates of the $dp \rightarrow p_{\text{spec}} d\pi^0$ reaction were corrected for the track reconstruction and proportional chamber efficiencies and the dead time of the data acquisition system. Monte Carlo simulations were performed at the three higher energies to take into account the effects of the ANKE acceptance on the experimental data. More details on the luminosity determination are to be found in Ref. [5].

Monte Carlo simulations were performed at these three energies in order to evaluate the ANKE acceptance also for the $dp \rightarrow \{pp\}_s X$ reaction. Events were generated according to the simple one-pion exchange mechanism of Fig. 1(a). By dividing the numbers of reconstructed events by the total, two-dimensional acceptance maps were obtained in θ_{pp} and M_X . The maximum value of the diproton polar angle θ_{pp} changes slightly with energy and M_X , reaching 4.5° in the laboratory system. In order to avoid potentially unsafe regions, where the acceptance drops very rapidly, the cut $\theta_{pp} < 3^\circ$ was applied at all energies, in both the simulation and analysis. The strong S -wave final-state interaction (FSI) between the two measured protons was taken into account according to the Migdal–Watson approach [16,17], using the pp 1S_0 scattering amplitude [18].

Since direct production of the Δ isobar necessarily involves relatively high momentum transfers, a P -wave contribution in the pp final state is non-negligible. This effect is clearly observed in the comparison between the uncorrected experimental and simulated E_{pp} distributions for all events shown in Fig. 2. The S -wave term falls well below the data for $E_{pp} > 1$ MeV. Any FSI will be much weaker in the P -waves, so that the weight for this contribution is proportional to the square of the pp relative momentum, i.e., the diproton excitation energy. By fitting the coefficients of the two

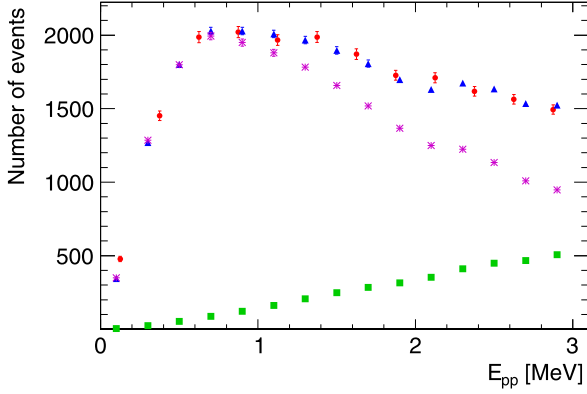


Fig. 2. Experimental (red dots) and simulated E_{pp} distributions, summed over all three beam energies. The simulation of the S -wave contribution (magenta stars) includes a Migdal–Watson factor [16,17]. The fitted value of the non-interacting P -wave (green squares) corresponds to a total contribution of 15% over this E_{pp} range. The overall simulation is shown by blue triangles. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

known shapes together, it was found that for all beam energies the P -wave contribution is about 15% of the total event rate when summed over the region $0 < E_{pp} < 3$ MeV.

The resulting $dp \rightarrow \{pp\}_s X$ missing-mass cross sections are shown in Fig. 3 for $E_{pp} < 3$ MeV. In the mass range accessible at COSY, single pion production is dominated by the formation and decay of the $\Delta(1232)$ isobar. It is therefore reassuring that the spectra at all three beam energies are maximal for $M_X \approx 1.2$ GeV/ c^2 . The evaluation of the isobar contribution to such spectra must depend on a theoretical model, to which we now turn.

Expressions for the two-dimensional cross section for the direct Δ production are given explicitly in Ref. [9]. The resulting one-dimensional cross section can be written as:

$$\frac{d\sigma}{dM_X} = \frac{1}{128\pi^3 m K^2 s} \int_{t_1}^{t_2} dt \int_0^{k_{\max}} k^2 dk \rho(M_X) |\overline{\mathcal{M}_{fi}}|^2, \quad (1)$$

where \mathcal{M}_{fi} is the $dp \rightarrow \{pp\}_s \Delta^0$ transition matrix element and M_X is the Δ^0 invariant mass. Here m is the proton mass, K the incident c.m. momentum, s the square of the c.m. energy, and k the internal momentum in the final diproton. In the ANKE experiment the maximum value k_{\max} is fixed by the cut in the excitation energy $E_{pp} = k^2/m < 3$ MeV. The integration over the four-momentum transfer t in Eq. (1) corresponds to the interval in the diproton polar angle in the laboratory system $0^\circ < \theta_{\text{lab}} < 3^\circ$.

The spectral function $\rho(M_X)$ in Eq. (1), which accounts for the finite width of the Δ -isobar, has the form [19]

$$\rho(M_X) = \frac{1}{\pi} \frac{M_\Delta \Gamma Z(M_X^2, t)}{(M_X^2 - M_\Delta^2)^2 + \Gamma^2 M_\Delta^2} \quad (2)$$

with

$$Z(M_X^2, t) = \frac{p^2(M_\Delta^2, t) + \kappa^2}{p^2(M_X^2, t) + \kappa^2}, \quad (3)$$

where $p^2(M_X^2, t) = \lambda(M_X^2, m^2, t)/4M_X^2$ and $\lambda(a, b, c)$ is the triangle function. The width of the Δ -isobar is

$$\Gamma = \Gamma_0 \left(\frac{p(M_\Delta^2, m_\pi^2)}{p(M_X^2, m_\pi^2)} \right)^3 Z(M_X^2, m_\pi^2), \quad (4)$$

with the following parameters: $M_\Delta = 1.232$ GeV/ c^2 , $\Gamma_0 = 0.115$ GeV/ c^2 , and $\kappa = 0.180$ GeV/ c [20].

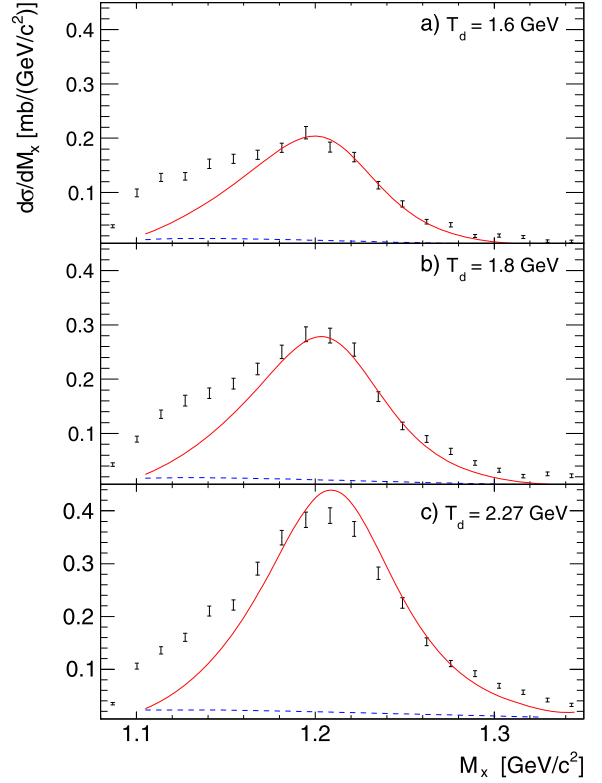


Fig. 3. Unpolarised differential cross section for the $dp \rightarrow \{pp\}_s X$ reaction with $E_{pp} < 3$ MeV for $M_X > M_N + M_\pi$ at three deuteron beam energies. The data are summed over the interval $0 < \theta_{\text{lab}} < 3^\circ$ in the diproton laboratory polar angle. Only statistical errors are shown; the overall normalisation uncertainties are less than 7%. The solid (red) curves correspond to the one-pion-exchange predictions for the direct mechanism of Fig. 1(a). The dashed (blue) lines show the contribution of the exchange mechanism (E) of Fig. 1(b). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

If we consider only the 1S_0 final pp state, the spin-average square of the one-pion-exchange transition matrix element in impulse approximation is

$$|\overline{\mathcal{M}_{fi}}|^2 = \frac{1}{6} \frac{[(M_X - m)^2 - t][(M_X + m)^2 - t]^2}{(t - m_\pi^2)^2 3M_X^2} \times \left[\frac{f_\pi}{m_\pi} \frac{f^*}{m_\pi} 8\sqrt{m^3} \sqrt{\frac{2}{3}} F_\pi^2(t) \sqrt{Z(M_X^2, t)} F(t, k^2) \right]^2 q^2, \quad (5)$$

where \vec{q} is the total three-momentum transfer. The $d \rightarrow \{pp\}_s$ transition form factor $F(t, k^2)$, which includes the effects of the S - and D -states in the deuteron [3], has been evaluated using the CD Bonn NN interaction [21] for both the deuteron and the pp S -wave scattering state. The πNN and $\pi N \Delta$ coupling constants used are $f_\pi = 1.0$ and $f^* = 2.15$, respectively, and a form factor $F_\pi(t) = (\Lambda_\pi^2 - m_\pi^2)/(\Lambda_\pi^2 - t)$ has been introduced at both vertices.

The size of the cut-off parameter Λ_π in the form factors affects the absolute values of the cross section predictions shown in Fig. 3. The value chosen here, $\Lambda_\pi = 0.5$ GeV/ c , gives a good description of the magnitude of the cross section at high M_X for all three beam energies. Its value is less than the $\Lambda_\pi = 0.63$ GeV/ c found from a one-pion-exchange fit to inclusive $pp \rightarrow \Delta^{++} n$ results [9], but it agrees well with $\Lambda_\pi = 0.5$ GeV/ c obtained from exclusive $pp \rightarrow pn\pi^+$ data [20].

The simple direct one-pion-exchange model for the $np \rightarrow p\Delta^0$ amplitude describes well the data in Fig. 3 at high M_X , though

it must be stressed that this calculation neglects the 15% P -state contribution shown in Fig. 2. However, the approach underestimates enormously the low mass results. This failure must be more general than the specific implementation of the model because the Δ is a p -wave pion–nucleon resonance. There can therefore be little strength at low M_X and this suggests that one should search for other mechanisms that might dominate near the πN threshold.

Exactly the same problem for the cross section in our angular domain was noted in the pioneering SATURNE experiment [6], where one pion exchange was only successful at high M_X . To investigate this further, the authors compared the small-angle hydrogen target data, $p(d, pp)X$, with quasi-free production in deuterium, $d(d, pp)X$. From this it is clear that the excess of events at low M_X is mainly to be associated with isospin $I = \frac{1}{2}$ πN pairs rather than the $I = \frac{3}{2}$ of direct Δ production [8].

It is easy to exclude the culprit being s -wave N^* resonance contributions to direct production. To get a rough estimate of the possible effects, the p -wave one-pion-exchange model predictions were modified as:

$$\left(\frac{d\sigma}{dm}\right)_s \approx \left(\frac{d\sigma}{dm}\right)_p \times \frac{2\sigma(S_{11}) + \sigma(S_{31})}{\sigma(P_{33})} \times \frac{p_0^2}{p^2}, \quad (6)$$

where $\sigma(S_{11})$, $\sigma(S_{31})$, and $\sigma(P_{33})$ are the πN elastic cross sections in the three partial waves noted, and p_0 and p are the momenta of the final and intermediate pion, respectively. Such an estimate indicates only a very tiny extra strength at low M_X and this would have to be increased by several orders of magnitude in order to agree with the experimental data. One must therefore seek an alternative explanation to direct isobar production to describe the data.

There are some similarities between the $dp \rightarrow \{pp\}_s X$ reaction and the inclusive $dp \rightarrow dX$ [22] or $\alpha p \rightarrow \alpha X$ [23] measurements that were dedicated to the search for the excitation of the $N^*(1440)$ Roper resonance. Due to conservation laws, the isospin of the unobserved state X in these cases must be $I = \frac{1}{2}$ but this does not necessarily correspond to an N^* resonance. In fact the largest strength in the data is seen at very low values of M_X , with only a small enhancement arising from the $N^*(1440)$. The dominant effect is believed to be associated with the excitation of the $\Delta(1232)$ isobar inside the projectile deuteron or α -particle [24, 25]. Although the mechanism is driven by the $\Delta(1232)$, the pion and nucleon that make up the state X are produced at different vertices and so X is not required to be in a p -wave and to have isospin $I = \frac{3}{2}$.

The exchange diagram E for the $dp \rightarrow \{pp\}_s X$ reaction is shown in Fig. 1(b). However, a preliminary investigation of this mechanism reported in Fig. 3 suggests that, although it can provide strength at low M_X , the overall magnitude is still far too small to provide an adequate description of the data in this region [26]. The relative reduction compared to the $dp \rightarrow dX$ or $\alpha p \rightarrow \alpha X$ calculations [24, 25] arises primarily from the spin-flip that is inherent in the $d \rightarrow \{pp\}_s$ transition. We therefore turn to the measurement of the tensor analysing powers for more information.

In the data analysis, we define the z -axis to lie along the beam direction and the y -axis, which is along the upward normal to the COSY plane, is also the stable spin axis. The x -axis is then defined by $\hat{x} = \hat{y} \times \hat{z}$. The three-momentum transfer can be usefully split into longitudinal q_z and transverse parts \mathbf{q}_t , so that in general $\mathbf{q} = (q_t \cos \phi, q_t \sin \phi, q_z)$, where we have introduced the azimuthal angle ϕ with respect to the x -direction. The longitudinal component of the momentum transfer may be written in terms of q_t and the missing mass M_X .

When only the tensor polarisation is considered, the numbers $N(q_t, M_X, \phi)$ of diprotons detected as a function of q_t , M_X , and ϕ are given in terms of the beam polarisation P_{zz} by¹

$$\frac{N(q_t, M_X, \phi)}{N_0(q_t, M_X)} = C_n \left\{ 1 + \frac{1}{2} P_{zz} [A_{xx}(q_t, M_X) \sin^2 \phi + A_{yy}(q_t, M_X) \cos^2 \phi] \right\}. \quad (7)$$

The value of C_n , the luminosity of the polarised relative to the unpolarised beam, was determined through measurements of single fast spectator protons [5]. Eq. (7) can be used at the calibration energy 1.2 GeV to determine the beam polarisation and at the higher energies of 1.6, 1.8, and 2.27 GeV to extract the tensor analysing powers of the $dp \rightarrow \{pp\}_s n$ and $\bar{d}p \rightarrow \{pp\}_s X$ reactions. Details on the count-rate calibration and the procedure for the beam polarisation determination are to be found in Ref. [13].

Due to limited statistics, it was not possible to measure A_{xx} and A_{yy} as functions of two variables. Data were binned instead in either M_X or in q_t , summing over the full range of the other variable. Since the acceptance is also a function of two variables, in such a procedure the acceptance will influence the measurements of the analysing powers. In order to minimise such effects in the analysis, the polarised and unpolarised data were weighted with the inverse of the two-dimensional acceptance that was evaluated for the extraction of the unpolarised cross section.

The possible existence of two mass regions, where different mechanisms might dominate, is also reflected in the behaviour of the tensor analysing power shown in Fig. 4. After summing the data over the momentum transfer, the sum and difference of the deuteron Cartesian tensor analysing powers A_{xx} and A_{yy} are presented as functions of the missing mass M_X . [These combinations are proportional to the spherical tensor components T_{20} and T_{22} , respectively.] No significant changes in the results were found when considering the stronger cut $E_{pp} < 2$ MeV, which might reduce any dilution of the analysing power signals by the P -waves apparent in Fig. 2.

It is interesting to note that the deviation of $A_{xx} + A_{yy}$ from zero is largest at $M_X \approx 1.15$ GeV/ c^2 , which is precisely the region where there is the biggest disagreement with the cross section predictions of Fig. 3. Furthermore, the values of $A_{xx} + A_{yy}$ seem to be remarkably stable, showing a behaviour that is independent of beam energy. Hence, whatever the mechanism is that drives the reaction, it seems to be similar at all energies. The error bars on $A_{xx} - A_{yy}$ are larger since in this case, according to Eq. (7), the slope in $\cos^2 \phi$ has to be extracted from the data. As a consequence it is harder to draw firm conclusions on the analysing power differences.

The SPESIV spectrometer at SATURNE had high resolution but very small angular acceptance. The $T_d = 2$ GeV data were therefore taken at discrete values in the laboratory diproton production angle, typically in steps of $\approx 2^\circ$. The limited acceptance also meant that only a linear combination of A_{xx} and A_{yy} (the “polarisation response”) could be determined and it was only at the larger angles that this approached a pure A_{yy} measurement. The ANKE data have been analysed in much finer angular bins but the M_X distribution in the Δ region of the cross section and polarisation response is quite similar to that measured at SATURNE at $\theta_{lab} = 2.1^\circ$ [6, 8], which is in the middle of the ANKE angular range.

Although the direct Δ production model of Fig. 1(a) fails to describe the differential cross section data of Fig. 3 near the pion

¹ The z subscript here refers conventionally to the axis in the source frame. In the COSY frame this becomes the y -axis.

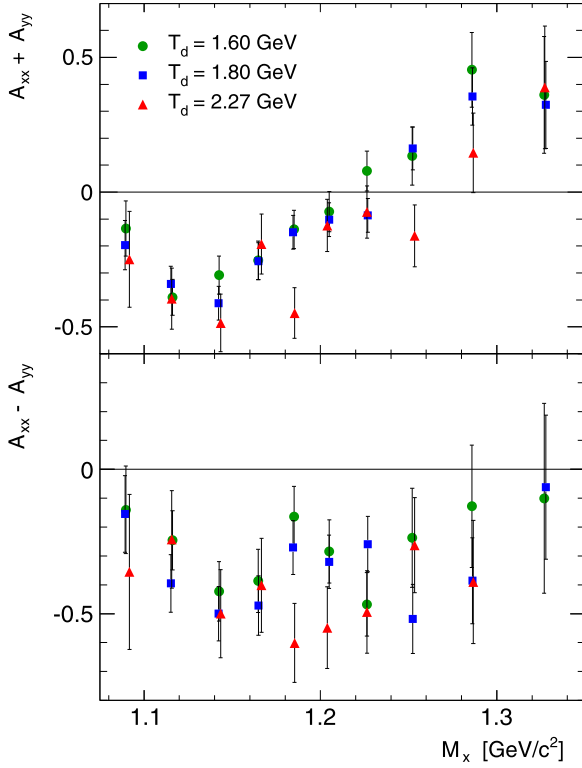


Fig. 4. The sum and difference of the Cartesian tensor analysing powers for the $\bar{d}p \rightarrow \{pp\}_s X$ reaction with $E_{pp} < 3$ MeV at three different beam energies. The data are corrected for the detector acceptance and summed over the range $0^\circ < \theta_{\text{lab}} < 3^\circ$ in diproton laboratory polar angle. Though the error bars are dominantly statistical, they include also the uncertainties from the beam polarisation and relative luminosity C_n . In addition, there is an overall uncertainty of up to 4% due to the use of the polarisation export technique [13].

production threshold, the situation is much more satisfactory at high M_X . To investigate this region further, the data have been summed over the range $1.19 < M_X < 1.35$ GeV/ c^2 and the tensor analysing powers A_{xx} and A_{yy} evaluated as functions of the transverse momentum transfer q_t . The results at the three energies are shown in Fig. 5.

Within the experimental uncertainties, the values of both A_{xx} and A_{yy} at fixed q_t seem to be largely independent of the beam energy. This is consistent with a similar feature found for the data at fixed M_X shown in Fig. 4. This suggests that there is a common reaction mechanism at all three energies. Another important point to note is that the signs of A_{xx} and A_{yy} are opposite to those measured in the $\bar{d}p \rightarrow \{pp\}_s n$ reaction [5] though, unlike the neutron channel case, they tend to be very small at $q_t \approx 0$.

Estimates for the $\bar{d}p \rightarrow \{pp\}_s \Delta^0$ analysing powers can be easily made for the direct one-pion-exchange production amplitude of Fig. 1(a). In the non-relativistic limit this gives

$$M_{fi} \sim \mathbf{q}_\pi \cdot \Psi^+ \varphi_p F(t, k^2) \mathbf{q} \cdot \boldsymbol{\varepsilon}, \quad (8)$$

where Ψ is the vector-spinor of the Δ -isobar, \mathbf{q}_π is the three-momentum of the virtual pion in the Δ -isobar rest frame, φ_p is the spinor of the initial proton, and $\boldsymbol{\varepsilon}$ represents the polarisation vector of the deuteron.

It follows from the $\mathbf{q} \cdot \boldsymbol{\varepsilon}$ factor of Eq. (8) that only deuterons with magnetic quantum number $M = 0$, when quantised along the direction of the three-momentum transfer \mathbf{q} , can lead to Δ production in the one-pion-exchange model. Due to the Δ - p mass difference, q_z is non-zero in the forward direction and \mathbf{q} then lies along the beam direction, so that in this limit $A_{xx} = A_{yy} = 1$.

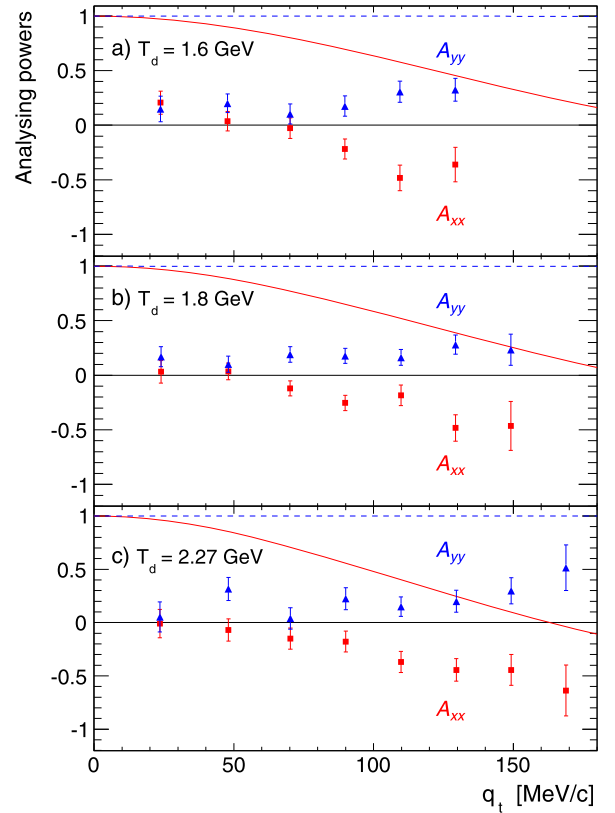


Fig. 5. Acceptance-corrected tensor analysing powers A_{xx} and A_{yy} of the $\bar{d}p \rightarrow \{pp\}_s X$ reaction with $E_{pp} < 3$ MeV at three deuteron beam energies as a function of the transverse momentum transfer q_t . Only high mass data ($1.19 < M_X < 1.35$ GeV/ c^2) are considered. Note that in the forward direction, $q_t = 0$ and $A_{xx} = A_{yy}$. Though the error bars are dominantly statistical, they include also the uncertainties from the beam polarisation and relative luminosity C_n . In addition, there is an overall uncertainty of up to 4% due to the use of the polarisation export technique. The one-pion-exchange predictions are shown by the blue dashed line for A_{yy} and red solid for A_{xx} . (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

For an arbitrary production angle, the tensor analysing powers become

$$A_{xx} = 1 - 3q_t^2/q^2 \quad \text{and} \quad A_{yy} = 1. \quad (9)$$

Since the longitudinal momentum transfer depends upon the mass distribution of the Δ , A_{xx} can only be estimated by integrating numerically over the spectral shape. However, as can be seen from Fig. 5, neither of the resulting predictions agrees even qualitatively with the experimental data, which show very small analysing powers for $q_t \approx 0$. Nevertheless, if one looks instead at the combination $A_{xx} - A_{yy}$ it seems the one-pion-exchange model does give a plausible description of the data. In particular it predicts that $A_{yy} > A_{xx}$ for Δ production.

To illustrate this in greater detail, we show in Fig. 6 the simple average over the three beam energies of the experimental data and the one-pion-exchange predictions for the spherical analysing power $T_{22} = (A_{xx} - A_{yy})/2\sqrt{3}$. Combining the energies in this way to improve the statistics is reasonable because of the similarities shown by the three sets of data in Fig. 5.

Δ production will also be studied in inverse kinematics with a polarised proton beam incident on a polarised deuterium gas cell, $\bar{p}d \rightarrow \{pp\}_s X$ [27], where the two slow protons will be detected in silicon tracking telescopes [28]. This will allow the studies reported here to be continued up to the maximum COSY proton energy of $T_p \approx 2.9$ GeV. A particularly intriguing possibility is the measurement in coincidence of a proton or π^- constituent from

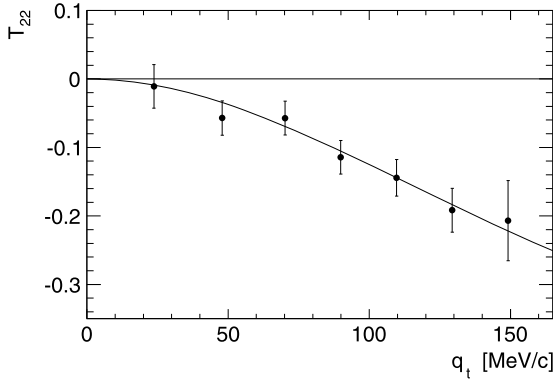


Fig. 6. Spherical tensor analysing power $T_{22} = (A_{xx} - A_{yy})/2\sqrt{3}$ for the $\bar{d}p \rightarrow \{pp\}_s X$ reaction with $E_{pp} < 3$ MeV, averaged over the three beam energies studied. Though the error bars are dominantly statistical, they include also the uncertainties from the beam polarisation and relative luminosity $C_{\bar{n}}$. In addition, there is an overall uncertainty of up to 4% due to the use of the polarisation export technique. When the same approach is applied to the predictions of the simple one-pion-exchange model of Fig. 1(a), the good agreement shown by the curve is achieved.

the state X . This would give access to the tensor polarisation of X which must, of course, vanish for an s -wave pion–nucleon system. This would therefore provide another tool to separate the s - and p -wave components of the system X .

In summary, we have measured the differential cross section and two tensor analysing powers A_{xx} and A_{yy} in the highly inelastic deuteron charge-exchange $\bar{d}p \rightarrow \{pp\}_s X$ reaction, where the effective mass M_X of the state X indicates that pion production is involved. The high M_X part of the cross section data at all three beam energies studied is well reproduced by a simple one-pion-exchange model. However, though this model fails to reproduce the measured values of A_{xx} and A_{yy} , the description of $A_{yy} - A_{xx}$ as a function of q_t shown in Fig. 6 is unexpectedly and perhaps fortuitously good.

In addition to a possible direct $\Delta^0(1232)$ peak, there is a surprising amount of production in the s -wave πN region. Attempts to explain this in terms of Δ excitation in the projectile deuteron give much too low cross sections. Strength in this region could also arise from higher-order diagrams involving a ΔN residual interaction [29], which have been neglected here. Although the other observables that will be measured may cast more light on the reaction mechanism, further theoretical work is needed in order

that these data may be reliably related to the $\bar{n}p \rightarrow \bar{p}\Delta^0$ reaction.

Acknowledgements

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 No. 283286.

References

- [1] I.Ya. Pomeranchuk, Dokl. Akad. Nauk SSSR 78 (1951) 249.
- [2] F. Lehar, C. Wilkin, Eur. Phys. J. A 37 (2008) 143; F. Lehar, C. Wilkin, Phys. Part. Nucl. Lett. 7 (2010) 235.
- [3] D.V. Bugg, C. Wilkin, Nucl. Phys. A 467 (1987) 575.
- [4] J. Carbonell, M.B. Barbaro, C. Wilkin, Nucl. Phys. A 529 (1991) 653.
- [5] D. Mchedlishvili, et al., Eur. Phys. J. A 49 (2013) 49.
- [6] C. Ellegaard, et al., Phys. Rev. Lett. 59 (1987) 974.
- [7] C. Ellegaard, et al., Phys. Lett. B 231 (1989) 365.
- [8] T. Sams, PhD thesis, Nils Bohr Institute, Copenhagen, 1991, <http://www.physics.dk/Sams1990.pdf>.
- [9] V. Dmitriev, O. Sushkov, C. Gaarde, Nucl. Phys. A 459 (1986) 503.
- [10] R. Maier, et al., Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 390 (1997) 1.
- [11] A. Khoukaz, et al., Eur. Phys. J. D 5 (1999) 275.
- [12] D. Chiladze, et al., Phys. Rev. ST Accel. Beams 9 (2006) 050101.
- [13] D. Mchedlishvili, D. Chiladze, J. Phys. Conf. Ser. 295 (2011) 012099.
- [14] S. Barsov, et al., Nucl. Instrum. Methods Phys. Res., Sect. A, Accel. Spectrom. Detect. Assoc. Equip. 462 (2001) 364.
- [15] R.A. Arndt, I.I. Strakovsky, R.L. Workman, D.V. Bugg, Phys. Rev. C 48 (1993) 1926, <http://gwdac.phys.gwu.edu>.
- [16] K.M. Watson, Phys. Rev. 88 (1952) 1163.
- [17] A.B. Migdal, Zh. Eksp. Teor. Fiz. 28 (1953) 3.
- [18] B.J. Morton, et al., Phys. Rev. 169 (1968) 825.
- [19] C. Ellegaard, et al., Phys. Lett. B 154 (1985) 110.
- [20] O. Imambekov, Yu.N. Uzikov, Yad. Fiz. 44 (1988) 1089.
- [21] R. Machleidt, Phys. Rev. C 63 (2000) 024001.
- [22] J. Banaigs, et al., Phys. Lett. 45B (1973) 535.
- [23] H.P. Morsch, et al., Phys. Rev. Lett. 69 (1992) 1336.
- [24] R. Baldini Celio, et al., Nucl. Phys. A 379 (1982) 477.
- [25] P. Fernández de Córdoba, et al., Nucl. Phys. A 586 (1995) 586.
- [26] Yu. Uzikov, J. Haidenbauer, C. Wilkin, The charge-exchange reaction $dp \rightarrow \{pp\}_s N\pi$ in the Δ -isobar region, ANKE internal report #97, 2012, available from <http://www.collaborations.fz-juelich.de/ikp/anke>.
- [27] D. Mchedlishvili, S. Barsov, C. Wilkin, COSY proposal #218 (2013), available from <http://www.collaborations.fz-juelich.de/ikp/anke>.
- [28] R. Schleichert, et al., IEEE Trans. Nucl. Sci. 50 (2003) 301.
- [29] H. Garcilazo, T. Mizutani, πNN Systems, World Scientific, Singapore, 1990.