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# Polarized deuteron charge-exchange reaction $dp \to \{pp\}_s N\pi$ in the $\Delta$ isobar region

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Mechanisms of the charge exchange reaction $dp \to \{pp\}_s N\pi$, where $\{pp\}_s$ is a two-proton system at low excitation energy, are studied at beam energies $1-2$ GeV and for invariant masses $M_X$ of the final $N\pi$ system that correspond to the formation of the $\Delta(1232)$ isobar. The direct mechanism, where the initial proton is excited into the $\Delta(1232)$, dominates and explains the existing data on the unpolarized differential cross section and spherical tensor analyzing power $T_{22}$ for $M_X > 1.2$ GeV/$c^2$. However, this model fails to describe $T_{20}$.

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The $dp \to \{pp\}_s n$ reaction at low momentum transfers from the incident deuteron to the final diproton $\{pp\}_s$ is sensitive to the spin-flip part of the nucleon-nucleon charge-exchange forces [1]. Here $\{pp\}_s$ is a $pp$ pair at very low excitation energy, typically $E_{pp} < 3$ MeV, where it is predominantly in the $^1S_0$ state. A systematic study of this reaction has been started at ANKE@COSY in both single [2] and double-polarized [3] experiments. In addition to the $pn \to np$ subprocess, there are variants of this reaction, namely $dp \to \{pp\}_s n\pi^0$ or $dp \to \{pp\}_s p\pi^-$, that involve the spin-flip part of the $pn \to \Delta^+(1232)n$ transition, which is difficult to measure directly.

A linear combination of the Cartesian tensor analyzing powers $A_{xx}$ and $A_{yy}$ in the $\vec{d}p \to \{pp\}_s\Delta^0(1232)$ reaction was measured at SATURNE with a polarized deuteron beam of energy 2 GeV [4, 5] and a phenomenological analysis performed using one-pion exchange [6]. New data on the unpolarized cross sections and tensor analyzing powers of the $\vec{d}p \to \{pp\}N\pi$ reaction were recently obtained at ANKE@COSY at energies 1.6, 1.8, and 2.3 GeV, where both $A_{xx}$ and $A_{yy}$ were determined individually [7, 8].

All data on the $dp \to \{pp\}_s n$ reaction can be well explained by the single-scattering mechanism with a $pn \to np$ sub-process, provided that one accounts for the final $pp$ interaction in the $^1S_0$ state. It is important to check whether the tensor analyzing powers of the $dp \to \{pp\}_s N\pi$ reaction can be similarly described.

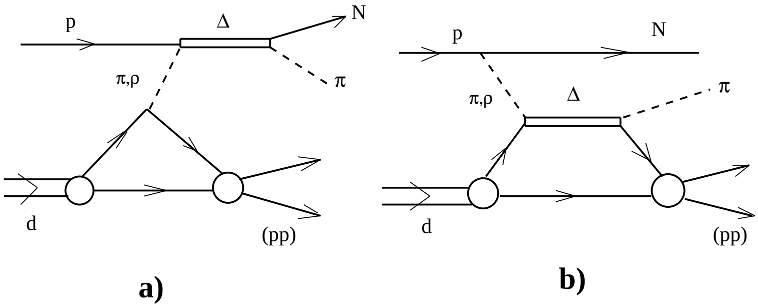


**Figure 1:** The mechanisms of the $dp \to \{pp\}_s N\pi$ reaction: a) direct (D), b) exchange (E).

It is expected that at low momentum transfers the $dp \to \{pp\}_s N\pi$ reaction is dominated by the direct (D) one-pion-exchange mechanism of Fig. 1a. The differential cross section was evaluated within this model [8] using a modified form of the input employed for the $p(^3\text{He},t)\Delta^{++}$ reaction [4]. At high $N\pi$ invariant masses, $M_X \sim 1.2-1.35$ GeV/$c^2$, this explains well the shape of the measured spectra, but it fails for lower masses [8]. The E-mechanism of Fig. 1b, where the $\Delta(1232)$ is excited in the deuteron, is of little importance and its influence on the analyzing powers will be neglected. For the elementary $pN \to \Delta N$ amplitudes we use both $\rho$-meson and pion exchange.

We consider the mechanisms of Fig. 1 on the basis of the Feynmann diagram technique. For the meson-baryon vertices we apply the formalism used in Ref. [9], where the exclusive $pp \to pn\pi^+$ data [10] were analyzed in the $\Delta$-isobar region and the cut-off parameters at the $\pi(\rho)NN$ and $\pi(\rho)N\Delta$ vertices were fixed from a fit to the data. The vertex form factors $\pi(\rho)NN$ and $\pi(\rho)N\Delta$ are taken in the monopole form, $F_{\pi(\rho)}(k^2) = (\Lambda^2 - m^2_{\pi(\rho)})/(\Lambda^2 - k^2)$, where $m_\pi$ $(m_\rho)$ is the pion ($\rho$ meson) mass, $k$ is the pion ($\rho$ meson) 4-momentum, and $\Lambda$ is the cut-off parameter. The $q^3$-dependence of the total width of the $\Delta$-isobar on the relative momentum $q$ in $\pi N$ system is taken into account. The transition form factor $d \to \{pp\}_s$ is evaluated using the CD-Bonn interaction potential [11].

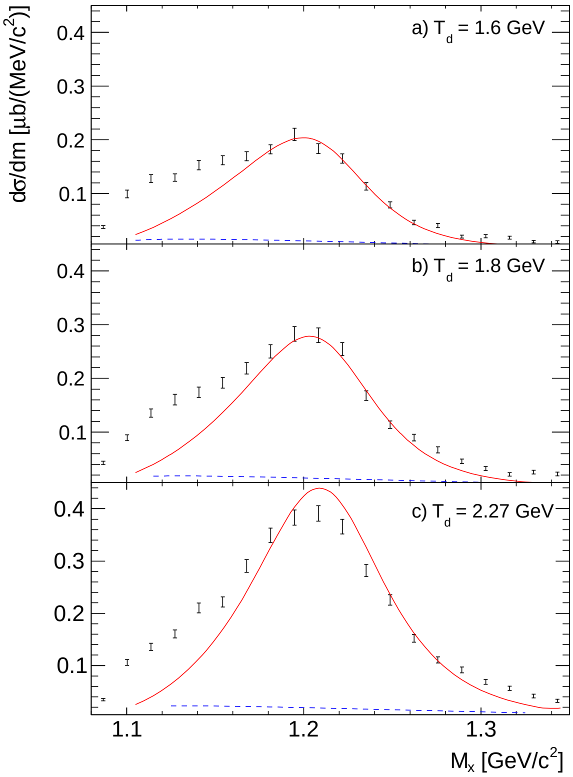


**Figure 2:** The $dp \to \{pp\}_s N\pi$ differential cross section as a function of the $\pi N$ invariant mass $M_X$ at three beam energies. The ANKE@COSY data [8] are compared with the calculations based on the D- (full line) and E-mechanisms (dashed line) in impulse approximation.

As shown in Fig. 2, the D-mechanism can explain the shape of $d\sigma/dM_X$ for $M_X > 1.2$ GeV/$c^2$ at all three beam energies studied [8]. The magnitudes of the cross section are also reasonably reproduced with a cutoff parameter value $\Lambda = 0.5$ GeV [9].

At lower masses, $M_X < 1.2$ GeV/$c^2$, the D-mechanism fails to explain the measured cross section [8] and other mechanisms must be investigated. The E-mechanism is calculated in a similar manner to the D. In this case, due to spin-flip in the loop caused by the $d \to \{pp\}_s$ transition, the vector product $[\mathbf{k} \times \mathbf{k}']$ of the momenta of pions appears in the reaction amplitude. The E-contribution has indeed a maximum at low masses $M_X \approx 1.1$ GeV/$c^2$. However, it is much smaller in absolute value than the D-contribution (see dashed line in Fig. 2) and therefore does not provide an explanation of the observed shape of the cross section as a function of $M_X$. The reasons for this small size are (i) the smallness of the $\Delta-$propagator for the E-mechanism as compared to the D-mechanism, and (ii) the smallness of the vector product $[\mathbf{k} \times \mathbf{k}']$ for E-kinematics as compared to the scalar product $(\mathbf{k} \cdot \mathbf{k}')$ for the D-kinematics.

As a check, we calculated the $dp \to dX$ cross section at almost the same kinematics. The E-mechanism is here allowed but the D-mechanism is forbidden by isospin. We found reasonable agreement with the experimental data on this reaction [13] and also with the model calculations given in this paper.

In impulse approximation the transition matrix element for the direct mechanism of the $dp \to \{pp\}_s \Delta^0$ reaction can be written as

$$M_{fi} = \Psi_j^+(\lambda_\Delta)(D_\pi k_j T_i + D_\rho M_{ji})\, e_i(\lambda_d)\, \chi_p(\sigma_p), \quad (1)$$

where $\Psi_j^+$ is the vector-spinor of the $\Delta$-isobar, $\chi_p$ is the spinor of the initial proton, $e_i$ is the polarization vector of the deuteron, $\lambda_\Delta$, $\lambda_d$ and $\sigma_p$ are spin-projections of the $\Delta$, deuteron, and proton, respectively, and $k_j$ is the 3-momentum of the pion in the $\Delta$-isobar rest frame ($i, j = x,y,z$). The factors $D_\pi$ and $D_\rho$ in Eq. (1) are given by products of the coupling constants $\pi NN$, $\rho NN$, $\pi N\Delta$, $\rho N\Delta$, form factors, and propagators of the $\pi$ and $\rho$ mesons. The vector operator for pion exchange $T_i$ is

$$T_i = \left(S_S(q) + \frac{1}{\sqrt{2}} S_D(q)\right) Q_i - \frac{3}{\sqrt{2}} S_D(q)(\mathbf{Q}\cdot\mathbf{n})n_i, \quad (2)$$

where $S_S(q)$ and $S_D(q)$ are the $S$- and $D$-wave $d \to \{pp\}_s$ transition form factors at 3-momentum transfer $\mathbf{q}$, and $\mathbf{n}$ is the unit vector along $\mathbf{q}$. The momentum $\mathbf{Q}$ is

$$\mathbf{Q} = \left[\frac{E_1 + m_N}{E_2 + m_N}\right]^{1/2} \mathbf{p}_2 - \left[\frac{E_2 + m_N}{E_1 + m_N}\right]^{1/2} \mathbf{p}_1, \quad (3)$$

where $E_i = \sqrt{p_i^2 + m_N^2}$ and $\mathbf{p}_1$ ($\mathbf{p}_2$) is the 3-momentum of the virtual proton (neutron).

The tensor $\mathscr{M}_{ji}$ describes $\rho$-meson exchange:

$$\mathscr{M}_{ji} = (S_S + \frac{1}{\sqrt{2}} S_D)\left[(\mathbf{Q}\cdot\mathbf{Q}')\delta_{ji} - Q_j Q_i'\right] - \frac{3}{\sqrt{2}} S_D \left[(\mathbf{Q}\cdot\mathbf{Q}')n_j - (\mathbf{Q}'\cdot\mathbf{n})Q_j\right] n_i, \quad (4)$$

where $\mathbf{Q}'$ is the momentum of the $\rho$ meson in the $\Delta$-isobar rest frame.

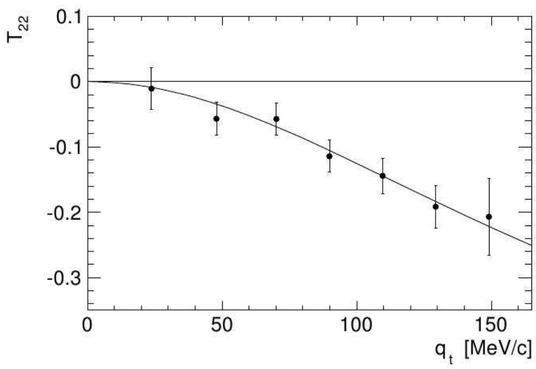


**Figure 3:** Spherical tensor analyzing power $T_{22} = (A_{xx} - A_{yy})/2\sqrt{3}$ for the $dp \to \{pp\}_s N\pi$ reaction averaged over the beam energies of Ref. [8], versus the transverse momentum transfer $q_t$.

The Cartesian tensor analyzing powers $A_{ij}$ are defined by $A_{ij} = Tr\{\mathscr{M}\hat{\mathscr{P}}_{ij}\mathscr{M}^+\}/Tr\{\mathscr{M}\mathscr{M}^+\}$, where $\mathscr{M}$ is the transition operator given by Eq. (1), $\hat{\mathscr{P}}_{ij} = \frac{3}{2}(S_iS_j + S_jS_i) - \delta_{ij}$, and $S_l$ is the spin-1 operator ($i, j, l = x,y,z$). Following the presentation of the ANKE@COSY experiment [8], we consider the Cartesian tensor analyzing powers $A_{xx}$ and $A_{yy}$ as functions of the transverse component of the momentum transfer $q_t$. The $z$ axis is chosen to lie along the deuteron beam momentum $\mathbf{p}_d$, $y$

along $\mathbf{p}_d \times \mathbf{p}_{pp}$, where $\mathbf{p}_d$ ($\mathbf{p}_{pp}$) is the total momentum of the deuteron ($pp$-pair), with $x$ being taken so as to form a right-handed coordinate system. The experimental data of Ref. [8] were summed over the invariant mass of the undetected $\pi + N$ system in the interval $1.19 < M_X < 1.35$ GeV/$c^2$ at fixed $q_t$. Thus, we obtain, for example,

$$A_{xx} = 1 - 3 \int_{M_X^{min}}^{M_X^{max}} \mathscr{M}_{\alpha x} \mathscr{M}^{+}_{\alpha x} dM_X \Big/ \int_{M_X^{min}}^{M_X^{max}} \mathscr{M}_{\alpha i} \mathscr{M}^{+}_{\alpha i} dM_X \cdot \qquad (5)$$

Non-relativistically $\mathbf{Q} = \mathbf{p}_p - \mathbf{p}_n = \mathbf{q}$. In this limit, and ignoring integration over $M_X$, one finds from Eq. (5) that, for pure $\pi$ and $\rho$ exchange,

$$A^{\pi}_{xx} = 1 - 3q_t^2/\mathbf{q}^2 \quad \text{and} \quad A^{\pi}_{yy} = 1,$$
$$A^{\rho}_{xx} = -\tfrac{1}{2} + 3q_t^2/2\mathbf{q}^2 \quad \text{and} \quad A^{\rho}_{yy} = -\tfrac{1}{2}. \qquad (6)$$

Both of these simple limits are in contradiction with experiment, for which $A_{xx}(q_t = 0) = A_{yy}(q_t = 0) \approx 0$ and $A_{yy}(q_t)$ has a smooth $q_t$ dependence [8]. Calculations for $\pi + \rho$ exchange have been performed with $\Lambda_{\pi NN} = \Lambda_{\pi N\Delta} = 0.5$ GeV and $\Lambda_{\rho NN} = \Lambda_{\rho N\Delta} = 0.7$ GeV [9], when $\rho$-exchange is almost negligible. For these parameters, $A_{xx}$ decreases with increasing $q_t$ from $A_{xx} = 1$ at $q_t = 0$ to $A_{xx} \approx 0.5$ at $q_t = 170$ MeV/c, whereas $A_{yy}$ is almost independent of $q_t$ and close to unity.

When the contribution of the $\rho$ meson is raised by increasing the cut-off parameter $\Lambda_{\rho NN} = \Lambda_{\rho N\Delta}$ to 1.3 GeV, both $A_{xx}$ and $A_{yy}$ decrease but stay far from experiment at $q_t = 0$. The $\pi + \rho$ model also fails to describe the spherical tensor analyzing power, $T_{20} = -(A_{xx} + A_{yy})/\sqrt{2}$. On the other hand, the spherical analyzing power $T_{22} = (A_{xx} - A_{yy})/2\sqrt{3}$ is well described by the direct one-pion exchange of Fig.1a, as demonstrated in Fig. 3.

To take into account an interference between the D and E mechanisms would require one to consider the quasi-three-body final states $\pi^0 n\{pp\}_s$ and $\pi^- p\{pp\}_s$ explicitly instead of the quasi-two-body state $\Delta^0\{pp\}_s$. However, this will not improve the results at lower masses $M_X < 1.2$ GeV/$c^2$. Our results suggest that one should use a $NN \to N\Delta$ amplitude beyond undistorted $\pi + \rho$ exchange.

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