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

David Mchedlishvili[*] **for the ANKE collaboration**
High Energy Physics Institute, Tbilisi State University, 0186 Tbilisi, Georgia
Institut für Kernphysik, Forschungszentrum Jülich, D-52425 Jülich, Germany
E-mail: `d.mchedlishvili@fz-juelich.de`

Deuteron charge-exchange break-up $\vec{d}p \to \{pp\}n$, where the final $\{pp\}$ diproton system is at very low excitation energy and hence in the $^1S_0$ state, is a powerful tool to probe the spin-flip terms in the proton-neutron charge-exchange reaction. Recent measurements with the ANKE spectrometer at the COSY storage ring at 1.6, 1.8, and 2.3 GeV have extended this study into the pion-production regime in order to investigate the excitation of the $\Delta(1232)$ isobar in the $dp \to \{pp\}\Delta^0$ reaction. Values of the differential cross section and two deuteron tensor analysing powers, A_{xx} and A_{yy}, have been extracted in terms of the diproton production angle or Δ^0 invariant mass. These data can be interpreted in terms of the spin-longitudinal or spin-transverse contributions to the elementary $\vec{n}p \to \vec{p}\Delta^0$ process. The results presented are compared to those obtained with the SPES-4 spectrometer at Saclay at 2 GeV, where only a single combination of A_{xx} and A_{yy} was measured.

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[*] Speaker.

1. Introduction

A good understanding of the Nucleon–Nucleon interaction (*NN*) remains one of the most important goals of nuclear and hadronic physics. Apart from their intrinsic importance for the study of nuclear forces, *NN* data are necessary ingredients in the modeling of meson production and other nuclear reactions at intermediate energies.

It was emphasised many years ago that quasi–free (p,n) or (n,p) reactions on the deuteron can act, in suitable kinematic regions, as a spin filter that selects the spin–dependent contribution to the np elastic cross section [1]. The comparison of this reaction with free backward elastic scattering on a nucleon target might allow a direct reconstruction of the np backward amplitudes [2].

Theory suggested that much information on the np charge-exchange amplitudes could be extracted by studying the deuteron charge-exchange break-up reaction, $\vec{d}p \to \{pp\}X$. Two channels are of interest here: $X = n$ and $X = \Delta^0$. By selecting the two final protons with low excitation energy, typically $E_{pp} < 3$ MeV, the emerging diproton is dominantly in the $^1S_0$ state. In impulse approximation these reactions can be considered as $np \to pn$ or $np \to p\Delta^0$ scattering with spectator proton. The impulse approximation model [3] had been implemented in detail for the neutron channel (Fig. 1) and predicts analysing powers, spin correlation coefficients and cross section for this reaction [4]. In the $^1S_0$ limit, the $\vec{d}\vec{p} \to \{pp\}_s n$ reaction observables are directly related to the np spin–dependent amplitudes [3].

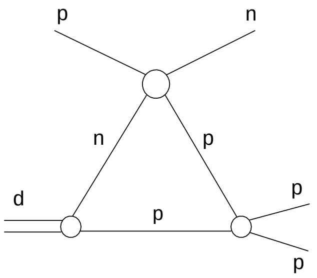

Figure 1: Deuteron charge–exchange break-up diagram for the neutron channel.

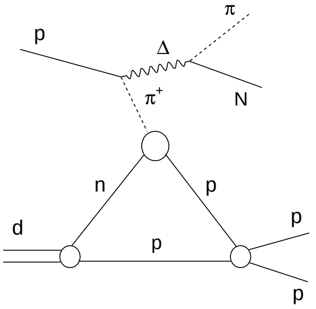

Figure 2: The simplest implementation of direct Δ^0 production in the deuteron charge–exchange break-up reaction.

Since, the SAID np data base has significant ambiguities above 800 MeV nucleon energy [5], the deuteron charge–exchange break-up reaction with low excited diproton system becomes a powerful tool to probe the spin-flip terms in the proton-neutron charge–exchange reaction.

The ANKE collaboration has embarked on a systematic programme to measure the differential cross section, analysing powers, and spin–correlation coefficients of the deuteron charge–exchange break-up reaction, $\vec{d}\vec{p} \to \{pp\}_s n$. The aim is to deduce the energy dependence of the spin–dependent np elastic amplitudes. The methodology has been checked at $T_d = 1.17$ GeV energy where the np amplitudes are reasonably well known [6]. The results presented there are in a good agreement with impulse approximation predictions. The success of this technique encourages its application at higher energies, where more precise np data are needed.

However, recent measurements at ANKE/COSY at high energies clearly show the possibility to extend this study into the pion-production regime in order to investigate the excitation of the $\Delta(1232)$ isobar. It was demonstrated many years ago at Saclay that at $T_d = 2.0$ GeV the $\Delta(1232)$ isobar can be excited in the charge–exchange reaction $dp \to \{pp\}\Delta^0$ [7]. The simplest interpretation of direct Δ production through a one-pion-exchange mechanism is shown in Fig. 2. Within this framework, such measurements would correspond to a spin transfer from the initial neutron to final proton in the $np \to \Delta^0 p$ process, and this would give valuable information about the spin structure in the excitation of the Δ isobar.

2. The experimental setup

Two experiments were carried out at the COoler SYnchrotron (COSY) of the Forschungszentrum Jülich using polarised deuteron beams at T_d = 1.2, 1.6, 1.8 (in 2005) and 1.2, 2.27 GeV (in 2006). This machine is capable of accelerating and storing polarised and unpolarised protons and deuterons with momenta up to 3.7 GeV/c. The forward part (FD) of the ANKE magnetic spectrometer [8], shown in Fig. 3, is used for the deuteron charge–exchange reaction studies.

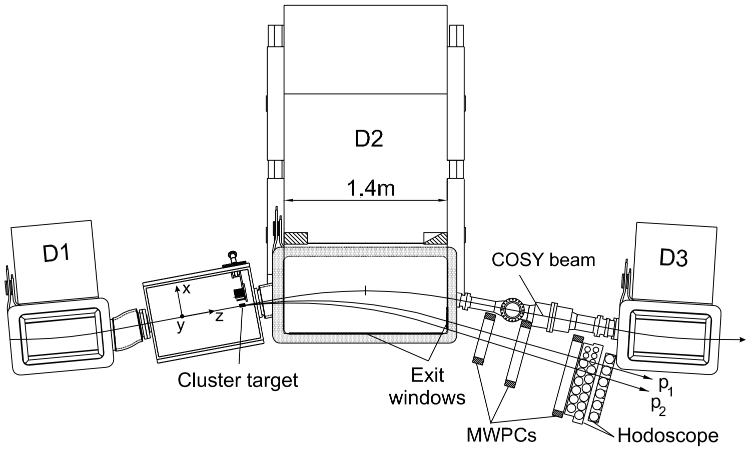

Figure 3: The ANKE experimental set–up showing the positions of the three dipole magnets D1, D2, and D3. The Forward Detector (FD) consists of three MWPCs and a hodoscope of three layers of scintillation counters.

The FD consists of multiwire chambers for track reconstruction and three layers of a scintillation hodoscope that permit time–of–flight and energy–loss determinations [9]. An unpolarised hydrogen cluster target was used during the experiments. Particles from the different reactions were tracked in the FD detector. Among the observed reactions, there are two that are of major interest, *viz.* deuteron charge–exchange $dp \to \{pp\}X$ and the quasi–free $dp \to p_{\text{sp}} d\pi^0$ reaction with a fast spectator proton, p_{sp}. The latter is used to measure the polarisation of the deuteron beam and also to determine the luminosity. In both cases, two particles are detected in the FD detector. In the subsequent data analysis the $p_{\text{sp}}p$ pairs are distinguished from $p_{\text{sp}}d$ by comparing the measured and calculated time–of–flight differences between these particles. Building missing–mass distributions for these final states allows one to identify the unobserved third particle.

3. Deuteron beam polarimetry

The first step when studying the spin observables of the charge–exchange reaction is to establish the polarimetry standards using the scattering asymmetries in a suitable nuclear reaction with known analysing powers. Polarisation calibration standards described in the previous study [10] are few and exist only at discrete energies. But, if one avoids depolarising resonances in the machine, the beam polarisation can be conserved when ramping the beam energy up or down [11]. Since there are no depolarising resonances for deuterons in the COSY energy region, this makes things easier. This polarisation export technique, which has been checked in practice [12], is a useful tool for the polarisation experiments at any available energy at COSY. The data on T_d = 1.6 GeV, 1.8 GeV and 2.27 GeV energy were taken using a COSY super–cycle that included the $T_d = 1.2$ GeV flat-top to provide the calibration standard.

The following reactions were used in our analysis in order to determine the polarisation of the deuteron beam at $T_d = 1.2$ GeV, where the analysing powers are well known: quasi–free $np \to d\pi^0$ for the vector component (P_z) and $dp \to \{pp\}n$ for the tensor (P_{zz}) component. In order to minimise systematic errors, several configurations of the ion source (with different vector and tensor polarisations) were employed and the beam polarisation had to be determined separately for each state. In order to achieve this, the relative luminosities C_n of each state with respect to the unpolarised mode had to be established so that one could then use:

$$N_{\mathrm{pol}}/N_0 = C_n\left[1+\tfrac{1}{4}P_{zz}\left[A_{xx}(q)(1-\cos2\phi)+A_{yy}(q)(1+\cos2\phi)\right]\right], \tag{3.1}$$

where N_{pol} and N_0 are the numbers of polarised and unpolarised counts, respectively. Details on the count calibration and the full procedure for the beam polarisation determination can be found in Ref. [12].

4. Luminosity determination

Cross section determinations require precise normalisation to obtain absolute values. Generally, the luminosity of the experiment can be fixed using any reaction with a well known cross section. Current analyses use the quasi-free $np \to d\pi^0$ reaction for this purpose since it is clearly identified at ANKE forward detector. Furthermore, the cross section of the $pp \to d\pi^+$ process is known from SAID [5] and this is larger than that for $np \to d\pi^0$ by an isospin factor of two. An additional advantage of this reaction is that the shadowing effect in the deuteron (where one nucleon hides behind the other) largely cancels out between the $dp \to \{pp\}X$ and $dp \to p_{\mathrm{sp}}d\pi^0$ reactions. The count rates of the reaction needs corrections for several factors, such as DAQ dead time, track reconstruction and proportional chamber efficiency, etc., but the most important one is detector geometric acceptance. A Monte Carlo simulation was used at all energies to estimate the geometric acceptance of the ANKE forward detector and make appropriate corrections.

5. Results

5.1 Differential cross section

Missing mass spectra of the $dp \to \{pp\}X$ at three different energies are presented in Fig. 4 (note: for clarity of presentation the high mass region is scaled by factor of eight). At higher M_x, above the πN threshold, there is a lot of strength that must be associated with the production of a single pion. It is therefore tempting to interpret the data in a form that is completely analogous to that used for the $dp \to \{pp\}_s n$ case. For example, if for simplicity one assumes one-pion-exchange then, for the excitation of the $\Delta^0(1232)$ isobar, we are looking rather at the diagram of Fig. 2. It should be noted that this includes the same triangle loop integration at the bottom as for the $dp \to \{pp\}_s n$ reaction, i.e., it depends on the same type of $d \to \{pp\}_s$ form factor.

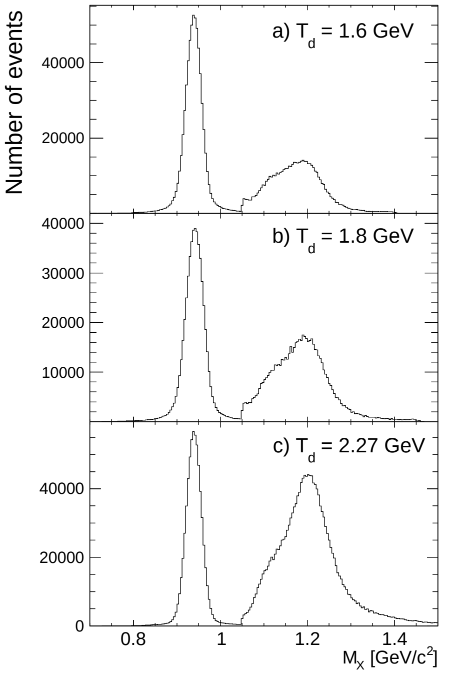

Figure 4: The missing–mass M_x distribution for the reaction $dp \to \{pp\}_S X$ at three deuteron beam energies. In addition to the neutron peak, one sees clear evidence for the excitation of the Δ^0 isobar.

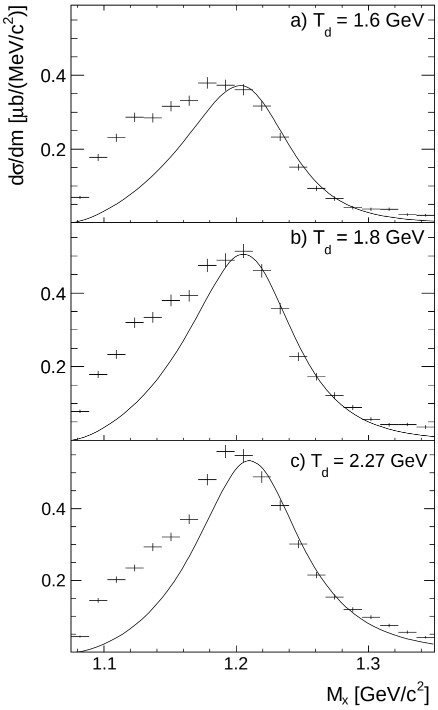

Figure 5: Differential cross section for the $dp \to \{pp\}X$ reaction for $M_x > M_N + M_\pi$ at three deuteron beam energies. Curves correspond to one-pion-exchange predictions [13]

However, if we take a simple one-pion-exchange model for the $pn \to p\Delta^0$ amplitude (we used the one of Dmitriev, quoted in [13]), the shape of the corresponding cross section predictions is wrong at low M_x, as can be seen in Fig. 5. There is some flexibility with the normalisation, because of uncertainty in the vertex functions but, if the model is adjusted to fit on the right, it is MUCH too low on the left. This problem is, of course, much more general than Dmitriev's implementation of the model. Since the Δ is a *p*-wave πN resonance, there can be little strength at low mass.

Exactly the same problem was noted in the pioneering experiments at Saclay [13], where the one-pion-exchange prediction also agrees with the data at high M_x but vastly underestimate them at low M_x. However, at Saclay they also measured the same reaction with a deuterium target. It should be noted here that the cross section for $dn \to \{pp\}_s\Delta^-$ should be THREE times bigger than that for $dp \to \{pp\}_s\Delta^0$. After taking shadowing into account, the authors divided their deuterium target data by a factor of four to compare with the hydrogen data. This works very well indeed at

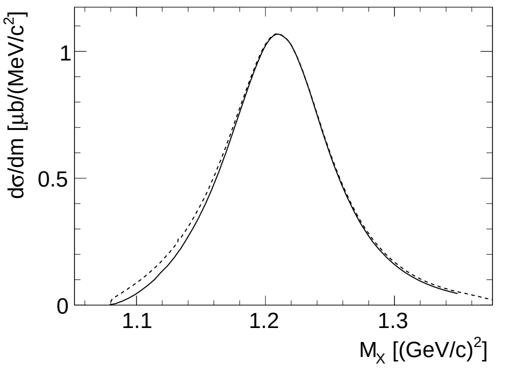

Figure 6: Differential cross section predictions for the $dp \to \{pp\}\Delta^0$ reaction at T_d = 2.27 GeV. Simple estimation of *s*-wave contribution (dashed) using SAID amplitudes gives little additional effect over the *p*-wave (solid).

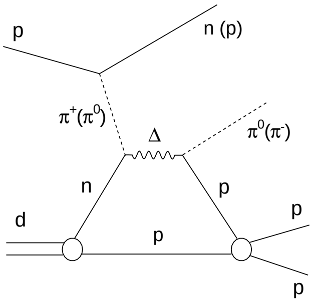

Figure 7: Δ excitation in the incident deuteron. This may be the dominant mechanism at the low M_x.

high M_x but fails miserably near threshold. This means that the excess of events at low M_x must be mainly associated with isospin $I = \frac{1}{2}$ so they are not compatible with the direct Δ production envisaged in Fig. 2.

In an attempt to salvage the approach, an attempt has been made to estimate the *s*-wave πN contribution to direct production. For this purpose, Dmitriev's model predictions were modified in the following way:

$$\left(\frac{d\sigma}{dm}\right)_{s-wave} \approx \left(\frac{d\sigma}{dm}\right)_{p-wave} \times \frac{2\sigma(S_{11}) + \sigma(S_{31})}{\sigma(P_{33})} \times \frac{p_0^2}{p^2} \tag{5.1}$$

where $\sigma(S_{11})$, $\sigma(S_{31})$ and $\sigma(P_{33})$ are SAID predictions for πN elastic scattering, and p_0 and p are the real and virtual pion momenta, respectively. As one can see in Fig. 6, it gives but little extra strength at low M_x. This *s*-wave contribution would have to be increased by orders of magnitude to agree with the data.

The problem that we are faced with here is very analogous to the search for the excitation of the $I = \frac{1}{2}$ Roper resonance in inclusive $dp \to dX$ or $\alpha p \to \alpha X$ measurements [14]. Although the X state here must have $I = \frac{1}{2}$, it does not need to be a N^* resonance. These measurements show the largest strength at very low values of M_x, with only a small enhancement connected with the $N^*(1440)$. The dominant background is connected with the possibility of exciting the $\Delta(1232)$ inside the projectile d or α, as mentioned in Ref. [14]. This means that the pion and nucleon that make up the state X are produced at different vertices. The corresponding diagram for the $dp \to \{pp\}_s X$ reaction is shown in Fig. 7.

The only real difference between this and the standard impulse approximation of Fig. 2 is an interchange of the two final nucleons, which means that the evaluation of the corresponding amplitudes require the same basic input. Calculations of the cross section and analysing powers for this mechanism are currently in progress. Note that the state X here no longer has to have isospin $I = \frac{3}{2}$ because it does not come from the decay of the Δ.

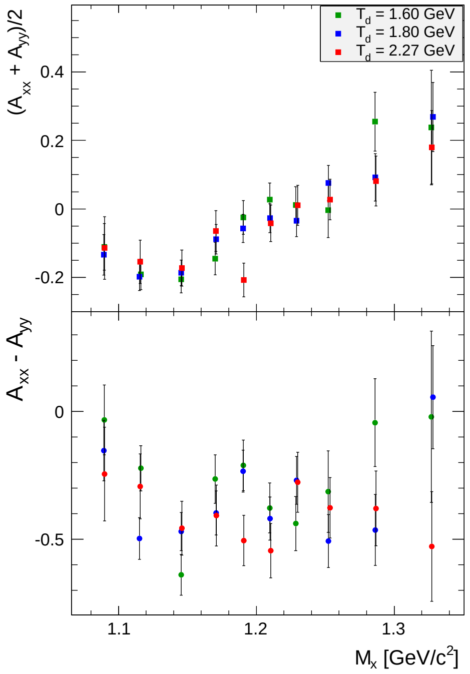

Figure 8: The sum and difference of the Cartesian tensor analysing powers at different beam energies.

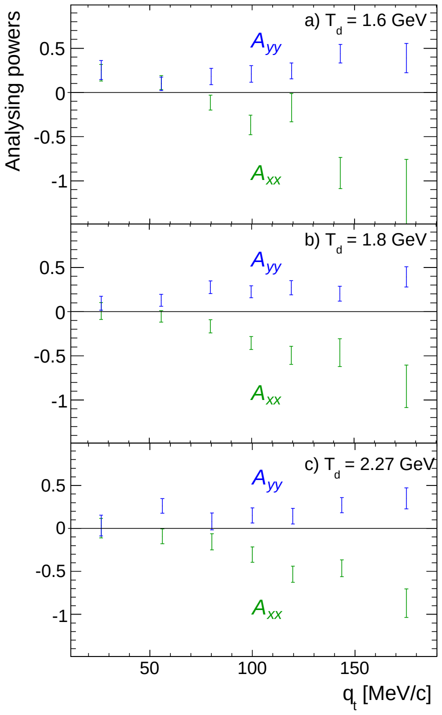

Figure 9: A_{xx} and A_{yy} tensor analysing powers at three deuteron beam energies. Only high mass data ($1.19 < M_x < 1.35$ GeV/c^2) are used.

5.2 Tensor analysing powers

The fact that we have two different mass regions, where different mechanisms are dominant, is also reflected in the tensor analysing power behaviour shown in Fig. 8. Here the sum and difference of deuteron Cartesian tensor analysing powers A_{xx} and A_{yy} are presented as functions of the missing mass M_x. [These quantities are proportional to the spherical tensor components T_{20} and T_{22}.] The first thing to note is the minimum in $A_{xx}+A_{yy}$ for $M_x \approx 1.15$ GeV/c^2. This is precisely the region where there is the biggest discrepancy with the cross section predictions in Fig. 5. The second point to notice is that the values of $A_{xx}+A_{yy}$ are remarkably stable and seem to show a universal behaviour, independent of beam energy. Hence, whatever the mechanism is driving the reaction, it seems to be similar at all energies.

Until the relative contributions of the two driving mechanisms (and their possible interferences) is sorted out, one can only assume that at high M_x the direct Δ production dominates. We show only such data in Fig. 9 as a function of the transverse momentum transfer q_t. In the forward direction, $q_t = 0$ and one must then have $A_{xx} = A_{yy}$ because there is no way of separating the x and y directions. The behaviour of both observables is similar at all three energies. However, it is important to note the differences from the charge-exchange with neutron channel: the signs are opposite to those of the $\vec{d}p \to \{pp\}_s n$ reaction [15] and they tend to be very small at $q_t = 0$. These will prove to be valuable constraints on the modeling of the $np \to p\Delta^0$ amplitudes, once we have identified the relative contributions of the two driving mechanisms.

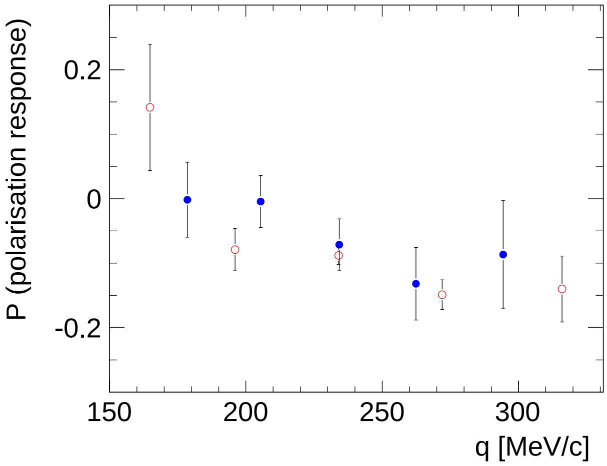

Figure 10: The comparison of the ANKE results at $T_d = 2.27$ GeV (blue points) with those of Saclay at $T_d = 2.0$ GeV (red circles).

In the Saclay experiments it was not possible to separate the two tensor analysing powers and at each production angle they could only evaluate a linear combination of the analysing powers that they called P (*Polarisation response*). The relative contributions from the A_{xx} and A_{yy} in P varies with angle. When this is reconstructed from the ANKE data, one can compare the results obtained at the two facilities. This is done in Fig. 10 for the 2 GeV Saclay data and the 2.27 GeV ANKE results as a function of the momentum transfer. The overall agreement is encouraging.

6. Summary and outlook

- ANKE data on deuteron charge–exchange allows one to investigate the $dp \to \{pp\}X$ reaction in Δ region. In the simplest interpretation these measurements would correspond to the spin transfer from an initial neutron to a final proton in the elementary $\vec{n}p \to \vec{p}\Delta^0$ process.

- Theoretical work is needed to quantify the second contributory mechanism (Fig. 7).

- A large amount of data was successfully obtained from the first double–polarised np scattering experiment at $T_d = 2.27$ GeV at ANKE [16]. It will be used for spin-correlation studies.

- The Δ production will also be studied in the near future in the $p\vec{d} \to \{pp\}\Delta$ channel at energies up to $T_p = 2.88$ GeV by using a polarised deuterium target.

Acknowledgments

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