PROCEEDINGS OF SCIENCE

Measurement of the charge exchange $np \to pn$ reaction by means of the deuteron beam

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The ratio of the differential cross sections of the charge exchange reaction $dp \to (pp)n$ to that of the $np \to pn$ elementary process, at small transferred momenta, has been discussed in order to estimate the spin-dependent part of the $np \to pn$ charge exchange amplitude. An estimation of the spin-dependent part of the $np \to pn$ charge exchange amplitude has been made on the basis of $dp \to (pp)n$ data, taken at 1.75 GeV/c momentum per nucleon, using the STRELA setup at the Nuclotron accelerator. The $np \to pn$ amplitude turned out to be predominantly spin-dependent.

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1. Introduction

Extracting complex amplitudes of the scattering matrix is a matter of fundamental importance in the theory of nucleon-nucleon scattering. For all amplitudes to be obtained, a complete experiment must be performed, i.e., an experiment with a set of experimentally observed quantities providing a complete and exhaustive description of this process. The complete experiment comprises measurements both with polarized projectile particles and with polarized targets. This task is large and laborious.

Nevertheless, under certain experimental conditions, there is a possibility to determine some amplitudes of the scattering matrix or a set of them. One of the chances is the charge exchange reaction on the deuteron $dp \to (pp)n$ with the use of unpolarized protons and unpolarized deuterons, which under certain conditions is determined only by the spin dependent amplitude. When studying the differential cross section of this reaction at small momentum transfer it is possible to estimate the spin-dependent term of the $np \to pn$ scattering amplitude in the context of the impulse approximation. This idea was proposed and mathematically formalized in a number of theoretical works [1–5]. Attempts were made to solve this problem experimentally, mainly, in separated neutron beams obtained by stripping accelerated deuterons.

Still, an experiment with monochromatic fast deuterons is more rational in respect to analysis of experimental data: two secondary protons products of charge exchange on the deuteron where both protons are fast moving in the forward direction at small angles, and so they are easily detectable. We performed this experiment on the synchrophasotron of the Laboratory of High Energy Physics, JINR, using a 1m hydrogen bubble chamber, which is simultaneously a detector and a target [6]. Before our investigations, no experiments with a fast deuteron beam were carried out. Simplified version of these two processes in the framework of the impulse approximation are shown in Fig. 1. The elementary $np \to pn$ (upper) and $dp \to (pp)n$ (lower) charge exchange reactions are shown. Empty circles stand for the neutron and full circles denote proton.

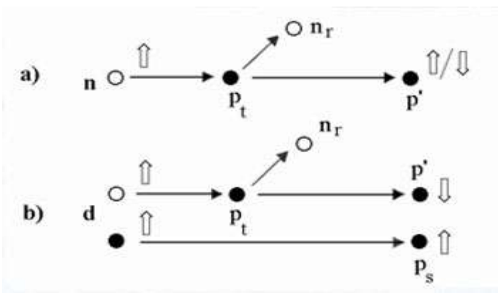

Figure 1: Elementary $np \to pn$ (upper) and $dp \to (pp)n$ (lower) charge exchange reactions. Empty circles stand for the neutron and full circles denote proton. Subscript t means target proton, double arrows show possible spin orientations.

Subscript t means target proton, double arrows show possible spin orientations. In the first case both spin orientations are allowed in the final state while in the second one for small angle scattering due to the produced charge symmetry (two protons moving in the very forward direction with small relative momenta) the reaction can proceed only the spin of a one the fast protons flips, as a consequence of the Pauli exclusive principle. In this way, the spin dependent part of the elementary charge exchange amplitude will be reflected through the probability of the charge exchange process on the deuteron.

The aim of present study was extraction of information on the elementary process $np \to pn$ charge exchange channel using the charge-exchange reaction $dp \to (pp)n$ at 3.5 GeV/c momenta. The existing data on that reaction are still very scanty and concern mainly the $d\sigma/dt$ distribution. During the past few years, interest in obtaining information on the cross section of the spin-dependent part on $np \to pn$ scattering renewed. This is partly connected with the appearance of accelerated deuteron at the JINR LPHE Nuclotron with energies over 1 GeV. Due to the high complexity of obtaining and processing data with hydrogen bubble chamber there was a need of transition to electronic methods. For the observation proton pairs in a narrow cone from the reaction $dp \to (pp)n$ several variants of experimental setup, named STRELA, were suggested and realized.

2. Extraction of the spin-dependent part of $np \to pn$ amplitude

The possibility to use the charge exchange reaction on the unpolarized deuteron for the determination the spin-dependent part of elementary $np \to pn$ charge exchange was emphasized in the series of works.The formalism is based on Pomeranchuk and Chew ideas published in 1951 [1, 2]. Later the mathematical formalism was developed by Dean [3, 4]. The mathematical formalism elaborated by Dean is based on two assumption, on the validity of impulse approximation and closure approximation. In the work by Lednicky and Lyuboshitz [7] it was shown that at relativistic energies these two assumptions are also justified.

The differential cross section of the elementary $np \to pn$ charge exchange can be represented as sum of the spin-independent (superscript SI) and spin-dependent (superscript SD) parts:

$$\left(\frac{d\sigma}{dt}\right)_{np\to pn} = \left(\frac{d\sigma}{dt}\right)^{SI}_{np\to pn} + \left(\frac{d\sigma}{dt}\right)^{SD}_{np\to pn}. \tag{2.1}$$

Mathematical formalism developed in [3–5] allows to connect the differential cross section for the deuteron charge exchange break-up and the elementary $np \to pn$ reaction. The differential cross section for $dp \to (pp)n$ charge exchange in the framework of the impulse approximation and at small t is :

$$\left(\frac{d\sigma}{dt}\right)_{dp\to(pp)n} = [1 - S(t)]\left(\frac{d\sigma}{dt}\right)^{SI}_{np\to pn} + [1 - \frac{1}{3}S(t)]\left(\frac{d\sigma}{dt}\right)^{SD}_{np\to pn}, \tag{2.2}$$

where $S(t)$ is the deuteron form factor, $t = (P_d - P_1 - P_2)^2$ is the 4-momentum transfer squared from the incoming deuteron to the two fast protons.
This expression implies that at 0° scattering angle $t = 0$, $S(0) = 1$ and the formula reduces to

$$\left(\frac{d\sigma}{dt}\right)_{dp\to(pp)n} = \frac{2}{3}\left(\frac{d\sigma}{dt}\right)^{SD}_{np\to pn}. \tag{2.3}$$

Thus, the charge exchange break-up reaction of the unpolarized deuteron on the unpolarized proton target in the forward direction is determined by the spin-flip part of the $np \to pn$ charge exchange process at 0 scattering angles. Deuteron acts as a spin filter. This result also remains valid when the deuteron D-state is taken into account. So, studying the process $dp \to (pp)n$ at small transferred momenta, allows to estimate the spin-dependent part of the elementary $np \to pn$ reaction. To extract the information we compare our experimental data (charge exchange differential cross section at $t = 0$) with the $np \to pn$ (charge exchange cross section) data at the same energy available in the literature.

3. Experimental facility STRELA

Based on the above mentioned ideas and experimental results, obtained using the 1m HBC [6] the experiment STRELA was designed and constructed in the LHEP JINR Dubna with the aim to select and detect charge exchange events in deuteron proton collisions. The experiment demands registration of two protons with momenta approximately equal to the half of the primary deuteron beam momenta. STRELA is a typical one-arm magnetic spectrometer composed of scintillator detectors (S1, S2) used to trigger the setup, block of drift chambers (DC1-DC4) used as coordinate detector and analyzing magnet (M). The recent version of the experimental setup is shown in Figure 2.

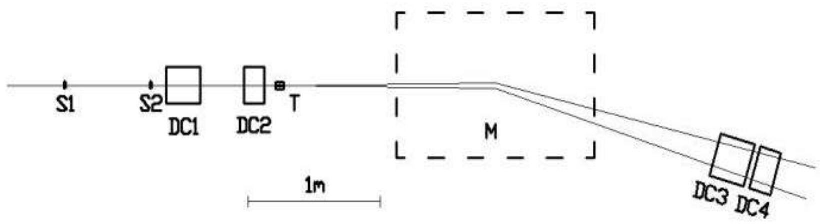

Figure 2: Layout of the experimental setup for determining the spin-dependent part of $np \to pn$ scattering: S1, S2 -scintillator counters, (DC1-DC4) drift chambers , M-analyzing magnet, T-target.

The sensitive areas of the drift chambers are the following: 125×125 mm^2 for $DC1, DC2$ and 250×250 mm^2 for $DC3, DC4$. Z axis is chosen in the beam direction. Chambers $DC1, DC3, DC4$ are equiped with xy wires and $DC2$ only with x-wires. $DC1$ and $DC3$ are composed of $8(4y, 4x)$ sensitive planes, $DC4$ is composed of $4(2y, 2x)$ sensitive planes while the $DC2$ contains $4(4x)$ sensitive planes. The intensity of the magnetic field $B = 0.85$ T are used to select deuterons and two protons, respectively. The drift length for all chambers is $r_{max} = 21$ mm. The control and read-out electronics were upgraded with new VME crates and all the modules were tested. The basic characteristics of the drift chambers were established from irradiation of a polyethylene target with a deuteron beam of 3.5 GeV/c momentum. For each wire the minimal (t_{min}) and maximal (t_{max}) drift times were determined. The average total drift time was found to be $\approx 450ns$. In the track finding procedure the relation between the measured drift time and the minimal distance (or radius (r)) from the anode wire to the track plays an important role. To find the function, transforming the drift time (t) to radius, also referred to as $r(t)$ relation, is the central task. This transformation function may depend on many parameters like: the electric field intensity, gas mixture, pressure, temperature and the chamber geometry. For determination of the transformation function two methods were applied: the linear one, mainly used for on-line and the cumulative or integral one suitable for on-line purposes. More technical detail and algorithm of the track reconstruction can be found in [8]. A view of the apparatus is shown on the Fig. 3. The lateral resolution of the drift chambers which are $(80 \div 90)$ μm and $(120 \div 130)$ μm for large and small drift chambers, respectively is demonstrated on Fig. 4. The acceptance of the experimental facility for the studied process of charge exchange reaction is 100%.

Figure 3: Drift chambers of the setup STRELA before magnet.

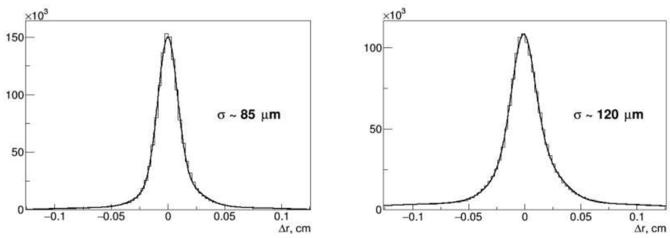

Figure 4: Lateral resolution drift chambers, $\Delta r-$ track residuals in xz plane of drift chamber.

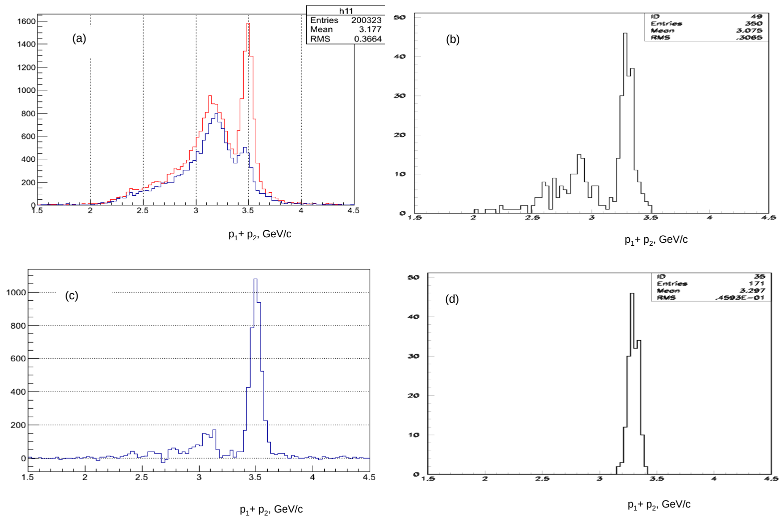

Figure 5: Distributions of the sum of the two proton momenta from dp reaction. Left side- experimental results, right side - simulation: a) targets CH_2-red, C- blue one; c) difference $CH_2 - C$; simulation included all channels dp- reaction (b) and only $dp \to ppn$ reaction (d).

The carbon and polyethylene targets were used to extract the dp interaction. The size of the targets were determined by carbon nuclei equivalent. Carbon target was used to account for the background events. The background from other channels of the dp reaction and the influence of carbon nuclei were estimated by the use of the GEANT simulation program for transporting the reaction products (taken from the corresponding events of the one meter bubble chamber at the momenta 3.3 GeV/c) through the experimental setup. More details about the chamber experiment see [6]. There is also shown that the $dp \to (pp)n$ reaction proceeding predominantly as a quasi free nucleon interaction with intermediate isobaric states does not influence the differential cross section at $t = 0$.

4. Experimental results

The experimental facility was irradiated in the beam of deuterons with 3.5 GeV/c momenta. In the run of March 2014 one billion triggers were received. The distribution of the sum the two proton momenta is shown in Fig. 5. The dependences of the sum two proton momenta from dp reaction are presented in Fig. 5 for CH2 and C targets (a) and difference CH2-C (c). The results of simulation include all channels dp-reaction (b) and channel $dp \to ppn$ only (d) are shown in Fig. 5 b,d. As we can see, the distribution has a characteristic peak near the incoming deuteron momentum kinematically associated with the pair of protons from the reaction $dp \to ppn$ (c). The contribution from the background reactions, other than the studied reaction $dp \to ppn$, which could also produce the two positively charged track in the forward direction, is negligible (5d).

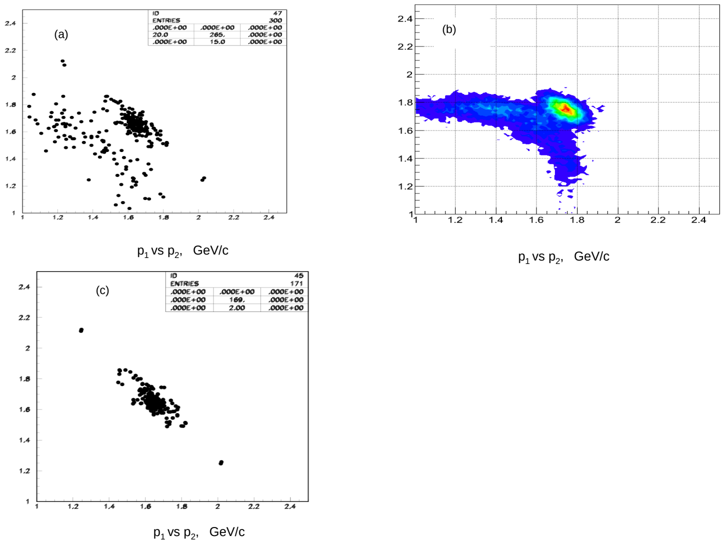

Figure 6: Two dimensional distribution of measured momenta p_1 versus p_2 of the two charged particles from dp-reaction: simulation includes all channel dp-reaction (a) and only $dp \to ppn$ channel (c) and experimental distribution is shown in (b).

The two dimensional distribution of momenta p_1 versus p_2 of the two charged particles from dp-reaction is shown in Fig.6. From comparison Fig.6(a,c) with experimental results Fig. 6b, it can be see that the background from other channels of the dp-reaction may be eliminated. The measured differential distribution dN/dt of the $dp \to (pp)n$ reaction is display on Fig. 7.

The obtained differential distribution dN/dt of the $dp \to (pp)n$ of the reaction (Fig.7) were extrapolated to $t = 0$ by the expression

$$\frac{dN}{dt} = (435.6 \pm 6.8) \bullet \exp((440.9 \pm 5.8)t) \tag{4.1}$$

with $\chi^2 = 77.93/78$.
Extrapolation to $t = 0$ gives:

$$\left.\frac{dN}{dt}\right|_{t=0} = 435.6 \pm 6.8 \,. \tag{4.2}$$

This value corresponds to charge exchange differential cross section

$$\left.\frac{d\sigma}{dt}\right|_{t=0} = 30.56 \pm 0.48\, mb/(GeV/c)^2 \,. \tag{4.3}$$

The cross section was calculated using the relation

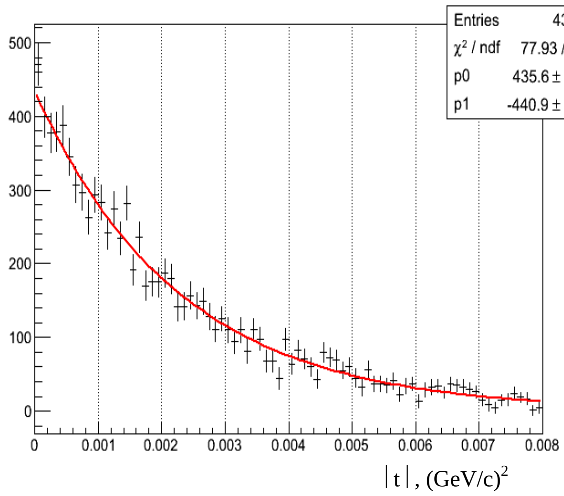

Figure 7: Differential distribution dN/dt of the $dp \to (pp)n$ reaction.

$$\sigma = \frac{1}{nl\Delta} \ln\left(\frac{1}{1-\frac{N_{int}}{N_0}}\right), \tag{4.4}$$

where l - length of the target ; n- density of H nuclei per cm^3 , N_0 - number of triggers ; N_{int} - number of interactions ; Δ - histogram bin width. The number of triggers was corrected for admixture of beam and efficiency of the drift chambers.

The obtained charge exchange differential cross section on the deuteron at $t = 0$ was compared with the available data from $np \to pn$ reaction at the same energy. The closest energy data comes from measurements made at the SATURN accelerator [9,10]. The values of $d\sigma/dt|_{t=0}$ of $np \to pn$ reaction as a function of the incident momenta is shown in Figure 8. The individual differential cross sections $d\sigma/dt$ versus t, from Bizard et al. [9] in the region of momenta $(1.4 \div 1.95)$ GeV/c, at each momentum were extrapolated to $t = 0$ by the expression

$$\frac{d\sigma}{dt} = a \bullet \exp(bt + ct^2)\ . \tag{4.5}$$

To determine the $d\sigma/dt|_{t=0}$ of the $np \to pn$ reaction at our incident momentum of 1.75 GeV/c per nucleon, an exponential fit was made to the results of Fig. 8, which gave the following value of $d\sigma/dt|_{t=0} = 48.0 \pm 0.2 mb/(GeV/c)^2$. The obtained value will be related to the estimated differential cross section of the quasi-elastic $dp \to (pp)n$ charge-exchange at $t = 0$ from our experiment. One would like to stress that the systematic error in the data by Bizard et al. [9] makes 5% .

One can introduce the ratio of the differential cross sections at $t = 0$ for the forward scattering (charge exchange) on the deuteron and proton

$$R = \frac{\left(\frac{d\sigma}{dt}\right)_{dp}}{\left(\frac{d\sigma}{dt}\right)_{np}} = 0.637 \pm 0.010\ . \tag{4.6}$$

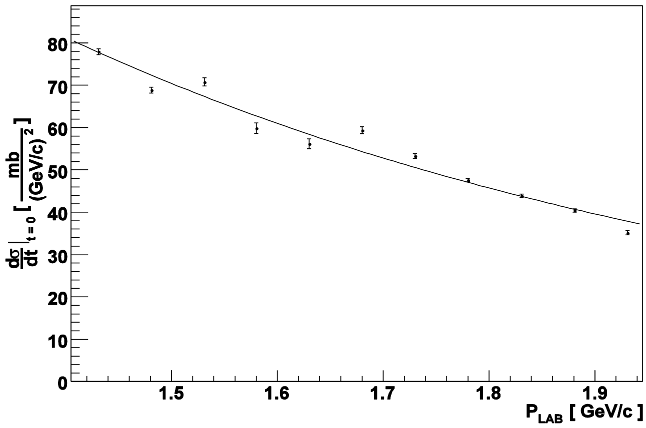

Figure 8: Dependence of the $d\sigma/dt|t = 0$ for the $np \to pn$ reaction on the beam momentum. The data points $d\sigma/dt|t = 0$ were computed from a fit (4.5) to the $np \to pn$ experimental results [9]. The solid curve is a simple exponential fit to the data points.

Under the assumption stated above this R can be related to

$$\frac{2}{3} \times \frac{\left(\frac{d\sigma}{dt}\right)_{np}^{SD}}{\left(\frac{d\sigma}{dt}\right)_{np}} . \tag{4.7}$$

and accordingly the value of the spin-independent part of the elastic $np \to pn$ charge exchange cross section has been obtained as

$$R_{np}^{ID} = \frac{\left(\frac{d\sigma}{dt}\right)_{np}^{SI}}{\left(\frac{d\sigma}{dt}\right)_{np}^{SD}} = \frac{2}{3 \times R} - 1 = 0.047 \pm 0.017 . \tag{4.8}$$

5. Conclusion

The spectrometric complex has been developed on the basis of the STRELA setup to study the charge-exchange reaction in the deuteron beam. The obtained ratio of the charge exchange differential cross sections at $t = 0$ for $dp \to (pp)n$ and $np \to pn$ reactions $R = 0.637 \pm 0.010$ testifies the prevailing contribution of the spin-dependent part to the $np \to pn$ cross section scattering. Continuation of these researches at higher energies on STRELA setup is important.

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