Eur. Phys. J. A manuscript No.
(will be inserted by the editor)

Charge exchange $dp \to (pp)n$ reaction study at 1.75 A GeV/c by the STRELA spectrometer

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Received: date / Accepted: date

Abstract The differential cross sections of the charge exchange reaction $dp \to (pp)n$ has been measured at 1.75 GeV/c per nucleon for small transferred momenta using the one arm magnetic spectrometer STRELA at the Nuclotron accelerator in JINR Dubna. The ratio of the differential cross section of the charge exchange reaction $dp \to (pp)n$ to that of the $np \to pn$ elementary process is discussed in order to estimate the spin-dependent part of the $np \to pn$ charge exchange amplitude. The $np \to pn$ amplitude turned out to be predominantly spin-dependent.

1 Introduction

In the theory of nucleon-nucleon scattering extracting complex amplitudes of the scattering matrix is a matter of fundamental importance. For all amplitudes to be obtained, a complete experiment must be performed, *i.e.*, an experiment with a set of observed quantities providing a full and exhaustive description of this process. Such an experiment comprises measurements with polarized both projectile and target what is large and laborious task.

However, 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 $dp \to (pp)n$ with the use of unpolarized protons and unpolarized deuterons, which under certain conditions is determined only by the spin dependent amplitude of the elementary $np \to pn$ scattering. When studying the differential cross section of this reaction at small four-momentum transfer squared, it is possible to estimate the spin-dependent term of the $np \to pn$ scattering amplitude in the context of the impulse approximation. The effect can be understood qualitatively in the following way. Two nucleons, bound in the deuteron may be in $^3S_1$ and $^3D_1$ ($T = 0$) spatial and spin-symmetric states; their isospin is antisymmetric. In the charge exchange at 0° w.r.t. laboratory frame (proton rest frame), the transition from $^3S_1$ or $^3D_1$ to a charge-symmetric $^1S_0$ or $^1D_2$ state of the two protons requires spin flip, in order to satisfy the Pauli principle and ensure an anti-symmetric total wave function. 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 original idea to take use of the charge exchange reaction on the unpolarized deuteron to determine the spin-dependent part of the $np \to pn$ charge exchange was proposed by Pomeranchuk [1] and Chew [2]. Later this possibility was emphasized in a series of works partly [3–10]. The mathematical description was developed later by Dean [6,7]. These formulas were obtained under certain assumptions, namely relying on the validity of the impulse and closure approximations. In the work by Lednicky and Lyuboshitz [11] it was shown that at relativistic energies these two assumptions are also justified.

In the general case the nucleon-nucleon (NN) amplitude in the centre of mass system can be presented as [12]

$$M = a + b(\boldsymbol{\sigma}_1\,\mathbf{n})(\boldsymbol{\sigma}_2\,\mathbf{n}) + c\big[(\boldsymbol{\sigma}_1\,\mathbf{n}) + (\boldsymbol{\sigma}_2\,\mathbf{n})\big] + \\ + e(\boldsymbol{\sigma}_1\,\mathbf{m})(\boldsymbol{\sigma}_2\,\mathbf{m}) + f(\boldsymbol{\sigma}_1\,\mathbf{l})(\boldsymbol{\sigma}_2\,\mathbf{l})\,, \tag{1}$$

where the orthonormal basis

$$\mathbf{l} = \frac{\mathbf{k}_f + \mathbf{k}_i}{|\mathbf{k}_f + \mathbf{k}_i|}\,, \quad \mathbf{m} = \frac{\mathbf{k}_f - \mathbf{k}_i}{|\mathbf{k}_f - \mathbf{k}_i|}\,, \quad \mathbf{n} = \frac{\mathbf{k}_i \times \mathbf{k}_f}{|\mathbf{k}_i \times \mathbf{k}_f|}\,, \tag{2}$$

introduced in [13] is used. The unit vectors $\mathbf{k}_i$ and $\mathbf{k}_f$ are the initial and final nucleons momenta, respectively. $\boldsymbol{\sigma}_1$ and $\boldsymbol{\sigma}_2$ are the Pauli 2×2 matrices corresponding to the beam and target nucleons. The coefficients a, b, c, e and f are complex scattering amplitudes which are functions of the interacting particles energies and scattering angles.

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

$$(d\sigma/dt)_{np\to pn} = (d\sigma/dt)^{SI}_{np\to pn} + (d\sigma/dt)^{SD}_{np\to pn}\,. \quad (3)$$

The mathematical formalism developed in [6,7,10] allows to connect the differential cross sections of the deuteron charge exchange and the elementary $np \to pn$ reactions. In the impulse approximation the dp charge exchange differential cross section at small momentum transfer $|t|$ is related to the NN-amplitudes via

$$(d\sigma/dt)_{dp\to(pp)n} = \left[1 - F_d(t)\right](d\sigma/dt)^{SI}_{np\to pn} \; + \left[1 - 1/3\,F_d(t)\right](d\sigma/dt)^{SD}_{np\to pn}\,, \quad (4)$$

where $F_d(t)$ denotes the deuteron form factor, t is the 4-momentum transfer squared, $t = (P_d - P_1 - P_2)^2$, P_1, P_2 are the final fast protons four-momenta w.r.t. laboratory frame,

$$(d\sigma/dt)^{SI}_{np\to pn} = |a|^2 + |c|^2\,, \qquad (d\sigma/dt)^{SD}_{np\to pn} = |b|^2 + |c|^2 + |e|^2 + |f|^2\,, \quad (5)$$

and the coefficients a, b, c, e and f refer to spin invariants of the elementary charge exchange amplitude in Eq. (1) [6,9].

In this paper we consider the case, when the scattering angle θ is very small, close to zero. Under such kinematical conditions one obtains $b = e$ and $c = 0$ and for the elementary cross sections simple expressions can be written

$$(d\sigma/dt)^{SI}_{np\to pn} = |a|^2\,, (d\sigma/dt)^{SD}_{np\to pn} = 2\,|b|^2 + |f|^2\,, \quad (6)$$

where the amplitude a is spin-independent, and b and f are spin-dependent. Equation (4) implies that at zero transfer $|t| = 0$, *i.e.* at the neutron CMS scattering angle 180°, when $F_d(0) = 1$, the differential cross section reduces to

$$(d\sigma/dt)_{dp\to(pp)n} = 2/3\,(d\sigma/dt)^{SD}_{np\to pn}\,. \quad (7)$$

So, the charge exchange break-up reaction of the unpolarized deuteron on the unpolarized proton target at zero transfer ($t = 0$) is completely determined by the spin-dependent part of the elementary $np \to pn$ backward scattering in CMS, so the deuteron acts as a spin filter. It should be noted that this result also remains valid when the deuteron D-state is taken into account [11]. Thus, studying the $dp \to (pp)n$ process at small transferred momenta allows to estimate the spin-dependent part of the elementary $np \to pn$ reaction.

The first experiment of such type has been realized at the JINR Synchrophasotron, irradiating the one meter hydrogen bubble chamber (HBC) with deuteron beams of 3.35 GeV/c momenta. The ratio of the elementary spin-independent to spin-dependent elastic $np \to pn$ charge exchange cross sections $R^{ID}_{np\to pn} = 0.21 \pm 0.17$ has been obtained [14]. This result testifies the prevailing contribution of the spin-dependent part to the the $np \to pn$ amplitude [12,14].

The study of the charge exchange reaction using the chamber-based technique made it possible to propose a layout of an electronic experiment for studying the charge exchange reaction with a deuteron in the energy range above 1 GeV. For the observation of the proton pairs in a narrow cone coming from the $dp \to (pp)n$ reaction several variants of experimental setup, named STRELA, have been suggested and realized [15].

The aim of the present study is to extract information on the elementary $np \to pn$ charge exchange channel using the $dp \to (pp)n$ charge exchange reaction at 3.5 GeV/c deuteron momenta by the STRELA spectrometer [15]. 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 of the $np \to pn$ scattering renewed. This is partly connected with the appearance of accelerated deuteron beams at the JINR VBLHEP Nuclotron with energies over 1 GeV. Before our investigations, no experiments with a fast deuteron beam have been carried out. In the region above 1 GeV the only results in a neutron beam of the Delta-Sigma group [16–18] are known, where the $R_{dp}(0) = (d\sigma/dt)_{nd}/(d\sigma/dt)_{np}$ ratios have been successfully measured. Seven data points at the energies $T_n = 0.5 - 2.0$ GeV have been obtained using liquid D_2 / H_2 and solid CD_2 / CH_2 / C targets. The contribution of non-flip to flip ratio in the $np \to pn$ charge-exchange process have been estimated via $R_{dp}(0)$ values. The experiment with monochromatic fast deuterons is more rational in respect to the analysis of experimental data: the two secondary protons, products of the charge exchange on deuteron $dp \to (pp)n$, are fast moving in the forward direction at small angles, and so they are easily detectable.

2 Experimental facility STRELA

Based on the above mentioned ideas and experimental results, obtained using the one meter HBC [12,14], the experiment STRELA has been designed and constructed in the Veksler Baldin Laboratory for High Energy Physics (VBLHEP) of the Joint Institute for Nuclear Research (JINR) in 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 and blocks of drift chambers (DC1 – DC4) used as coordinate detector and analyzing magnet M. The recent version of the experimental setup is shown in Fig. 1.

The sensitive areas of the drift chambers are the following: 12.5 × 12.5 cm for DC1, DC2 (small chambers) and 25 × 25 cm for DC3, DC4 (large chambers). The right-handed

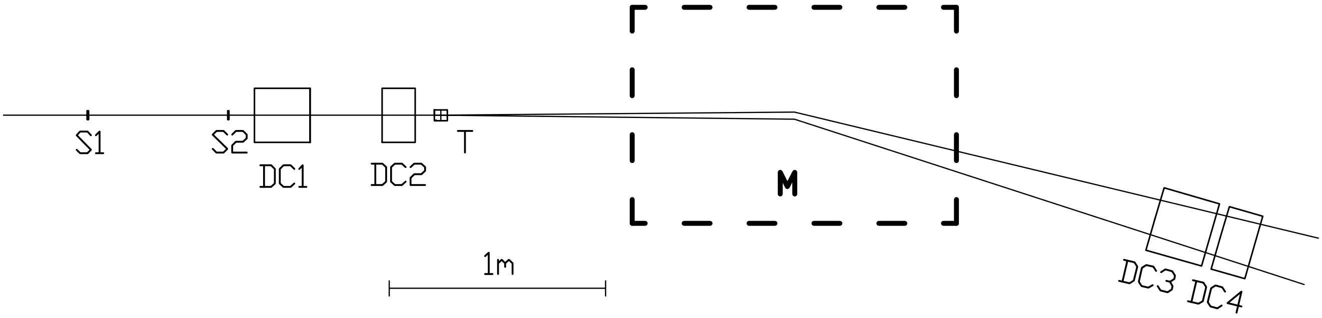

Fig. 1 Layout of the experimental setup for determining the spin-dependent part of $np \to pn$ scattering: scintillator counters S1 and S2, drift chambers (DC1 – DC4), analyzing magnet M and target T.

coordinate system has been used, where the z axis is in the beam direction and x and y axis lie in the plane of the chambers. All chambers contain an (Ar_2CH_4) gas mixture and have alternating, orthogonal x and y coordinate planes. DC1 and DC3 are composed of 8 sensitive planes ($4x$, $4y$) while DC2 and DC4 are composed of 4 sensitive planes ($2x$, $2y$). The analyzing magnet M of field intensity $B = 0.85$ T is used to separate deuterons and two protons, respectively.

The drift length for all chambers is $r_{max} = 21$ mm. The basic characteristics of the drift chambers have been 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 have been determined. The average total drift time was found to be ~ 450 ns. In the track finding procedure the relation between the measured drift time and the minimal distance from the anode wire to the track plays an important role. To find the function, transforming the drift time t to radius r, also referred to as $r(t)$ relation, is the central task. This transformation function may depend on many parameters like: the electric field strength, the gas mixture, the pressure, the temperature and the drift chamber geometry. For determination of the transformation function two methods are applied: the linear or quick one, mainly used for the preliminary results and online monitoring, the second method, called cumulative or integral one suitable for offline purposes, which gives the final results. The spatial resolution of the drift chambers used in the STRELA setup is in the range of ~ 80 –120 μm (Fig. 2). More technical details and the algorithm of the track reconstruction can be found in [15].

The experimental setup was started by the two polystyrene based scintillation counters S1 (dimensions 10 × 10 × 0.5 cm) and S2 (dimensions 7 × 7 × 0.5 cm). The light guides are made of plexiglass. For light read-out XP 2020 photomultipliers were used. The signals from the photomultipliers are connected to the shaper inputs. The use of these shapers allows to compensate the time spread of the signals caused by the leading edge of the amplitude of the photomultiplier signal. The time and amplitude information from the counters is digitized and recorded in each event for the subsequent monitoring of the counters and the entire trigger system functionality. The trigger system of the setup must ensure selection of events of the deuteron breakup reaction at zero angle (or close to zero) between the incoming deuteron and scattering protons. The acceptance of the experimental facility for the studied process of charge exchange reaction is close to 100 %.

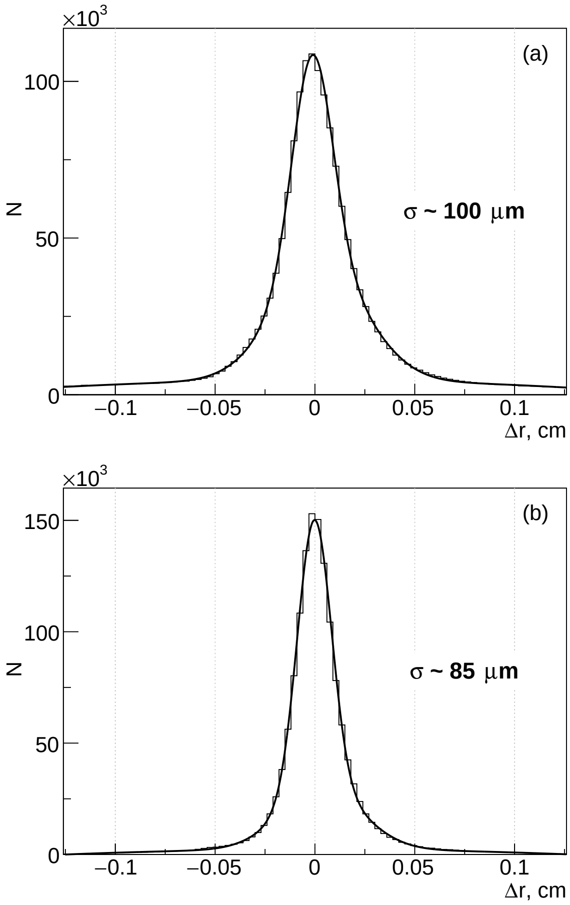

Fig. 2 Example of distribution of track residuals Δr in the xz plane of drift chambers: (a) small and (b) large. The solid curve is a double Gaussian approximation.

The dipole electromagnet 2SP-40, with transverse dimensions 100 × 30 cm, was used as an analyzing magnet. The magnet creates the required magnetic field in the range of 0.7 –1.0 T at a distance of 150 cm along the path of the particles. The spreads in space of the non-interacting deuteron beam and that of the recorded protons from the examined reaction are bended to the blocks of large drift chambers for detection. The radius of the curvature of the stripping protons trajectory in the magnet is about 7 m at the value of the magnetic field 0.83 T.

The STRELA setup is irradiated with a deuteron beam of an incident momentum of 3.5 GeV/c. The detected events are supposed to contain either two protons with close momenta (equal to the half of the incident deuteron beam momenta), from the charge-exchange reaction of a deuteron with a proton $dp \to (pp)n$ or a single-proton from the charge retention deuteron breakup $dp \to (pn)p$. The extracted beam intensity from the accelerator is not lower then $\sim 10^7$ particles per spill. Since the drift chambers are operable at intensities lower than $\sim 10^6$ particles/spill, a steel collimator with a rectangular aperture of 4×4 mm and a length of 1.2 m has to be used to reduce the intensity. After applying the collimator the deuteron beam intensity of $\sim 5 \times 10^5$ particles per spill or below is reached at the target. The deuteron flux (number of triggers) has been determined using S1 and S2 scintillation counters (monitored numbers) in coincidence. This is corrected for the efficiency of the drift chambers and admixture in the beam using a direct deuteron beam. The track of deuteron beam in drift chambers DC1, DC2 before magnet and behind DC3, DC4 are reconstructed using the track reconstruction algorithm [15]. The value of the correction is different from run to run and is in the interval 0.85 – 0.89.

Carbon (C) and polyethylene (CH_2) targets have been used to extract the dp interaction. The final distributions of the dp interactions are obtained by subtracting CH_2 and C distributions. The size of the targets have been determined by carbon nuclei equivalent. Carbon target was used to account for the background events. The shape of targets CH_2 and C are cylindrical with diameters of 59.93 mm and 60.05 mm, respectively; the length of targets CH_2 and C are 48.00 mm and 53.75 mm, respectively. The density of H nuclei per cm^2 for CH_2 target is $(4.7347 \pm 0.0453)\times 10^{23}$???/cm^2. The background from other channels of the dp reaction and the influence of carbon nuclei have been estimated by the use of the GEANT3 simulation package for transporting the reaction products (taken from the corresponding events of the one meter bubble chamber at the momenta 3.35 GeV/c) through the experimental setup. More details about the chamber experiment can be found in [12, 14]. There is also shown that the $dp \to (pp)n$ reaction proceeding predominantly as a quasi-free nucleon interaction and intermediate isobaric states does not influence the differential cross section at $t = 0$.

3 Data analysis and experimental results

The experimental facility has been irradiated in the beam of deuterons with 3.5 GeV/c momenta. In the last run of March 2014 one billion triggers were received. The first step in the analysis was to decode events. Calibration procedure and the track reconstruction in the drift chambers transformed the raw data into physical quantities. For the further processing and physical analysis three tracks in the xz plane were selected: one before the target and two behind it. The topology of this events is shown in Fig. 1.

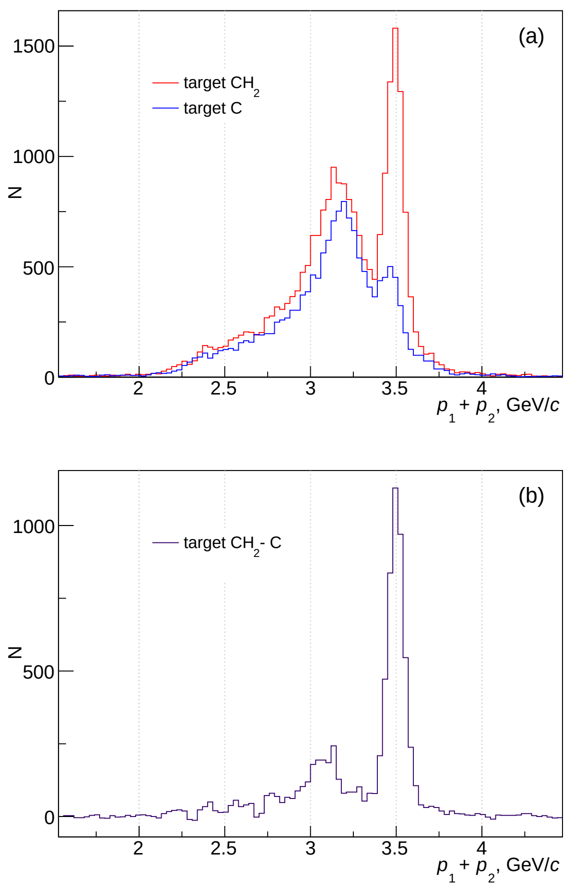

Fig. 3 Distributions of the sum of the two protons momenta from dp reaction, experimental results: (a) target CH_2 red line, target C blue line, (b) difference between $CH_2 -$ C targets.

The distribution of the sum of the two charged particles (two protons) momenta for both targets are obtained. The background from C and CH_2 targets can be neglected. The dependences of the sum of the two proton momenta from dp reaction are presented in Fig. 3 for CH_2 and C targets (a) and their difference $CH_2 -$ C (b). The results of simulation (Fig. 4) include all channels dp reaction (a) and channel $dp \to (pp)n$ only (b). Note that for simulation was used real events from the one meter bubble chamber at the momenta

3.35 GeV/c (with relative small statistics). As one can see, the distribution has a characteristic peak near the incoming deuteron momentum kinematically associated with the pair of protons from the $dp \to ppn$ reaction (Fig. 3 (b)). The contribution from the background reactions, other than the studied $dp \to (pp)n$ reaction, which could also produce the two positively charged track in the forward direction, is negligible (Fig. 4 (b)). Into the differential cross section $d\sigma/dt$ for $dp \to (pp)n$ reaction only those events have been included, where the sum of the two charged particle momenta is in the interval 3.5 ± 0.2 GeV/c (Fig. 3 (b)).

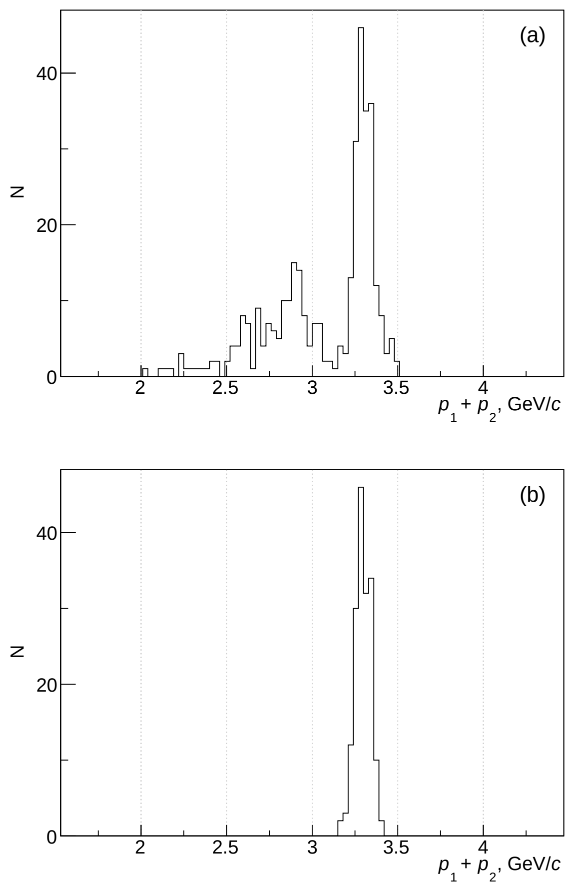

Fig. 4 Distributions of the sum of the two protons momenta from dp reaction, simulation results: (a) include all channels dp reaction and (b) channel $dp \to (pp)n$ only.

The plot of momenta p_1 *vs.* p_2 of the two charged particles (two protons) from dp reaction is shown in Fig. 5. From comparison simulation results (a) and (c) with experimental results (b), it can be seen that the background from other channels of the dp reaction may be eliminated, extracted.

The measured differential distribution $dN\,/\,dt$ of the $dp \to (pp)n$ reaction is displayed in Fig. 6 together with

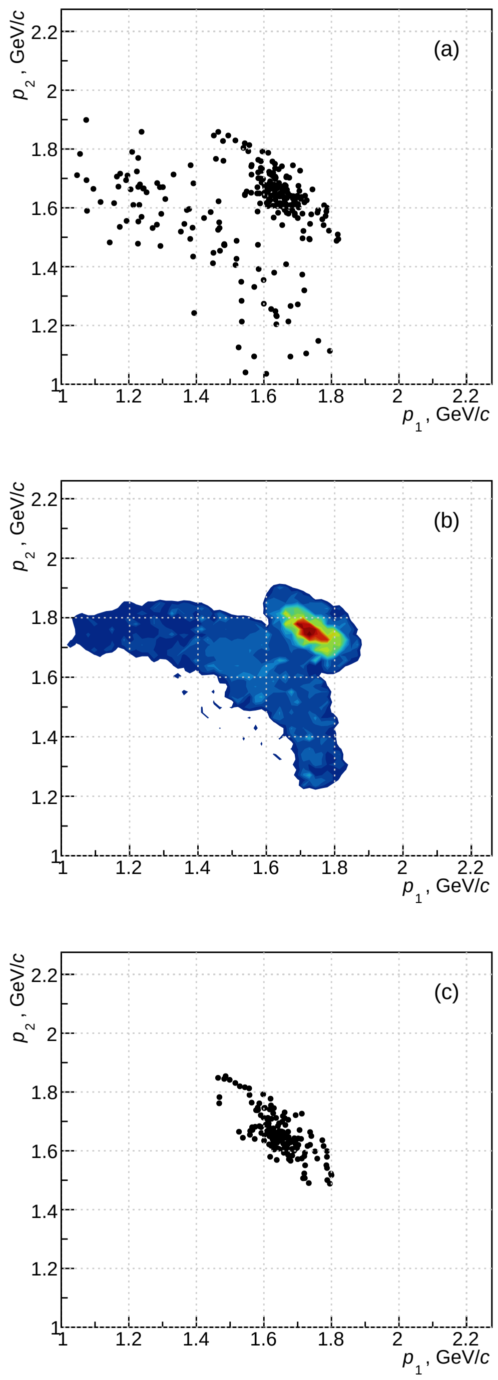

Fig. 5 Two dimensional distribution of the measured momenta p_1 *vs.* p_2 of the two protons from dp reaction: (a) simulation includes all channels dp reaction, (c) simulation only $dp \to (pp)n$ channel and (b) experimental distribution.

the curve corresponding to fit by expression

$$dN/dt = p_1 \exp(p_2\, t)\,, \tag{8}$$

with parameters $p_1 = (435.6 \pm 6.8)$ and $p_2 = (-440.9 \pm 9.1)$. Extrapolation to $t = 0$ gives $(dN/dt)|_{t=0} = (435.6 \pm$

6.8). This value corresponds to a value of the charge exchange reaction differential cross section $(d\sigma/dt)|_{t=0}$ = 30.56 ± 0.48 mb/(GeV/c)^2. The quoted error is statistical only. Systematic uncertainties which affect the overall normalization of the cross sections have been estimated to be about 5 %. This uncertainty stems mainly from the deuteron flux determination. The uncertainty from the target thickness and the histogram bin width are comparably small.

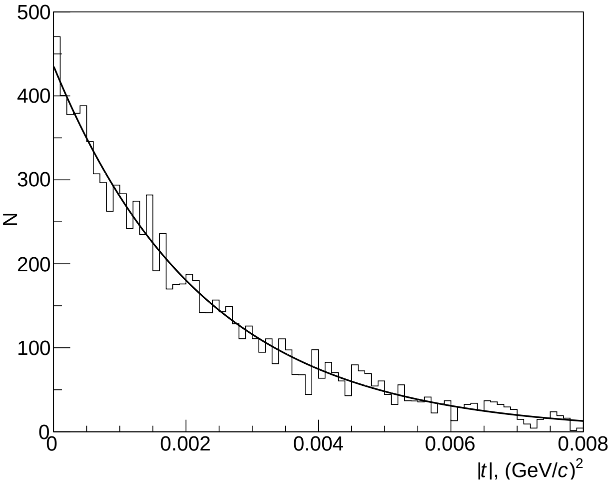

Fig. 6 Differential distribution dN/dt of the $dp \to (pp)n$ reaction. The solid line is approximation by Eq. (8), see details in the text.

The cross section was calculated using the relation

$$\sigma = \frac{1}{n\,l b_w} \ln\left(1\Big/\left(1 - \frac{N_{int}}{N_0}\right)\right), \tag{9}$$

where n is the number of H nuclei ?in cm^3? in target, l is the target length, b_w is the histogram bin width, N_{int} is the number of interactions and N_0 is the number of beam triggers. The number of triggers is corrected for the efficiency of 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 interpolated energy from published data. The closest energy data comes from measurements made at the SATURN accelerator [19, 20]. Unlike to the other similar experiments, Bizard et al. [19] used quasi monochromatic neutrons from accelerated deuteron stripping with a momentum spread of 5 %. New data about $np \to pn$ scattering at the momenta of incident quasi monochromatic neutrons at 1.43, 2.23 and 5.20 GeV/c have been obtained in [21].

The values of $(d\sigma/dt)|_{t=0}$ of $np \to pn$ reaction as a function of the incident momenta is shown in Fig. 7. Each individual differential cross sections from Bizard et al. [19] are transformed into $d\sigma/dt$ versus t in the region of momenta 1.4 – 2.0 GeV/c and extrapolated at each momentum to $t = 0$ by fitting the expression $d\sigma/dt = p_1 \exp(p_2\, t + p_3\, t^2)$.

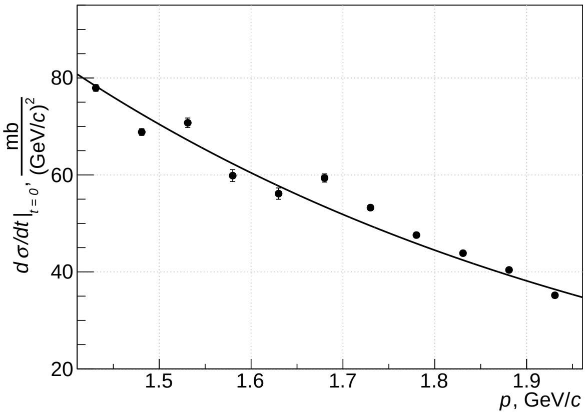

Fig. 7 The dependence of the $(d\sigma/dt)|_{t=0}$ for the $np \to pn$ reaction on the beam momentum. The data points are computed from the experimental results [19]. The solid curve is a simple exponential fit to the data points.

To determine the $(d\sigma/dt)|_{t=0}$ of the $np \to pn$ reaction at “our incident” proton momentum of 1.75 GeV/c/nucleon, an exponential fit is made to the results of Fig. 7, which gives the following value of $(d\sigma/dt)|_{t=0}$ = 48.0 ± 0.2 mb/(GeV/c)^2. The systematical error due to fit procedure is approximately 5 %. 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 can introduce the ratio of the differential cross sections for the forward scattering (charge exchange) on the deuteron and proton

$$\begin{aligned} R_{np\to pn} &= \frac{(d\sigma/dt)_{dp\to(pp)n}}{(d\sigma/dt)_{np\to pn}} \\ &= 0.64 \pm 0.01\,(\text{stat.}) \pm 0.04\,(\text{syst.}). \end{aligned} \tag{10}$$

Under the assumption Eq. (7) and Eq. (3) stated above this, $R_{np\to pn}$ can be related to

$$R_{np\to pn} = \frac{2}{3}\frac{(d\sigma/dt)^{SD}_{np\to pn}}{(d\sigma/dt)_{np\to pn}} \tag{11}$$

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

$$\begin{aligned} R^{ID}_{np\to pn} &= \frac{(d\sigma/dt)^{SI}_{np\to pn}}{(d\sigma/dt)^{SD}_{np\to pn}} = \frac{2}{3\,R_{np\to pn}} - 1 \\ &= 0.05 \pm 0.02\,(\text{stat.}) \pm 0.07\,(\text{syst.}). \end{aligned} \tag{12}$$

It should be emphasized that the obtained contribution, of course, depends on the elementary $np \to pn$ charge exchange cross section which is taken from another experiment and on the systematical errors of approximately 5 % which is due to the fit procedure. Preliminary data have been published in [22, 23].

4 Conclusion

The spectrometric complex has been developed on the basis of the STRELA setup to study the charge-exchange reaction in unpolarized deuteron beam. The obtained ratio of the charge exchange differential cross sections at $dp \to (pp)n$ at $t = 0$ for $dp \to (pp)n$ and $np \to pn$ reactions $R_{np\to pn} = 0.64 \pm 0.01$ (stat.) $\pm\ 0.04$ (syst.) 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 in progress.

Acknowledgements The authors are grateful to the JINR VBLHEP directorate for supporting their experiment and the Nuclotron accelerator team. This research was supported by the Ministry of Education, Science, Research and Sport of the Slovak Republic (VEGA Grant No. 1/0113/18).

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