Eur. Phys. J. A **15**, 471–475 (2002)
DOI 10.1140/epja/i2002-10053-5

THE EUROPEAN PHYSICAL JOURNAL A

Spin-dependent np → pn amplitude estimated from dp → ppn

V.V. Glagolev[1], J. Hlaváčová[2], M.S. Khvastunov[1], N.B. Ladygina[1], G. Martinská[3,a], J. Mušinský[1,3], B. Pastirčák[4], N.M. Piskunov[1], T. Siemiarczuk[5], and J. Urbán[3]

[1] Joint Institute for Nuclear Research, 141980 Dubna, Russia
[2] Technical University, Park Komenského 2, SK-04200, Košice, Slovak Republic
[3] University of P.J. Šafárik, Jesenná 5, SK-04154 Košice, Slovak Republic
[4] Institute of Experimental Physics SAS, Watsonova 47, SK-04353, Košice, Slovak Republic
[5] Institute of Nuclear Studies,ul. Hoza 69, Warsaw, PL-00 681, Poland

Received: 25 February 2002 / Revised version: 17 July 2002 /
Published online: 3 December 2002 –
Communicated by M. Garçon

Abstract. An estimation of the spin-dependent part of the $np \to pn$ charge exchange amplitude was made on the basis of $dp \to (pp)n$ data, taken at 1.67 GeV/c per nucleon in a full solid-angle arrangement. The $np \to pn$ amplitude turned out to be entirely spin-dependent. This result shows new possibilities for experiments using polarized deuteron beams and polarized proton targets.

PACS. 25.10.+s Nuclear reactions involving few-nucleon systems – 25.45.-z ^{2}H-induced reactions – 25.45.Kk Charge exchange reactions

1 Introduction

The task to build up a theory for the nucleon-nucleon scattering, especially in the region above 1 GeV, is an outstanding issue and therefore new experimental data are appreciated. A complete determination of spin-dependent nucleon-nucleon elastic amplitudes requires many measurements. It requires both spin correlation parameters A_{NN}, etc. and spin transfer parameters K_{NN}, etc. [1]. However, in some cases the picture may be simplified. For example in the case of the investigation of the spin-dependent contribution to the elementary $np \to pn$ charge exchange reaction, unpolarized deuteron-proton interactions can be used, where the neutron spin-orbital state is well established.

The possibility to use the charge exchange reaction on the unpolarized deuteron for the determination of the spin-dependent part of the $np \to pn$ charge exchange was emphasized partly in the series of works in [2–7]. 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°, the transition from $^3S_1$ or $^3D_1$ to a charge-symmetric $^1S_0$ or $^1D_2$ state of 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.

In the general case the nucleon-nucleon amplitude in the centre of mass can be presented as

$$M = a + b(\vec{\sigma}\hat{n})(\vec{\sigma}_i\hat{n}) + c[(\vec{\sigma}\hat{n}) + (\vec{\sigma}_i\hat{n})] + e(\vec{\sigma}\hat{m})(\vec{\sigma}_i\hat{m}) + f(\vec{\sigma}\hat{l})(\vec{\sigma}_i\hat{l}), \quad (1)$$

where the orthonormal basis

$$\hat{l} = \frac{\vec{k}+\vec{k}'}{|\vec{k}+\vec{k}'|}, \quad \hat{m} = \frac{\vec{k}-\vec{k}'}{|\vec{k}-\vec{k}'|}, \quad \hat{n} = \frac{\vec{k}\times\vec{k}'}{|\vec{k}\times\vec{k}'|} \quad (2)$$

introduced in [8] is used. The vectors $\vec{k}$ and $\vec{k}'$ are the initial and final momenta, respectively, $\vec{\sigma}$ and $\vec{\sigma}_i$ are the Pauli matrices corresponding to the fast particle and the struck nucleon from the deuteron, respectively.

In the impulse approximation the dp charge exchange differential cross-section at small momentum transfer $|t|$ is related to the NN-amplitudes via

$$\left(\frac{\mathrm{d}\sigma}{\mathrm{d}t}\right)(pd \to n(pp)) = [1 - F_d(t)]\left(\frac{\mathrm{d}\sigma_1}{\mathrm{d}t}\right) + \left[1 - \frac{1}{3}F_d(t)\right]\left(\frac{\mathrm{d}\sigma_2}{\mathrm{d}t}\right), \quad (3)$$

where

$$\frac{\mathrm{d}\sigma_1}{\mathrm{d}t} = |a|^2 + |c|^2, \quad \frac{\mathrm{d}\sigma_2}{\mathrm{d}t} = |b|^2 + |c|^2 + |e|^2 + |f|^2, \quad (4)$$

[a] e-mail: martinov@kosice.upjs.sk

$F_d(t)$ denotes the deuteron form factor and the coefficients a, b, c, e and f refer to spin invariants of the elementary charge exchange amplitude eq. (1) [5,9].

In this paper we consider the case, when the scattering angle θ is very small, close to zero. Under such kinematical conditions one obtains

$$b = e \qquad \text{and} \qquad c = 0 \tag{5}$$

and for the elementary cross-section a simple expression can be written,

$$\frac{\mathrm{d}\sigma_1}{\mathrm{d}t} = |a|^2 , \qquad \frac{\mathrm{d}\sigma_2}{\mathrm{d}t} = 2|b|^2 + |f|^2 . \tag{6}$$

The amplitude a is spin-independent, and b and f are spin-dependent.

At momentum transfer $|t| \sim 0$, when $F_d(0) = 1$, eq. (3) reduces to

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}(pd \to n(pp)) = \frac{2}{3}\frac{\mathrm{d}\sigma_2}{\mathrm{d}t}(np \to pn) . \tag{7}$$

Thus, the dp charge exchange differential cross-section is fully determined by the spin-dependent parts of the elementary $np \to pn$ amplitude.

During recent years considerable progress has been achieved in solving the problem of the construction of the scattering matrix. In the intervening period a substantial amount of new np data has been accumulated. Nowadays the pp analysis is extended up to a laboratory kinetic energy of 2.5 GeV; the np analysis was truncated at 1.3 GeV. While the situation in the complete reconstruction of the pp scattering amplitude in the region above 1 GeV is already satisfactory, the same cannot be stated for np scattering [10].

The aim of the present study was the extraction of information on the elementary process $np \to pn$. The existing data on that reaction are still very scanty and concern mainly the $\mathrm{d}\sigma/\mathrm{d}t$ distribution. As a consequence of the definite isotopic spin of the two protons, the study of the $dp \to (pp)n$ reaction in the region of the symmetric spatial part of their wave function may give information on the spin structure of the elementary amplitude. A study of the deuteron-proton charge exchange differential cross-section $\mathrm{d}\sigma/\mathrm{d}t$ allows one to estimate the spin-dependent contribution to the $np \to pn$ reaction amplitude. Such experimental data do not yet exist. Acceleration of deuterium beams allows to use them for the determination of the spin-dependent part of the elementary $np \to pn$ charge exchange process in a wide region of energy.

2 Experiment

The experimental data were taken with the JINR 1 m hydrogen bubble chamber in a full solid angle geometry and at an incident deuteron momentum of 3.35 GeV/c. The use of nuclear beams impinging on a fixed proton target makes all the fragments of the incoming nuclei fast in the laboratory frame, and thus they can be detected, well measured and identified practically without losses. On the other hand, almost all losses, due to the chamber threshold momenta, are concentrated in the elastic channel. These conditions allow one to study reactions containing not more than one neutral particle in an exclusive approach. A more detailed description of the experimental set-up and the processing chain can be found in [11].

The recorded pictures were scanned twice for all topologies. Measurements on three projections were used for geometrical reconstruction and subsequent kinematical analysis of events, if an event failed on any of the processing steps, all four existing projections were remeasured. The geometrical reconstruction and the kinematical analysis were carried out using an appropriate version of the CERN program package based on the HYDRA library [12]. The ionization of charged secondary particles was estimated visually. The complete data summary tape contains 237413 events of dp interactions. A sample of 102757 events fitting the reaction $dp \to ppn$ was collected. The studied events of the $dp \to ppn$ reaction could be divided in a natural way into two channels:

1) the charge retention channel, where the proton is the fastest secondary particle with respect to the deuteron rest frame, and
2) the charge exchange channel, where the neutron is the fastest secondary particle with respect to the deuteron rest frame.

As a result 85239 events are attributed to the charge retention channel and 17518 events corresponding to the charge exchange reaction. The separation of these two channels is illustrated in fig. 1, showing the distribution of the four-momentum transfer squared t, between target proton and secondary neutron in the laboratory frame. A quantity defined this way does not depend on the final proton state, whether it is a spectator or participant (indifferent to the proton interferency).

The first attempt to determine the contribution of the spin-dependent amplitude of the $np \to pn$ elementary charge exchange from the differential cross-section of the $dp \to (pp)n$ reaction [9], using the available pp and np scattering data, was carried out in the intial stage of the experiment on a relatively small part of the processed events. The pp and np scattering data were ambiguous, the statistics poor and correspondingly the obtained estimate was indefinite, though it dropped a hint to the enhanced role of the spin-dependent amplitude in the $np \to pn$ charge exchange.

Using the final statistics of over 10^5 events of the $dp \to ppn$ reaction, we came back to this problem for two reasons:

1) To make a direct estimate of the $dp \to (pp)n$ differential cross-section at $t = 0$ on the basis of the Dean formalism [5].
2) To estimate the possibilities and limitations of a prepared counter experiment [13].

In the study of high-energy nuclear reactions, the coordinate system in which the nucleus is at rest is customarily used. For that reason all the physical quantities given below are in the deuteron rest frame if not stated otherwise.

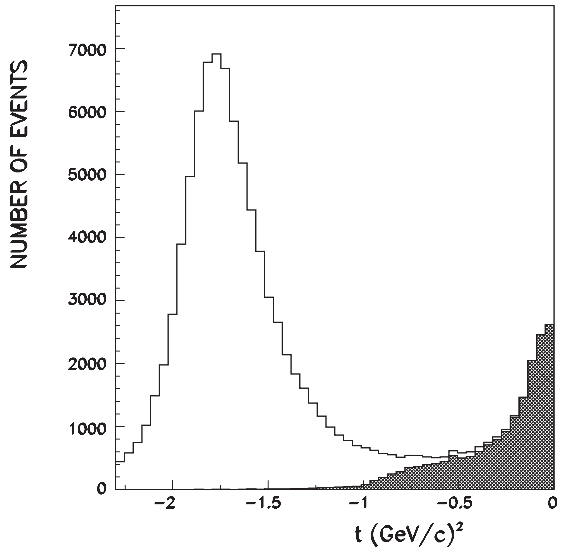

Fig. 1. Distribution of four-momentum transfer squared from the target proton to the neutron for the $dp \to ppn$ events (dark shaded area: charge exchange channel, white area: charge retention channel).

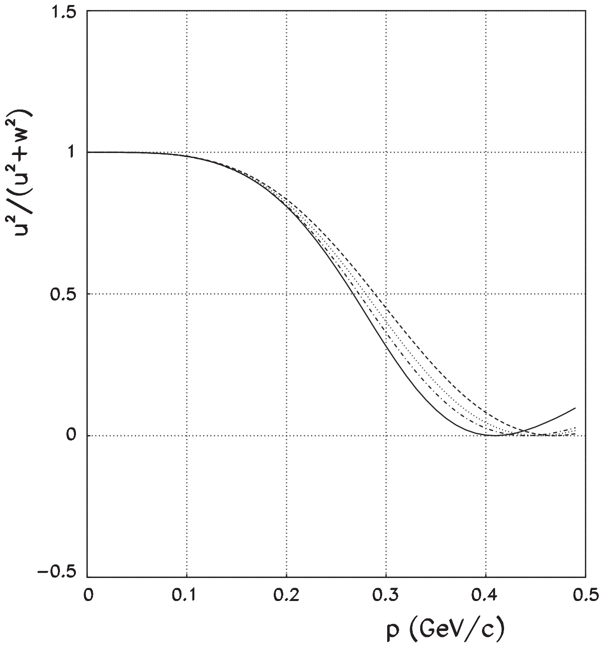

Fig. 2. The S-wave probability as a function of the nucleon Fermi momentum. Full line: Paris; dashed line: Bonn A; dotted line: Bonn B; dash-dotted line: Bonn C wave function.

3 Results and discussion

In order to extract the spin-dependent part of the $np \to pn$ amplitude from the $dp \to (pp)n$ charge exchange data applying eq. (7), at least the two following conditions have to be satisfied:

1) the momentum transfer of the quasielastic np scattering is small,
2) the intrinsic momenta (q) of the nucleons in the deuteron are small.

The second condition means S-wave dominance in the deuteron wave function, which is shown in fig. 2, where the S-wave probability distribution is plotted as a function of the nucleon intrinsic momentum. In the region below $q = 0.07$ GeV/c this probability practically does not depend on the nucleon intrinsic momentum.

Both the above-mentioned conditions can be fulfilled simultaneously, if one selects events in the laboratory frame containing two fast protons at small production angle relative to the incoming deuteron momentum and with momenta close to half that of the deuteron. We would like to stress that this task can be realized successfuly using accelerated deuteron beams. In the case of a deuteron target the two protons are too slow to be detected and the reaction cannot be identified. All dedicated charge exchange experiments on a deuteron so far have been carried out with proton beams.

In addition to the above mentioned, as follows from eq. (2), to address the question of the spin-dependent contribution to the $np \to pn$ amplitude, one has to turn to the data on the differential cross-section at $t = 0$. Such kind of data do exist [14,15]. They have been obtained at Brookhaven [14] for the region of 1–8 GeV and can be reasonably approximated by $1/p^2$, where p is the momentum of the incoming neutron. These data imply at $t = 0$ $\mathrm{d}\sigma/\mathrm{d}t = (36.9 \pm 3.0)$ mb/(GeV/c)^2 at 1.67 GeV/c. The quoted value is in good agreement with that obtained from the $np \to pn$ experimental data [15] at 1.729 GeV/c, fitted by a sum of two exponentials $\mathrm{d}\sigma/\mathrm{d}t = (36.5 \pm 1.4)$ mb/(GeV/c)^2 (without systematical uncertainties). A similar behaviour of the differential cross-section $\mathrm{d}\sigma/\mathrm{d}t$ at $t = 0$ has been observed below our energies, a peak is present at $u \to 0$ [16].

The task is to compare the differential cross-section of the charge exchange on the deuteron, obtained in our experiment at $t = 0$ with that for the $np \to pn$ at the corresponding beam energy.

For a reasonable approximation of $\mathrm{d}\sigma/\mathrm{d}t$ to $t = 0$, it is inevitable to select a region of production angles, excluding the high momentum tails of the nucleon intrinsic motion and also those regions of momentum transfer, where more complicated mechanisms than quasi-elastic scattering can come into play. The changes of the differential cross-section at four different values of the two proton selection angles are illustrated in fig. 3. With the increase of the angle the character of the $\mathrm{d}\sigma/\mathrm{d}t$ distribution at small $|t|$ remains unchanged, while at larger $|t|$ the contribution increases.

An estimation of the production angle θ can be obtained, using the experimental and theoretical maxima ($p_f = 50$ MeV/c) of the Fermi momentum distribution of the nucleons in the deuteron as a measure of transverse momentum and the value of $p_0 = 1.67$ GeV/c for the longitudinal momentum per nucleon in the laboratory frame. It provides the value $\theta = \mathrm{arctg}(p_f/p_0) = 1.6°$. This requires that the two protons should be produced within a cone having an opening angle of $\approx 3°$.

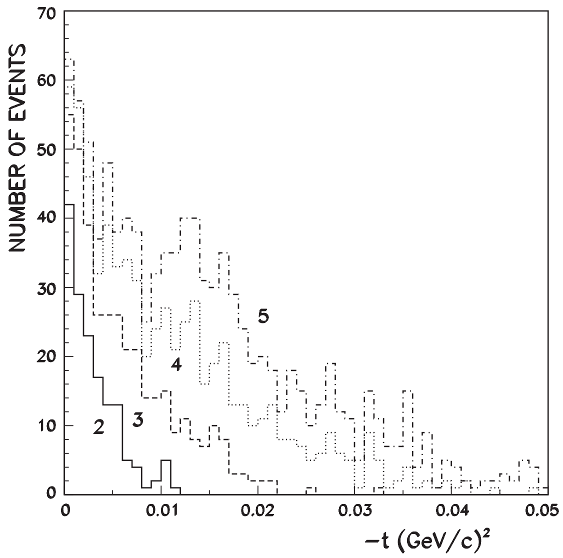

Fig. 3. Distribution of $|t|$ for the charge exchange channel with the production angles of both protons below 2, 3, 4 and 5 degrees.

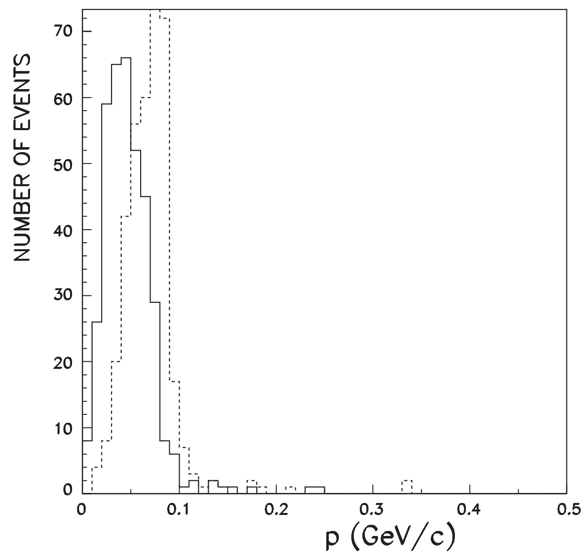

Fig. 5. Momentum distributions of spectator (full line) and scattered protons (dashed line) in the deuteron rest frame. The proton production angles in the laboratory frame are below 3°.

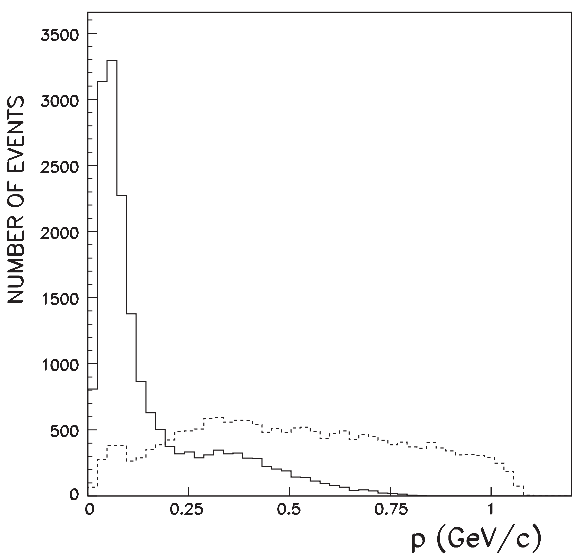

Fig. 4. Momentum distributions of spectator (full line) and scattered protons (dashed line) in the deuteron rest frame.

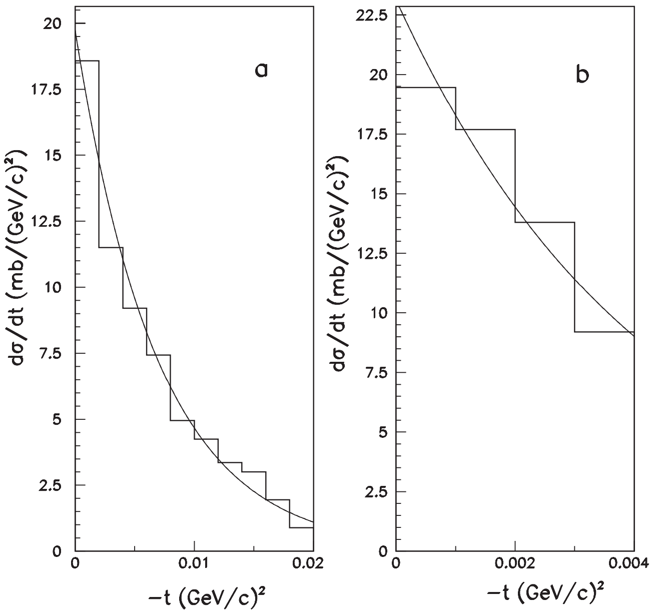

Fig. 6. Differential cross-section of the charge exchange reaction in the region of small $|t|$. The production angle of both protons in the laboratory frame is in the interval 0–3°. (b) shows finer binning than (a).

In this context we remind the used definitions: the slowest proton in the deuteron rest frame is referred to as a spectator; the other one we call scattered. If no cuts are imposed on the proton production angles, their momentum distributions differ significantly as shown in fig. 4.

The spectator proton distribution (full line) follows a curve, typical for the Fermi momentum distribution in the deuteron. When the above-mentioned cut of 3° is applied to the production angles of spectator and scattered proton, their momentum distributions overlap, as one can see in fig. 5.

The differential cross-section for small values of $|t|$ is displayed in fig. 6 together with the curves, corresponding to a fit of $\mathrm{d}\sigma/\mathrm{d}t = ae^{bt}$ to the data. The fit gives the following results: $a = (19.0 \pm 1.1)$ mb/(GeV/c)^2 ($\chi^2/ND = 4.3/8$) for the interval of $|t| = \{0.0\text{–}0.02\}$(GeV/$c$)^2 (fig. 6a) and $a = (23.1^{+3.6}_{-3.1})$ mb/(GeV/c)^2 ($\chi^2/ND = 1.0/2$) for the interval $|t| = \{0.0\text{–}0.004\}$(GeV/$c$)^2 (fig. 6b).

Figure 7 demonstrates the differential cross-section at $t = 0$ as a function of the cut, imposed on the proton production angles. It can be seen in agreement with eq. (7), that around $\theta = 3°$ the quantity $\mathrm{d}\sigma/\mathrm{d}t$ at $t = 0$ reaches the level of 2/3 ($\mathrm{d}\sigma/\mathrm{d}t$) at $t = 0$ of the elemen-

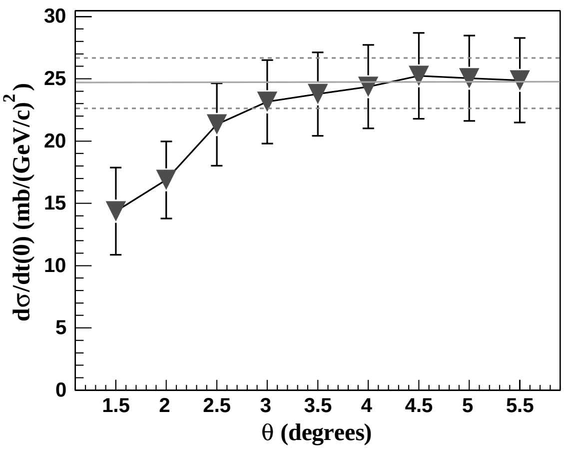

Fig. 7. Differential cross-section at $t = 0$ when both protons are within a cone of opening angle θ. The full line corresponds to 2/3 $(\mathrm{d}\sigma/\mathrm{d}t)_{np\to pn}$ at $t = 0$, the dashed lines show the uncertainties.

tary $np \to pn$ process. For the value of $\theta = 3°$ we get a contribution of the spin-dependent part to the elementary $np \to pn$ of 0.94 ± 0.15. The obtained contribution of course depends on the systematical errors of the elementary $np \to pn$ charge exchange cross-section $\approx 20\%$ [15]. In any case the obtained probability is large enough and does not exclude the amplitude being 100% spin-dependent in $np \to pn$. The estimate of the spin-independent part of the amplitude in [9] based on a different approach and poor statistics (the number of charge exchange events is more than one order less), did not exclude the nonzero spin-dependent contribution. Therefore, the present results obtained here in a more straightforward way using eq. (7) are not in contradiction to our earlier findings [9]. Our experiment allows us to extract only the spin-dependent part of the $np \to pn$ charge exchange amplitude. Therefore, the obtained results cannot be directly compared with the data taken in polarized proton beam experiments, *e.g.* [17]. In a future study of the process $dp \to (pp)n$ using a beam of polarized deuterons one could separate the two spin-dependent terms in the amplitude of the charge exchange reaction $np \to pn$, one of which does not conserve while the other conserves the projection of the nucleon spin onto the direction of momentum at the transition of the neutron into the proton [18]. The proposed method is applicable in the energy range up to 10 GeV, where the charge exchange cross-section is not too small. At these energies the phase-shift analysis due to large number of partial waves is complicated.

4 Conclusion

The study of the $dp \to (pp)n$ reaction in full solid angle conditions showed, that the amplitude of the elementary $np \to pn$ charge exchange at 1.67 GeV/c is practically fully spin-dependent. The obtained result offers new possibilities to measure the energy dependence of this effect by simultaneous use of both polarized deuteron beams and polarized proton target.

This work was in part supported by the Grant Agency for Science at the Ministry of Education of the Slovak Republic (grant No. 1/8041/01).

References

1. S.M. Bilenkij, L.I. Lapidus, R.M. Ryndin, Usp. Fiz. Nauk (in Russian) **LXXXIV**, 243 (1964).
2. A.B. Migdal, Zh. Eksp. Teor. Fiz. (in Russian) **28**, 3 (1955).
3. I. Pomeranchuk, Dokl. Akad. Nauk (in Russian) **LXXVIII**, 249 (1951).
4. L.I. Lapidus, Zh. Eksp. Teor. Fiz. (in Russian) **32**, 1437 (1957).
5. N.W. Dean, Phys. Rev. D **5**, 1661 (1972).
6. N.W. Dean, Phys. Rev. D **5**, 2832 (1972).
7. D.V. Bugg, C. Wilkin, Nucl. Phys. A **167**, 575 (1987).
8. M. Goldberger, K. Watson, *Collision Theory* (Wiley, New York, 1966).
9. B.S. Aladashvili *et al.*, Nucl. Phys. B **86**, 461 (1975).
10. R.A. Arndt, I.I. Strakovsky, R.L. Workman, Phys. Rev. C **50**, 2731 (1994); **56**, 3005 (1997); A. de Lesquen *et al.*, Eur. Phys. J. C **11**, 69 (1999); C. Lechanoine-Leluc, F. Lehar, P. Winternitz, J. Bystricky, J. Phys. (Paris) **48**, 985 (1987); R.A. Arndt, I.I. Strakovsky, R.L. Workman, Phys. Rev. C **62**, 034005 (2000).
11. B.S. Aladashvili *et al.*, Nucl. Instrum. Methods, **129**, 109 (1975); JINR Commun. 1-7645, Dubna, 1973.
12. V. Framery *et al.*, *Hydra Topical Manual TQ Title Package*, CERN Program Library (1982).
13. S.N. Bazylev *et al.*, in *Proceedings of the International Workshop Relativistic Nuclear Physics from Hundreds MeV to TeV, Slovak Republic, Stara Lesna, June 26-July 1, 2000* (JINR, Dubna, 2001) p. 234, E1, 2-2001-76.
14. J.L. Friedes, H. Palevsky, R.L. Stearns, R.J. Sutter, Phys. Rev. Lett. **15**, 38 (1965).
15. P.F. Shepard, T.J. Devlin, R.E. Mischke, J. Solomon, Phys. Rev. D **10**, 2735 (1974).
16. B.E. Bonner *et al.*, Phys. Rev. Lett. **41**, 1200 (1978).
17. R.D. Ransome *et al.*, Phys. Rev. Lett. **48**, 781 (1982).
18. V.V. Glagolev, V.L. Lyuboshitz, V.V. Lyuboshitz, N.M. Piskunov, JINR Commun. E1-99-280, Dubna, 1999.