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# OBSERVATION OF TENSOR POLARIZATION OF DEUTERON BEAM TRAVELING THROUGH MATTER

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Наблюдение тензорной поляризации проходящего
через вещество пучка дейтронов

Измерена тензорная поляризация пучка дейтронов, возникающая при его прохождении через вещество. Эксперимент проводился на выведенном из нуклотрона пучке неполяризованных дейтронов с импульсом 5 ГэВ/$c$. Наблюдавшийся эффект сравнивается с вычислениями, выполненными в рамках теории многократного рассеяния Глаубера.

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Observation of Tensor Polarization of Deuteron Beam
Traveling through Matter

The tensor polarization of the deuteron beam arising as deuterons pass through a carbon target was measured. The experiment was performed at an extracted unpolarized 5-GeV/$c$ deuteron beam of the Nuclotron. The effect observed is compared with the calculations made within the framework of the Glauber multiple scattering theory.

The investigation has been performed at the Veksler and Baldin Laboratory of High Energies and the Dzhelepov Laboratory of Nuclear Problems, JINR.

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## INTRODUCTION

The deuteron is a loosely bound pair of nucleons with aligned spins (spin-1 triplet state). The $A$ small quadruple moment of the deuteron implies that it is not spherical in configuration space; i. e., these two nucleons are not in a pure $S$ state of the relative orbital angular momentum, and there is an additional $D$ wave component. These properties of the deuteron give rise to a number of polarization effects in the nuclear reactions involving the deuteron.

First of all, the calculations of the angular dependence of the elastic $dp$ scattering [1, 2] made within the framework of the Glauber multiple scattering theory [3] show that if one would direct the unpolarized deuteron beam onto an unpolarized hydrogen target, the scattered deuterons would be strongly aligned. The source of this effect is the quadruple deformation of the deuteron.

Secondly, a marked tensor analyzing power was observed in the inclusive inelastic reaction $A(d, d')X$ in the region of 4-momentum transfer near $|t| = 0.3$ GeV/$c$ in the scattering of polarized deuterons with initial momenta of 4.5 and 5.5 GeV/$c$ on nuclei at $0^\circ$ [4].

At last, it was shown by Baryshevsky [5] that as particles of spin $\geqslant 1$ pass through matter, effects of spin rotation and oscillations may occur. These effects may give rise to polarization of the beam crossing the target. The first attempt to measure spin dichroism, i. e., occurrence of tensor polarization of an unpolarized deuteron beam by an unpolarized target, was made with deuterons up to 20 MeV in a carbon target [6]. Although the magnitude of the deuteron polarization was not determined precisely, the authors argue that evidence for existence of dichroism was obtained in this experiment.

In this report we describe an experimental investigation devoted to the first attempt to measure tensor polarization of an unpolarized 5 GeV/$c$ deuteron beam after its passing through a carbon target.

## 1. EXPERIMENT

The experiment has been performed at an unpolarized deuteron beam extracted from the Nuclotron of JINR. The layout of the experimental equipment is shown in Fig. 1. In this figure F3, F4, F5 and F6 are the foci of the magnetic

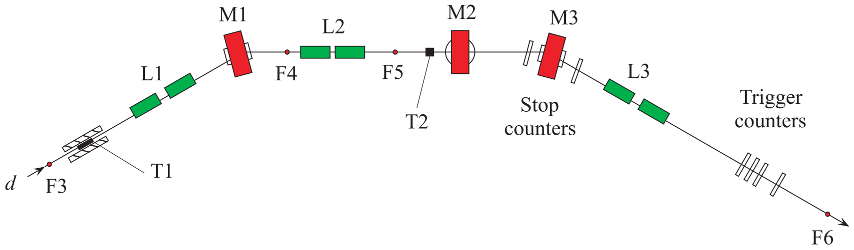

Fig. 1. Layout of the experimental equipment

system of the beam line. Magnetic lenses and magnets are schematically denoted as L1, L2, L3 and M1, M2, M3. The part of the beam line up to F5 was tuned to a momentum of $\sim 5$ GeV/$c$, and the part behind F5 was tuned to 3.3 GeV/$c$.

The slowly extracted beam of $\sim 5$ GeV/$c$ deuterons with an intensity of $5 \cdot 10^8 - 3 \cdot 10^9$ particles per beam spill was incident on 40, 83 and 123 g/cm$^2$-thick carbon targets T1 placed near F3. The values of the extracted beam momenta were taken to be exactly 5.0 GeV/$c$ after crossing the target irrespective of the target thickness. The measurements without the target were also made. The beam intensities near F3, F4 and F5 were monitored by ionization chambers. The intensity of the secondary beam between F4 and F5 was $5 \cdot 10^6 - 3 \cdot 10^7$ particles per beam spill.

The tensor polarization of the deuteron beam scattered at the target T1 at 0° was determined by means of the second scattering on the 10-cm thick beryllium target T2 placed near F5 [7]. It is known that the reaction $d + \mathrm{Be} \to p + X$ for proton emission at the zero angle with the momentum $p_p \sim \frac{2}{3} p_d$ has a very large tensor analyzing power $T_{20} = -0.82 \pm 0.04$, which is independent of the atomic number of the target $(A > 4)$ and the momentum of incident deuterons between 2.5 and 9.0 GeV/$c$ [8].

The secondary particles emitted from the target T2 at 0° were transported to the focus F6 by means of bending magnets and magnetic lens doublets. The momentum and polar angle acceptances of the setup defined by the Monte Carlo simulation were $\Delta p/p \sim \pm 2\%$ and $\pm 8$ mrad, respectively.

Coincidences of the signals from the scintillation counters placed near the focus F6 were used as a trigger. Along with the secondary protons, the apparatus detected the deuterons from inelastic scattering. The detected particles were identified off-line on the basis of time-of-flight measurements with a base line of $\sim 28$ m between the start counters and four stop counters. The TOF resolution ($\sim 0.2$ ns) allowed one to separate protons and deuterons completely. The quality of the separation is illustrated in Fig. 2, where left (right) peaks correspond to deuterons (protons).

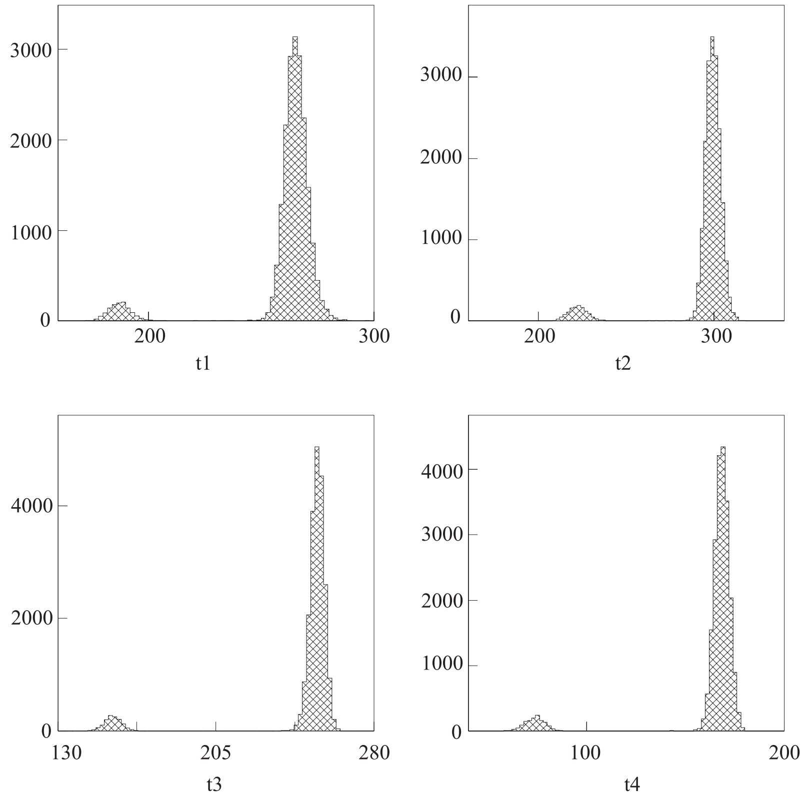

Fig. 2. The TOF spectra for four detection channels. Left (right) peaks correspond to deuterons (protons)

Since the experiment was carried out with beams of considerably different intensities, the question of the linearity of monitors had a dominant role. The examination of the linearity was made in separate measurements with the results shown in Fig. 3.

The general expression for the invariant differential cross section of the reaction with the polarized deuteron beam has the form [9]

$$\frac{Ed\sigma}{d\mathbf{p}}(\theta,\phi) = \left(\frac{Ed\sigma}{d\mathbf{p}}(\theta)\right)_0 \times$$
$$\times \left[1 + \sqrt{2}\rho_{10} iT_{11}(\theta)\sin\beta\cos\phi + \frac{1}{2}\rho_{20}T_{20}(\theta)(3\cos^2\beta - 1) + \right.$$
$$\left. + \sqrt{6}\rho_{20}T_{21}(\theta)\sin\beta\sin\phi - \sqrt{\frac{3}{2}}\rho_{20}T_{22}(\theta)\sin^2\beta\cos 2\phi\right]. \qquad (1)$$

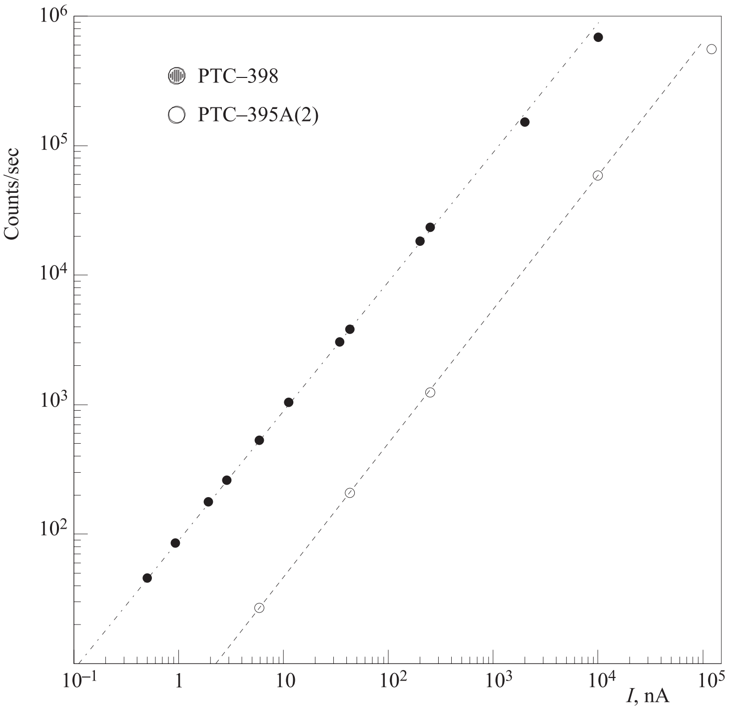

Fig. 3. The characteristics of current-to-digit convertors of ionization chambers placed at foci 5 (dark points) and 3 (light points)

Here, $(Ed\sigma/\mathbf{p})_0$ is the invariant differential cross section for the unpolarized beam, and the parameters $\rho_{10} = \sqrt{3/2}p_Z$ and $\rho_{20} = \sqrt{1/2}p_{ZZ}$ are connected with the vector $p_Z$ and tensor $p_{ZZ}$ beam polarization components, respectively, in the coordinate system in which the quantization axis coincides with the axis of symmetry. The values $iT_{11}, T_{20}, T_{21}$ and $T_{22}$ are the analyzing powers in the representation of irreducible tensors $T_{\kappa q}$. The angles $\theta$ and $\phi$ define the direction of a scattered particle, and $\beta$ is the angle between the quantization axis and the direction of an incident particle. In our case all these angles are equal to zero, which converts (1) to

$$\sigma' = \sigma_0\left(1 + \frac{1}{\sqrt{2}}p_{ZZ}T_{20}\right), \qquad (2)$$

where the polarized and unpolarized cross sections are referred to as $\sigma'$ and $\sigma_0$, respectively.

The ionization chamber placed upstream of the analyzer target T2 served as a monitor. The numbers of protons normalized to the monitor counts detected in exposures with carbon targets of different thickness are shown in Fig. 4. Here

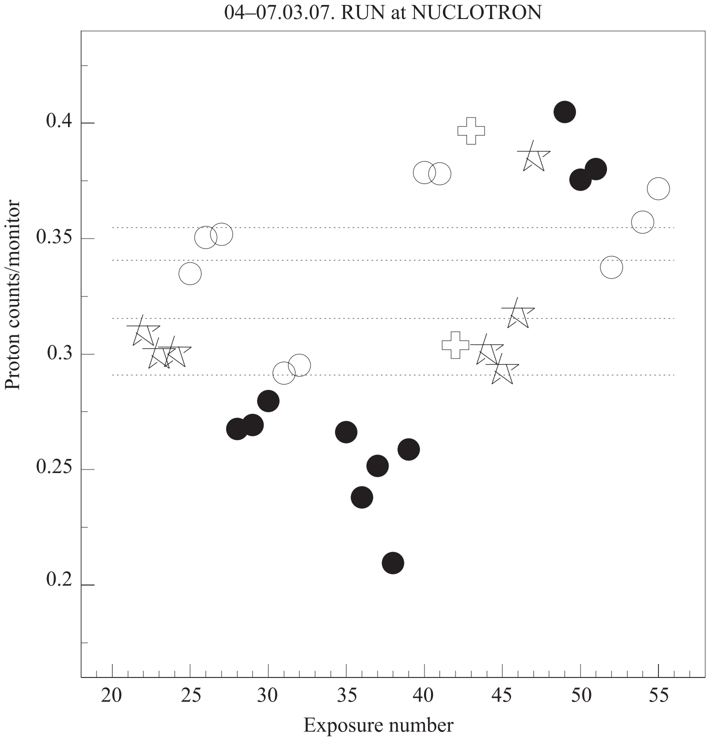

Fig. 4. Ratios of proton counts to the monitor for targets T1 of different thickness: black points — 123 g/cm$^2$, stars — 83 g/cm$^2$, crosses — 40 g/cm$^2$, light points — 0 g/cm$^2$

dark points, stars and crosses refer to the 123-, 83- and 40-g/cm$^2$-thick carbon targets, respectively, and the light points correspond to the measurements without target T1. The values of these ratios averaged for all the exposures are shown with dashed lines. It is seen that the points corresponding to different target thickness are grouped in different regions of the picture. The spread of the points exceeds statistical errors that are less than point sizes. This spread is likely to be caused by the nonstabilities of currents in the magnetic elements of the beam line. Considerable deviations of the points obtained in the last exposures from the averaged values are due to the fact that the control over the head end of the magnet-optical channel was lost during these exposures.

The possible systematic errors resulting from such current fluctuations were estimated in the following way. It is known that the differential cross section of the proton emission at forward angles in the deuteron breakup is a sharp function of the secondary proton momentum [10, 11]. As to the cross section of the $A(d, d')$ reaction, it has considerably smoother behaviour [12]. Thus, deviations

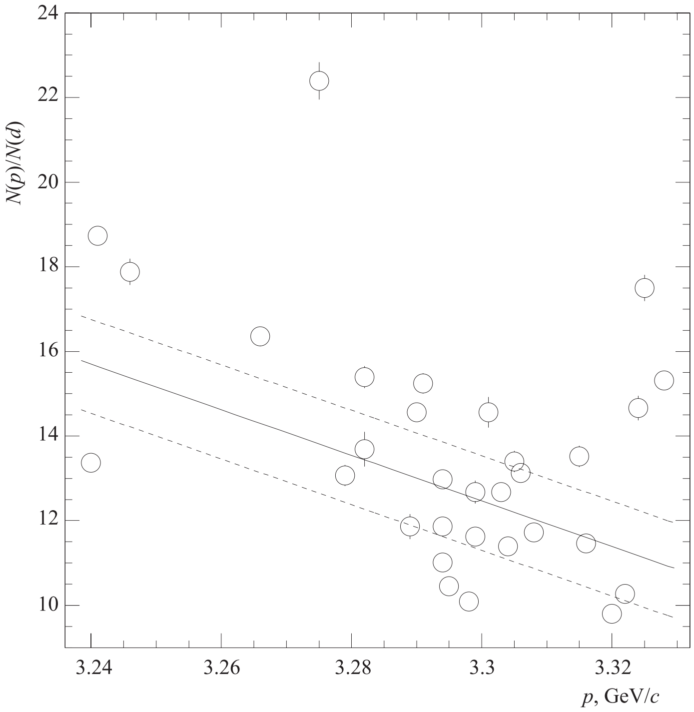

Fig. 5. The correlation between the ratio $N(p)/N(d)$ (averaged over four detection channels) and the momentum $p$ calculated from the difference $\Delta t$

of the proton/deuteron ratio from the constant value can reflect changes in the currents of magnetic elements, or in the momentum of detected particles. On the other hand, the difference $\Delta t$ in the arrival of signals caused by protons and deuterons is also connected with the spread $\Delta p$ in the momentum of these particles; for our experimental arrangement $\delta p/\Delta t = -0.172$ GeV/$c$/ns. The correlation between the ratio $N(p)/N(d)$ and the momentum $p$ calculated from the experimental difference $\Delta t$ is shown in Fig. 5. Analytically, this correlation is expressed by the equation

$$\frac{N(p)}{N(d)} = (190.14 \pm 0.54) - (53.84 \pm 0.16)p \text{ (GeV}/c). \tag{3}$$

Recall that the magnetic channel was tuned to the rated momentum of 3.3 GeV/$c$. It follows from Eq. (3) that correction factors to proton counts should vary from 1.26 to 0.88 as the proton momentum varies from 3.24 to 3.33 GeV/$c$. An estimate of the possible systematic error is thus seen to be $\pm 20\%$.

The tensor polarizations $P_{ZZ}$ of the deuterons that passed through target T1 were calculated in accordance with Eq. (2) for each of four channels separately,

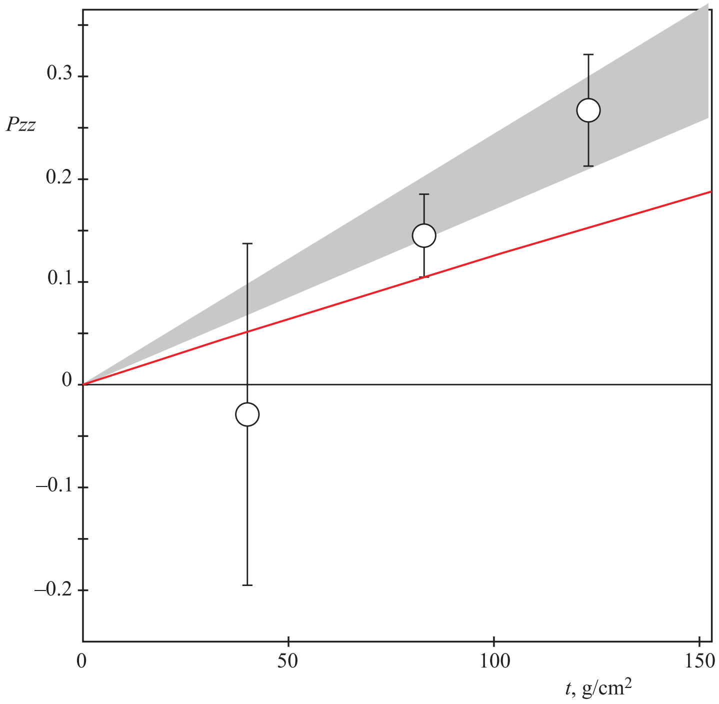

Fig. 6. Tensor polarization of deuterons vs thickness of target T1. The dashed region shows the error corridor, the solid curve is the calculation result

and they were averaged thereafter; the counts without T1 were taken as $\sigma_0$. The values of the tensor polarization as a function of the target T1 thickness are shown in Fig. 6. Error bars of the points at 83 and 123 g/cm$^2$ are the dispersions of $p_{ZZ}$ values measured in different exposures at a fixed target thickness. The large error bars at 40 g/cm$^2$ reflect an uncertainty arising if one takes no account of the beam ionization losses in a thick target: this point was obtained as the result of interpolation between two measurements with $\pm 1.5\%$ deviations of the beam momentum behind T1 from the required value of 5.0 GeV/*c*.

## 2. THEORY

On the assumption that the $NN$ scattering amplitude has the form

$$f(\mathbf{q}) = \frac{k\sigma_{NN}}{4\pi}(i + \alpha_{NN}) \exp\left(-\frac{1}{2}Bq^2\right), \tag{4}$$

where $\mathbf{q}$ is the momentum transfer, and if one takes a multi-Gaussian representation of the deuteron wave function [13]

$$\psi_0(p) = \sum_i a_i \exp{(-\alpha_i p^2)}, \quad \psi_2(p) = p^2 \sum_i b_i \exp{(-\beta_i p^2)}, \tag{5}$$

with $\psi_0$ and $\psi_2$ defined by

$$\psi(p) = \psi_0(p) - \frac{1}{\sqrt{2}} \left[ 3(\mathbf{J}\cdot\mathbf{p})^2 \ \psi_2(p) \right],$$

where $\mathbf{J}$ is the spin operator of the deuteron, in line with the multiple scattering theory [3, 14], the difference of the total cross sections of the nuclear scattering of deuterons in different spin states (0) and $(\pm 1)$ may be written in the form

$$\Delta\sigma = \frac{1}{N_S + N_D} \sum_{N=1}^{A} (-1)^N \frac{A!}{(A-N)!} \Delta\sigma^{(N)}, \tag{6}$$

where the cross section difference for the $N$th collision is given by

$$\Delta\sigma^{(N)} = \pi R_1 R_2 \sum_{m=0}^{N} \sum_{n=0}^{N-m} \times \\ \times \frac{\Delta^{(N)}_{m,n} a_1^{m+n} a_2^{N-m-n}}{[(m+n)R_2 + (N-m-n)R_1] \ n! \ m! \ (N-m-n)!}. \tag{7}$$

Here

$$\Delta^{(N)}_{m,n} = 3 \sum_{i=1}^{5} \sum_{k=1}^{5} C_i D_k \Big(\frac{\pi}{\tau_{i,k}}\Big)^{3/2} \frac{\lambda^{(N)}_{m,n}}{(\lambda^{(N)}_{m,n} + \tau_{i,k})^2} + \\ + \frac{3}{2} \sum_{i=1}^{5} \sum_{k=1}^{5} D_i D_k \Big(\frac{\pi}{\nu_{i,k}}\Big)^{3/2} \frac{\lambda^{(N)}_{m,n}(3\lambda^{(N)}_{m,n} + 7\nu_{i,k})}{\nu_{i,k}(\lambda^{(N)}_{m,n} + \nu_{i,k})^3} \tag{8}$$

with

$$\lambda^{(N)}_{m,n} = \frac{1}{4} \left( \frac{N-m-n}{B} + \frac{4mnR_2 + (m+n)(N-m-n)R_1}{R_1 \left[(m+n)R_2 + (N-m-n)R_1\right]} \right). \tag{9}$$

The parameters $R_1$, $R_2$, $a_1$ and $a_2$ are expressed in terms of constants peculiar to this problem:

$$R_1 = \frac{2}{3}\langle r^2 \rangle_A + 2B, \quad R_2 = \frac{2}{3}\langle r^2 \rangle_A + B, \\ a_1 = \frac{\sigma_{NN}}{2\pi R_1}, \quad a_2 = -\frac{\sigma_{NN}^2}{16\pi^2 B R_2}, \tag{10}$$

where $\langle r^2 \rangle$ is the rms radius of a nucleus. Effective numbers for $S$- and $D$-states are

$$N_S = \sum_{i=1}^{5} \sum_{k=1}^{5} \frac{C_i C_k \pi^{3/2}}{(\rho_i + \rho_k)^{3/2}}, \quad N_D = \frac{15}{8} \sum_{i=1}^{5} \sum_{k=1}^{5} \frac{D_i D_k \pi^{3/2}}{(\omega_i + \omega_k)^{7/2}}, \tag{11}$$

where

$$\begin{gathered} C_i = A_i \left(2.5/\alpha_i\right)^{3/2}, \quad D_i = \sqrt{2} B_i \left(2.5/\beta_i\right)^{7/2}, \\ \rho_i = 6.25/\alpha_i, \quad \omega_i = 6.25/\beta_i, \\ \tau_{i,k} = \rho_i + \omega_k, \quad \nu_{i,k} = \omega_i + \omega_k. \end{gathered} \tag{12}$$

The following values of the parameters were used in the calculations: $\sigma_{NN} = 4.40$ fm$^2$, $\alpha_{NN} = -0.339$, $B = 0.297$ fm$^2$ [15], $\langle r_C^2 \rangle = 5.86$ fm$^2$, and the constants $a_i$, $b_i$, $\alpha_i$ and $\beta_i$ were taken from [13]. The calculated difference of total cross sections of $d-^{12}$C scattering in the deuteron spin states $(0)$ and $(\pm 1)$ turns out to be $\Delta\sigma = 3.87$ fm$^2$.

It can be shown that the tensor polarization of the deuteron beam arising from this cross section difference is

$$P_{ZZ} = \frac{1 - \exp\left(-N \Delta\sigma x\right)}{1 + \frac{1}{2} \exp\left(-N \Delta\sigma x\right)}, \tag{13}$$

where $N$ is the number of nuclei in cm$^3$ of matter with thickness of $x$ cm. The calculation results for our experiment are shown in Fig. 6 by the solid curve.

## CONCLUSION

- The tensor polarization of an unpolarized deuteron beam arising as deuterons pass through carbon targets of different thickness was measured.
- The phenomenon of deuteron spin dichroism (defined as the spin alignment in an unpolarized beam passing through matter) was first observed using an extracted unpolarized 5-GeV/$c$ deuteron beam of the Nuclotron.
- A formalism was elaborated to describe the effect observed within the framework of the Glauber multiple scattering theory.
- The calculation results are in qualitative agreement with the experimental data obtained.
- The observed effect can be used to produce spin-aligned high-energy deuteron beams at the sacrifice of beam intensity.

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## REFERENCES

1. *Franco V., Glauber R. J.* // Phys. Rev. Lett. 1969. V. 22. P. 370.
2. *Harrington D.* // Phys. Lett. B. 1969. V. 29. P. 188.
3. *Glauber R. J.* // Lectures in Theoretical Physics / Ed. by W. E. Brittin et al. V. 1. New York: Intrascience Publishers, Inc., 1959. P. 315.
4. *Azhgirey L. S. et al.* // Phys. Lett. B. 1995. V. 361. P. 21.
5. *Baryshevsky V. G.* // J. Phys. G: Nucl. Part. Phys. 1993. V. 19. P. 273.
6. *Baryshevsky V. et al.* arXiv:hep-ex/0501045 v2 (2005).
7. *Zolin L. S. et al.* // JINR Rapid Commun. 1998. No. 2[88]-98. P. 27.
8. *Perdrisat C. F. et al.* // Phys. Rev. Lett. 1987. V. 59. P. 2840;
   *Punjabi V. et al.* // Phys. Rev. C. 1989. V. 39. P. 608;
   *Ableev V. G. et al.* // Pis'ma ZhETF. 1988. V. 47. P. 558; JINR Rapid Commun. 1990. No. 4[43]-90. P. 5;
   *Aono T. et al.* // Phys. Rev. Lett. 1995. V. 74. P. 4997.
9. *Haeberli W.* // Ann. Rev. Nucl. Sci. 1967. V. 17. P. 373.
10. *Ableev V. G. et al.* // Nucl. Phys. A. 1983. V. 393. P. 491;
    *Zaporozhets S. A. et al.* // Proc. VIII Intern. Seminar on High Energy Physics Problems, Dubna, 1986. V. 1. P. 341 (in Russian).
11. *Azhgirey L. S., Ignatenko M. A., Yudin N. P.* // Z. Physik A. 1992. V. 343. P. 35.
12. *Azhgirey L. S. et al.* // Yad. Fiz. 1978. V. 27. P. 1027 (in Russian).
13. *Alberi G., Rosa L. P., Thomé Z. D.* // Phys. Rev. Lett. 1975. V. 34. P. 503.
14. *Franco V., Glauber R. J.* // Phys. Rev. 1966. V. 142. P. 1195.
15. pdg.lbl.gov/2006.tables.html

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