ALIGNMENT OF UNPOLARIZED DEUTERONS TRAVELING THROUGH MATTER

L.S. Azhgirey

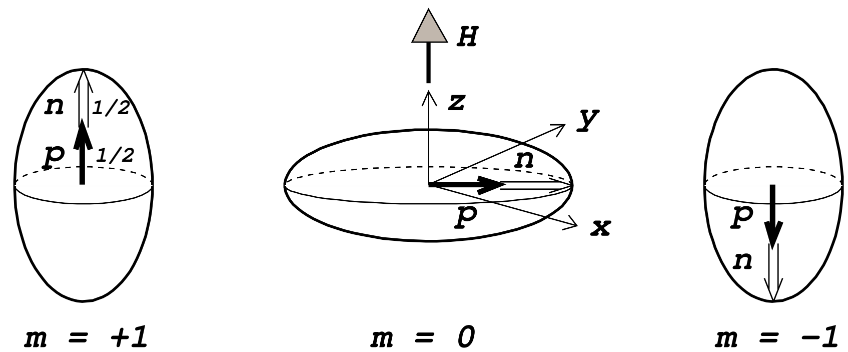
JINR, Dubna, Russia

Introduction

- The deuteron represents a loosely bound pair of nucleons with spins aligned (spin 1 triplet state).
- The availability of 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 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.

Deuteron polarization

Let us assume a deuteron in a magnetic field H. In a reference frame whose quantization axis Z coincides with the direction of H the spin projection on Z can only take values $m_d = +1,\ 0,\ -1$.



If $N_+,\ N_0,\ N_-$ are the relative numbers of deuterons populating the magnetic substates $m_d = +1,\ 0,\ -1$, ($N_+ + N_0 + N_- = 1$), then vector p_Z and tensor p_{ZZ} polarizations of a deuteron beam are

$$
\begin{aligned}
p_Z &= N_+ - N_-, \\
p_{ZZ} &= N_+ + N_- - 2N_0 = 1 - 3N_0.
\end{aligned}
$$

Since the quantization axis Z is the symmetry axis, $p_{XX} = p_{YY} = -\frac{1}{2}\, p_{ZZ}$.

Polarization effects

The quadruple deformation of the deuteron is the cause for a number of polarization effects:

- First of all, the calculations of the angular dependence of the elastic dp scattering [**Franco,Glauber,Harrington**] in the framework of the Glauber multiple scattering theory show that if one would direct the unpolarized deuteron beam on to an unpolarized hydrogen target, the scattered deuterons would be strongly aligned.
- Secondly, 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° [**Azhgirey et al.**].
- At last, it was shown by Baryshevsky [**Baryshevsky**] that as particles of spin ≥ 1 pass through matter, effects of spin rotation and oscillations may occur.

Elastic dp scattering

Calculations of the angular dependence of the elastic dp scattering [Franco,Glauber,Harrington] made in the framework of the Glauber multiple scattering theory show that if one would direct the unpolarized deuteron beam on to an unpolarized hydrogen target, the scattered deuterons would be strongly aligned.

range of momentum transfers $S_2(\frac{1}{2}q)$ happens to be comparable in magnitude with $S_0(\frac{1}{2}q)$. For spins polarized along the $\hat{q}$ direction, for example, the form factor $\langle\hat{q},1|S|\hat{q}1\rangle = S_0 - S_2$ decreases much more rapidly with increasing momentum transfer than the two form factors $\langle\hat{\kappa},1|S|\hat{\kappa},1\rangle = \langle\hat{n},1|S|\hat{n},1\rangle = S_0 + \frac{1}{2}S_2$ and thus leads to a minimum at an appreciably smaller momentum

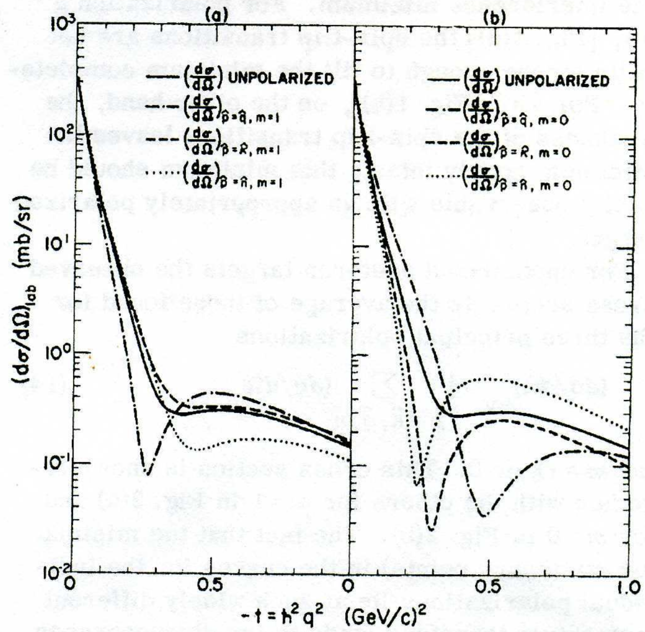
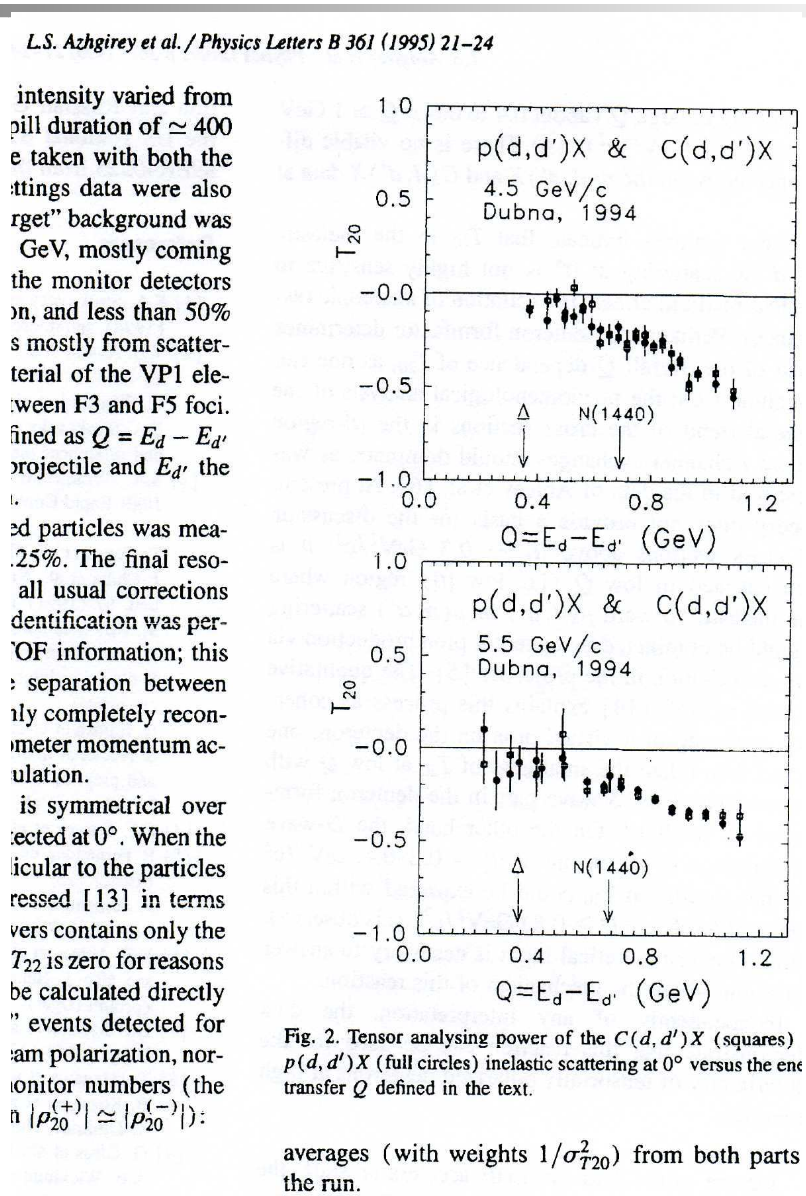


FIG. 2. Scattering of 1-GeV protons by unpolarized deuterons (solid curves) together with those found for the three principal polarization directions for (a) $m = 1$ and (b) $m = 0$.

Inelastic deuteron scattering

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° [Azhgirey et al.].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intensity varied from
pill duration of ≃ 400
e taken with both the
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GeV, mostly coming
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s mostly from scatter-
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tween F3 and F5 foci.
fined as $Q = E_d - E_{d'}$
projectile and $E_{d'}$ the
ed particles was mea-
.25%. The final reso-
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onitor numbers (the
n $|\rho_{20}^{(+)}| \simeq |\rho_{20}^{(-)}|$):

Fig. 2. Tensor analysing power of the $C(d,d')X$ (squares) $p(d,d')X$ (full circles) inelastic scattering at 0° versus the ene transfer Q defined in the text.

averages (with weights $1/\sigma^2_{T20}$) from both parts the run.

Spin dichroism

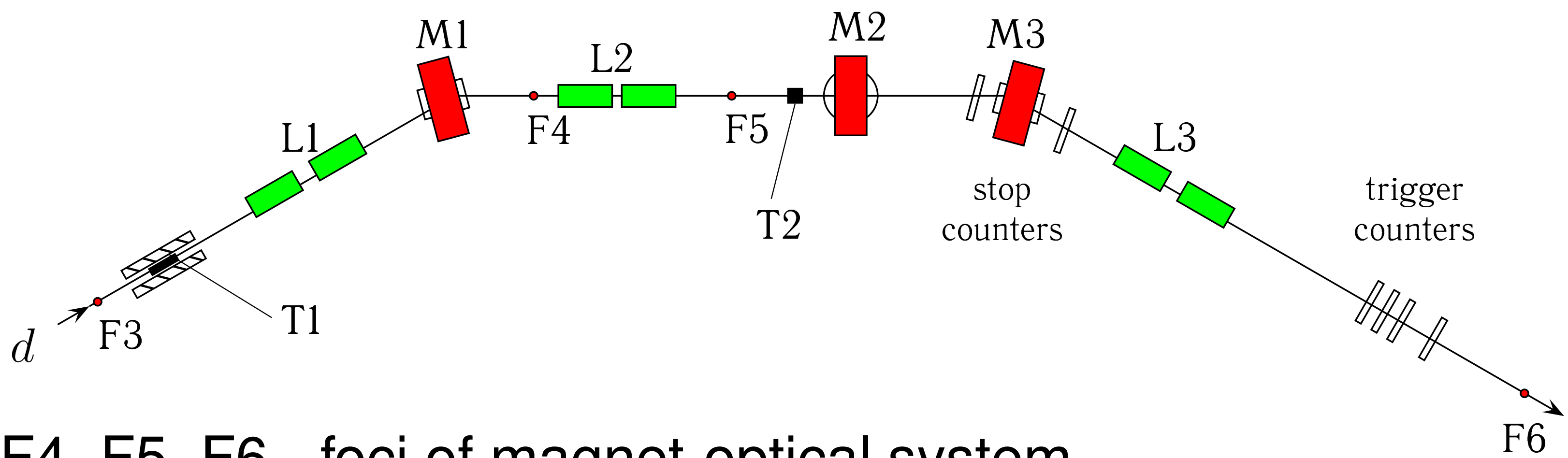
- Effects of spin rotation and oscillations, occuring when particles of spin ≥ 1 pass through matter, may give rise to a polarization of beam [**Baryshevsky**]
- The first attempt to measure spin dichroism, i.e. occurrence of tensor polarization of an unpolarized deuteron beam by unpolarized target, was made with deuterons up to 20 MeV in a carbon target [**Baryshevsky et al.**]
- Although the magnitude of the deuteron polarization was not determined precisely, authors argue that evidence for existence of dichroism was obtained in this experiment.

Experiment at Nuclotron

The first attempt to measure tensor polarization of an unpolarized 5 Gev/c deuteron beam after the passing of a carbon target was made at an unpolarized deuteron beam extracted from the Nuclotron of JINR.

L.S. Azhgirey, Yu.V. Gurchin, A.Yu. Isupov, A.N. Khrenov, A.S. Kiselev, A.K. Kurilkin, P.K. Kurilkin, V.P. Ladygin, A.G. Litvinenko, V.F. Peresedov, S.M. Piyadin, S.G. Reznikov, P.A. Rukoyatkin, A.V. Tarasov, T.A. Vasiliev, V.N. Zhmyrov and L.S. Zolin

Layout of the equipment



F3, F4, F5, F6 - foci of magnet-optical system

L1, L2, L3 - lenses; M1, M2, M3 - magnets; $T1, T2$ - targets

- The part of the beam line up to F5 focus was tuned to the momentum of ~ 5 GeV/c, and the part after F5 was tuned to 3.3 GeV/c.

Pursuance of the experiment

- The slowly extracted beam of ~ 5 GeV/c deuterons with an intensity of $5 \times 10^8 - 3 \times 10^9$ particles per beam spill was incident on 40, 83 and 123 g/cm^2-thick carbon targets T1 that in turn placed in the beam near F3 focus.
- Values of the extracted beam momenta were adopted to have exactly 5.0 GeV/c after crossing a target independent on the target thick. The measurements without target were made also.
- The beam intensities near F3, F4 and F5 foci were monitored by ionization chambers.

Deuteron polarization measurement

- The tensor polarization of the deuteron beam scattered at the T1 target at 0° was determined by means of the second scattering on the 10 cm-thick beryllium target T2 placed near F5 focus [**Zolin**].

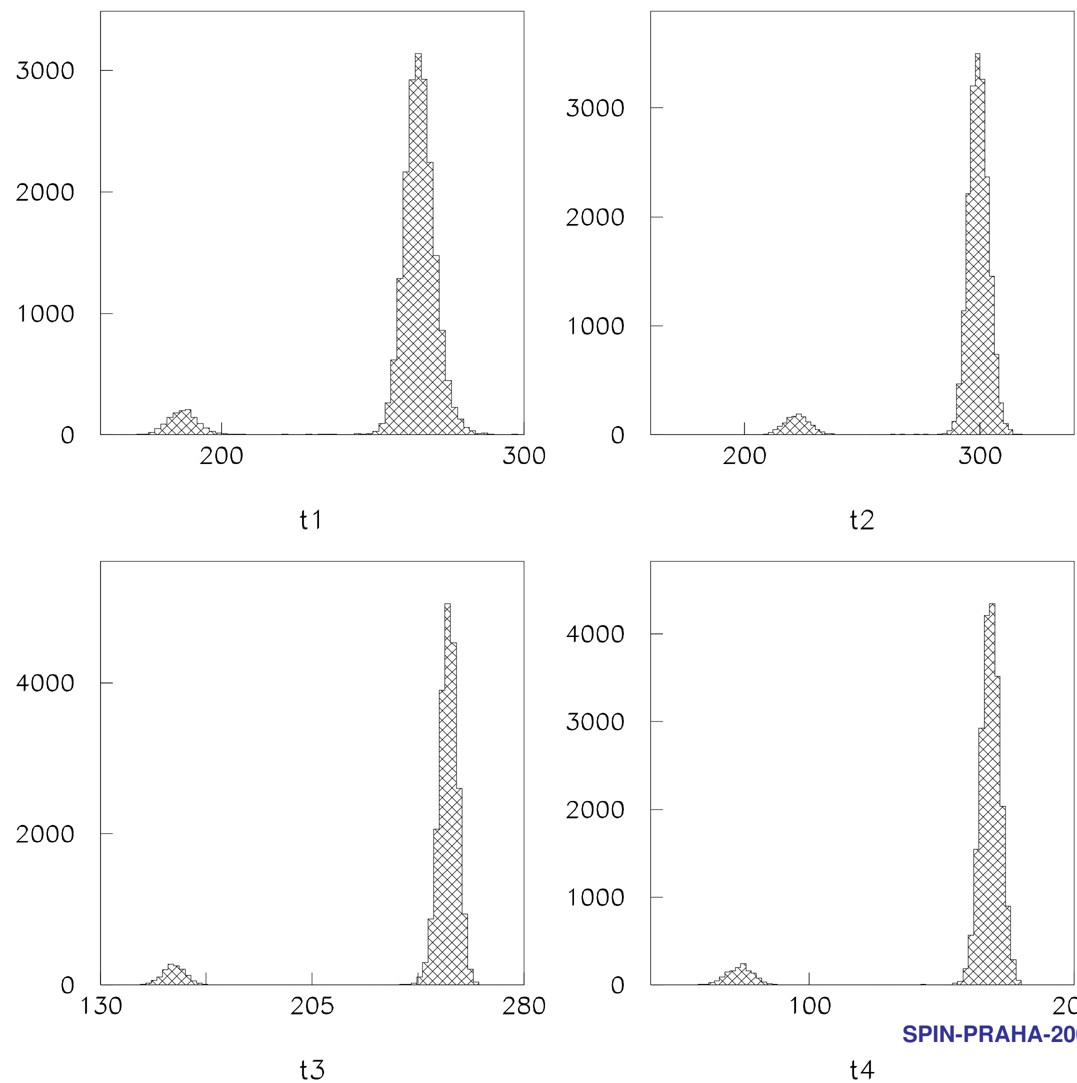
- It is known that the reaction $d + \mathrm{A} \rightarrow p + X$ for proton emission at zero angle with momentum of $p_p \sim \frac{2}{3} p_d$ has a very large tensor analyzing power $T_{20} = -0.82 \pm 0.04$, which is independent on the atomic number of the target (A > 4) and on the momentum of incident deuterons between 2.5 and 9.0 GeV/c [**Perdrisat,Ableev,Aono**].

Experimental procedure

- The secondary particles emitted from 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 ± 8 **mr**, respectively.
- Coincidences of the signals from the scintillation counters placed near the F6 focus were used as a trigger. Along with the secondary protons, the apparatus detected the deuterons from inelastic scattering.

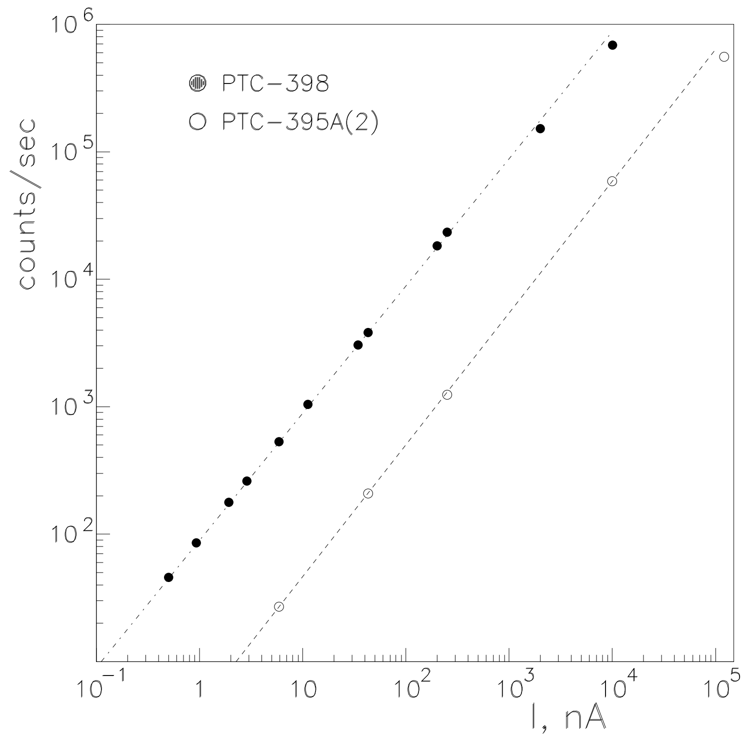
Secondaries identification

The particles detected were identified off-line on the basis of time-of-flight measurements with a base line of $\sim$ 28 m between the start and four stop counters. The TOF resolution attained **(~ 0.2 ns)** allowed one separate protons(right peaks) and deuterons (left peaks) completely.



Linearity of monitors

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



Characteristics of current-to-digit convertors of ionization chambers placed at F5 (dark points) and F3 (light points)

Cross section for polarized deuterons

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

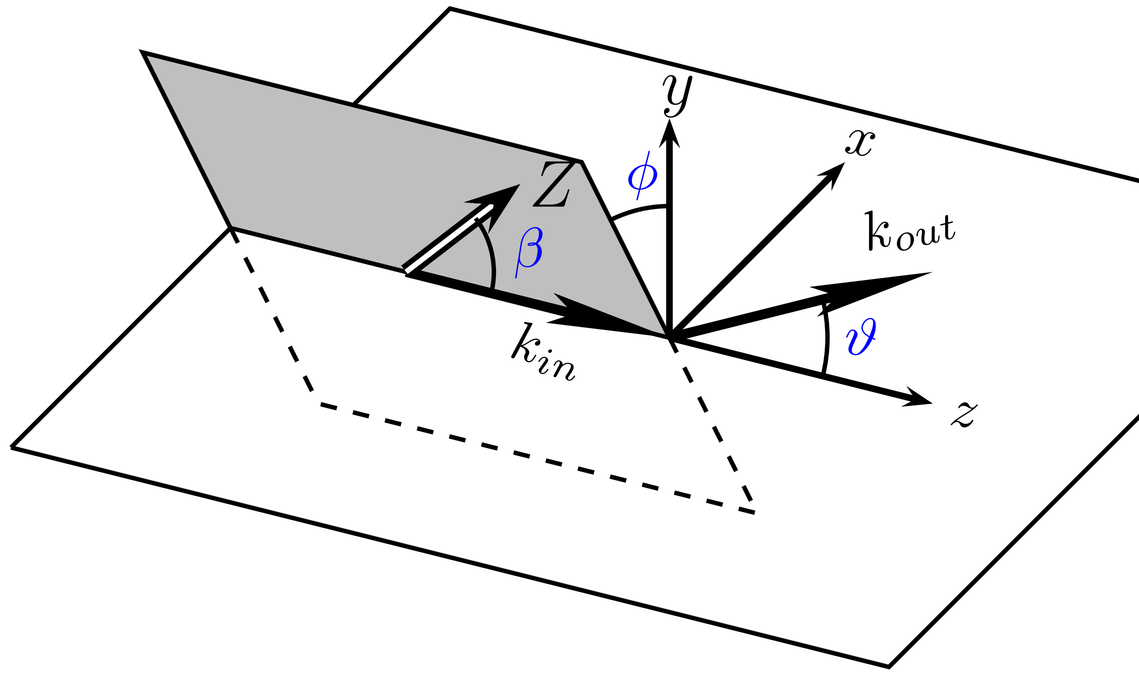
$$
\begin{aligned}
\frac{Ed\sigma}{d\mathbf{p}}(\theta,\phi) &= \left(\frac{Ed\sigma}{d\mathbf{p}}(\theta)\right)_0 \Big[1+\sqrt{2}\rho_{10} iT_{11}(\theta)\sin\beta\cos\phi \\
&+ \frac{1}{2}\rho_{20}T_{20}(\theta)(3\cos^2\beta-1)+\sqrt{6}\rho_{20}T_{21}(\theta)\sin\beta\sin\phi \\
&- \sqrt{\frac{3}{2}}\rho_{20}T_{22}(\theta)\sin^2\beta\cos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

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.

Coordinate system

The values iT_{11}, T_{20}, T_{21} and T_{22} represent the analyzing powers in the representation of irreducible tensors $T_{\kappa q}$. The angles θ and ϕ define the direction of a scattered particle, and β is the angle between the quantization axis and the direction of an incident particle.

Coordinate system for describing the incident polarization. Quantization axis is taken along the symmetry axis. The incident and final momenta are indicated by k_{in} and k_{out}.



Formula for ρ_{20}

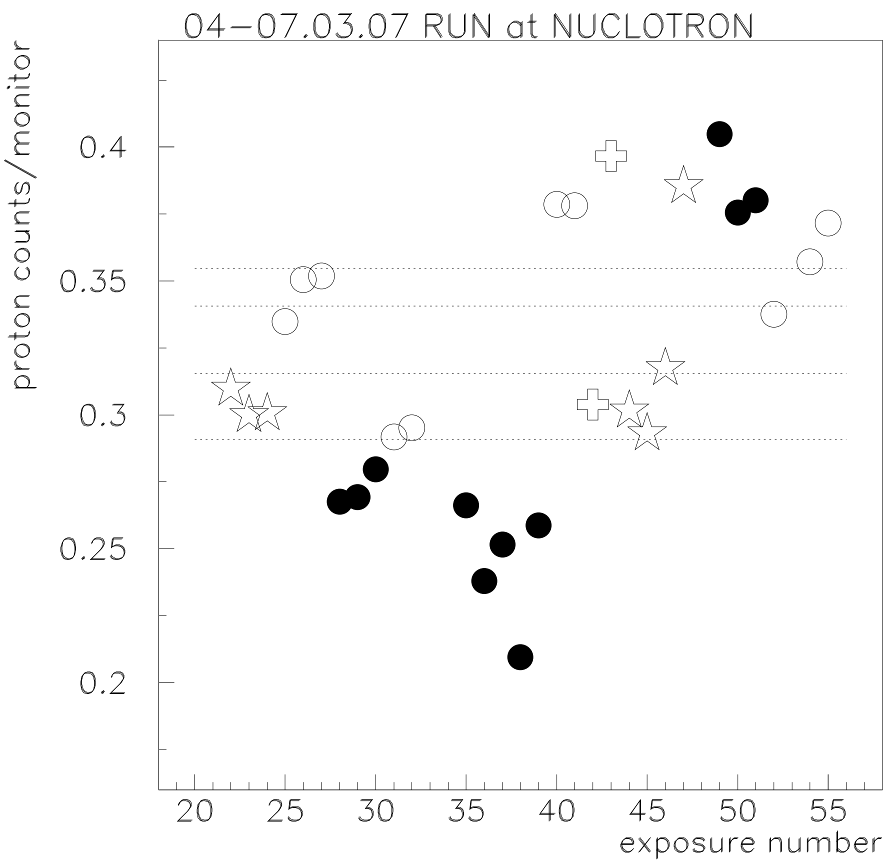
- In our case all these angles are equal to zero, and we have

$$\sigma' = \sigma_0(1 + \frac{1}{\sqrt{2}} p_{ZZ} T_{20}), \quad \rho_{20} = \frac{1}{T_{20}}(\frac{\sigma'}{\sigma_0} - 1)$$

(where polarized and unpolarized cross sections for brevity have been referred to as σ' and σ_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 thick were used to calculate asymmetries.

$N(p)$/monitor ratuos



Ratios of proton counts to the monitor for targets $T1$ of different thick: black points - 123 g/cm^2, stars - 83 g/cm^2, crosses - 40 g/cm^2, light points - 0 g/cm^2. Dashed lines - averaged for all the exposures ratios. The points corresponding to the different target thick are grouped in the different regions of the picture. The spread of the points is caused by the non-stabilities of currents in the magnetic elements of the beam line.

Systematic errors

The possible systematic errors resulting from 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 [**ableev,azhgirey**]. As to the cross section of the A(d,d') reaction, it has a considerably more smooth behaviour [**azhgirey et al.**]. So deviations of the proton/deuteron ratio from the constant value can reflect changes in the currents of magnetic elements, i.e. in the momentum of detected particles.
- On the other hand, the difference Δt in the arrival of signals caused by protons and deuterons also is connected with the spread Δp in the momentum of these particle; for our experimental arrangement $\Delta p/\Delta t = -0.172$ **GeV/c/ns**.

N(p)/N(d) ratio

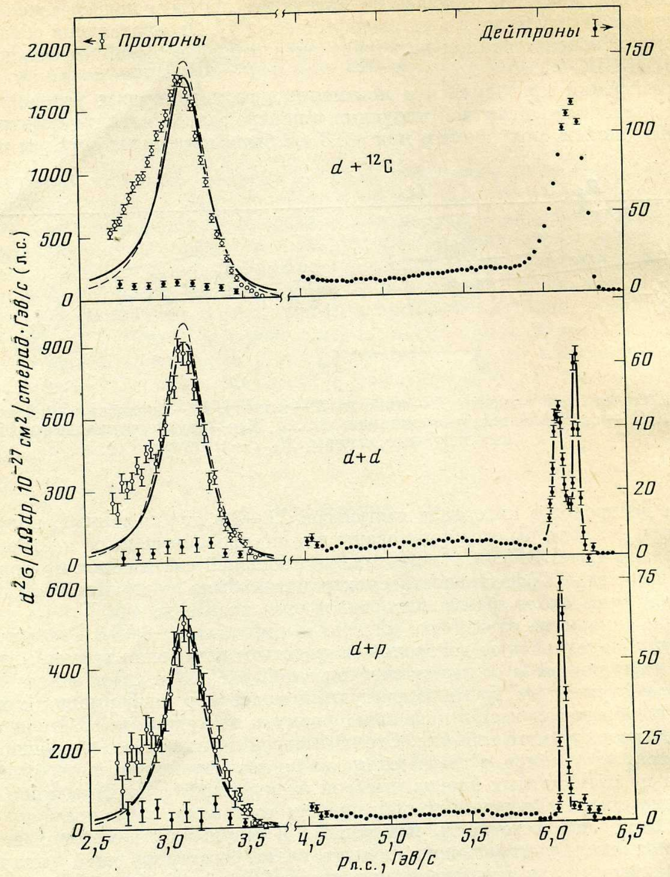
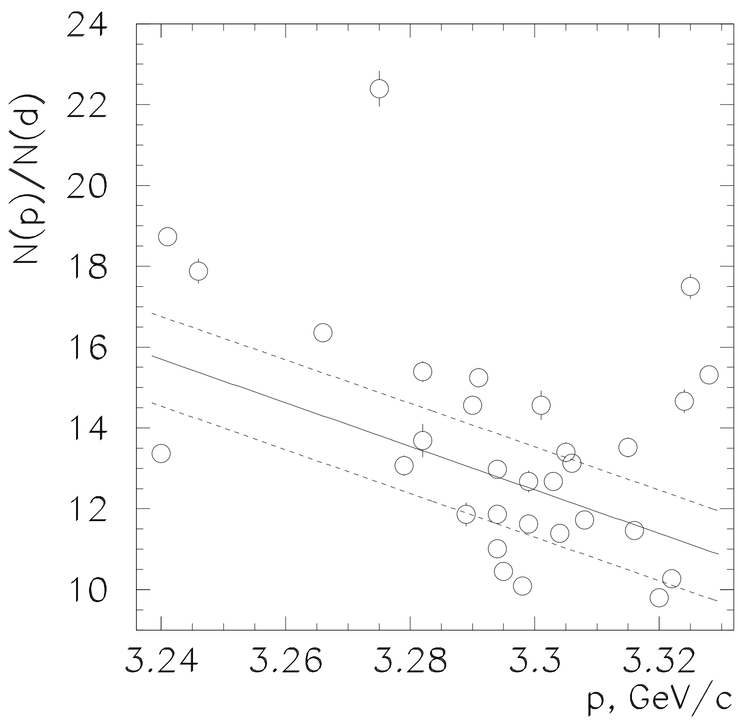


Рис. 2. Импульсные спектры протонов (светлые точки) и дейтронов (черные точки) от соударений дейтронов с протонами, дейтронами и ядрами углерода при p_0=6,3 *Гэв/с*, $\theta_{л.с.}$=103 *мрад*. Дейтронные пики в *dp*- и *dd*-спектрах обведены кривыми визуально. На спектрах протонов сплошные кривые — результат вычислений по формуле (4) с использованием волновой функции Рейда; штриховые кривые — то же с волновой функцией Моравчика — Гартенхауза

1. *dp*-соударения. При 6,07 *Гэв/с* в спектре виден пик, соответству

Momentum spectra of protons(light points) and deuterons (dark points) from 6.3-GeV/c deuteron collisions with ^{1}H, ^{2}H and ^{12}C nuclei detected at 103 mr.

Correlation between N(p)/N(d) and p

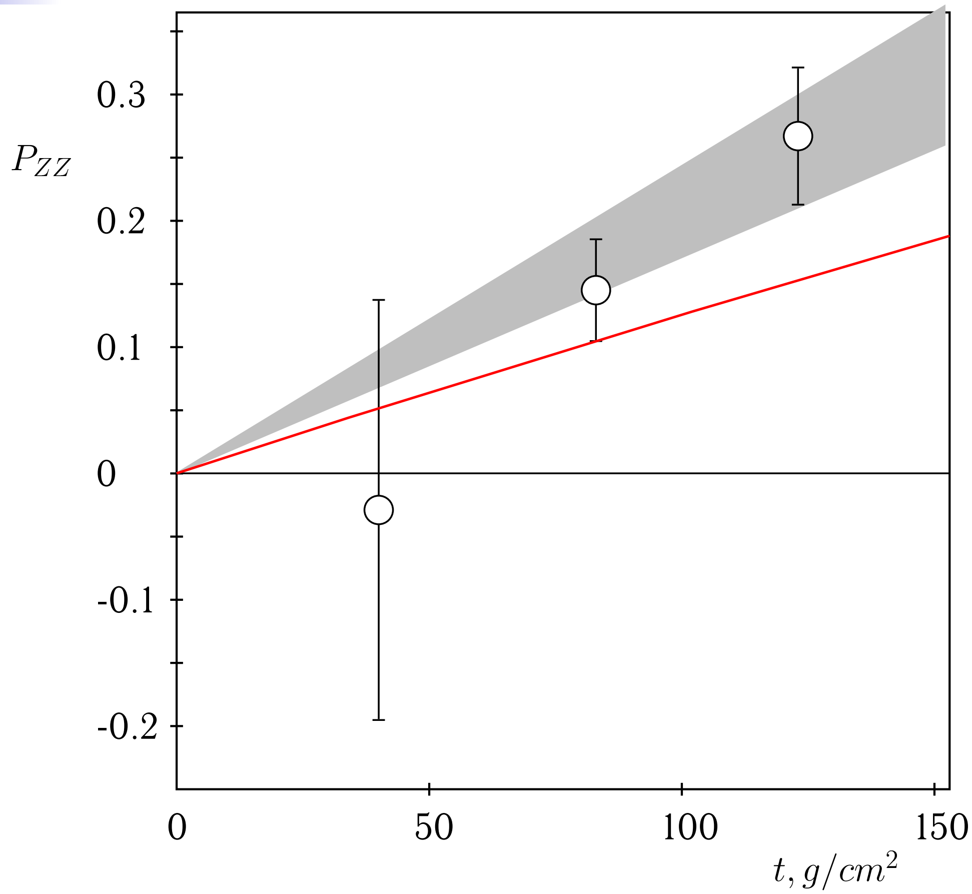


Correlation between the ratio $N(p)/N(d)$ (averaged on four detection channels) and momentum p calculated from the difference Δt:

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

Correction factors to proton counts should vary from 1.26 to 0.88 under changes of the proton momentum from 3.24 to 3.33 GeV/c. An estimate of the possible systematic error is thus seen to be $\pm 20\%$.

Tensor polarization vs target thick



Tensor polarization of deuterons vs thick of target $T1$. The dashed region shows the error corridor, the solid curve represent the calculation result.

The tensor polarizations P_{ZZ} of the deuterons passed through target $T1$ were calculated for each of four channels separately, and they were averaged thereafter; in so doing the counts without $T1$ were taken as σ_0.

Input assumptions

On the assumption that NN scattering amplitude has the form

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

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

$$\psi_0(p) = \sum_i a_i \exp(-\alpha_i p^2), \psi_2(p) = p^2 \sum_i b_i \exp(-\beta_i p^2),$$

with ψ_0 and ψ_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,

The difference of total cross sections $\Delta\sigma$

in line with the multiple scattering theory [glauber,franco], the difference of the total cross sections of the nuclear scattering of deuterons in different spin states (0) and (± 1) may be written in the form:

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

where the cross section difference for Nth collision is given by

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

Notations

Here

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

with

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

Parameters $R_1,\ R_2,\ a_1$ and a_2 are expressed through constants peculiar to this problem:

$$R_1 = \frac{2}{3} < r^2 >_A + 2B, \quad R_2 = \frac{2}{3} < r^2 >_A + B, \quad a_1 = \frac{\sigma_{NN}}{2\pi R_1}, \quad a_2 = -\frac{\sigma^2_{NN}}{16\pi^2 B}$$

where $< r^2 >$ is rms radius of a nucleus.

Effective numbers

Effective numbers for S- and D-states are

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

where

$$\begin{aligned} C_i &= A_i\,(2.5/\alpha_i)^{3/2}, & D_i &= \sqrt{2}B_i\,(2.5/\beta_i)^{7/2} \\ \rho_i &= 6.25/\alpha_i, & \omega_i &= 6.25/\beta_i \\ \tau_{i,k} &= \rho_i + \omega_k, & \nu_{i,k} &= \omega_i + \omega_k \end{aligned}$$

Input parameters

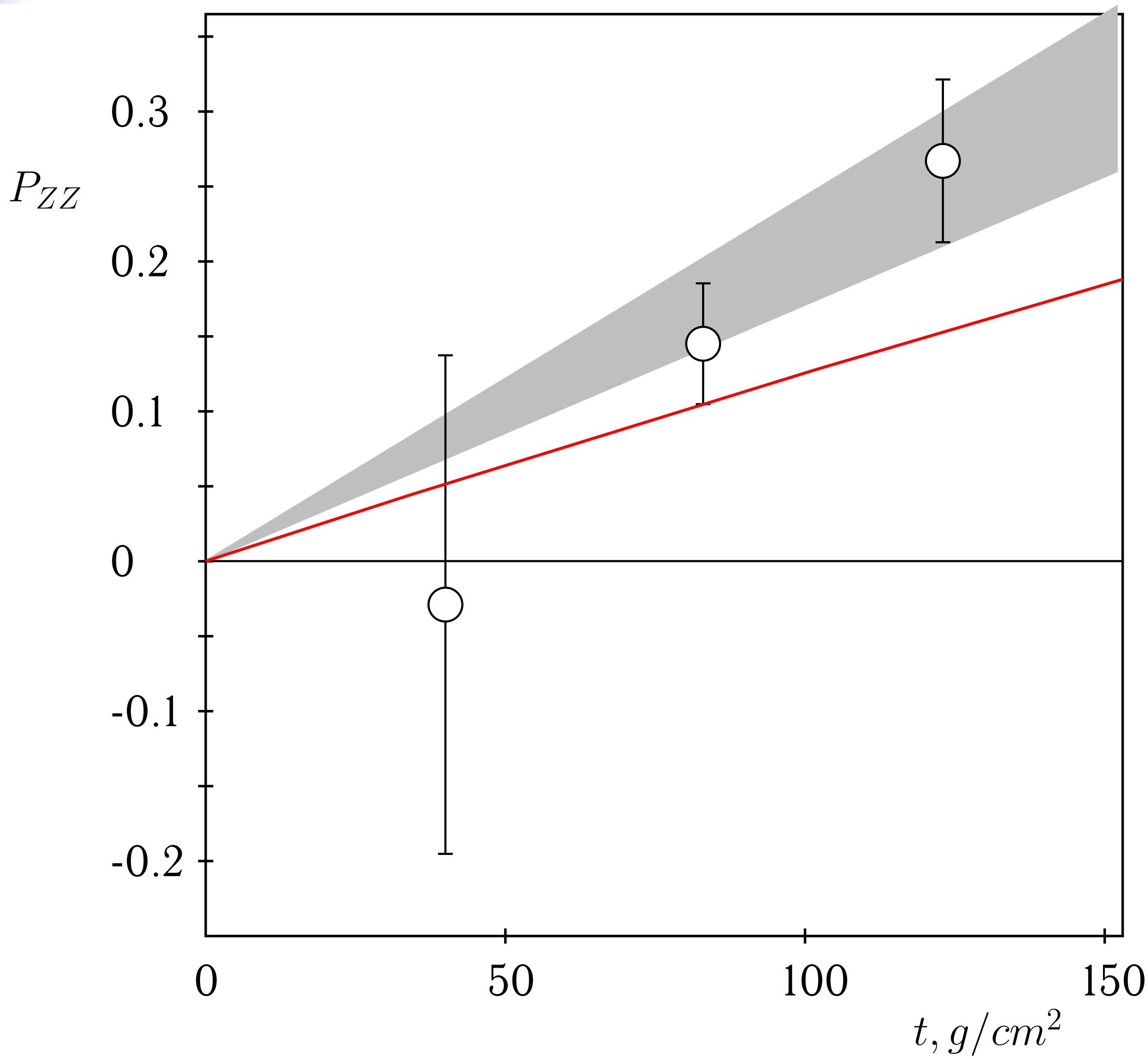
The following values of parameters were used in the calculations: $\sigma_{NN} = 4.40$ **fm**^{2}, $\alpha_{NN} = -0.339$, $B = 0.297$ **fm**^{2}, $< r_C^2 >= 5.86$ **fm**^{2}, and constants $a_i,\ b_i,\ \alpha_i$ **and** β_i were taken from [**alberi**]. The calculated difference of total cross sections of $d -^{12} C$ scattering in the deuteron spin states (0) and (± 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

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

where N is the number of nuclei in cm^3 of matter with thick of x cm. The calculation results for our experiment are shown in picture with the solid curve.

Tensor polarization vs target thick



Multiple scattering theory

- The problem was treated [**L.S. Azhgirey and A.V.Tarasov**] within the framework of the Glauber multiple scattering theory.
- The differences

$$\Delta\sigma_t = \sigma_t(m = 0) - \sigma_t(m = \pm 1),$$

where m is the projection of the deuteron spin on the quantization axe, were calculated for different nuclei.

Cross section differences

- It can be shown that the tensor polarization of the deuteron beam arising from these cross section differences is

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

where N is the number of nuclei in cm^3 of matter with thick of x cm.

- On the other hand

$$I = I_0 \exp(-N\sigma_t x)$$

Table of cross sections

Root-mean-square radii $< R_A >$, cross section differences $\Delta\sigma$, P_{ZZ}, and target thicknesses x for different nuclei A calculated under the assumption that the beam intensity behind the target falls down to 0.01 of the initial one.

Values of the cross sections and P_{ZZ}

A	$< R_A >$,fm	σ_t, mb	$\Delta\sigma$,mb	P_{ZZ}	x,cm
^{9}Be	2.26	540	31.6	0.171	68.8
^{12}C	2.42	650	37.9	0.174	83.0
^{27}Al	3.06	1090	62.5	0.170	70.3
^{40}Ca	3.52	1400	77.8	0.165	141.2
^{64}Cu	3.88	1880	95.8	0.151	29.0
^{106}Ag	4.40	2630	119.1	0.135	30.0
^{197}Au	5.33	3850	155.6	0.121	20.3
^{207}Pb	5.42	3980	159.3	0.120	35.2

Results for CH_2 and CD_2

A	$< R_A >$,fm	σ_t, mb	$\Delta\sigma$,mb	P_{ZZ}	x,cm
^1H	0.81	73	4.3	0.173	1475
^2D	1.98	138	8.6	0.182	660
^{12}C	2.42	650	37.9	0.174	83
CH_2		568	42.2	0.170	204
CD_2		522	46.2	0.171	221

Conclusion

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- The phenomenon of spin dichroism (defined as the production of spin polarization in an unpolarized beam) predicted earlier by V.Baryshevsky [**baryshevsky**] was first observed using an extracted unpolarized 5-GeV/c deuteron beam of the Nuclotron.

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- A formalism was elaborated to describe the effect observed in the framework of the Glauber multiple scattering theory.
- The calculation results are in qualitative agreement with the experimental data obtained.
- The effect observed can be used to produce tensor polarized deuteron beams of small intensity at high energies.

Acknowledgments

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The End