Influence of Coulomb-nuclear interference on the deuteron spin dichroism phenomenon in a carbon target in the energy interval 5–20 MeV

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ABSTRACT

Theoretical studies of the deuteron beam transmission through the unpolarized target predict the appearance of tensor polarization in transmitted beam due to deuteron spin dichroism. If only nuclear interaction is taken into account when considering this phenomenon, the tensor polarization (spin dichroism) of transmitted beam has a positive sign which agree with conception of different “transverse dimensions” of deuteron in different spin state. However, the first experiments with deuteron with the energy of 5–20 MeV transmitting through unpolarized carbon target show that accumulated polarization in a deuteron beam firstly, has a negative sign and secondly, the increase in the target thickness (and primary deuteron energy) does not bring about the increase in the value of polarization. This can be explained by changing the sign of deuteron spin dichroism in the considered energy interval. In this Letter is shown that the account of the Coulomb interaction by means of the Coulomb-nuclear interference, can qualitatively explain behavior of deuteron spin dichroism in a carbon target in the energy interval from 5 to 20 MeV.

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1. Introduction

Spin rotation and spin dichroism (birefringence effect) phenomena arise for deuterons (in general for all particles with spin $S \geq 1$) passing through unpolarized matter [1,2]. The above phenomena are caused by the difference of the spin-dependent coherent forward scattering amplitude for deuterons with the spin projections $m = 0$ and $m = \pm 1$ ($m$ is a magnetic quantum number).

As a result, the refraction index and the absorption coefficient for a deuteron transmitting through matter depend on the deuteron spin state. So, an unpolarized deuteron beam transmitting through an unpolarized target acquires tensor polarization due to the deuteron spin dichroism (dependence of the absorption coefficient on deuteron spin).

The first experimental study of the deuteron spin dichroism in carbon targets was carried out at the electrostatic HVEC tandem Van de Graaff accelerator with deuteron energy up to 20 MeV (Institut für Kernphysik of Universität zu Köln) [3,4]. In the experiments [3,4] it was found out that in the energy interval 5–20 MeV both the value and the sign of the deuteron spin dichroism in a carbon target changes with the energy change. In 2007 another experiment at the Nuclotron in JINR [5] provided the measurement of spin dichroism for 5.5 GeV/c deuterons transmitted through carbon targets.

According to [1,2] to describe the effect, it is necessary to take into account both nuclear and Coulomb interaction of the deuteron with the nucleus. For high energy deuterons the nuclear interaction of a deuteron with a light nucleus gives the main contribution to the birefringence effect. Comparison of the theoretical estimation [1,2], which includes consideration of nuclear interaction with the experimental results [5] demonstrates their qualitative agreement. Moreover the sign of the effect obtained in theoretical calculations coincides with that measured in the experiment.

The role of the Coulomb interaction (Coulomb-nuclear interference) increases with decreasing deuteron energy even for interaction of deuterons with light nuclei.

In the present Letter is shown that the consideration of the Coulomb interaction in analysis makes it possible to explain experimentally observed sign change of the deuteron spin dichroism with the change in the deuteron energy [3,4].

2. Birefringence of deuteron in unpolarized matter

According to [1,2], the index of refraction for a deuteron (spin $S = 1$) can be written as follows:
where \( \rho \) is the density of matter (the number of scatterers in 1 cm\(^3\)), \( k \) is the deuteron wave number, \( \hat{f}(0) = \text{Tr} \hat{\rho}_j \hat{F}(0), \hat{\rho}_j \) is the spin density matrix of the scatterers, \( \hat{F}(0) \) is the operator of the forward scattering amplitude acting in the combined spin space of the deuteron and scatterer spin \( \hat{J} \).

Let us choose the direction of the particle wave vector \( \vec{k} \) as the quantization axis \( z \). Then, for an unpolarized target the forward scattering amplitude \( \hat{f}(0) \) can be presented [1,2] as \( \hat{f}(0) = d + d_1 \hat{S}_z \), \( \hat{S}_z \) is the operator of spin projection on the \( z \) axis, \( d \) and \( d_1 \) are the spin-independent and spin-dependent parts of the forward scattering amplitude, respectively.

The refractive index \( N_m \) for deuterons in unpolarized matter can be written as

\[
\hat{N} = 1 + \frac{2 \pi \rho}{k^2} \hat{f}(0),
\]

where \( \hat{N} \) is the index of refraction, \( N_m \) depends on deuteron spin orientation with respect to the deuteron momentum. The refractive index \( N_m \) for a deuteron in the eigenstate of operator \( \hat{S}_z \) is

\[
N_m = 1 + \frac{2 \pi \rho}{k^2} f_m(0), \quad f_m(0) = d + d_1 m^2.
\]

According to Eq. (3), the index of refraction \( N_m \) depends on deuteron spin orientation with respect to the deuteron momentum.

The refractive index \( N_m \) for a deuteron in the eigenstate of operator \( \hat{S}_z \) is

\[
N_m = 1 + \frac{2 \pi \rho}{k^2} f_m(0), \quad f_m(0) = d + d_1 m^2.
\]

3. Deuteron spin dichroism in a carbon target

Let a deuteron beam in state \( m = 1 \) pass through a target. The beam intensity changes as \( I_{1}(z) = I_{1}^{0}e^{-\sigma_{\parallel 1} \rho z}, \) where \( I_{1}^{0} \) is the beam intensity before entering the target. Similarly for states \( m = -1 \) and \( m = 0 \) the intensity changes as \( I_{-1}(z) = I_{-1}^{0}e^{-\sigma_{\parallel -1} \rho z}, \) and \( I_{0}(z) = I_{0}^{0}e^{-\sigma_{\perp 0} \rho z}, \) where \( I_{1}^{0} \) and \( I_{0}^{0} \) are the beam intensities before entering the target, respectively.

Let us consider transmission of an unpolarized deuteron beam through an unpolarized target. The unpolarized deuteron beam can be described as a composition of three polarized beams with equal intensities \( I = I_{1}^{0} + I_{-1}^{0} + I_{0}^{0} \), \( I_{1}^{0} = I_{-1}^{0} = I_{0}^{0} = Ig/3 \). In reality in experiment \( \sigma_{\parallel 1,0} \rho z \ll 1 \) and the change of intensity for each beam can be expressed as \( I_{1}(z) = I_{1}^{0}(1 - \sigma_{\parallel 1} \rho z) \) and \( I_{0}(z) = I_{0}^{0}(1 - \sigma_{\perp 0} \rho z). \) Since \( \sigma_{-1} = \sigma_1, \) the deuteron spin dichroism can be characterized by the ratio \( D \) as follows:

\[
D(z) = \frac{I_{1}(z) - I_{0}(z)}{I_{1}(z) + I_{0}(z)} \approx \frac{1}{2} (\sigma_0 - \sigma_{\pm 1}) \rho z = -\frac{2 \pi \rho z \text{Im} f_1(0)}{k}.
\]

where Eqs. (4) and (5) are used.

Then Eq. (6) can be rewritten as

\[
D(L) = -\frac{2 \pi N_a L \text{Im} f_1(0)}{k M_r} = \frac{N_a L (\sigma_0 - \sigma_{\pm 1})}{2 M_r}.
\]

where \( N_a \) is the Avogadro number, \( L \) is the target thickness in g/cm\(^2\), \( M_r \) is the molar mass of the target matter.

According to [6] the tensor polarization of the beam can be expressed as \( P_{zz} = l_{11} + l_{22} - 2 l_{12}. \)

The tensor polarization of the initially unpolarized deuteron beam transmitting through the target of the thickness \( L \) arising from deuteron spin dichroism reads as follows:

\[
p_{zz}(L) = \frac{L_{11}(L) + l_{11}(L) - 2 l_{12}(L)}{L_{11}(L) + l_{11}(L) + l_{12}(L)} \approx \frac{2 N_a L (\sigma_0 - \sigma_{\pm 1})}{3 M_r} \approx \frac{8 \pi N_a L \text{Im} f_1(0)}{3 M_r}.
\]

The relation between \( D \) and \( P_{zz} \) follows from Eqs. (7) and (8):

\[
p_{zz}(L) \approx 4/3 D.
\]

Note that a deuteron transmitting through a target loses energy for the ionization of matter, then, taking into account the energy change, we can write the tensor polarization as

\[
p_{zz}(L) = \frac{2 N_a}{3 M_r} \int_{0}^{L} (\sigma_0(E(L')) - \sigma_{\pm 1}(E'(L')) ) dL'.
\]
According to Eq. (10) the imaginary part of the spin-dependent forward scattering amplitude can be measured directly in transmission experiment by means of deuteron beam tensor polarization, which arises due to deuteron spin dichroism.

4. The amplitude of deuteron forward scattering

Let us estimate the value of deuteron spin dichroism. In view of the aforesaid it is necessary to find amplitudes of coherent elastic zero-angle scattering of a deuteron with a nucleus \( f_{\pm 1}(0) \) and \( f_0(0) \).

The Hamiltonian \( H \) describing interaction of a deuteron by a nucleus can be written as

\[
H = H_D(\vec{r}_p, \vec{r}_n) + H_N(\{\xi_i\}) + V(\vec{r}_p, \vec{r}_n, \{\xi_i\}),
\]

where \( H_D \) is the deuteron Hamiltonian; \( H_N \) is the nucleus Hamiltonian; \( V = V_{DN} + V_{DC} \) is the potential of deuteron–nucleus interaction, \( V_{DN} \) is the nuclear potential of the deuteron–nucleus interaction, \( V_{DC} \) is the Coulomb potential of the deuteron–nucleus interaction, \( \vec{r}_p(\xi_i) \) is the coordinate of the proton (nucleus) composing the deuteron, \( \{\xi_i\} \) is the set of coordinates of nucleons in the target nucleus.

In terms of coordinate of deuteron center-of-mass \( \vec{R} \) and the relative distance between the proton and the neutron in the deuteron \( \vec{r} = \vec{r}_p - \vec{r}_n \) we can rewrite Eq. (11) as

\[
H = -\frac{\hbar^2}{2m_D} \Delta(\vec{R}) + H_D(\vec{R}) + H_N(\{\xi_i\}) + V_{DN}(\vec{R}, \vec{r}, \{\xi_i\})
+ V_{DC}(\vec{R}, \vec{r}, \{\xi_i\}).
\] (12)

Let us consider scattering of deuterons with energy \( E \) exceeding deuterons binding energy \( \varepsilon_d \). Suppose that \( \varepsilon_d/E \ll 1 \). Then, we can neglect \( H_D(\vec{R}) \) in Eq. (12) (i.e., we can apply the impulse approximation [7]). Note that for deuterons with energy of 10 MeV the characteristic time of the Coulomb deuteron–nucleus interaction \( \tau_C \sim 8\pi \hbar / e \varepsilon_d \) is much longer than the characteristic period of nuclear oscillations in deuteron \( \tau_D \sim 2\pi \hbar / e \varepsilon_d \) (here \( R_{SR} \) is the radius of the Coulomb screening, \( \nu \) is the deuteron speed). Therefore, the Coulomb interaction in Eq. (12) can be averaged over wave functions of deuteron ground state [8,9]. As a result, Eq. (12) can be written as

\[
H = -\frac{\hbar^2}{2m_D} \Delta(\vec{R}) + V_p(\vec{R} + \vec{r}) + V_n(\vec{R} - \vec{r}) + V_C(\vec{R}),
\]

where \( V_p \) and \( V_n \) are the nuclear potentials of proton–nucleus and neutron–nucleus, respectively, \( V_C \) is the Coulomb deuteron–nucleus potential averaged over the wave functions of deuteron ground state.

To find the amplitude of coherent elastic zero-angle scattering of a deuteron by a nucleus, it suffices to consider scattering of a structureless particle by a nucleus. In this case the coordinate \( \vec{r} \) is a parameter. Therefore, the expressions obtained for the forward scattering amplitude should be averaged over the parameter \( \vec{r} \).

The amplitude of coherent zero-angle scattering [7,10], averaged over the deuteron wave functions of the ground state can be written as follows

\[
f_m(0) = -\frac{m_D}{2\pi \hbar^2} \times \int V_D(b, z, \vec{r}) \psi(b, z, \vec{r}) e^{-i k \vec{r}} d^2 b \, d^2 z |\psi_m(\vec{r})|^2 d^3 r,
\]

(14)

where \( V_D(b, z, \vec{r}) = V_P(b, z, \vec{r}) + V_p(b, z, \vec{r}) + V_C(b, z) \) is the potential of deuteron–nucleus interaction, \( b = \vec{R} \) is the deuteron impact parameter, \( \psi \) is the wave function satisfying the Schrödinger equation \( H \psi = E \psi \), where \( H \) is determined by Eq. (13), \( \psi_m(\vec{r}) \) is the wave function of the deuteron ground state with the magnetic quantum number \( m \).

For the deuteron with energy 5–20 MeV the product \( kr_{nuc} \sim 3 \), where \( r_{nuc} \) is the radius of nuclear interaction of a deuteron with a target nucleus. Then, to estimate \( f_m(0) \), we can use WKB (Wentzel–Kramers–Brillouin) approximation for the deuteron wave function \( \psi [7,10,11] \):

\[
\psi(\vec{r}, \vec{z}) = e^{\frac{ik}{\hbar}(\vec{r} - \vec{z}) - V_{Dnuc}(\vec{r}, \vec{z}) \Delta} \int_{-\infty}^{+\infty} d^2 b \, d^2 z |\psi_m(\vec{r})|^2 d^3 r.
\]

(15)

In the considered model the deuteron energy \( E \) is higher than the energy of Coulomb deuteron–nucleus interaction, i.e. \( E \gg V_C \), then

\[
n(b, z, \vec{r}) = \sqrt{1 - \frac{V_{Dnuc}(b, z, \vec{r})}{V_C(b, z)}}.
\]

(16)

The forward scattering amplitude \( f_m(0) \) can be rewritten as follows:

\[
f_m(0) = f_m^P(0) + f_m^C(0),
\]

where

\[
f_m^P(0) = \frac{k}{2\pi \hbar} \int [e^{i k \vec{r}} - 1] d^2 b |\psi_m(\vec{r})|^2 d^3 r,
\]

\[
f_m^C(0) = \frac{m}{\pi \hbar^2} \int \left( E (n(b, z, \vec{r}) - 1) - \frac{V_P(b, z, \vec{r})}{2\sqrt{n(b, z, \vec{r})}} \right) d^2 b \, d^2 z |\psi_m(\vec{r})|^2 d^3 r.
\]

(17)

Phases \( \chi_D \) and \( \chi_D' \) are determined as

\[
\chi_D(b, \vec{r}) = \chi_n(b, \vec{r}) + \chi_p(b, \vec{r}) + \chi_C(b, \vec{r}),
\]

(18)

where

\[
\chi_n = -\frac{i k}{E} \int_{-\infty}^{+\infty} \frac{V_n(b, z, \vec{r})}{1 + n_{nuc}(b, z, \vec{r})} d z,
\]

\[
\chi_p = -\frac{i k}{E} \int_{-\infty}^{+\infty} \frac{V_p(b, z, \vec{r})}{1 + n_{nuc}(b, z, \vec{r})} d z,
\]

\[
\chi_C = -\frac{i k}{E} \int_{-\infty}^{+\infty} \frac{V_C(b, z)}{2n_{nuc}(b, z, \vec{r})} d z,
\]

(19)

and

\[
\chi_D'(b, z, \vec{r}) = \chi_n(b, z, \vec{r}) + \chi_p'(b, z, \vec{r}) + \chi_C'(b, z, \vec{r}),
\]

(20)

where
\[ X_n' = -\frac{ik}{E} \int_{-\infty}^{z} \frac{V_n(b, z', \vec{r})}{1 + n_{\text{nuc}}(b, z', \vec{r})} dz', \]
\[ X_p' = -\frac{ik}{E} \int_{-\infty}^{z} \frac{V_p(b, z', \vec{r})}{1 + n_{\text{nuc}}(b, z', \vec{r})} dz', \]
\[ X_C' = -\frac{ik}{E} \int_{-\infty}^{z} \frac{V_C(b, z', \vec{r})}{2n_{\text{nuc}}(b, z', \vec{r})} dz'. \]  

(21)

For high energy \( E \gg V_D(b, z, \vec{r}) \) the amplitude \( f_m'(0) \) in Eq. (17) converts into the amplitude in eikonal approximation [7,10]

\[ f_m'(0) \approx \frac{k}{2\pi} \int \left( e^{i\vec{p} \cdot \vec{r}} \int_{-\infty}^{\infty} V_n(b, z, \vec{r}) + V_p(b, z, \vec{r}) + V_C(b, z) dz - 1 \right) d^2b \times |\phi_m(\vec{r})|^2 d^2r. \]

The amplitude \( f_m^{\text{cor}}(0) \) describes the correction to \( f_m(0) \) in the range, where \( E < V_D(b, z, \vec{r}) \).

At high energy \( f_m^{\text{cor}}(0) \to 0 \) and \( f_m(0) \to f_m'(0) \), but at low energy \( f_m^{\text{cor}}(0) \) cannot be neglected. The term \( f_m'(0) \) in Eq. (17) can be rewritten as

\[ f_m'(0) = \frac{k}{\pi} \int \left( t_n(b, \vec{r}) + t_p(b, \vec{r}) + t_C(b, \vec{r}) \right) d^2b |\phi_m(\vec{r})|^2 d\]
\[ + 2ik \pi \int \left( t_n(b, \vec{r}) t_C(b, \vec{r}) + t_p(b, \vec{r}) t_C(b, \vec{r}) \right) d^2b |\phi_m(\vec{r})|^2 d\]
\[ + 4k \pi \int \left( t_n(b, \vec{r}) t_C(b, \vec{r}) t_C(b, \vec{r}) \right) d^2b |\phi_m(\vec{r})|^2 d^2r, \]

(22)

where \( t_n(b, \vec{r}) = (e^{2iE(b, \vec{r})} - 1)/2i \), \( t_p(b, \vec{r}) = (e^{2iE(b, \vec{r})} - 1)/2i \), \( t_C(b, \vec{r}) = (e^{2iE(b, \vec{r})} - 1)/2i \).

The deuteron spin dichroism is caused by the spin-dependent part of the forward scattering amplitude \( d_1 \) (see Eqs. (7), (10));

\[ d_1 = f_{\pm}(0) - f_0(0). \]

Let us change the variables: \( \vec{x} = \vec{R}_z + \vec{r}_z/2, \vec{y} = \vec{R}_z - \vec{r}_z/2, \vec{z}, \vec{\eta} \) are the impact parameters of the proton and the neutron composing the deuteron, respectively.

The deuteron is a weakly bound particle with larger dimensions than a light nucleon. Hence, to estimate the amplitude of deuteron forward scattering by a light nucleus in integral (22), we can neglect the change in the deuteron wave functions. As a result we obtain:

\[ d_1' \approx \frac{2ik}{\pi} \int t_n(\vec{x}, \vec{\eta}, \vec{z}) s_{\text{nuc}}(\vec{x}, \vec{\eta}, \vec{z}) A(0, z, d) d^2\vec{x} d^2\vec{\eta} dz d\]
\[ - \frac{4k}{\pi} \int t_n(\vec{x}, \vec{\eta}, \vec{z}) s_{\text{nuc}}(\vec{x}, \vec{\eta}, \vec{z}) t_C(\vec{x}, \vec{\eta}, \vec{z}) d^2\vec{x} d^2\vec{\eta} dz d\]
\[ \approx \Delta(0, z, d) d^2\vec{x} d^2\vec{\eta} dz d\]

(23)

where \( \Delta(0, z, d) \) is \( |\phi_{1+}(0, z, d)|^2 - |\phi_{0}(0, z, d)|^2 \).

According to Eq. (23) the main contributions to amplitude \( d_1' \) are given by the nuclear interaction and interference of the Coulomb-nuclear interactions of deuteron nucleons with the target nucleons.

According to Eq. (23) the value of \( d_1' \) is determined by the difference \( |\phi_{1+}(0, z, d)|^2 - |\phi_{0}(0, z, d)|^2 \). By difference of the nucleon distribution in deuterons in different spin states. It is known that the deuteron wave function \( \psi_m \) can be written as [12]

\[ \psi_m(\vec{r}) = \frac{1}{\sqrt{4\pi}} \left( \frac{u(r)}{r} + \frac{1}{\sqrt{8}} \frac{w(r)}{r} S_{12} \right) \chi_m, \]

(24)

where \( u(r) \) is the radial wave function of a deuteron in the S-state; \( w(r) \) is the radial wave function of a deuteron in the D-state; \( S_{12} = 6(\delta_{R})^2 - 2\delta_{R}^2, \delta_{R} = 1/2(\delta_{G} + \delta_{A}), \delta_{G}, \delta_{A} \) are the spin matrices of the proton (neutron), respectively. Applying Eq. (24), we obtain:

\[ \Delta(\vec{r}) = \frac{3}{4\pi} \left( \frac{1}{\sqrt{2}} \frac{u(\vec{r})}{r^2} - \frac{1}{4} \frac{w(\vec{r})^2}{r^2} \right) \left( n_{1n} + n_{1p} - 2n_{2z} \right). \]

(25)

That allows us to write \( \Delta(0, z_d) \) as

\[ \Delta(0, z_d) \approx \frac{3}{2\pi} \left( \frac{1}{\sqrt{2}} \frac{u(z_d)}{z_d^2} - \frac{1}{4} \frac{w(z_d)^2}{z_d^2} \right). \]

(26)

Let us consider the correction \( f_m^{\text{cor}}(0) \) (Eq. (17)). Repeating the derivation of Eq. (23) using the above assumptions, we can obtain the expression describing the correction into \( d_1 \) within the considered model:

\[ d_1^{\text{cor}} \approx \frac{8m}{\pi \hbar^2} \int \left( \frac{E}{n(\vec{x}, \vec{y}, \vec{z}, \vec{d})} - \frac{V_p(\vec{x}, \vec{y}, \vec{z}, \vec{d})}{V_p(\vec{x}, \vec{y}, \vec{z}, \vec{d})} \right) t_\text{p}(\vec{x}, \vec{y}, \vec{z}, \vec{d}) d\vec{x} d\vec{y} d\vec{z} d\vec{d}, \]

(27)

where \( t_\text{p}(\vec{x}, \vec{y}, \vec{z}, \vec{d}) = (e^{2iE(\vec{x}, \vec{y}, \vec{z}, \vec{d})} - 1)/2i \), \( t_\text{p}(\vec{x}, \vec{y}, \vec{z}, \vec{d}) = (e^{2iE(\vec{x}, \vec{y}, \vec{z}, \vec{d})} - 1)/2i \). Remind that phases \( \chi_m, X_P, \chi_C \) are determined by Eq. (21). According to Eq. (26) the value of \( \Delta(0, z_d) \) and amplitudes \( d_1, d_1^{\text{cor}} \) are sensitive to the wave function of the deuteron ground state at a small distance.

5. The influence of the Coulomb-nuclear interference on deuteron spin dichroism in a carbon target

Now we can evaluate the amplitude \( d_1 = d_1' + d_1^{\text{cor}} \) and the difference in total cross-sections for deuterons in different spin state.

Let us consider scattering of a deuteron by a carbon nucleus. The potential of nuclear interaction of the deuteron nucleons with the target nucleus can be expressed by means of optical Woods–Saxon potential, which for 5.25 MeV nucleons [14] reads as

\[ V_{NN}(r) = \frac{V_{PN}(r)}{1 + \exp(20r - 1.33A^{1/3})/5} \]

where \( A \) is the atomic number of the target nuclei. The energy chosen for optical potential corresponds to the deuteron energy 10.5 MeV which is approximately equal to the deuteron average energy in the considered range. Moreover, according to [14] in the considered deuteron energy range the coefficients in this potential do not significantly change. To verify the optical potential and WKB approximation the total cross-section for \( n - ^{12}C \) scattering at 5.25 MeV is calculated and comes to about 1 barn, which agrees with the experimental data. For calculation of the Coulomb deuteron–nucleus interaction the charge distribution \( Z(r) \) in a nucleus is taken as \( Z(r) \sim \frac{1}{1 + \exp(20r - 1.33A^{1/3})} \). The radial deuteron wave functions \( u(\vec{r}) \),
and \( w(r) \) are expressed as parameterized deuteron wave functions from [13].

According to Eq. (7) the spin dichroism arises for a deuteron beam transmitting through a target because \( \sigma_0 - \sigma_{\pm 1} \neq 0 \).

The results of \( \sigma_0 - \sigma_{\pm 1} \) calculations for carbon \(^{12}\)C target in the investigated energy range are shown in Fig. 2. We can see from Fig. 2 that the difference \( \sigma_0 - \sigma_{\pm 1} \) caused by nuclear interference has the sign “+” for the considered target. It agrees with the presentation of deuteron in Fig. 1, where transversal deuteron dimension in the state with \( m = 0 \) is larger then that for the state with \( m = \pm 1 \).

Another situation arises for the difference \( \sigma_0 - \sigma_{\pm 1} \) caused by the Coulomb-nuclear interference. We can see that Coulomb-nuclear part oscillates with the energy change. As a result, for the carbon target the difference \( \sigma_0 - \sigma_{\pm 1} \) changes its sign at energy 5.5 MeV and 11 MeV.

It is necessary to note that according to Fig. 2 the correction (27) significantly contributes to the effect value in the energy range 5–10 MeV. So, for example, in the energy range 5–7 MeV the value of the correction is \( \sim 30\% \) of the contribution of nuclear interference. But with the energy increase the contribution of this correction decreases and becomes negligible at energy 15–20 MeV.

The tensor polarizations measured in the experiments [3,4] for three targets are shown in Fig. 3. From Fig. 3 we can see that the tensor polarization for the thickest target of 188 mg/cm\(^2\) is less than that for the target with the medium thickness of 129 mg/cm\(^2\). Such a behavior of polarization and the sign of tensor polarization can be explained in view of Fig. 2.

Let us consider the measurement of tensor polarization (spin dichroism) for a deuteron beam with the energy 5.5 MeV. In view of energy losses inside the target by the ionization, the energy of the beam before entering the target should exceed 5.5 MeV. The thicker the carbon target is the higher the initial deuteron beam energy should be. In the energy range of 5.5–11 MeV the difference \( \sigma_0 - \sigma_{\pm 1} < 0 \), but this inequality changes its sign \( \sigma_0 - \sigma_{\pm 1} > 0 \) when the deuteron energy exceeds 11 MeV. Therefore, according to Eq. (10) for this energy range the absolute value of tensor polarization increases with the growth of the target thickness and reaches its maximal value for the target thickness \( L^* \), corresponding to the initial deuteron beam energy 11 MeV. Further increase in the target thickness requires the energy of deuteron beam higher than 11 MeV and positive polarization is accumulated in the beam in the part of the target, where the beam energy decreases from the initial value to 11 MeV.

In the rest of the target where the beam energy is within the range of 11–5.5 MeV, the negative tensor polarization is accumulated.

Thus, total polarization of the beam is the sum of positive polarization acquired from the part of the target where the beam has energy >11 MeV and negative polarization from the rest of the target of the thickness \( L^* \).

Therefore, the resulting absolute value of polarization for such a target appears to be smaller than that for the target of thickness \( L^* \). Hence, non-monotonic dependence of the spin dichroism on the target thickness in the deuteron energy range 5–20 MeV can be explained by the change of sign for \( \sigma_0 - \sigma_{\pm 1} \) caused by the Coulomb-nuclear interference.

According to the above analysis the Coulomb-nuclear interference must be taken into account in experiments for spin dichroism study at low energies. To obtain the maximum absolute value of deuteron spin dichroism (tensor polarization), it is necessary to select the initial deuteron energy and target thickness carefully. The maximum absolute values of the tensor polarization for the presented model are presented in Table 1. There are some factors that can essentially affect the estimation of the value of deuteron spin dichroism. First of all, it is nucleon–nucleus interaction. We use simple Woods–Saxon potential for our model, but actual potential is more complicated, first of all, due to numerous resonances, which exist, particularly, for carbon [15]. In addition, the parameter \( \Delta \) is sensitive to the deuteron wave functions at small distances. But wave functions at small distances have discrepancies in different theoretical models [13].

It is necessary to add that it is obvious from experiment the phenomenon of deuteron spin dichroism can be used for obtaining inexpensive source of tensor-polarized deuterons [16].
6. Summary

The results obtained for spin dichroism in the carbon target qualitatively explain the results of experiments [3,4] (the sign and non-monotonic dependence of dichroism on target thickness).

In compliance with the above analysis, the change of sign of deuteron spin dichroism with change in the deuteron beam energy observed in the experiments [3,4] as well as the non-monotonic dependence of dichroism on target thickness can be explained by the influence of the Coulomb-nuclear interference on interaction of deuteron with nucleus.

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