Study of electromagnetic dipole moment, electric quadrupole moment and weak T-odd (CP-odd) interactions of high energy short-lived particles in straight crystals

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A particle, which moves in a crystal, experiences weak interactions with electrons and nuclei alongside with electromagnetic interaction. Measuring the polarization vector and the angular distribution of charged and neutral particles scattered by axes (planes) of an unbent (straight) crystal enables to obtain restrictions for the EDM value and for magnitudes of constants describing T-odd (CP-odd) interactions Beyond the Standard Model. Spin rotation and polarization conversion from vector to tensor one and vice versa for a channelled in a crystal $\Omega^\pm$ hyperon enable measuring hyperon’s quadrupole moment that is not possible to measure by use of laboratory available noncrystalline electric fields.
I. INTRODUCTION

Violation of parity (P) and time reversal (T) symmetries lead to appearance of numerous processes allowing investigation of physics Beyond the Standard Model. Recently, the experimental approach was proposed \[1\] to search for the electromagnetic dipole moments (EDM) of charged short-lived heavy baryons and \(\tau\)-leptons using bent crystals at LHC. According to \[3, 4\] the same approach gives unique possibility for investigation of P-odd T-even and P-odd T-odd (CP-odd) interactions of short lived baryons (\(\tau\)-leptons) with electrons and nuclei. Constraints on constants of the above interactions can also be obtained.

This paper demonstrates that measuring the polarization vector and the angular distribution of charged and neutral particles scattered by axes (planes) of an unbent (straight) crystal enables to obtain restrictions for the EDM value and for magnitudes of constants describing T-odd (CP-odd) interactions Beyond the Standard Model. It is shown that spin rotation and polarization conversion from vector to tensor one and vice versa for a channelled in a crystal \(\Omega^\pm\) hyperon enable measuring hyperon’s quadrupole moment that is not possible to measure by use of laboratory available noncrystalline electric fields.

II. RELATIVISTIC PARTICLES SPIN INTERACTIONS WITH CRYSTALS

Since high energy particle motion in a crystal is of quasiclassical nature, so to describe evolution of particle’s spin in electromagnetic fields inside the crystal Thomas–Bargmann–Michel–Telegdi (T-BMT) equations \[8\] are used. The T-BMT equation equation description spin motion in the rest frame of the particle, wherein spin is described by three component vector \(\vec{S}\). In practice the T-BMT equation well describes the spin precession in external electric and magnetic fields encountered in typical present accelerators. Study of the T-BMT equation enables one to determine the major peculiarities of spin motion in an external electromagnetic field, to describe the spin rotation effect for particles in a crystal and to apply it for measuring magnetic moments of unstable particles \[2, 9, 10, 14, 20\]. However, it should be taken into account that particles in an accelerator or a bent crystal have energy spread and move along different orbits. This necessitates to average the spin–dependent parameters of the particle over phase space of the particle beam. That is why one should always bear in mind the distinction between beam polarization \(\vec{P}\) and spin vector \(\vec{s}\). Complete description of particle spin motion can be made by the use of spin density matrices equation (in more details see \[10, 21\]). For the case of ultra relativistic baryons with spin \(S = 1/2\) the T-BMT equations supplied with the term, which is responsible for interaction between particle EDM and electric field, can be written as follows (\(\gamma \gg 1\), \(\gamma\) is the Lorentz-factor) \[1, 2, 22, 23\]:

\[
\frac{d\vec{S}}{dt} = [\vec{S} \times \vec{\Omega}_{magn}] + [\vec{S} \times \vec{\Omega}_{EDM}],
\]

where \(\vec{S}\) is the particle polarization vector, \(\vec{\Omega}_{magn} = -\frac{e}{2mc}[\vec{\beta} \times \vec{E}]\), \(g\) is the gyromagnetic ratio (by definition, the particle magnetic moment \(\mu = \frac{eg}{2mc}S\), where \(S\) is the particle spin), \(\vec{\Omega}_{EDM} = \frac{2ed}{\hbar}\vec{E}\), \(\vec{E}\) is an electric field component perpendicular to the particle velocity \(\vec{\varepsilon}\), the unit vector \(\vec{\beta}\) is parallel to the velocity \(\vec{\varepsilon}\), quantity \(D = ed\) is the electric dipole moment.

Note that authors of \[3\] use for electric dipole moment the following expression: \(\delta = Jd\mu_B\vec{s}\), where \(\mu_B = \frac{eh}{2mc}\) is the particle magneton, \(s\) is the spin polarization ratio, \(J\) is the particle spin, \(d\) is the dimensionless factor referred to as the gyroelectric ratio. To avoid confusion with notation \(d\), which is conventionally used for electric dipole moment, the gyroelectric ratio is hereinafter denoted by \(d_e\).

It should be mentioned that for particles with spin \(3/2\) (\(\Omega^\pm\) hyperon) T-BMT equations should be supplemented by the terms, which consider possession of electric quadrupole moment by the particle \[10, 14\]. Moreover, \(\Omega^\pm\) hyperon could also possesses the T-odd magnetic quadrupole moment, because its spin value is as high as \(3/2\). Equations that compile the T-BTM one for \(\Omega^\pm\) hyperons case are as follows:

\[
\frac{dS_i}{dt} = [(\vec{S} \times \vec{\Omega}_{magn})_i + [(\vec{S} \times \vec{\Omega}_{EDM})_i + \frac{e}{3\hbar}\varepsilon_{ikl} \varphi_{kn}(\vec{Q}_{ln})],
\]

where \(\vec{\Omega}_{magn} = -\frac{e(a-2)}{2\hbar}\lambda_c[\vec{\beta} \times \vec{E}]\), \(\vec{\Omega}_{EDM} = \frac{e}{\hbar}\lambda_c\vec{E}\). Here \(e\) is particle electrical charge, \(\lambda_c = \frac{\hbar}{mc}\) is the Compton wavelength of a particle, \(\varphi_{kn} = \frac{\partial^2\varphi}{\partial x_k \partial x_n}\) is the second derivative of the electrostatic potential at the point of particle location in crystal; \(\varepsilon_{ikl}\) is the totally antisymmetric unit tensor \[3, 10\], \(S_i = S\vec{p}\vec{S}_i\), \(\langle \vec{Q}_{ln} \rangle = S\vec{p}\vec{Q}_{ln}\), \(\vec{Q}_{ln} = \vec{Q}_{ln}\).
The scattering cross-section for a thin crystal can be written as \[14\]:

\[ d\sigma \approx \frac{2Q}{S(S+1)} \{ \hat{S}_l \hat{S}_n + \hat{S}_n \hat{S}_l - \frac{2}{S} S(S+1)\delta_{ln} \}, \]

where \( S \) is the quadrupole moment of the particle, \( \hat{S} \) is the particle spin density matrix, \( \hat{S}_n \) is the \( n \)-component of the spin-operator \( \hat{S} \).

Equation for \( (Q_{ln}(t)) \) see in [9, 10]. Contribution caused by T-odd magnetic quadrupole interaction is not included in (2) because of its smallness, though obtaining evaluation of this contribution is interesting. As follows from (2), for a particle moving in a planar channel, formed by planes orthogonal to \( x \) axis, the spin rotation frequency caused by quadrupole moment is \( \Omega_Q \approx \frac{eQ}{\hbar} \varphi_{xx}. \) According to estimations made in [11–13] for quadrupole moment the value \( Q \approx 10^{-27} \text{cm} \) is expected. As a result, for \( \varphi_{xx} \approx 10^{18} \frac{\text{rad}}{\text{s}} \) we have \( \Omega_Q \approx 10^9 \text{s}^{-1} \). Hence distance passed by particle in crystal \( L = 10 \text{cm} \) rotation angle is \( \vartheta \approx 10^{-3} \text{rad} \), that corresponds to experiments for EDM limitations of heavy baryons [1–4]. Let us note, that in experiments in a straight crystal spin rotation caused by the magnetic moment of \( \Omega^\pm \) hyperon is suppressed. It is also important that for \( \Omega^\pm \) hyperons moving in a channel conversion of vector polarization to quadrupolarization tensor \( (Q_{ln}) \) occurs that enables to choose the most sensitive measuring method depending on initial conditions.

According to [11, 14] investigation of spin rotation for \( \Omega^\pm \)-hyperons in straight and bent crystals enables to measure the quadrupole moment of \( \Omega^\pm \)-hyperon, which cannot be measured by the use of available in a laboratory noncrystalline macroscopic nonlinear electric fields.

III. P- AND T-ODD SPIN INTERACTIONS IN CRYSTALS

General expression for the amplitude of elastic coherent scattering of a spin 1/2 particle by a spinless (unpolarized) atom in presence of electromagnetic, strong and \( P^- \), T-odd weak interactions can be written as:

\[ F(q) = A(q) + B(q)\sigma \hat{N}_w + B(q)\sigma \hat{N}_n + B_T \sigma \hat{N}_T, \]  

(3)

where \( A(q) \) is the spin-independent part of scattering amplitude, which is caused by electromagnetic, strong and weak interactions of the particle with electrons and nucleus of the atom, \( \hbar q = \hbar k' - \hbar k \) is the transmitted momentum, \( h k' \) is the momentum of the scattered particle, \( h k \) is the momentum of the incident baryon, \( k' \) and \( k \) are the wave vectors, \( \hat{N}_w = \frac{k}{|k|} \frac{k'}{|k'|} \), \( \hat{N}_n = \frac{k+k}{|k|+|k'|} \), \( \hat{N}_T = \frac{k-k}{|k|-|k'|} \), \( \sigma = (\sigma_x, \sigma_y, \sigma_z) \) are the Pauli matrices.

The term, which is proportional to \( \sigma \hat{N}_w \), is responsible for the contribution to scattering process, which is caused by spin-orbit interaction.

For electromagnetic interaction the spin-orbit interaction is determined by the particle magnetic moment. P-odd T-even part of the scattering amplitude (it is proportional to \( \sigma \hat{N}_w \)) is determined by P-odd T-even interactions of baryon (\( \tau \)-lepton) with electrons and nuclei. T-odd part of scattering amplitude (it is proportional to \( \sigma \hat{N}_T \)) is determined by the electric dipole moment and short range particle-electron and particle-nucleus T-odd interactions. Measurement of amplitude \( B_T \) enables studying of physics beyond standard model and getting limits for the constants, which determine such interactions in hadron and lepton sectors.

With amplitude \( F(q) \) one can find the cross-section of particle scattering by a crystal and polarization vector of the scattered particle. Let us now consider a thin crystal, for which effects caused by channelling are not essential. The scattering cross-section for a thin crystal can be written as [14]:

\[ \frac{d\sigma_{cr}}{d\Omega} = \frac{d\sigma}{d\Omega} \left\{ (1 - e^{-\bar{u}q^2}) + \frac{1}{N} \sum_n e^{i\bar{q}_n^0} \left| \frac{e^{-\bar{u}q^2}}{e^{i\bar{q}_n^0}} \right|^2 \right\}, \]  

(4)

where \( \bar{r}_n^0 \) is the coordinate of the center of gravity of the crystal nucleus, \( \bar{u}^2 \) is the mean square of thermal oscillations of nuclei in the crystal. The first term describes incoherent scattering, caused by the thermal vibration of crystal nuclei and the second one describes the coherent scattering due to periodic arrangement of crystal nuclei (atoms).

Quantity \( \frac{d\sigma}{d\Omega} \) describes cross-section of baryon scattering by atoms of the crystal:

\[ \frac{d\sigma}{d\Omega} = tr \hat{\rho} \hat{F}^+(\hat{q}) \hat{F}(\hat{q}), \]  

(5)

where \( \hat{\rho} \) is the spin density matrix of the incident particle.

The polarization vector of the particle, which has undergone a single scattering event, can be found using the following expression:

\[ \hat{\zeta} = \frac{tr \hat{\rho} \hat{F}^+ + \sigma \hat{F}}{tr \hat{\rho} \hat{F}^+ \hat{F}} = \frac{tr \hat{\rho} \hat{F}^+ + \sigma \hat{F}}{\frac{d\sigma}{d\Omega}}. \]  

(6)
Using (3) one can obtain the following expressions for polarization vector of the scattered particle (7):

\[ \tilde{\xi} = \xi_{so} + \xi_{w} + \xi_{T}, \]

where \( \xi_{so} \) is the contribution to polarization vector due to spin-orbit interaction, \( \xi_{w} \) is that due to weak parity violating interaction, \( \xi_{T} \) is contribution caused by \( T \)-odd interaction:

\[
\xi_{so} = \left\{ (|A|^2 - |B|^2)\tilde{\xi}_0 + 2|B|^2\tilde{N} \cdot \tilde{\xi}_0 + 2iM(AB^*)(\tilde{N} \times \tilde{\xi}_0) + 2\tilde{N}Re(AB^*) \right\} \cdot \left( \frac{d\sigma}{d\Omega} \right)^{-1}, \]

(8)

\[
\xi_{w} = \left\{ (|A|^2 - |B_w|^2)\tilde{\xi}_0 + 2|B_w|^2\tilde{N}_w \cdot \tilde{\xi}_0 + 2iM(AB_w^*)(\tilde{N}_w \times \tilde{\xi}_0) + 2\tilde{N}_wRe(AB_w^*) \right\} \cdot \left( \frac{d\sigma}{d\Omega} \right)^{-1}, \]

(9)

\[
\xi_{T} = \left\{ (|A|^2 - |B_T|^2)\tilde{\xi}_0 + 2|B_T|^2\tilde{N}_T \cdot \tilde{\xi}_0 + 2iM(AB_T^*)(\tilde{N}_T \times \tilde{\xi}_0) + 2\tilde{N}_TRe(AB_T^*) \right\} \cdot \left( \frac{d\sigma}{d\Omega} \right)^{-1}, \]

(10)

where \( \tilde{\xi}_0 \) is the polarization vector of a particle incident on a target.

The differential cross-section in the same case reads as follows:

\[
\frac{d\sigma}{d\Omega} = \text{tr} \rho F^+ F = |A|^2 + |B|^2 + |B_w|^2 + |B_T|^2 + 2Re(AB^*)\tilde{N} \cdot \tilde{\xi}_0 + 2Re(AB_w^*)\tilde{N}_w \cdot \tilde{\xi}_0 + 2Re(AB_T^*)\tilde{N}_T \cdot \tilde{\xi}_0. \]

(11)

While deriving expressions (8)-(10) and (11) the small terms containing productions \( BB_T, BB_w \) and \( B_w B_T \), which describe interference between spin-orbit P-odd T-even and P-odd T-odd interactions, are omitted.

These terms are much smaller as compared to those ones proportional to productions \( AB_w \) and \( AB_T \), which describe interference of weak interaction with strong and electromagnetic interactions.

However, the omitted here contributions could be significant for neutral particles (see comments hereinafter).

In case of neutral particles there is no Coulomb scattering, therefore, the terms proportional to \( BB_w \) and \( BB_T \) could also significantly contribute to anisotropy and spin rotation. In this case expression (3) for \( \xi_w \) should be appended with addition as follows:

\[
\Delta \xi_w = \left\{ 2Re(B^*B_w) \left[ (\tilde{\xi}_0^0 \tilde{N}) \tilde{N}_w + (\tilde{\xi}_0 \tilde{N}_w) \tilde{N} \right] + 2iM(B^*B_w)(\tilde{N} \times \tilde{N}_w) \right\} \frac{d\sigma}{d\Omega}^{-1}. \]

(12)

Expression (10) for \( \xi_T \) should be appended with the following summand:

\[
\Delta \xi_T = \left\{ 2Re(B^*B_T) \left[ (\tilde{\xi}_0^0 \tilde{N}) \tilde{N}_T + (\tilde{\xi}_0 \tilde{N}_T) \tilde{N} \right] + 2iM(B^*B_T)(\tilde{N} \times \tilde{N}_T) \right\} \frac{d\sigma}{d\Omega}^{-1}. \]

(13)

Expression (11) for \( \frac{d\sigma}{d\Omega} \) should be appended with summand \( \frac{d\sigma_{app}}{d\Omega} \) as follows:

\[
\frac{d\sigma_{app}}{d\Omega} = -2Im(B^*B_w)\tilde{\xi}_0(\tilde{N} \times \tilde{N}_w) - 2Im(B^*B_T)\tilde{\xi}_0(\tilde{N} \times \tilde{N}_T). \]

(14)

According to (3) the angle of polarization vector rotation for a baryon scattered in a crystal is determined by rotations around three mutually orthogonal directions (see terms proportional to \( N, N_w, N_T \)). The indicated rotations are determined by electromagnetic, strong and weak P, T-odd interactions. It should also be noted that initially
unpolarized particle beam (ξ₀ = 0) in a crystal acquires polarization directed along one of three vectors \( \vec{N} \), \( \vec{N}_w \), \( \vec{N}_T \), which carries information about all types of interaction too. According to (11) amplitudes interference results in asymmetry in scattering caused by orientation of vectors \( \vec{N}_T \), \( \vec{N} \), \( \vec{N}_w \) with respect to \( \xi_0, \vec{k}' \) and \( \vec{k} \). Therefore, the angular distribution of scattered particles intensity is anisotropic. Thus, measurements of the rotation angle and of the angular distribution of intensity for a particle beam scattered by crystal axes enables to study T-odd interactions of positive(negative) charged and neutral short-lived baryons and \( \tau \)-leptons. In particular, such measurements allow one to obtain restrictions on electric dipole moment of short-lived particles and other T-odd interactions in hadron and lepton sectors. According to [23–25] the mentioned interactions can be much stronger than those predicted by Standard Model. Obtaining experimental restrictions on this interactions is important [24, 26].

Computer modelling is essential for further analysis. Note that analyzing angle of rotation and angular distributions one should consider trajectories of the scattered particles with azimuth angles, which are in the vicinity \( \varphi \) and \( \varphi + \pi \) (z axes is directed along the momentum of the incident particle). For such particles contributions to spin rotation caused by EDM (T-odd interaction) have opposite signs. As a result the T-odd spin rotation can be observed in unbent crystal if we use subtraction of the measurements results for angle ranges \( \varphi \) and \( \varphi + \pi \) from each other. Such procedure leads to summation of contributions from T-odd rotation. Simultaneous measurement of spin orientation for all \( \varphi \) values (as well as for all polar angles) provides intensity increase.

Let us now evaluate the described effects starting from estimation of anisotropy of the angular distribution of scattered particles. According to (11) the anisotropy value is determined by interference of amplitude \( A \) with amplitudes \( B_w \) and \( B_T \). The respective contributions to the intensity of scattered particles associated with amplitudes’ interference are given by the following ratios:

\[
G = \frac{2\text{Re}(AB)}{|A|^2}, \quad G_w = \frac{2\text{Re}(AB^* w)}{|A|^2}, \quad G_T = \frac{2\text{Re}(AB^* T)}{|A|^2}.
\]

(15)

To observe anisotropy \( G \), \( G_w \) or \( G_T \) the relative value of fluctuations in number of scattered particles \( \delta \approx \frac{1}{\sqrt{G}} \) should be made smaller as compared to \( G \), \( G_w \) and \( G_T \), respectively. In other words the number of scattered particles should satisfy the conditions as follows:

\[
N > \frac{1}{G}; \quad \frac{1}{G^2}; \quad \frac{1}{G^2}.
\]

(16)

Let us now consider expressions (15) and (16) in more details. Amplitude \( A \) is the sum of amplitudes \( A_{coul} \) and \( A_s \) caused by Coulomb and strong nuclear scattering, respectively. Amplitude of spin-orbit scattering \( B = B_{magn} + B_{so} \) is caused by particle magnetic moment interaction \( B_{magn} \) and by strong nuclear spin-orbit interaction \( B_{so} \). Let us start with evaluation of anisotropy \( G \) caused by magnetic and strong nuclear spin-orbit interaction:

\[
G = \frac{2\text{Re}(A_s B_{magn}^* + A_s B_{so}^* + A_{coul} B_{magn}^* + A_{coul} B_{so}^*)}{|A_{coul} + A_s|^2}.
\]

(17)

For further analysis let us pay attention to the fact that from results presented in [27] the amplitude of scattering of a particle, which possesses magnetic moment, by a Coulomb field can be expressed as follows:

\[
A = A_{coul}(\vartheta) + \frac{i}{2} \left( \frac{g - 2 \gamma^2 - 1}{g \gamma} + \frac{\gamma - 1}{\gamma} \right) \vartheta A_{coul}(\vartheta) \delta \vec{N}.
\]

(18)

From (18) the following expression for amplitude \( B_{magn} \) can be obtained:

\[
B_{magn} = \frac{i}{2} \left( \frac{g - 2 \gamma^2 - 1}{g \gamma} + \frac{\gamma - 1}{\gamma} \right) \vartheta A_{coul}(\vartheta).
\]

(19)

As a result in case of elastic Coulomb scattering \( \text{Re}(A_{coul} B_{magn}^*) = 0 \). Analysis shows that for the contribution to the scattering amplitude caused by the spin-orbit strong interaction one can obtain the expression similar to (19) by using the optical model of a nucleus:

\[
B_{so} = \frac{i}{2} \left( \frac{g_{so} - 2 \gamma^2 - 1}{g \gamma} + \frac{\gamma - 1}{\gamma} \right) \vartheta A_s(\vartheta).
\]

(20)

Introduced in (20) quantity \( g_{so} \) is similar to magnetic g-factor and depends on the particle energy.
From (20) it follows that $Re(A_s B_{st}^*) = 0$. Therefore, 

$$Re(AB^*) \simeq A''_\text{coul} \left( \frac{g-2}{4} + \frac{g_{so} - 2}{4} \right) \gamma \vartheta,$$

where $A'_{\text{coul}} = ReA_{\text{coul}}$ and $A''_\text{coul} = ImA_s$). The above expression is obtained with consideration of the imaginary part of Coulomb amplitude $A''_{\text{coul}}$ to be smaller as compared to its real part $A'_{\text{coul}}$: $A''_{\text{coul}}$ is $Z\alpha$ times smaller as compared to $A'_{\text{coul}}$ (here $\alpha$ is the fine-structure constant).

To evaluate the imaginary part of amplitude $A''$ of baryon scattering by a nucleus let us use a model of diffraction scattering. As a result in eikonal approximation $A''$ reads as follows:

$$A'' = R_{\text{nuc}} \frac{J_1(R_{\text{nuc}} k \vartheta)}{\vartheta},$$  \hspace{1cm} (21)$$

where $R_{\text{nuc}}$ is the radius of nucleus, $J_1$ is the Bessel function of the first order. From (21) it follows that for scattering angles $\vartheta \leq \frac{\pi}{2R_{\text{nuc}}}$ the imaginary part of scattering amplitude $A'' \approx k R_{\text{nuc}}^2$. The real part of Coulomb amplitude $A'_{\text{coul}} = \frac{Z \alpha}{k \vartheta}$ becomes comparable or even greater than $A''$ for scattering angles $\vartheta \leq \frac{\pi}{k R_{\text{nuc}}}$. For a baryon with energy $1$ TeV the scattering angle is $\vartheta \leq \sqrt{Z\alpha} \cdot 10^{-5}$. Therefore, in the range of angles, within which $A'' \approx A'$, parameter $G \approx (\frac{2\pi Z\alpha}{2} - 2) \gamma \vartheta \approx (\frac{2\pi Z\alpha}{2} - 2) 10^{-2}$. As a result, to comply inequality $N > \frac{1}{G^2}$, the number of scattered particles should be $N \approx 10^4 \div 10^5$.

Parameter $g_{so}$ depends on the energy of the incident particle in contrast to $g$-factor, which does not at currently present particle energies. This fact makes it possible to distinguish contributions from $g$ and $g_{so}$ from each other.

Number $N_{\Lambda^+}$ of charmed lambda baryons produced by $10^{17} \div 10^{18}$ photons in a tungsten target can be find using data published in [1] that gives $N_{\Lambda^+} \approx 10^{13} \div 10^{14}$. These particles, move within angle $\frac{1}{2} \approx 10^{-3}$.

Hereinafter let us consider the incidence of $\Lambda^+_\text{coul}$ baryons on a target at the angle, which is equal or greater as compared to the Lindhard critical angle, which is for Si (Ge) of order $\vartheta_L \approx (67) \cdot 10^{-6}$ rad. Let us consider angles range $\Delta \vartheta \sim 10^{-5}$, which amounts several Lindhard angles. Within this range $\Delta \vartheta \sim 10^{-2}$, therefore, the number of $\Lambda^+_\text{coul}$ baryons within this range is $\Delta N_{\Lambda^+} \approx 10^{11} \div 10^{12}$. Let us now give evaluation for number of these particles scattered in crystal of thickness $l = 0.1$ cm:

$$N \approx \frac{d\sigma}{dl \Omega} \Delta \Omega N_{\text{at}} l \Delta N_{\Lambda^+} \approx 10^{-2} \Delta N_{\Lambda^+} \approx 10^9 \div 10^{10},$$

here $N_{\text{at}}$ is the number of atoms in $1$ cm$^3$ of target. This value complies condition $N > \frac{1}{G^2} \approx 10^4 \div 10^5$ that enables carrying measurement of baryon magnetic moment by means of magnetic scattering of angular distribution of scattered baryons.

Let us now evaluate baryon scattering anisotropy, which is caused by T-odd processes, for example, presence of particle EDM of order $e \cdot d \sim 10^{-17} e$ cm.

For a particle possessing EDM, which is scattered in an electric field, the following expression for amplitude $B_T$ in eikonal approximation can be used:

$$B_T(\vartheta) = i d k \vartheta A_{\text{coul}} = \frac{d}{\lambda_c} \gamma \vartheta A_{\text{coul}}(\vartheta)$$  \hspace{1cm} (22)$$

where $\lambda_c = \frac{h}{m_e}$ is the Compton wavelength of the particle. For the supposed EDM value amplitude $B_T$ appears to be three orders smaller as compared to amplitude of magnetic scattering $B_{\text{magn}}$. Therefore, $G_T \approx 10^{-3} G$ and the number of particles required to make anisotropy, which is associated with amplitude $B_T$, is higher $10^6$ times i.e. required number of particles $N > 10^{10} \div 10^{11}$. Recall that hereinafore for the target with high $Z$ and thickness $l = 0.1$ cm we have obtained $N \approx 10^9 \div 10^{10}$. Therefore, increasing the target thickness to $l = 1$ cm (such target is still quite thin) and optimizing all the experiment parameters one could expect to observe EDM-caused anisotropy and that caused by other T-odd interactions. Such possibility is important for studying EDM and T-odd interactions of short-lived particles.

Let us now dwell on possibility to investigate EDM and other T-odd interactions for $\tau$-leptons, for which do not undergo strong interactions. The EDM-caused anisotropy for $\tau$-leptons is suppressed, because the contribution to the cross-section, which is caused by interference of Coulomb amplitude and amplitude $B_T$ defined by (22), is equal to zero. The non-zero summand is due to interference of Coulomb amplitude and T-odd amplitude caused by neutral currents. Restriction for the magnitude of the latter amplitude enables to evaluate the constant of corresponding interaction. The mentioned interaction is now persistently studied for electrons in optical experiments with atoms [20].
Let us now evaluate the angle of spin rotation for a scattered particle, which possesses EDM. According to (10) the additional polarization component, which arises due to rotation around $\vec{N}_T$ is determined by the expression as follows:

$$\Delta \xi_{T,rot} = \frac{2Im(AB^*_T)}{|A|^2}. \quad (23)$$

Therefore, for a particle scattered in Coulomb field the angle of spin rotation can be evaluated using (23) as follows:

$$\vartheta_s \simeq \Delta \xi_{T,rot} \simeq \frac{d}{\lambda_c} \gamma \theta. \quad (24)$$

According to (24) the angle of spin rotation grows with growth of scattering angle and $\gamma$ (with scattering angle growth the angles of spin rotation caused by other T-odd interactions also grow). For $d = 10^{-17}$ cm and $\lambda_c = 10^{-14}$ cm the angle of rotation is $\Delta \xi_{T,rot} \simeq 10^{-3} \gamma \theta$, therefore for a particle with $\gamma \sim 10^3$ the angle of spin rotation is expected to be as high as the scattering angle: $\vartheta_s \simeq \Delta \xi_{T,rot} \simeq \theta$. Hence, for $\gamma = 10^3$ and scattering angle $\theta \simeq 10^{-4} \div 10^{-5}$ the angle of spin rotation $\vartheta_s \simeq \Delta \xi_{T,rot} \simeq 10^{-4} \div 10^{-5}$. The number of detected particles is $N > \frac{1}{\vartheta_s} \simeq 10^8 \div 10^{10}$. Recall that in this case spin rotates around direction $\vec{N}_T$, which is determined by the direction of transferred momentum $\vec{q}$.

Investigation of anisotropy and rotation angle caused by amplitude of of weak P-odd interaction $B_{\nu}$, which is determined by neutral P-odd currents is of interest for short-lived baryons and $\tau$-leptons. Recall that for electrons the neutral currents were observed in two types of experiments: at deep inelastic scattering at SLAC accelerator [28, 31] and in optical experiments in Novosibirsk [32].

IV. CONCLUSION

The channelled particle, which moves in a crystal, besides electromagnetic interaction experiences weak interaction with electrons and nuclei, as well as strong interaction with nuclei. Measurements of polarization vector and angular distribution of charged and neutral particles particles scattered by axes (planes) of unbent crystal enable to obtain limits for the EDM value and for the values of constants describing P- and T-odd interactions beyond Standard Model. The experimental capabilities available at LHC make it possible for a channelled in a crystal $\Omega^{\pm}$ hyperon to observe and apply spin rotation effect and polarization conversion from vector to tensor one and vice versa for measuring hyperon’s quadrupole moment that is not possible to measure by use of laboratory available noncrystalline electric fields.

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