Search for the neutron EDM and time reversal symmetry violation in noncentrosymmetric crystals

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CP-violating spin rotation and spin dichroism in noncentrosymmetric crystals is discussed.

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The origin of CP-symmetry violation (where C is a charge conjugation and P is a spatial inversion) is of a great interest since its discovery in the decay o neutral K-mesons about 40 years ago. CP-violation leads in turn to the violation of the time reversal symmetry (T) through the CPT invariance (CPT-theorem). Existence of nonzero neutron EDM requires violation of both P and T invariance. Different theories of CP violation give widely varying predictions for a neutron EDM. This is the reason now for discussion of two types of experiments:

1. study of spin precession frequency for ultracold neutrons in magnetic and electric fields [1, 2, 3]
2. study of neutron diffraction in a noncentrosymmetric crystal [4, 5, 6, 7, 8, 9].

Experiments studying neutron diffraction in the noncentrosymmetric crystal are of particular interest because they provide to get limits for the T-violating term in the amplitude of coherent elastic scattering at a non-zero angle $f_T(\vec{k},\vec{k}') \sim \vec{\sigma}(\vec{k}'-\vec{k})$, where $\vec{k}$ is the wave vector of the neutron incident on the crystal, $\vec{k}'$ is the wave vector of the scattered neutron, $\vec{\sigma} = (\sigma_x, \sigma_y, \sigma)$ are the Pauli matrices, which describe neutron spin. According to [4, 5] the amplitude $f_T(\vec{k},\vec{k}')$ contributes to the index of refraction for neutrons in the noncentrosymmetric crystal and arouses T-violating spin rotation and spin dichroism even for neutrons, for which condition of Bragg diffraction is not fulfilled. Requirements for crystal quality in this case appear less strict [4, 5] in comparison with those necessary for observation of spin rotation and spin dichroism in conditions of dynamical diffraction. As a result, even observation of spin rotation and spin dichroism for neutrons in the range of P-resonances appears possible [4, 5].

Experimental methods for study of neutron spin rotation in crystals have been developed recent years. Application of these methods can significantly increase sensitivity of EDM measurement for neutrons moving in noncentrosymmetric crystals [8]. The limit for the neutron EDM in such experiments is expected about $d_n \leq 10^{-27}\mathrm{e}\cdot\mathrm{cm}$.

According to [4, 5] in such experiments the T-odd scattering amplitude $f_T(\vec{k}', \vec{k})$, which is caused by T-odd nuclear interactions, also can be measured. Therefore, increasing of the experiment sensitivity makes possible more accurate measurement of $f_T(\vec{k}', \vec{k})$, which, in its turn, provides more strict limits for the CP-violating constant of nucleon-nucleon interactions.

I. NEUTRON SPIN ROTATION AND SPIN DICHROISM IN MEDIA

Neutron spin rotation and spin dichroism in media caused by parity (P) violation and possible time (T) noninvariance under neutron interaction with nuclei are described by the refractive index of neutrons in media

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

where k is the neutron wave number, ρ is the scatters density, $\hat{f}(0)$ is the coherent elastic forward scattering amplitude of neutrons on a nucleus.

To find the refraction index for neutrons in the noncentrosymmetric crystal let us consider the Schrodinger equation describing propagation of a coherent neutron wave Ψ in a crystal [4, 5]:

$$\left(k^2 - k_0^2\right)\Psi\left(\vec{k}\right) + \sum_{\vec{\tau}} \frac{2m}{\hbar^2}\hat{U}_{eff}\left(\vec{\tau}\right)\Psi\left(\vec{k} - 2\pi\vec{\tau}\right) = 0, \tag{2}$$

where k_0 is the neutron wave number in vacuum, k is the neutron wave number in a crystal. The Fourier transform of neutron effective potential energy in a crystal is

$$\hat{U}_{eff}\left(\vec{\tau}\right) = -\frac{2\pi\hbar^2}{mV_0}\hat{F}\left(\vec{\tau}\right); \hat{F}\left(\vec{\tau}\right) = \sum_j \hat{f}_j\left(\vec{\tau}\right)e^{-w_j(\vec{\tau})}e^{-i2\pi\vec{\tau}\vec{R}_j}, \tag{3}$$

$\hat{F}\left(\vec{\tau}\right)$ is the amplitude of neutron coherent scattering on crystal unit cell in the direction $\vec{k}' = \vec{k} + 2\pi\vec{\tau}$, where $2\pi\vec{\tau}$ is the vector of crystal reciprocal lattice, $\hat{f}_j\left(\vec{\tau}\right) = Re\hat{f}_j\left(\vec{\tau}\right) + iIm\hat{f}_j\left(\vec{\tau}\right)$ is the amplitude $\hat{f}_j\left(\vec{k}', \vec{k}\right)$ of coherent elastic scattering from a j-type nucleus in the direction of $\vec{k}^{'} = \vec{k} + 2\pi\vec{\tau}$, $Re\hat{f}_j\left(\vec{\tau}\right)$ is the real part of the amplitude, $Im\hat{f}_j\left(\vec{\tau}\right)$ is its imaginary part, $\vec{R}_j$ is the coordinate of the j nucleus in the unit cell, $e^{-w_j(\vec{\tau})}$ is the Debay-Waller factor.

For a non-polarized nucleus

$$\hat{f}_j\left(\vec{k}^{'},\vec{k}\right) = A_j + f^j_{so}\vec{\sigma}[\vec{k}\times\vec{k}'] + C_j\vec{\sigma}\vec{\nu}_1 + C'_j\vec{\sigma}\vec{\nu}_2 \tag{4}$$

where A_j is the spin-independent part of the amplitude of neutron scattering by the nucleus due to strong interaction, $f^j_{so}\vec{\sigma}[\vec{k}\times\vec{k}']$ is the spin-orbit scattering amplitude of a neutron by a nucleus, $f^j_{so} = f^j_{son} + f^j_{Sch}$, where the amplitudes f^j_{son} and f^j_{Sch} describe nuclear and Schwinger interactions, respectively, $C_j\vec{\sigma}\vec{\nu}_1$ is the P-violating T-invariant scattering amplitude, $C'_j\vec{\sigma}\vec{\nu}_2$ is the T- and P-violating scattering amplitude, and the vectors $\vec{\nu}_1$ and $\vec{\nu}_2$ are

$$\vec{\nu}_1 = \frac{\vec{k}'+\vec{k}}{|\vec{k}'+\vec{k}|}\vec{\nu}_2 = \frac{\vec{k}'-\vec{k}}{|\vec{k}'-\vec{k}|} \tag{5}$$

The system of homogeneous equations (2) permits to determine the dependence of k on k_0, i.e. to determine the neutron refractive index in a crystal.

It is well-known that the area $\Delta\vartheta$ of neutron incidence angle on a crystal in which strong diffraction is observed (when the diffracted wave amplitude is comparable with the amplitude of incident wave) is very small $\Delta\vartheta \sim 10^{-5} \div 10^{-6}$ rad even for thermal neutrons.

Outside this narrow angle area the diffracted wave amplitude is small and the system of equations (2) can be analyzed according to the perturbation theory. As a result, we have

$$\hat{N} = \frac{k}{k_0} \simeq 1 + \frac{1}{2}\hat{g}\left(0\right) + \frac{\hat{g}\left(-\vec{\tau}\right)\hat{g}\left(\vec{\tau}\right)}{2\alpha_B}, \tag{6}$$

where

$$\hat{g}\left(\vec{\tau}\right) = -\frac{2m}{\hbar^2 k_0^2}\hat{U}_{eff}\left(\vec{\tau}\right), \alpha_B = \frac{2\pi\vec{\tau}\left(2\pi\vec{\tau}+2\vec{k}_0\right)}{k_0^2}$$

As we see, the correction to the neutron refractive index in crystals contains the scattering amplitude at the non-zero angle $\hat{f}\left(\vec{\tau}\right)$.

According to [4, 5] the expression for $\hat{g}\left(\vec{\tau}\right)$ can be written as a sum

$$\hat{g}\left(\vec{\tau}\right) = \hat{g}_s\left(\vec{\tau}\right) + \hat{g}_{so}\left(\vec{\tau}\right) + \hat{g}_w\left(\vec{\tau}\right), \tag{7}$$

where $\hat{g}_s\left(\vec{\tau}\right)$ is proportional to the amplitude of scattering off the nucleus $\hat{f}_s\left(\vec{\tau}\right)$ due to strong interactions without consideration spin-orbital interactions; $\hat{g}_w\left(\vec{\tau}\right)$ is proportional to the P and T-violating amplitude; $\hat{g}_{so} = \hat{g}_{son} + \hat{g}_{shw}$, $\hat{g}_{son}$ is proportional to the amplitude of spin-orbital neutron scattering on the nucleus due to nuclear forces $\hat{f}_{son}(\vec{\tau}) = f_{son}\vec{\sigma}\left[\vec{k} \times 2\pi\vec{\tau}\right]$, $\hat{g}_{shw}$ is proportional to the amplitude of spin orbital neutron scattering on the nucleus due to neutron magnetic momentum interaction with the nucleus electric field (the so-called Schwinger scattering):

$$\hat{g}_{shw} = i\frac{2m}{V_0\hbar^2 k_0^2}\frac{\mu\hbar}{mc}\sum_j \Phi_j(\vec{\tau})\, e^{-w_j(\vec{\tau})}\vec{\sigma}\left[\vec{k} \times 2\pi\vec{\tau}\right] e^{-i2\pi\vec{\tau}\vec{\tau}_j}, \tag{8}$$

μ is the magnetic neutron momentum, $\Phi_j(\vec{\tau})$ is the Fourier component of electrostatic potential induced by nucleus j.

From equations (4,7) we can write

$$\hat{g}(\vec{\tau}) = \hat{g}_s(\vec{\tau}) + \hat{g}_{so}(\vec{\tau})\vec{\sigma}[\vec{k} \times 2\pi\vec{\tau}] + g_p(\vec{\tau})\vec{\sigma}\vec{\nu}_{1\tau} + g_t(\vec{\tau})\vec{\sigma}\vec{\nu}_{2\tau} \tag{9}$$

where $g_p(\vec{\tau})$ is proportional to the P-violating scattering amplitude, $g_t(\vec{\tau})$ is proportional to the T-violating scattering, $\vec{\nu}_{2\tau} = \vec{\tau}/\tau$. From (4) we also have that the amplitudes $g_\alpha(\vec{\tau})$ (α denotes s, so, p, t) can be represented in the form

$$\hat{g}_\alpha^{(\tau)} = g_{1\alpha}(\vec{\tau}) - ig_{2\alpha}(\vec{\tau}) \tag{10}$$

where $g_{1\alpha}(\vec{\tau}) = g_{1\alpha}(-\vec{\tau})$ and $g_{2\alpha}(\vec{\tau}) = -g_{2\alpha}(-\vec{\tau})$.

$$\begin{aligned}
\hat{g}_\alpha(\vec{\tau}) &= -\frac{2m}{\hbar^2 k_0^2}\hat{U}_{eff}^{(\alpha)}(\vec{\tau}) = -\frac{2m}{\hbar^2 k_0^2}(-\frac{2\pi\hbar^2}{mV_0})\hat{F}_\alpha(\vec{\tau}) = \\
&= \frac{4\pi}{k_0^2}\frac{1}{V_0}\sum_j \hat{f}_{\alpha j}(\vec{\tau})e^{-W_j(\vec{\tau})}e^{-i2\pi\vec{\tau}\vec{R}_j}, \\
\hat{g}_{1\alpha}(\vec{\tau}) &= \frac{4\pi}{k_0^2}\frac{1}{V_0}\sum_j \hat{f}_{\alpha j}(\vec{\tau})e^{-W_j(\vec{\tau})}\cos 2\pi\vec{\tau}\vec{R}_j, \\
\hat{g}_{2\alpha}(\vec{\tau}) &= \frac{4\pi}{k_0^2}\frac{1}{V_0}\sum_j \hat{f}_{\alpha j}(\vec{\tau})e^{-W_j(\vec{\tau})}\sin 2\pi\vec{\tau}\vec{R}_j, \\
\hat{g}_{1t}(\vec{\tau}) &= g_{1T}(\vec{\tau})\vec{\sigma}\vec{\nu}_{2\vec{\tau}},\ \hat{g}_{2t}(\vec{\tau}) = g_{2T}(\vec{\tau})\vec{\sigma}\vec{\nu}_{2\vec{\tau}}, \\
\hat{f}_{Tj}(\vec{\tau}) &= f_{Tj}(\vec{\tau})\vec{\sigma}\vec{\nu}_{2\vec{\tau}} = f_{Tj}(\vec{\tau})\vec{\sigma}\frac{\vec{\tau}}{|\vec{\tau}|}, \\
g_{1T}(\vec{\tau}) &= \frac{4\pi}{k_0^2 V_0}\sum_j f_{Tj}(\vec{\tau})e^{-W_j(\vec{\tau})}\cos 2\pi\vec{\tau}\vec{R}_j, \\
g_{2T}(\vec{\tau}) &= \frac{4\pi}{k_0^2 V_0}\sum_j f_{Tj}(\vec{\tau})e^{-W_j(\vec{\tau})}\sin 2\pi\vec{\tau}\vec{R}_j
\end{aligned} \tag{11}$$

When target nuclei are nonpolarized $\hat{g}_s(\vec{\tau}) = g_s(\vec{\tau})$ does not depend on neutron spin. Besides, for slow neutrons $g_{so} \ll g_s$. It allows to write the contribution to caused by diffraction in the following way

$$\delta\hat{N} = \frac{\hat{g}(-\vec{\tau})\,\hat{g}(\vec{\tau})}{2\alpha_B} = \frac{g_s(-\vec{\tau})\,g_s(\vec{\tau})}{2\alpha_B} + \frac{1}{2\alpha_B} g_s(-\vec{\tau})\left[\hat{g}_{so}(\vec{\tau}) + \hat{g}_w(\vec{\tau})\right] + \tag{12}$$

$$+\frac{1}{2\alpha_B} g_s(\vec{\tau})\left[\hat{g}_{so}(-\vec{\tau}) + \hat{g}_w(-\vec{\tau})\right].$$

Let the target be nonpolarized. In this case T-noninvariant part of $\hat{g}(\vec{\tau})$ is [4, 5]

$$\hat{g}^T_w(\vec{\tau}) = \frac{4\pi}{k^2 V_0}\sum_j \hat{f}^T_{jw}(\vec{\tau})\, e^{-w_j(\vec{\tau})} e^{-i2\pi\vec{\tau}\vec{R}_j}, \tag{13}$$

$$\hat{f}^T_{jw}(\vec{\tau}) = C'_j(\vec{\tau})\,\vec{\sigma}\frac{\vec{\tau}}{\tau}, C'_j(\vec{\tau}) = ReC'_j + ImC'_j.$$

From (12),(13) we see that the T-noninvariant contribution to the refractive index in a nonpolarized crystals may occur only in a non-center-symmetric crystals.

As a result, for the refractive index we can obtain

$$\begin{aligned}
\hat{N} &= 1 + \frac{1}{2}g_s(0) + \frac{1}{2}g_p(0)\frac{\vec{\sigma}\vec{k}}{k} + \\
&+ \sum_{r\neq 0}\frac{1}{2\alpha_B(\vec{\tau})}\Big\{-2i[g_{1s}(\vec{\tau})g_{2so}(\vec{\tau}) - g_{2s}(\vec{\tau})g_{1so}(\vec{\tau})]\vec{\sigma}[\vec{k}\times 2\pi\vec{\tau}] + \\
&+ 2[g_{1s}(\vec{\tau})g_{1p}(\vec{\tau}) + g_{2s}(\vec{\tau})g_{2p}(\vec{\tau})]\vec{\sigma}\vec{\nu}_{1s} - \\
&- 2i[g_{1s}(\vec{\tau})g_{2T}(\vec{\tau}) - g_{2s}(\vec{\tau})g_{1T}(\vec{\tau})]\vec{\sigma}\vec{\nu}_{1\tau} - \\
&- 2i[g_{1so}(\vec{\tau})g_{1p}(\vec{\tau}) + g_{2so}(\vec{\tau})g_{2p}(\vec{\tau})]\vec{\sigma}[[\vec{k}\times 2\pi\vec{\tau}]\times\vec{\nu}_{1\tau}] - \\
&- 2i[g_{1so}(\vec{\tau})g_{2T}(\vec{\tau}) - g_{2so}(\vec{\tau})g_{2T}(\vec{\tau})]\vec{\sigma}[[\vec{k}\times 2\pi\vec{\tau}]\times\vec{\nu}_{2\tau}]\Big\}
\end{aligned} \tag{14}$$

Spin-independent terms, which are proportional to $g^2(\tau)$ are omitted because they do not influence the spin-dependent effects.

According to (14) we can present $\hat{N}$ in the form

$$\hat{N} = 1 + \frac{1}{2}g_s(0) + \vec{\sigma}\vec{M} = 1 + \frac{1}{2}g_s(0) + \vec{\sigma}\vec{M}' + i\vec{\sigma}\vec{M}'' \tag{15}$$

where $\vec{M}'$ and $\vec{M}''$ are the real and imaginary parts of $\vec{M}$, respectively. The term $\vec{\sigma}\vec{M}'$ describes the neutron spin rotation about the direction of $\vec{M}'$, the term $\vec{\sigma}\vec{M}''$ describes the spin dichroism, i.e. the dependence of the neutron absorption on the spin orientation (parallel or antiparallel to $\vec{M}''$). The spinor wavefunction of a neutron $\psi(l)$ can be represented in the form

$$\psi(l) = e^{ik\hat{N}l}\psi(0) \tag{16}$$

where $\psi(0)$ is the spinor neutron wavefunction in vacuum and l is the neutron path length in a crystal.

The spin-dependent part of the phase in (16) is only a small part of the whole phase. As a result, we can write (16) as

$$\psi(l) \simeq [1 + ik\vec{\sigma}\vec{M}l]e^{ik(1+\frac{1}{2}g_s(0)l)}\psi(0) \tag{17}$$

From equation (17) we obtain that the number of neutrons passing through a crystal the path l depends o the direction of the neutron polarization vector $\vec{p}$:

$$J(\vec{p}) = J_0 e^{-\kappa l}[1 - 2k(\vec{p}\vec{M}''l)], \tag{18}$$

where κ is the coefficient of the neutron absorption in a crystal caused by the ordinary nuclear interaction, $|\vec{p}| = 1$ for a completely polarized beam. As we see, the intensity $J(\vec{p})$ depends on the orientation of polarization vector $\vec{p}$ relative to $\vec{M}''$. The difference between the intensities $J_{\uparrow\uparrow}$ (for $\vec{p}$ parallel to $\vec{M}''$) and $J_{\uparrow\downarrow}$ (for $\vec{p}$ antiparallel to $\vec{M}''$) is

$$\frac{J_{\uparrow\uparrow} - J_{\uparrow\downarrow}}{J_{\uparrow\uparrow} + J_{\uparrow\downarrow}} = -2kpM''l. \tag{19}$$

It follows from (17) that the polarization vector $\vec{p}_1$ of the neutron passing through a crystal is

$$\vec{p}_1 = \frac{\langle\psi(l)|\vec{\sigma}|\psi(l)\rangle}{\langle\psi(l)|\psi(l)\rangle} = \vec{p} + 2k[(\vec{p}\vec{M}'')\vec{p} - \vec{M}'']l + 2k[\vec{p}\times\vec{M}']l. \tag{20}$$

The second term on the right hand side in (20) describes the appearance of neutron beam polarization due to the spin dichroism effect. This term exists even when the initial neutron polarization $\vec{p}$ is zero. In this case

$$\vec{p}_1 = -2k\vec{M}''l. \tag{21}$$

As we see, $\vec{p}_1$ is parallel to $\vec{M}''$. From equation (14) it follows that T-violating spin rotation and spin dichroism phenomena appear only in crystals without a center of symmetry. We also see that the spin-orbital and P-violating, but T-invariant, interactions contribute to spin rotation and dichroism, too. That is why the problem of separating T-violation effects from the background of T-invariant phenomena arises.

Detailed analysis of possibility to distinguish different contributions was done in [4, 5]. Let us consider more intently the term, for which $\vec{k}' = \vec{k} + 2\pi\vec{\tau}_1 \simeq -\vec{k}$ i.e. addition to the refraction index from backward Bragg reflection. For this term the spin-orbital and P-violating, but T-invariant, interactions are zero.

Suppose also that for the certain neutron energy Bragg parameter $\alpha_B(\tau_1)$ for this term is $\alpha_B(\tau_1) \ll \alpha_B(\tau)$, where $\tau_1 \neq \tau$.

According to (20) the neutron polarization vector $\vec{p}_1$ rotates in a crystal about the vector $\vec{M}'$.

As a result, the angle of particle spin rotation is

$$\vartheta = 2k\vec{M}'l = kRe(N_+ - N_-)L = \vartheta_P + \vartheta_T. \tag{22}$$

where ϑ_P is the angle of spin rotation due to P-odd T-even interactions of neutrons with nuclei described by the term proportional to $\vec{\sigma}\frac{\vec{k}}{k}$ (see (15)), ϑ_T is the angle of spin rotation caused by P,T-odd interaction of neutrons with nuclei. This rotation appears only due to diffraction. The T-odd part of the scattering amplitude $f_T(\vec{\tau})$ sums up two contributions: one caused by interaction of the nuclear electric dipole moment with the electric field of nucleus $f_{EDM}(\vec{\tau})$ and another appearing due to T-odd nuclear interaction of the neutron with the nucleus $f_{TN}(\vec{\tau})$, i.e. $f_T(\vec{\tau}) = f_{EDM}(\vec{\tau}) + f_{TN}(\vec{\tau})$. Therefore, the angle of rotation

$$\vartheta = \vartheta_P + \vartheta_{EDM} + \vartheta_{TN}. \tag{23}$$

The term ϑ_P does not depend on α_B that makes possible to distinguish it. It also can be separated by the method considered in [8, 9], which is based on double pass of the beam through the crystal in forward and backward direction.

Let us consider the T-odd angle of rotation

$$\vartheta_T = \vartheta_{EDM} + \vartheta_{TN} = kRe(-\frac{2i}{\alpha_B(\vec{\tau})}[g_{1s}(\vec{\tau})g_{2T}(\vec{\tau}) - g_{2s}(\vec{\tau})g_{1T}(\vec{\tau})])\frac{\tau_z}{\tau}l. \tag{24}$$

When the axis z is directed along $\vec{k}$, then $\tau_z = -\tau$. Therefore,

$$\begin{aligned}\vartheta_T = \vartheta_{EDM} + \vartheta_{TN} = \frac{2k}{\alpha_B}Re\left(i\left[g_{1s}(\vec{\tau})g_{2T}(\tau) - g_{2s}(\vec{\tau})g_{1T}(\vec{\tau})\right]\right)l = \\ = \frac{2k}{\alpha_B}Re\left(i\left[g_{1s}(\vec{\tau})g_{2EDM}(\vec{\tau}) - g_{2s}(\vec{\tau})g_{1EDM}(\vec{\tau})\right]\right)l + \\ + \frac{2k}{\alpha_B}Re\left(i\left[g_{1s}(\vec{\tau})g_{2TN}(\vec{\tau}) - g_{2s}(\vec{\tau})g_{1TN}(\vec{\tau})\right]\right)l\end{aligned} \tag{25}$$

As it can be seen, measurement of the scattering angle ϑ_T provides to find g_t and, in its turn, to find sum of contributions caused by EDM and P,T-odd interactions. All this gives the limit for the scattering amplitude $f_T(\vec{\tau}) = f_{EDM} + f_{TN}$, where the amplitude f_{EDM} deals with the neutron EDM and f_{TN} is determined by the constant of the T-odd interaction.

The expression for the angle of rotation can be written as:

$$\vartheta_T = \frac{2k}{\alpha_B(\tau)} \times \tag{26}$$
$$\times Re\left\{ i \left[\frac{4\pi}{k^2V_0}\left(\sum_j f_{sj}(\tau) e^{-W_j(\tau)\cos 2\pi\vec{\tau}\vec{R}_j}\right) \frac{4\pi}{k^2V_0}\left(\sum_j f_{Tj}(\tau) e^{-W_j(\tau)\sin 2\pi\vec{\tau}\vec{R}_j}\right) - \right.\right.$$
$$\left.\left. - \frac{4\pi}{k^2V_0}\left(\sum_j f_{sj}(\tau) e^{-W_j(\tau)\cos 2\pi\vec{\tau}\vec{R}_j}\right) \frac{4\pi}{k^2V_0}\left(\sum_j f_{Tj}(\tau) e^{-W_j(\tau)\sin 2\pi\vec{\tau}\vec{R}_j}\right)\right]\right\} L$$

When the energy of interaction is far from resonances then the potential scattering prevails. In this case $Ref_s \gg Imf_s$ and the T-odd scattering amplitude f_T is purely imaginary. Therefore, the expression in (26) is purely real.

In this case from (26) it follows that the angle ϑ_t can be expressed as:

$$\vartheta_T \simeq kRe(N_s - 1)L\frac{Re(N_s-1)}{\alpha_B}\frac{Re\, f_T}{Im\, f_s} \tag{27}$$

From (27) it follows that the effect of P-,T-odd spin rotation is maximal when the value of $(N_s - 1)$ is maximal. The similar is also right for dichroism.

In particular, this is the reason for neutrons with the energy close to the range of P-resonances to be interesting for study [4, 5]. In this range both the amplitude f_{TN} and the amplitude f_{EDM}, which is caused by interaction of the electric dipole moment of neutron with the nuclear electric field, demonstrate resonant behavior.

Thus in the experiments for study of spin rotation and spin dichroism for neutrons in non-center-symmetric crystals both contributions to the T,P-odd amplitude are considered: contribution from the EDM and that from T,P-odd nucleon-nucleon interaction. It is interesting that for neutrons with the energy within the thermal range and far from resonances the contribution from EDM plays the major role in (27) [10].

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