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Neutron spin optics in noncentrosymmetric crystals as a new way for nEDM search

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Abstract

A new way is proposed and investigated for observing and fine tuning a neutron spin rotation effect caused by the Schwinger interaction of the moving neutron with the strong interplanar electric field of the noncentrosymmetric quartz crystal. By that we have got an opportunity to control the electric field acting on neutron. The value and sign of this field depend on the deviation of a neutron energy from the Bragg one. We used a second crystal parallel to the main one for selection of the neutrons with the given deviation parameter. The possibility to control the electric field acting on the registered neutrons has been realized by heating (or cooling) the second crystal. Observed effects give a real prospects to improve essentially the scheme and sensitivity of the experiment for a search for neutron electric dipole moment (EDM) using the crystal diffraction technique.

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1. Introduction

Recently a new method of a neutron EDM search was proposed [1,2], developed [3,4] and tested experimentally [5]. It is based on the interaction of the diffracted neutron with the interplanar electric field of a crystal without centre of symmetry. Values of the electric fields for some crystallogaphic plane systems of noncentrosymmetric crystals can reach (10^8-10^9) V/cm. Estimated sensitivity of the method for the available noncentrosymmetric quartz crystal turned out to be $\sim 10^{-25}$ e cm/day[1] [3,4]. We remind that the sensitivity of any method to measure the neutron EDM is determined by the product $E\tau\sqrt{N}$, where E is the value of electric field, τ is the time of neutron interaction with the field and N is the number of accumulated neutrons, the latter being determined by quality of the modern cold and ultracold neutron sources. For the quartz crystal maximum value of the electric field is $\sim 2\times 10^8$ V/cm [9,10], and $\tau \approx 1$ ms [3,11] is restricted by absorption in the crystal. The future essential progress of this method could be expected with the use of other crystals. Now the most perspective ones seems to be the BSO ($Bi_{12}SiO_{20}$, $Bi_4Si_3O_{12}$) and PbO crystals. Calculations have shown that the sensitivity of the method using the BSO or PbO crystals can be improved by about an order of magnitude in comparison with that using the quartz one. Unfortunately, the present scheme of the experiment [4] does not allow to realize the potential of the BSO and PbO crystals, so additional investigations of the neutron spin effects in noncentrosymmetric crystals are needed to develop new variants of the experimental scheme.

Originally, two known crystal diffraction schemes were tried in theory to apply them for a neutron EDM search using noncentrosymmetric crystals. The first was Laue

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[1] The sensitivity of the most sensitive now magnetic resonance method using ultracold neutrons (UCN-method) is $(3-6)\times 10^{-25}$ e cm/day [6–8]. The last result is $d_n \leqslant 6.3\times 10^{-26}$ e cm at the 90% confidence level [8].

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diffraction method, it was proposed and tested experimentally [1–5], the second was the Bragg diffraction one [12–14]. The main advantage of the Laue diffraction scheme is the possibility to increase essentially the time τ of neutron passage through the crystal using the Bragg angles θ_B close to $\pi/2$ [1]. This bonus allows us to reach the time of neutron stay in the quartz crystal close to the time of neutron absorption $\tau_a \approx 1$ ms [3,11]. The detailed consideration of the Laue diffraction method has shown that we cannot increase essentially its sensitivity using different noncentrosymmetric crystals with the advanced parameters (with a stronger field, for instance) due to the following factors:

- We have to use the crystals with the thickness determined by [4]
$$L_0 = \frac{\pi m_p c^2}{2\mu_n e E_g}, \tag{1}$$
to get the depolarisation effect (spin rotation angles equal to $\pm\pi/2$ for two kinds of neutron waves propagating in the crystal), here E_g is the electric field affecting the neutron for the exact Bragg condition [9]. Therefore the greater value of the field E_g requires decreasing the crystal thickness and, accordingly, the time of neutron passage through the crystal.
- It is impossible to increase the sensitivity using the Bragg angles extremely close to $\pi/2$, because of the essential decreasing of the neutron count rate for such angles [5,15].

The main advantage of the Bragg diffraction scheme [12,13] in comparison with the Laue diffraction one [4] is that the measurable spin rotation angle arises due to Schwinger or EDM interaction with the interplanar electric field for the neutron passing through the crystal near the Bragg condition. In principle, one can control the sign and value of the electric field selecting the neutrons with the different sign and value of the parameter of deviation from the Bragg condition. However, in this case the effect due to neutron EDM does not increase for the Bragg angles close to $\pi/2$ as it takes place for the Laue diffraction scheme, because for the Bragg diffraction the time of the neutron passage through the crystal τ is determined by the total neutron velocity v, while for the Laue diffraction this time is determined by the velocity component along the crystallographic plane, which can be essentially decreased for Bragg angles close to $\pi/2$. However, this disadvantage in principle can be corrected by increasing the crystal thickness.

In the work [16] it was reported that the effect of the neutron spin rotation has been observed due to the spin–orbit (Schwinger) interaction, using Bragg scheme of the diffraction in the noncentrosymmetric crystal with a small deviation of a neutron momentum direction (by about a few Bragg width) from the Bragg one, because the effect disappears for the exact Bragg direction in this case. However, the experimental value of the spin rotation angle [16] turned out to be a few times less than the expected one. Authors were in difficulty to explain the origin of such discrepancy, but it was very likely due to imperfection of the used crystal.

The main problem, the authors [16] had met and solved in a very complicated way, was how to obtain the neutrons with the given deviation parameter.

Here a very simple solution of this problem is proposed.

2. Spin rotation for the Bragg reflected neutrons

Let us consider the symmetric Bragg diffraction case. Neutron falls on the crystal in the direction close to the Bragg one for the crystallographic plane **g** (**g** is the reciprocal lattice vector). Deviation from the exact Bragg condition is described by the parameter $\Delta = E_k - E_{k_g}$, where $E_k = \hbar^2 k^2/2m$ and $E_{k_g} = \hbar^2 \mid \mathbf{k}+\mathbf{g}|^2/2m$ are the energies of a neutron in the states $|k\rangle$ and $|k+\mathrm{g}\rangle$ respectively.

In this case the neutron wave function inside the crystal in the first order of perturbation theory can be written [14]
$$\psi(\mathbf{r}) = \mathrm{e}^{-\mathrm{i}\mathbf{kr}} + a\cdot \mathrm{e}^{-\mathrm{i}(\mathbf{k}+\mathbf{g})\mathbf{r}}, \tag{2}$$
where
$$a = \frac{|V_g|}{E_k - E_{k_g}} = \frac{|V_g|}{\Delta}. \tag{3}$$
Here V_g is g-harmonic of interaction potential of neutron with crystal. For simplicity we consider the case $a \ll 1$, so we can use the perturbation theory.

The electric field acting on the neutron in the crystal will be equal to [14]
$$\mathbf{E} = \mathbf{E}_g \cdot a, \tag{4}$$
where $\mathbf{E}_g$ is the interplanar electric field for the exact Bragg condition.

One can see that the sign and value of the electric field Eq. (4) are determined respectively by the sign and value of deviation Δ from the exact Bragg condition, therefore to have the given electric field (and so the given angle of a neutron spin rotation) we should select from the whole beam the neutrons with the corresponding deviation parameter Δ.

The presence of the electric field will lead to appearance of the Schwinger magnetic field
$$\mathbf{H}_S = [\mathbf{E}\times \mathbf{v}_{\parallel}]/c. \tag{5}$$
The neutron spin will rotate around the $\mathbf{H}_S$ by the angle
$$\varphi_s = \frac{4\mu \mathbf{H}_S L_c}{\hbar v_{\perp}}, \tag{6}$$
L_c is the crystal thickness, $v_{\parallel}$ and $v_{\perp}$ are the components of neutron velocity parallel and perpendicular to the crystallographic plane correspondingly.

In the experiment [17] we have observed the effect of neutron spin rotation in neutron optics for the large ($\sim 10^3$–10^4 Bragg width) deviations from the exact Bragg condition. The measured effect has coincided with the theoretical one.