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Redoubled effect of a neutron spin rotation in deformed noncentrosymmetric crystal for the Bragg diffraction scheme

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A doubled effect of a neutron spin rotation in the noncentrosymmetric quartz crystal for the Bragg reflected neutrons from the deformed exit crystal side is first observed. The effect arises due to a neutron Schwinger interaction with the crystal and depends on a value of a crystal deformation near its back exit face. Electric field acting on a neutron in the quartz crystal is about $\sim 10^8$ V/cm. This field affects the neutron during the whole time of its passage through the crystal both ways there and back. This time is limited only by the available size of crystal (14 and 27 cm in our case) or the neutron absorption length. Observation of such effects gives a real perspective to improve essentially the scheme and sensitivity of the experiment for a search for neutron electric dipole moment (EDM) by the crystal-diffraction technique. Moreover, the presented experimental scheme can be applied for neutron with energy close to the P wave resonance one to search for T-odd part of a neutron-nuclei interaction, for example, because of relatively low requirements to a crystal quality.

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1. Introduction. Recently a new method of the neutron electric dipole moment (EDM) search was proposed [1, 2] and developed [3, 4]. It is based on the interaction of the diffracted neutron with the interplanar electric field of a crystal without centre of symmetry. Value of the electric field can reach $(10^8 - 10^9)$ V/cm. An estimated sensitivity of the method for the available noncentrosymmetric quartz crystal turned out to be $\sim 10^{-25}$ e·cm per day [3, 4]. We note 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 accumulated statistics. For the quartz crystal maximum value of the electric field is $\sim 2 \cdot 10^8$ V/cm [5, 6], and $\tau \approx 1$ ms [7, 3] is restricted by absorption in the crystal. The future essential progress of this method could be expected with using 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] doesn't allow to realize the potential of the BSO and PbO crystals, so additional investigations of the neutron spin effects in a noncentrosymmetric crystal are needed to develop the new experimental scheme.

Originally, two different crystal-diffraction schemes for a neutron EDM search were proposed. The first was the Laue diffraction method [1 – 3] and the second was the Bragg diffraction one [8, 9]. The main advantage of the Laue diffraction scheme is the possibility to increase the time τ of neutron staying in crystal using the Bragg angles θ_B close to $\pi/2$ [2]. 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 [7, 3]. The detailed consideration of the Laue diffraction method has shown that we can not increase essentially the sensitivity of the method using other noncentrosymmetric crystals with the advanced parameters due to the following factors:

- We have to use the crystals with the thickness determined by [4]

$$L_0 = \frac{\pi m_p c^2}{2\mu_n e E_g}, \qquad (1)$$

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 affected the neutron for the exact Bragg condition. Therefore the greater value of the field E_g requires decreasing the crystal thickness and, accordingly, the time of neutron passage through the crystal.

- We can not increase the sensitivity using the Bragg angles extremely close to $\pi/2$, because of the very

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low luminosity of the experiment for such angles [10].

The main advantage of the Bragg diffraction scheme [8, 11] in comparison with the Laue diffraction one [4] is that the effect of spin rotation arises due to Schwinger or EDM interaction with the interplanar electric field for the neutron passing through the crystal near the Bragg condition, and one can control the sign and value of the electric field acting on the registered neutrons by selecting the neutrons with the different sign and value of the parameter of deviation from the Bragg condition. Moreover, the sensitivity of the Bragg diffraction method is not limited by the given crystal thickness, as it is for the Laue diffraction one [4]. However, in this case the effect due to neutron EDM doesn't increase for the Bragg angles close to $\pi/2$ as it takes place for the Laue diffraction scheme. For the Bragg diffraction the time of neutron stay in crystal τ is determined by the total neutron velocity v while for the Laue diffraction τ is determined by the component along the crystallographic plane, but this fault in principle can be repaired by increasing the crystal thickness. The main problem, the authors [11] had met and solved in a very complicated way, was how to obtain the neutrons with the given deviation parameter.

Here also a very simple solution of this problem is given.

2. Spin rotation for the Bragg reflected neutrons. Let's consider the symmetric Bragg diffraction case. Neutron falls on the crystal in the direction close to the Bragg one for the crystallographic plane g. 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 $E_{k_g} = \hbar^2|\mathbf{k}+\mathbf{g}|^2/2m$ are the energies of a neutron in the states $|k\rangle$ and $|k+g\rangle$ respectively.

In this case the neutron wave function inside the crystal in the first order of perturbation theory can be written [12]

$$\psi(\mathbf{r}) = e^{-i\,\mathbf{kr}} + a\cdot e^{-i(\mathbf{k}+\mathbf{g})\mathbf{r}}, \tag{2}$$

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 affected the diffracted neutron will be equal to [12]

$$\mathbf{E} = \mathbf{E}_g \cdot a, \tag{4}$$

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 (4) are determined by the sign and value of deviation Δ from the exact Bragg condition, therefore to have the given electric field and so the effect of 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 an appearance of the Schwinger magnetic field

$$\mathbf{H}_S = 1/c[\mathbf{E}\times\mathbf{v}_{\|}]. \tag{5}$$

The neutron spin will rotate around the $\mathbf{H}_S$ by the angle

$$\varphi_s = \frac{4\mu H_S L_c}{\hbar \mathrm{v}_\perp}, \tag{6}$$

L_c is the crystal thickness, $\mathrm{v}_{\|}$ and $\mathrm{v}_\perp$ are the components of neutron velocity parallel and perpendicular to the crystallographic plane correspondingly.

In the experiment [11] the effect of neutron spin rotation due to spin-orbit (Schwinger) interaction was experimentally observed in the Bragg diffraction scheme for small ($\sim$ a few Bragg width) deviations from the Bragg condition, but the measured value was about 3 times less than that was theoretically predicted. In the experiment [13] 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.

The main idea of the present work is the following. We use a small controlled variation of the interplanar distance Δd (caused by heating, for example) near the exit crystal edge. So some part of neutrons passed through the crystal will reflect from this small crystal part. These back diffracted neutrons have the deviation parameter for the main part of crystal determined by Δd and so they propagate under corresponding electric field in both directions there and back. Thermal deformation of the crystal edge is used to create such variation of the interplanar distance.

We can use also two separate crystals in parallel position for this purpose (see Fig.1). One can heat (or cool) the second small crystal. The part of neutrons passed through the first crystal with the corresponding Bragg wave length will reflect by the second crystal with the given deviation parameter for the first (large) crystal. This deviation parameter will directly depend on the temperature difference between crystals.

Value of the wave length Bragg width for (110) quartz plane ($d = 2.45$Å) is $\Delta\lambda_B/\lambda \approx 10^{-5}$. To shift the reflex wave length by the one Bragg width we should

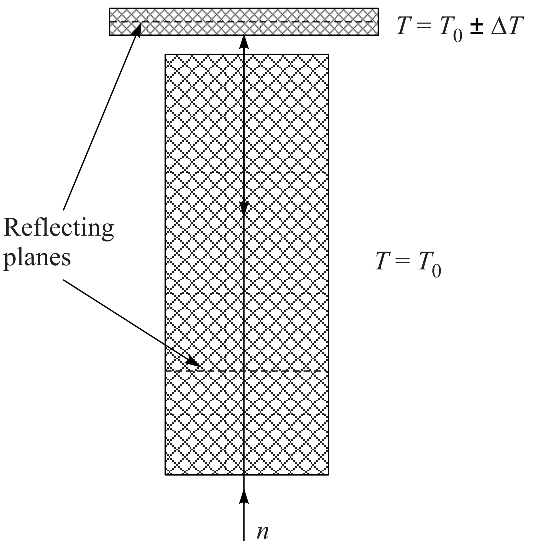

Fig.1. Two crystals are in parallel position. Neutron reflected by the small crystal pass twice through the large crystal. The deviation parameter Δ for the large crystal is determined by the temperature difference ΔT

have the same value of $\Delta d/d$. Linear coefficient of the thermal expansion for quartz crystal is $\Delta L/L \approx 10^{-5}$ per degree. Therefore, the deviation $\pm\Delta\lambda_B$ corresponds to difference of the crystal temperatures $\Delta T \approx \pm 1^0$. We note that the different signs of this temperature difference will correspond to different signs of the electric field acting on the neutron.

3. Experiment. Scheme of the neutron behavior in the crystal is shown in Fig.2. Two samples of quartz crystal has been used in this experiment with the thicknesses along X axis $L_c = 14$ and 27 cm. The Peltier element has been attached to the back face of the crystal. That allows to create the temperature gradient in the crystal along the neutron trajectory. So the Bragg condition will vary along the neutron trajectory and different parts of crystal reflect the neutrons with the different λ. Therefore, the reflected beam will contain not only the reflex from the entrance crystal face (corresponding to Bragg condition for d) but also the reflection from the back exit face (corresponding $d \pm \Delta d$) that twice pass through the crystal there and back. Moreover, the value of the deviation parameter Δ for this reflection is directly depend on the value of temperature gradient. In the case of higher temperature of the back crystal face the neutron with $E_k - E_{k_g} > 0$ will be reflected, while in the case of its lower temperature the neutron with $E_k - E_{k_g} < 0$ will be reflected.

Examples of the time of flight spectra of the reflected neutrons for the Bragg angle $\sim 90^0$ are shown in Fig.3. One can see a formation of the reflex from the back crystal surface and increasing its intensity with the rise of the temperature gradient.

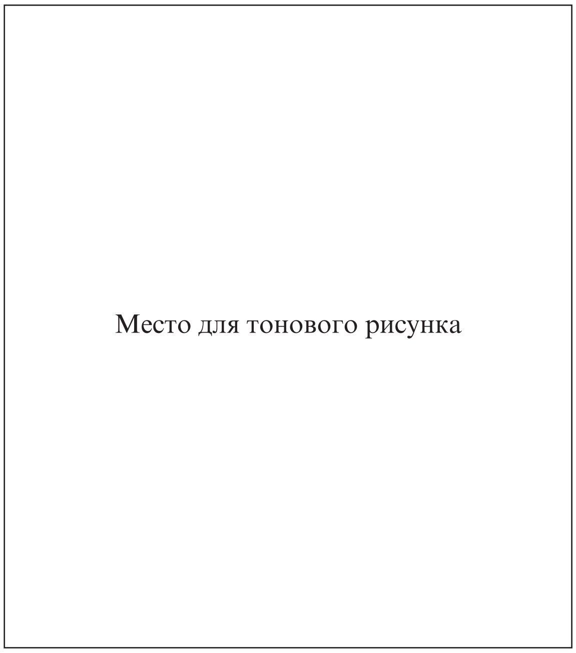

Fig.2. Passage of the neutron through the crystal. Presence of the interplanar distance gradient result in forming the reflex near the back face of crystal

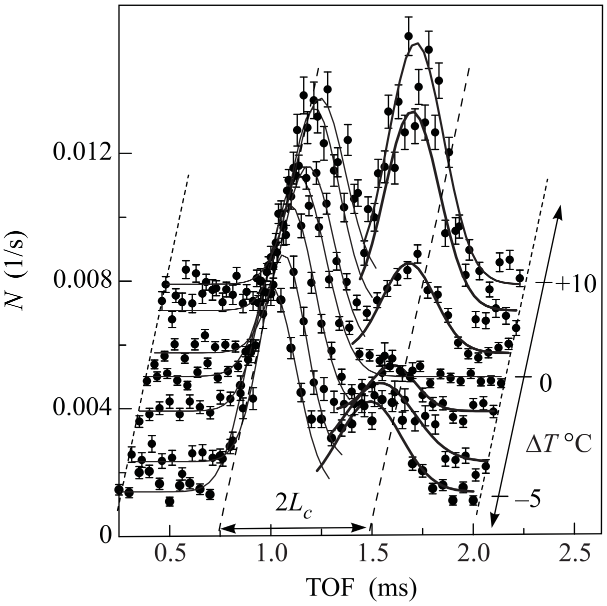

Fig.3. Dependence of the time of flight (TOF) spectra of the neutron reflected by the (110) plane of quartz on the temperature gradient applied to the crystal. Bragg angle $\sim 90^0$, $L_c = 27$ cm. One can see the reflexes from the front surface and from the back part of crystal

The scheme of the experiment on the observation of neutron spin rotation is similar to that described in [3].

To observe the effect of neutron spin rotation due to Schwinger interaction it is necessary to turn the crystal in a position, for which Bragg angle is different from 90^0, because in the case of Bragg diffraction the Schwinger effect disappears for 90^0 Bragg angle:

$$\varphi_s = \frac{4\mathbf{E}\mu L_c \mathrm{v}_\parallel}{c\hbar \mathrm{v}_\perp} = \frac{4\mathbf{E}\mu L_c}{c\hbar}\mathrm{ctg}(\theta_B) \underset{\theta_B\to\pi/2}{\longrightarrow} 0 \qquad (7)$$

The experiment on the observation of neutron spin rotation was carried out with the $L_c = 14$ cm crystal thickness and Bragg angle $\approx 86^0$.

The dependence of the angle of neutron spin rotation around $\mathbf{H}_S$ on the value of temperature gradient is shown in Fig.4.

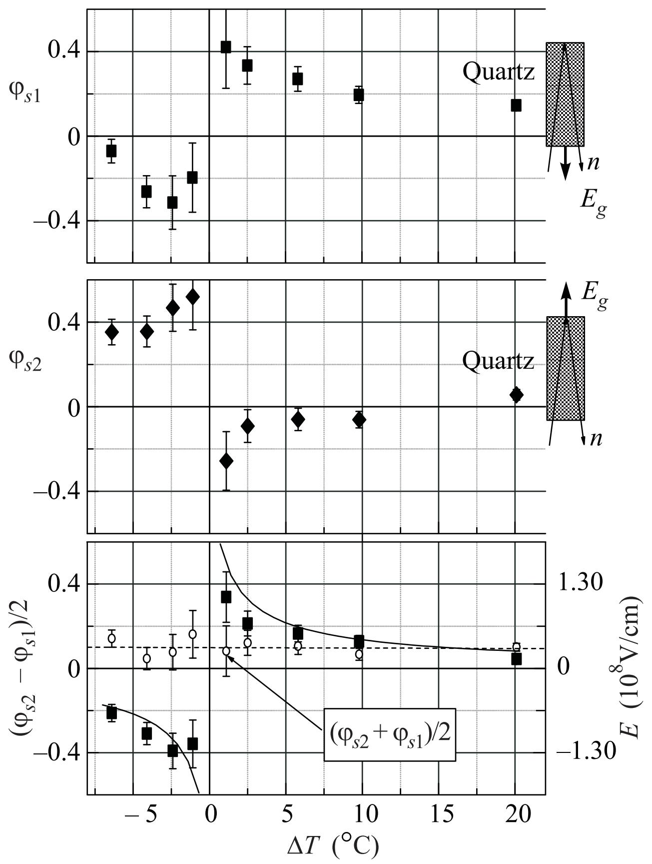

Fig.4. The dependence of the angle of neutron spin rotation due to Schwinger interaction on the value of temperature gradient. Two upper figure corresponds to two crystal positions differing by the angle 180^0. One can see a good coincidence of the theoretical dependence (solid curve in the bottom plot) with the experimental points

We can change the sign of the effect by turn the crystal by the 180^0 around $\mathbf{H}_S$. One can see that the experiment confirms that such a crystal rotation indeed change the sigh of the observed effect. On the right axis the effective electric field that is necessary to get the corresponding spin rotation effect is shown. One can see that the value of the electric field reaches $\sim 1.3 \cdot 10^8$ V/cm, that is only 1.5 times less than in the Laue diffraction case for exact Bragg condition [5, 6].

4. Conclusions. The doubled effect of spin rotation in a noncentrosymmetric quartz crystal for neutrons Bragg reflected by the deformed part of crystal was first observed. This effect is caused by the Schwinger interaction and depends on a deformation degree of crystal near its back surface. For the quartz crystal the effective electric field affected the neutron during the time of its staying inside the crystal can reach $\sim 1.3 \cdot 10^8$ V/cm. The sensitivity to neutron EDM is determined by the product $E\tau\sqrt{N}$, there E is the electric field affected the neutron, τ is the time of neutron interaction with the field and N is the total statistics accumulated in the experiment. Simple estimation has shown that in our case the depth of neutron penetration into the crystal and so the time of neutron interaction with the electric field can be about four or even five orders more than in the well known Shull and Nathans experiment for the neutron EDM search [14].

In addition, the requirements to the crystal perfection are relatively low for this scheme. For the case $\gamma_B << w_m$ the effective electric field affected the neutron depends on an effective crystal mosaicity w_m as $E = E_0(\gamma_B/w_m)$, where γ_B is the angular Bragg width, but the reflex intensity increase as $I = I_0(w_m/\gamma_B)$, therefore the sensitivity to measure the neutron EDM will be reduced only by a factor $\sqrt{w_m/\gamma_B}$, that give us a hope that such a scheme can be applied to search the T-odd part of neutron-nuclei interaction [15] using neutrons with energies near the P wave resonance one.

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1. V. V. Fedorov, V. V. Voronin, E. G. Lapin, and O. I. Sumbaev, Preprint PNPI-1944, Gatchina, 1994; Tech. Phys. Lett. **21**, 884 (1995); Physica **B234–236**, 8 (1997).

2. V. V. Fedorov, V. V. Voronin, and E. G. Lapin, Preprint LNPI-1644, Leningrad, 1990; J. Phys. **G**: Nucl. Part. Phys. **18**, 1133 (1992).

3. V.V. Fedorov, E.G. Lapin, S.Yu. Semenikhin, and V.V. Voronin, Physica **B297**, 293 (2001).
4. V.V. Fedorov and V.V. Voronin, NIM **B201**, 230 (2003).
5. V.L. Alexeev, V.V. Fedorov, E.G. Lapin et al., NIM **A284**, 181 (1989); Sov. Phys. JETP **69**, 1083 (1989).
6. V.V. Voronin, E.G. Lapin, S.Yu. Semenikhin, and V.V. Fedorov, Preprint PNPI-2376, Gatchina, 2000; JETP Lett. **72**, 308 (2000).
7. V.V. Voronin, E.G. Lapin, S.Yu. Semenikhin, and V.V. Fedorov, JETP Lett. **71**, 76 (2000); Preprint PNPI-2337, Gatchina, 2000.
8. M. Forte, J. Phys. **G**: Nucl. Phys. **9**, 745 (1983).
9. V.G. Baryshevskii and S.V. Cherepitsa, Phys. Stat. Sol. **b128**, 379 (1985).
10. V.V. Fedorov et al., ILL Experimental Report, Test-731 (2002).
11. M. Forte and C.M.E. Zeyen, NIM **A284**, 147 (1989).
12. V.V. Fedorov, *XXVI Winter LNPI School*, vol. **1**, Leningrad, 1991.
13. V.V. Voronin, E.G. Lapin, S.Yu. Semenikhin, and V.V. Fedorov, JETP Lett. **74**, 251 (2001).
14. C.G. Shull and R. Nathans, Phys. Rev. Lett. **19**, 384 (1967).
15. V.G. Baryshevsky, J. Phys. **G**: Nucl. Part. Phys. **23**, 509 (1997).