DIFFRACTION AND NEUTRON OPTICS IN NONCENTROSYMMETRIC CRYSTALS. NEW FEASIBILITY OF A SEARCH FOR NEUTRON EDM

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A b s t r a c t

Recently strong electric fields (up to 10^9 V/cm) have been discovered, which affect the neutrons moving in noncentrosymmetric crystals. Such fields result in some new polarization phenomena observable in neutron diffraction and optics. That opens, for example, a new way for searching the electric dipole moment (EDM) of a neutron with the sensitivity comparable or exceeding that for the most sensitive now magnetic resonance method using ultra cold neutrons. Now the pilot setup for searching the neutron EDM has been created. It allows to study the dynamical diffraction and optics of polarized neutrons in thick (1–10 cm) crystals, using the direct diffraction beam and Bragg angles close to 90°. The setup is mounted at the horizontal channel of WWR-M reactor in Gatchina.

Physics of the phenomena and the first experimental results are discussed on observing new effects both in neutron Laue diffraction and neutron optics.

ДИФРАКЦИЯ И НЕЙТРОННАЯ ОПТИКА В КРИСТАЛЛАХ БЕЗ ЦЕНТРА СИММЕТРИИ. НОВАЯ ВОЗМОЖНОСТЬ ПОИСКА ЭДМ НЕЙТРОНА

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А н н о т а ц и я

Недавно были обнаружены сильные электрические поля (до 10^9 В/см), которые действуют на нейтроны при их распространении в нецентросимметричных кристаллах. Такие поля приводят к новым наблюдаемым в нейтронной дифракции и оптике поляризационным явлениям. Это открывает, в свою очередь, новую возможность поиска электрического дипольного момента (ЭДМ) нейтрона с чувствительностью, сопоставимой или превышающей чувствительность наиболее точного в настоящее время магниторезонансного метода, использующего ультрахолодные нейтроны.

Создан макет экспериментальной установки для поиска ЭДМ нейтрона, который позволяет изучать динамическую дифракцию и оптику поляризованных нейтронов в толстых (1 – 10 см) кристаллах, используя прямой дифракционный пучок и брэгговские углы, близкие к 90°. Установка смонтирована на горизонтальном канале реактора ВВР-М в Гатчине.

Обсуждаются физика явлений и первые экспериментальные результаты по наблюдению новых эффектов в нейтронной лауэвской дифракции и нейтронной оптике.

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1 Introduction

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 of neutral K-mesons about 40 years ago [1]. CP violation leads in turn to the violation of time reversal symmetry (T) through the CPT invariance (CPT-theorem, see [2] and [3])). Existence of nonzero neutron EDM requires violation of both P and T invariances. These problems were repeatedly discussed in our Winter schools (see, for example, [4]). The different theories of CP violation give widely varying predictions for neutron EDM (see [5–10]). So the new experimental limits on the EDM value would be of great importance for understanding the nature of the CP violation as well as of the Universe baryon asymmetry.

The most precision method of the EDM measurement is the magnetic resonance one, using ultracold neutrons (UCN method). It is developing now in PNPI (Gatchina, Russia) and ILL (Grenoble, France) [11–13]. [2]

Here we shall discuss another possible way for the neutron EDM search, using the neutron interaction with a noncentrosymmetric crystal. Earlier [14] we have shown, that the neutron, moving through the noncentrosymmetric crystal, may be influenced with a strong interplanar electric field. Its value depends on the direction and the value of a neutron momentum, reaching a maximum (up to 10^9 V/cm), when the Bragg condition for some system of crystallographic planes is satisfied. These fields result in some new polarization phenomena observable in neutron diffraction and optics. Such a field was first observed in the experiment on dynamical diffraction of polarized neutrons by measuring the Pendellösung phase shift, accompanying a spin flip of neutrons, due to Schwinger interaction [14]. Experimental value of the field for the (110) system of crystallographic planes of α-quartz crystal turned out to be equal $E_{(110)} = (2.10 \pm 0.12) \times 10^8$ V/cm and had coincided with the theoretical one.

The inerplanar electric fields are more than four orders of magnitude higher than those used in the UCN method [11–13] of the neutron EDM search. So it was a natural idea [15–17] (arisen again after Shull and Nathans [18]) to use these crystal fields for searching the neutron EDM (see also [19, 20]).

Two variants of the method, using Laue diffraction of neutrons in the crystals without a centre of symmetry, were proposed for this purpose. One of them is the double crystal variant [15] based on a spin dependence of the Pendellösung picture phase and the second is the polarization method [16] using the depolarization effect for neutrons diffracted in the noncentrosymmetric crystals. It was shown in these works [15, 16] that for Laue diffraction case the sensitivity of the method to neutron EDM may be increased more than by an order of magnitude by a choice of Bragg angles close to $\pi/2$, so it may reach the sensitivity of the UCN method [11–13]. That is possible for Laue diffraction only because of the essential delay of the diffracting neutrons inside the crystal for Bragg angles close to $\pi/2$.

But only the experimental research of these effects in dynamical Laue diffraction of neutrons in the noncentrosymmetric crystals for Bragg angles close to $\pi/2$ can answer the question on actual sensitivity of the diffraction method to neutron EDM.

A similar hypothetical idea to use the interplanar electric fields (if they did exist) for the neutron EDM search was discussed earlier by Golub and Pendlebury in the review [20]. But the crystals with such properties were not known at that time.

The importance to consider the crystal noncentrosymmetricity was previously pointed

[2]Last experimental result of searching a neutron EDM by this method is $d_n \leq 6.3 \cdot 10^{-26}$ e·cm at the 90% confidence level [13].

out in ref. [21]. Forte [17] was the first who payed attention to existence of an interference between the electric and nuclear structure amplitudes for neutrons diffracted in a noncentrosymmetric crystal. In the work [17] the effect of neutron spin rotation due to such interference has been predicted. Similar, but more detailed theory of neutron optical activity and dichroism for diffraction in noncentrosymmetric crystals has been developed by Baryshevskii and Cherepitsa [19].

It has been shown [17] that the spin rotation effect in a non-absorbing crystal can take place only for Bragg scheme of diffraction. But in this case the deviation from the Bragg condition by about Bragg width is necessary to observe the effect for the transmitted beam that reduces the effect (which is proportional to $1/\sqrt{1+w^2}$, where w is the parameter of angular deviation measured in the units of Bragg halfwidth, see [15]). The nuclear absorbtion is necessary to have a spin rotation effect in the case of Laue diffraction [17, 19].

The possibility of a search for neutron EDM by measuring a spin rotation angle was analyzed for the Bragg diffraction scheme [17] and for the Laue scheme [19].

We have shown [14] that the mentioned above interference of structure amplitudes leads to the shift of the electric crystallographic planes with respect to the nuclear ones and, accordingly, to appearance of the strong electric field acting on the diffracting neutron. Such concept turned out to be very fruitful for further consideration and understanding the different phenomena, concerning the diffraction and neutron optics in a noncentrosymmetric crystals [14, 15]. For example it allowed to predict and give a simple description of such new effects as the spin dependence of the pendulum phase, depolarization of diffracting neutron beams, the independence of the effects due to the Schwinger interaction on the neutron wave length and Bragg angle for given crystallographic planes etc. [16, 22, 23].

We should note also, that the Bragg reflection of neutrons from the neutron-absorbing centrosymmetric crystal of CdS was used earlier by Shull and Nathans [18] for EDM search. But the sensitivity of this method is much lower than that of UCN-method because the depth of neutron penetration into the crystal, which determines a time the neutron stays in crystal, was very small (about $7 \cdot 10^{-2}$ cm). Now a new variant of the method is proposed and developed [24, 25], using the multiple reflections from the silicon centrosymmetric crystal [26, 27].

In the work [28] (Forte and Zeyen) the effect of the neutron spin rotation has been observed due to the spin-orbit (Schwinger) interaction, using the 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 [28] turned out to be a few times less than the theoretical one. The origin of that was very likely due to imperfection of the used crystal.

Here we consider the neutron-optic effects for the neutron passage through the noncentrosymmetric crystal for the case, when the deviation from the exact Bragg condition reaches $(10^3 - 10^5)$ Bragg widths. The theoretical estimations have shown [29], that for the polar noncentrosymmetric crystal ($PbTiO_3$, for example) the value of resultant electric field, acting on the neutron, moving through the crystal, can reach $\approx 2 \times 10^6$ V/cm for the wide range (that by about four orders exceeds the Bragg width) of the neutron directions and wavelengths. Such a field is a result of a field combination of a number of different crystallographic planes. So the spin effects turn out to be not too small for the case of neutron optics in comparison with the diffraction case.

The observation of such effects may be of interest for a search for the neutron EDM and also, for example, for searching a T-odd part of the nuclear interaction, using neutrons with the energy close to the neutron P-resonance position [30], because one can hardly observe a dynamical diffraction for neutrons with such energies (~ 1 eV) because of the crystal imperfection.

2 Diffraction in a noncentrosymmetric crystal

As it follows from the dynamical diffraction theory, a movement of a neutron through the crystal in a direction close to the Bragg one for some system of crystallographic planes can be described by two kinds of Bloch waves $\psi^{(1)}$ and $\psi^{(2)}$ (see for example, [31]), formed as a result of neutron interaction with the periodic nuclear potential [15] $V_g^N(\mathbf{r}) = V_0^N + 2V_g^N \cos(\mathbf{gr})$, where $\mathbf{g}$ is a reciprocal lattice vector describing the system of crystallographic planes, $|\mathbf{g}| = 2\pi/d$, d is an interplanar spacing, V_0^N is the average nuclear potential of the crystal,

$$\psi^{(1)} = \frac{1}{\sqrt{2}}[e^{i\mathbf{k}^{(1)}\mathbf{r}} + e^{i(\mathbf{k}^{(1)}+\mathbf{g})\mathbf{r}}] = \sqrt{2}\cos(\mathbf{g}r/2)\exp[i(\mathbf{k}^{(1)} + \mathbf{g}/2)\mathbf{r}], \tag{1}$$

$$\psi^{(2)} = \frac{1}{\sqrt{2}}[e^{i\mathbf{k}^{(2)}\mathbf{r}} - e^{i(\mathbf{k}^{(2)}+\mathbf{g})\mathbf{r}}] = i\sqrt{2}\sin(\mathbf{g}r/2)\exp[i(\mathbf{k}^{(2)} + \mathbf{g}/2)\mathbf{r}]. \tag{2}$$

The expressions (1), (2) describe two standing waves (in the direction $\mathbf{g}$ normal to the crystallographic planes), which are moving in the direction $\mathbf{k}_{\parallel}^{(1,2)} = \mathbf{k}^{(1,2)} + \mathbf{g}/2$ along the planes. A small difference of the wave vectors $k^{(1)}$, $k^{(2)}$ is a result of neutron concentration on "nuclear" planes (for $\psi^{(1)}$) and between them (for $\psi^{(2)}$), ${k^{(1,2)}}^2 = K^2 \mp U_g^N$, where $U_g^N = 2mV_g^N/\hbar^2$, $K^2 = k^2 + U_0^N \equiv 2m(E + V_0^N)/\hbar^2$, m, E, k are respectively the mass, energy and wave vector of the incident neutron. The values V_0^N, V_g^N have an order of 10^{-7} eV, so for thermal and cold neutrons with the energies of $10^{-1} - 10^{-3}$ eV we can consider that $k^{(1)} \approx k^{(2)} \approx k$. The propagation velocity of these waves along the crystallographic planes is[3]

$$v_{\parallel}^{(1,2)} = \frac{\hbar}{m}|\mathbf{k}^{(1,2)} + \mathbf{g}/2| = \frac{\hbar}{m}k^{(1,2)}\cos\theta_B \approx v\cos\theta_B, \tag{3}$$

where $v = \hbar k/m = 2\pi\hbar/(\lambda m) = \pi\hbar/(md\sin\theta_B)$ is the velocity of the impinging neutron, θ_B is the Bragg angle, $\lambda = 2\pi/k$ is the wave length of the incident neutron ($\lambda = 2d\sin\theta_B$). A number of the dynamical diffraction phenomena (see, for example, [31–33]), including effects caused by the neutron EDM [15, 16], are determined not by a total neutron velocity v, but its component along the crystallographic planes $v_{\parallel} = v\cos\theta_B$. In particular, the time the diffracting neutron spends in crystal, which equal to $\tau_L = L/(v\cos\theta_B) \approx L/[v(\pi/2 - \theta_B)]$, sharply grows for Bragg angles close to $\pi/2$, where L is the thickness of a crystal. That allows to increase the sensitivity of the diffraction method to neutron EDM at least by an order of magnitude [15, 16]. Therefore the values [4] $E\tau$ can be of the same order for UCN and diffraction method (for Bragg angles sufficiently close to $\pi/2$) [15, 16] despite the fact

[3] Here we neglect the Pendellosung oscillations (arising from the interference of waves of different type) because in our case they are averaged over Bragg angles for a slightly divergent beam.

[4] The set-up sensitivity is determined by $\sigma(D) \propto 1/E\tau\sqrt{N}$, where $\sigma(D)$ is an absolute error of EDM measurement, N is a total value of accumulated events.

that the storage time for UCN (~ 100 s [11]) is essentially more than time of neutron passage through the crystal[5].

We proposed the polarization method for searching a neutron EDM based on the predicted effect of depolarization of the diffracted neutron beam [16]. This method has some advantages (such as its relative simplicity and less sensitivity to crystal imperfection) over the method based on the spin dependence of the neutron Pendellosung phase [15].

Essence of the effect is as follows. In the noncentrosymmetric crystal the diffracting neutrons in two Bloch states are moving under opposite electric fields [14, 15, 22], therefore spins in these states will rotate in the opposite directions due to Schwinger interaction, that in turn will lead to a decrease of the neutron beam polarization (see Fig. 1). If an initial spin orientation is normal to the "Schwinger" magnetic field $\mathbf{H}_g^S = [\mathbf{E}_g \times \mathbf{v}_\parallel]/c$, then the spin rotation angle in both states will be equal to [15, 22]

$$\Delta\phi_0^S = \pm \frac{2\mu H_g^S L}{\hbar v_\parallel} = \pm \mu_n \frac{eE_g L}{m_p c^2}, \tag{4}$$

because $\mathbf{E}_g \perp \mathbf{v}_\parallel$ and $H_g^S = E_g v_\parallel / c$. Here the signs $\pm$ are related to different states (1), (2) respectively. As a result the value of neutron beam polarization P will depend on $\Delta\phi_0^S$ in the following way[6]:

$$P = P_0 \cos\Delta\phi_0^S = P_0 \cos\left(\frac{\mu_n e E_g L}{m_p c^2}\right), \tag{5}$$

P_0 is the incident beam polarization (see Fig. 1).

The polarization P can be decreased down to zero by the choice of such a crystal thickness L_0 that makes the spin rotation angles equal to $\pm\pi/2$. Theoretical calculation for (110)-planes of α-quartz gives $L_0 = 3.6$ cm.

The existence of the neutron EDM leads to a slight polarization P_h along $\mathbf{H}_g^S$, equal to

$$P_h = \frac{4DE_g L_0}{\pi\hbar v_\parallel} = \frac{4D}{\pi\mu} \cdot \frac{c}{v\cos\theta_B} \propto \frac{1}{\pi/2 - \theta_B}, \tag{6}$$

because $\cos\theta_B \propto \pi/2 - \theta_B$ for $\theta_B \to \pi/2$. Here D is the neutron EDM. The turn of the crystal by the angle $2\theta_B$ (see Fig. 1) will change the P_h sign but will not do that for residual polarization. That gives the possibility to select the EDM effect.

As it follows from (4) the effect due to the Schwinger interaction does not depend on such neutron properties as the energy, wave length and the Bragg angle. It is determined by the property of a crystal and by the fundamental constants only. For a given crystal it is the same for any Bragg angles. That gives an additional way to eliminate the Schwinger interaction by measuring for two Bragg angles, for example. The EDM effect (6) (in contrast to the Schwinger one) depends on the Bragg angle. It essentially increases for $\theta_B \to \pi/2$.

3 Measurement of the neutron stay time in crystal

The scheme of experimental setup is shown in Fig. 2a [35]. The neutron beam formed by neutron guides 1,2 is diffracted by the noncentrosymmetric α-quartz crystal 6 (the reflecting (110) planes are normal to the large crystal surfaces) and is registered by the detectors 11.

[5]The ways of possible improving the UCN-method are discussed [34].

[6]This result is obtained averaging the Pendellösung oscillations over Bragg angles. The angular period of this oscillations in our case is $\sim 10^{-5}$ rad and the angular divergence of the neutron beam is $\sim 10^{-2}$ rad.

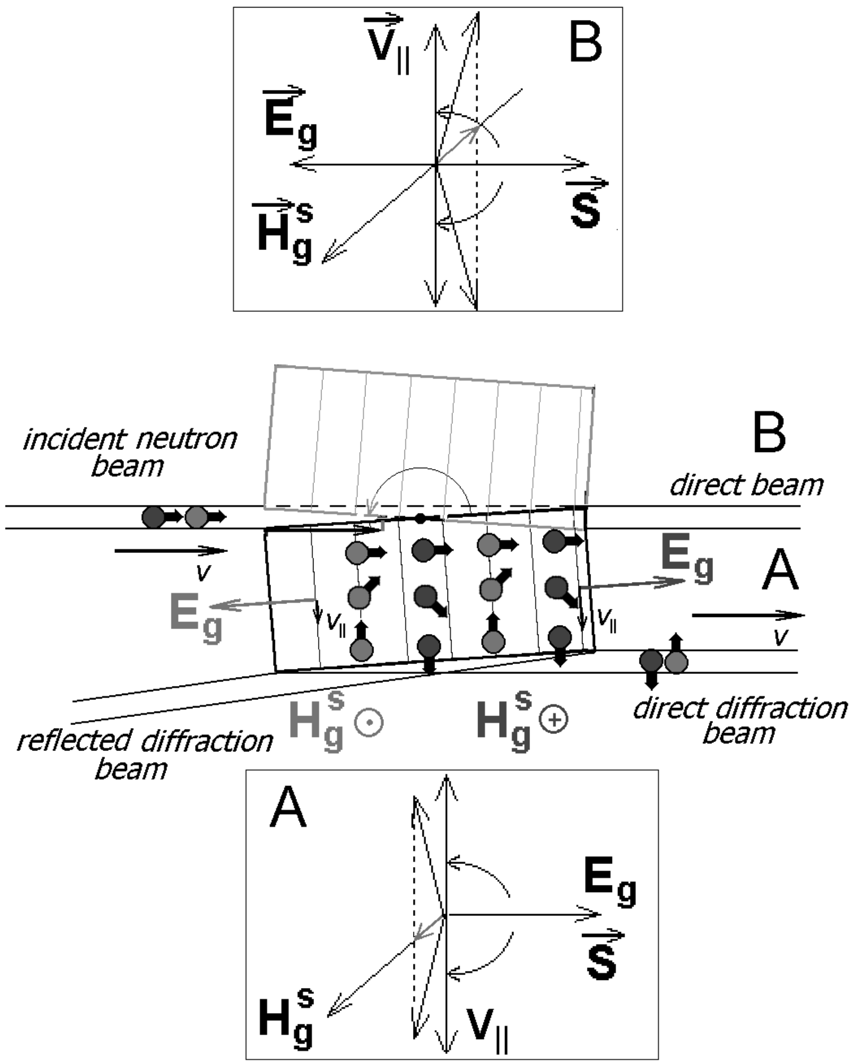

Figure 1: For Bragg angle close to $\pi/2$ the neutrons inside the crystal are moving along the crystallographic planes almost perpendicular to the incidence direction (it leads, in particular, to essential increasing of the time of neutron stay in crystal). The spins of moving neutron for two Bloch neutron states (concentrated on and between "nuclear planes") will rotate in opposite direction under opposite fields. When the angles of spin rotation become equal to $\pi/2$, the both diffracted neutron beams will be depolarized entirely. The existence of EDM will lead to a slight polarization along Schwinger magnetic field

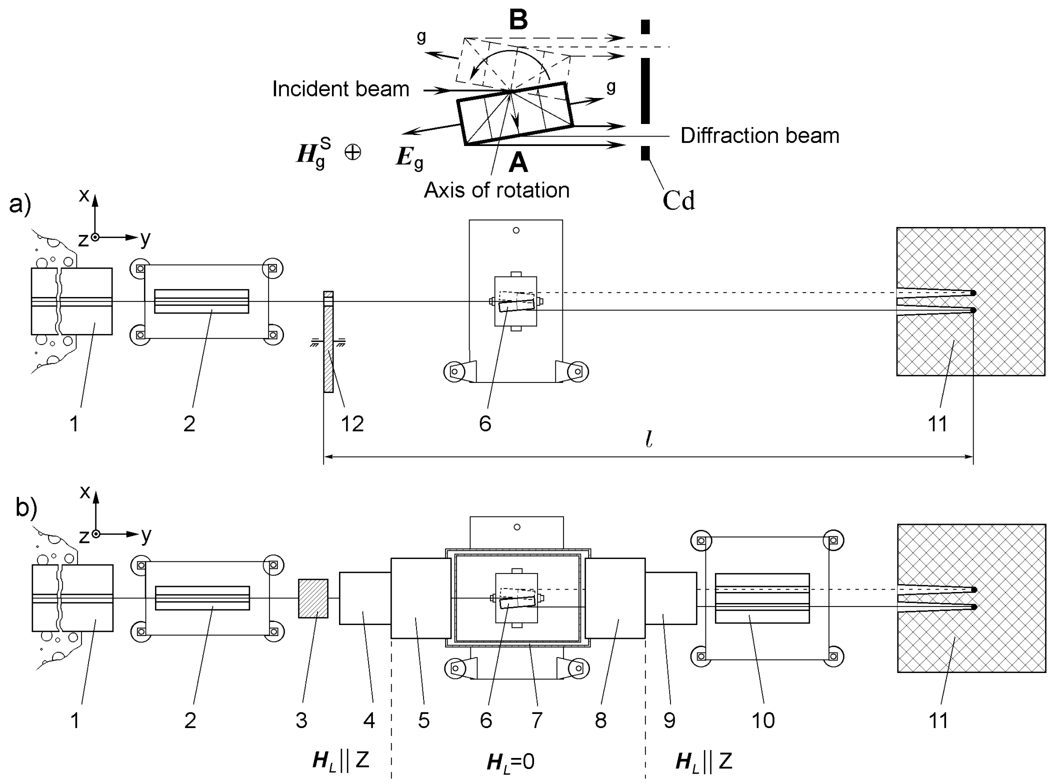

Figure 2: Two modifications of the experimental set-up: **a)** for time-of-flight measurement, **b)** for measurement of the depolarization effect. **1** is a reactor interchannel neutron guide, **2** is a multislit polarizing neutron guide, **3** is BeO filter (120 mm), **4,9** are spin-guide coils, **5,8** are spin-rotation coils, **6** is the α-quartz single crystal, (sizes are $14 \times 14 \times 3.5$ cm^3), **10** is a double multislit polarizing neutron guide, **11** are neutron detectors, **12** is the beam chopper. **A** and **B** are two crystal positions with the same Bragg angles, **g** is the reciprocal lattice vector for the (110)-plane, $\mathbf{H_L}$ is the guiding magnetic field, l is the TOF length

All neutrons diffracted by the different crystallographic plane systems (for which the Bragg conditions are satisfied) give the contribution to intensity of the direct diffracted beam. To select the specified reflection, we used the TOF technique. The mechanical chopper of beam 12 was placed before the crystal. The typical TOF spectrum is given in Fig. 3. The peaks corresponding to neutrons diffracted by the different crystallographic planes are well visible in the figure.

If the crystal is located between the beam chopper and detector of neutrons, the total time of flight of neutron with the wave length $\lambda = 2d\sin\theta_B$ will be:

$$\tau_f = \tau_l + \tau_L = \frac{l}{v} + \frac{L}{v\cos\theta_B} = \frac{dm}{\hbar\pi}(l\sin\theta_B + L\,\mathrm{tg}\,\theta_B), \qquad (7)$$

where τ_l is the neutron time of flight for a distance l, τ_L is the time the neutron spends in crystal (L is the thickness of crystal, θ_B is the Bragg angle, for (110) plane α-quartz

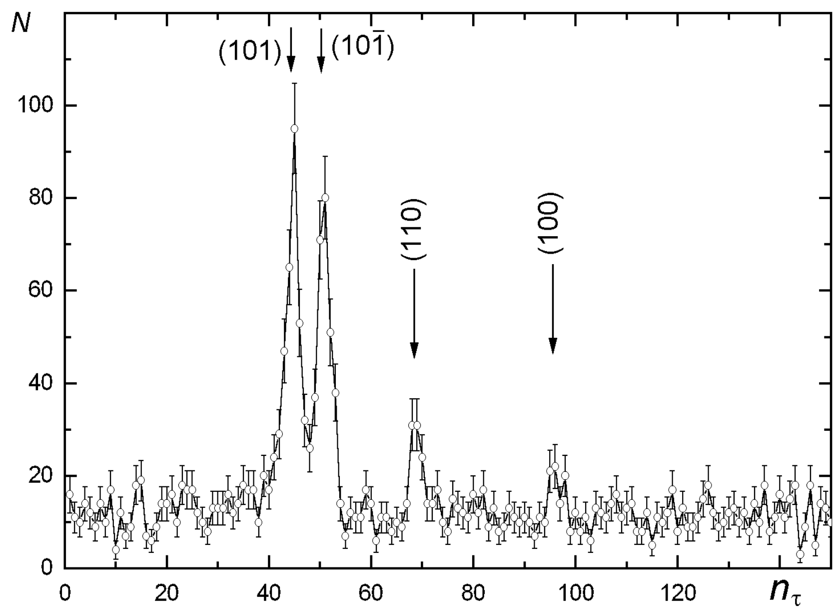

Figure 3: TOF spectrum of the direct diffracted neutrons for Bragg angle $\theta_B = 75°$. n_τ is the order number of the TOF channel. The width of the TOF channel is equal $\simeq 51.2$ μs. N is the number of accumulated events

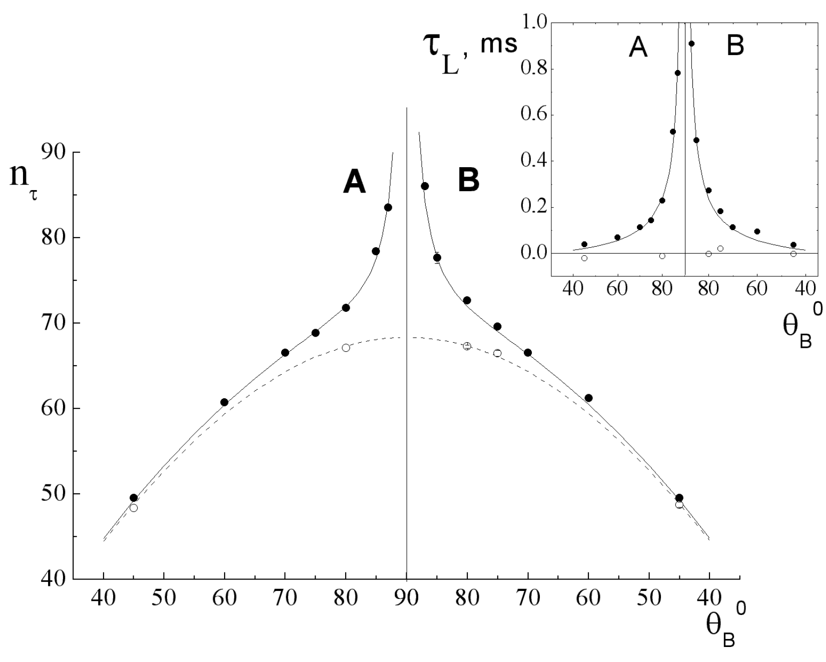

Figure 4: Dependence of the neutron TOF on the Bragg angle for direct diffracted beam

$d = 2.4564$Å). As follows from (7) the time τ_L of a neutron delay in crystal depends on the Bragg angle as $\mathrm{tg}\,\theta_B$, while the TOF τ_l as $\sin\theta_B$, so τ_L may give a very essential contribution to total TOF of neutrons τ_f for θ_B close to $\pi/2$, because $\tau_L/\tau_l \simeq L/[l(\pi/2-\theta_B)]$.

A dependence on the Bragg angle of the neutron TOF for direct beam diffracted by the (110)-plane is given in Fig. 4.

A solid curve describes the calculated dependence $\tau_f(\theta_B)$ (see (7)), and the dotted curve does that for $\tau_l(\theta_B)$. One can see a good agreement between experimental (black points) and theoretical dependencies $\tau_f(\theta_B)$. A control experiment, when the chopper of a neutron beam was placed between the crystal and detector, was also carried out. In this case the delay of neutron in the crystal does not give a contribution to the measured value and the position of the line $\tau_l(\theta_B)$ for (110)-reflection should coincide with the dotted curve. That is what we have observed experimentally (open points). On insertion in Fig. 4 the theoretical and experimental dependencies $\tau_L(\theta_B)$ are shown.

So the experiment has shown that the time of neutron delay in crystal is not determined by full velocity of neutrons v, but its component $v_\parallel$ along the crystallographic plane. In particular, for $\theta_B = 87°$ we have $\tau_L = (0.90 \pm 0.02)$ ms and $v_\parallel = (39 \pm 1)$ m/s, while $v = 808$ m/s.

4 Measurement of the depolarization effect

The scheme of experimental setup is shown in Fig. 2b [36, 37]. The polarization vector of a neutron after passage through the polarizing neutron guide 2 and filter 3 is directed along $\mathbf{H}_g^S$ by coil 4, then it turns round by the angle α by the coil 5. If the crystal does not influence the spin orientation, then the polarization vector will be restored in the initial direction along the axis $\mathbf{H}_g^S$ by the coil 8. The behaviour of the neutron spin for the case $\alpha = 90°$ is shown in Fig. 5. Fig. 5 and Fig. 2 have the same coordinate system (X, Y, Z).

To observe the effect of depolarization of diffracted neutrons the dependence on the angle α of a neutron beam intensity after the analyzer 10 was studied. The analyzer transmits the neutrons with the polarization parallel to $\mathbf{H}_g^S$ only. The measurements are similar to those, using a spin-echo technique.

The polycrystalline BeO filter of a 120 mm thickness 3 was placed in the beam to reduce the contribution of the background reflections (see Fig. 3). The residual contribution of them was estimated to be $\simeq (20 \pm 10)\%$ of the useful intensity of neutrons diffracted by the (110) plane. The uncertainty of this contribution results in a systematic error of a measured value.

If the neutron spins turn round in the crystal by the angles $\pm\Delta\phi_0^S$ for $\psi^{(1)}$ and $\psi^{(2)}$ waves, the dependence on the angle α of counting rate N in the detectors after the analyzer will be:

$$N = N_0(1 + P_Z) = N_0(1 + P_0(\cos\Delta\phi_0^S \sin^2\alpha + \cos^2\alpha)), \tag{8}$$

where P_Z is the projection of a neutron polarization on the direction $\mathbf{H}_g^S$. One can see, that $P_Z \equiv P_0$ and N does not depend on the angle α for the case $\Delta\phi_0^S = 0$. The value of initial polarization of neutrons with the wave-length $\lambda \simeq 4.8$Å, corresponding to Bragg angles $\theta_B \geq 84°$ for (110) plane was $P_0 = (87 \pm 3)\%$. The example of dependence $N(\alpha)$ is shown in Fig. 6. The corresponding value of polarization P_Z is shown on the left axis of ordinates. The solid curve in Fig. 6 is a result of fitting of experimental points by the theoretical dependence (8).

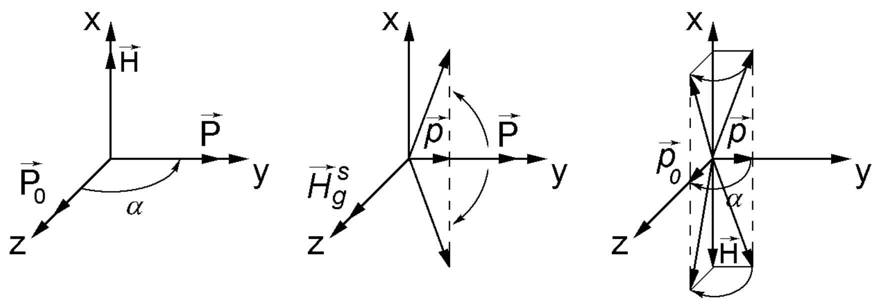

Figure 5: The behaviour of the diffracted neutron spin for the case $\alpha = 90°$

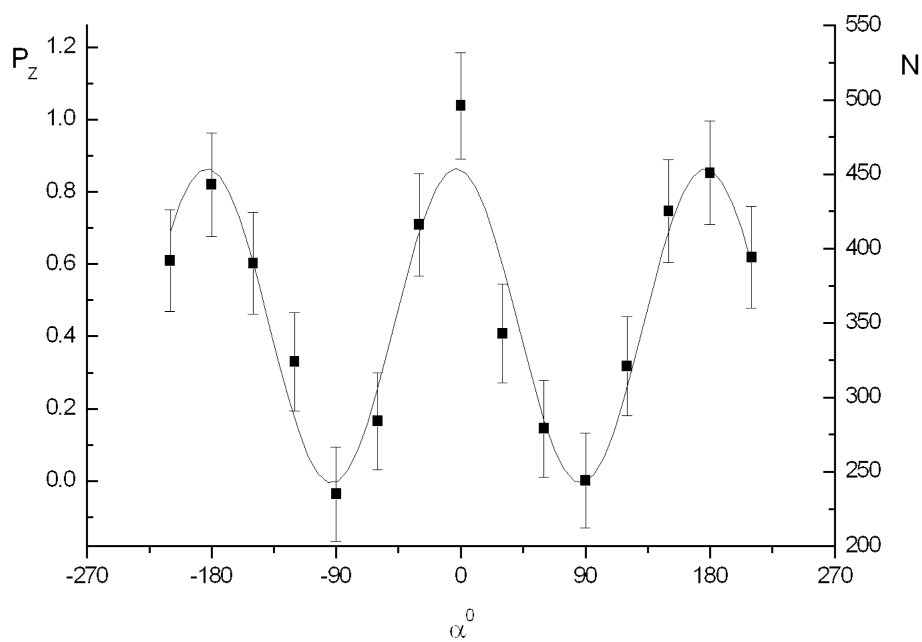

Figure 6: Example of dependence of neutron intensity N on an angle $\alpha°$ between Schwinger magnetic field $\mathbf{H}_g^S$ and vector of polarization of incident neutrons for Bragg angle $\theta_B = 84°$

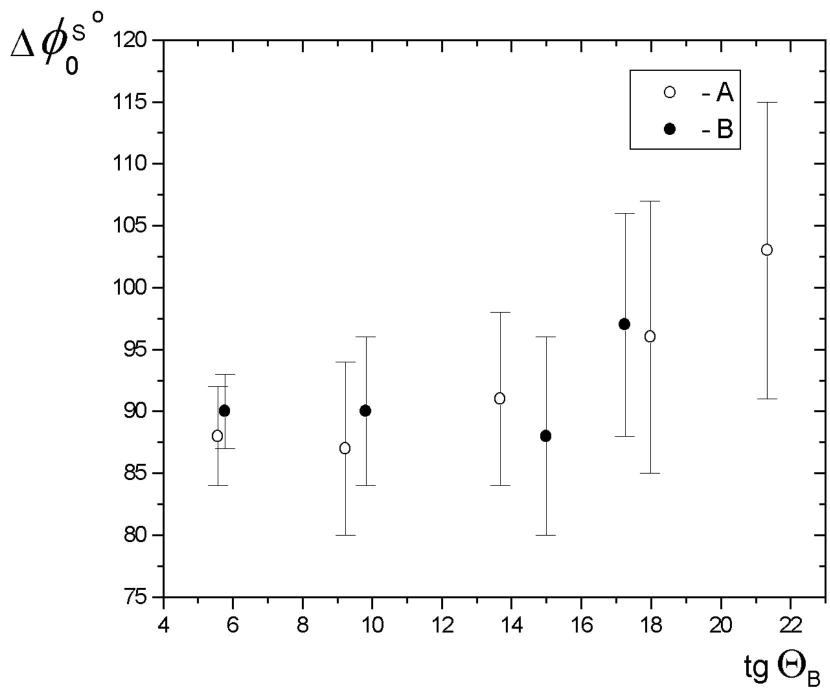

Figure 7: The dependence of an angle of neutron spin rotation due to Schwinger interaction $\Delta\phi_0^S$ on the tangent of Bragg angle. **A** and **B** – two crystal positions (see Fig. 1 and Fig. 2)

As it has been noted earlier [15, 16], the angle of neutron spin rotation due to Schwinger interaction doesn't depend on the Bragg angle, and that is experimentally proved (see Fig. 7).

The experimentally observed result corresponds to an interplanar electric field, acting on a diffracted neutron, equal to

$$E_{(110)} = (2.24 \pm 0.05(0.20))10^8 \text{ V/cm}. \quad (9)$$

The systematic error caused by uncertainty of the contribution of background reflections is pointed in parentheses.

The experimental values are in good agreement with the earlier theoretical predictions and confirm the opportunity to increase more than by an order of magnitude the sensitivity of the method to neutron EDM, using the angles of diffraction close to 90°. It is experimentally shown that the value $E\tau$ determining the sensitivity of the method in our case can reach $\sim 0.2 \cdot 10^6$ V s/cm, what is comparable with that of the UCN method ($\sim 0.6 \cdot 10^6$ V s/cm)[13] and much more than the value obtained by Shull and Nathans ($\sim 0.2 \cdot 10^3$ V s/cm)[18]. The comparison with the magnetic resonance method using ultracold neutrons (UCN-method) [11–13] is given in Table 1.

The calculated values of the maximum electric fields E_g and the times $\tau_a = l_a/v_\parallel$ the neutrons can stay in the crystals (l_a is the absorption length) are given in the Table 2 for a few noncentrosymmetric crystals. One can see that using of other crystals may enhance the sensitivity of the diffraction method to neutron EDM more than an order of magnitude.

Table: 1. The comparison of the Laue diffraction method with the UCN one. The intensity for the Laue diffraction scheme is calculated for the cold neutron channel of the ILL reactor. The crystal dimensions are $3.5 \times 14 \times 25$ cm^3. The (110) crystallographic plane system is using (2d=4.9 Å) and $\theta_B = 87°$ ($\pi/2 - \theta_B \simeq 1/20$)

	UCN-method [13]	Laue diffraction method [37]
E, kV/cm	4.5	$2.2 \cdot 10^5$
t, s	130 (v =5-6 m/s)	$0.9 \cdot 10^{-3}$ ($v_\parallel = 40$ m/s)
Et, kV s/cm	585	200
N, neutrons/s	60	$1 \cdot 10^4$
σ_D, e·cm per day	$6 \cdot 10^{-25}$	$1.5 \cdot 10^{-25}$

Table: 2. The characteristics of some crystals suitable for the neutron EDM search. The group symmetries for crystals are given for room temperature

Crystal	Symmetry Group	hkl	d, Å	E_g, 10^9V/cm	τ_a, ms	$E_g\tau_a$, kV s/cm
α-quartz	$32(D_3^6)$	111	2.236	0.23	1.0	230
(SiO_2)		110	2.457	0.20		220
$Bi_{12}GeO_{20}$	$I23$	433	1.739	0.52	0.9	468
		312	2.711	0.24		216
$BaTiO_3$	$4mm$	004	1.008	0.96	0.03	30
		002	2.016	0.57		17
$PbTiO_3$	$4mm$	$41\bar{1}$	0.923	1.78	0.03	53
		002	2.075	1.42		43
BeO	$6mm$	011	2.06	0.54	7.0	3700
		201	1.13	0.65		4500
$LiTaO_3$	$3m$	$\bar{4}44$	1.061	1.38	0.003	4
		006	2.297	0.92		3

5 Neutron optics in a noncentrosymmetric crystal

Here we shall consider the neutron-optic effects for neutron passage through the noncentrosymmetric crystal for the case, when the deviation from the exact Bragg condition reaches $(10^3 \div 10^5)$ of Bragg width.

The essence of the phenomenon is the following. Let a neutron is moving through the crystal and the Bragg condition isn't satisfied for any crystallographic plane. In this case the distribution of the neutron density $|\psi(\mathbf{r})|^2$ in the crystal can be written using a perturbation theory [38]:

$$|\psi(\mathbf{r})|^2 = 1 + \sum_g \frac{2v_g}{E_k - E_{k_g}} \cos(\mathbf{gr} + \phi_g), \tag{10}$$

where E_k and E_{k_g} are the energies of the neutron with the wave vectors $\mathbf{k}$ and $\mathbf{k}+\mathbf{g}$, the values v_g, ϕ_g are respectively the amplitude and the phase of g-harmonics of the interaction neutron-crystal potential, which has a form $V(\mathbf{r}) = \sum_g V_g \exp i(\mathbf{gr}) = V_0 + \sum_g 2v_g \cos(\mathbf{gr} + \phi_g)$. Difference $E_k - E_{k_g}$ describes the deviation from the Bragg condition measured in the energy units. One can see that the neutrons are concentrating either on the maxima or on the minima of the periodic potential, depending on the sign of $E_k - E_{k_g}$ (see Fig. 8,9), the degree of this concentration being determined by the value of $E_k - E_{k_g}$. So the neutron kinetic energy in crystal will be equal to

$$\tilde{E}_k = E - V_0 - \sum_g \frac{V_g V_{-g}}{E_k - E_{k_g}}, \tag{11}$$

where $E = \hbar^2 k_0^2/2m$ is the energy of incident neutron. As follows from (11), the neutron, moving through the crystal far from the Bragg directions, nevertheless, "feels" the crystal structure.

For the case of non-magnetic nonabsorbing crystal the expression for V_g can be written as [38]:

$$V_g = v_g^N e^{i\phi_g^N} + iv_g^E e^{i\phi_g^E} \mu \frac{\boldsymbol{\sigma}[\mathbf{g} \times \mathbf{v}]}{c}, \tag{12}$$

where v_g^N, ϕ_g^N are respectively the amplitude and the phase of g-harmonic of the nuclear interaction potential of neutron with crystal, v_g^E, ϕ_g^E are the amplitude and the phase of g-harmonic of the electric potential of crystal, μ, v are the magnetic moment and the velocity of neutron, c is the light speed.

By substituting this expression into (11) and taking into account that for non-absorbing crystal $V_g = V_{-g}^*$, we shall obtain[7]:

$$\tilde{E}_k = E - V_0 - \sum_g \frac{(v_g^N)^2}{E_k - E_{k_g}} - \mu \frac{\boldsymbol{\sigma}[\mathbf{E}_{sum} \times \mathbf{v}]}{c}, \tag{13}$$

where

$$\mathbf{E}_{sum} = \sum_g \frac{2v_g^N}{E_k - E_{k_g}} v_g^E \sin(\Delta\phi_g)\mathbf{g} \tag{14}$$

is a resultant electric field affecting a neutron in the crystal. Here $\Delta\phi_g \equiv \phi_g^N - \phi_g^E$ is the phase shift between g-harmonics of nuclear and electric potentials of crystal.

[7] We note that the neutron refraction index n in this notations is $n = k/k_0 = \sqrt{\tilde{E}_k/E}$.

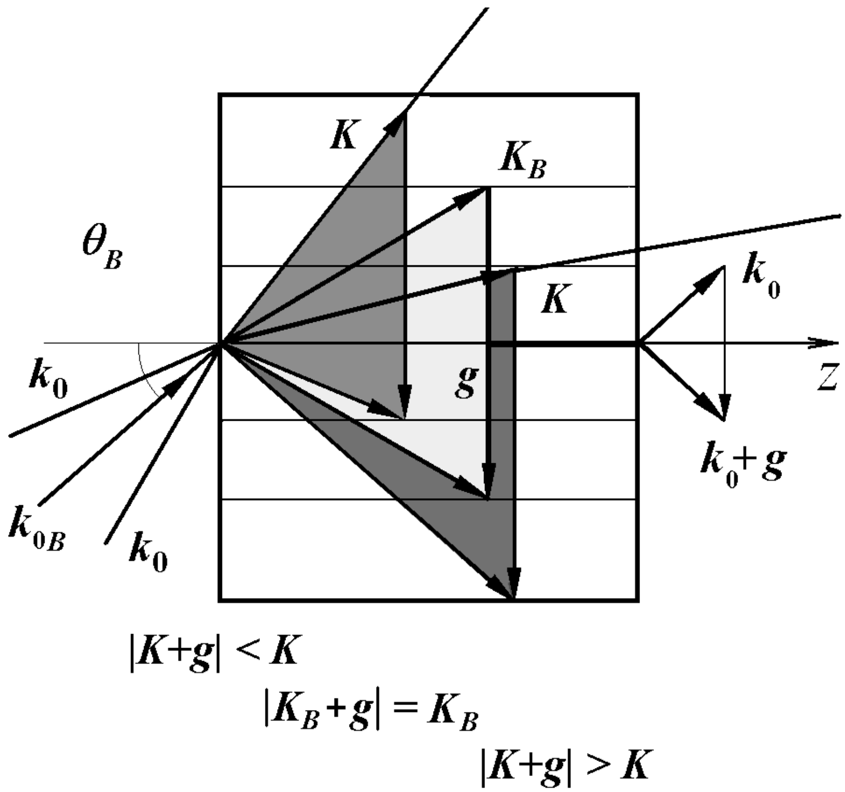

Figure 8: Scheme of the neutron movement in the crystal with the wave vectors $\mathbf{K}$ of different directions with respect to reciprocal vector $\mathbf{g}$ characterized some system of crystallographic planes. a) $|\mathbf{K}+\mathbf{g}| > K$ (neutrons are concentrated at the "nuclear planes" (maxima of nuclear potential)). b) $|\mathbf{K}+\mathbf{g}| < K$ (neutrons are concentrated between the "nuclear planes". These two cases correspond to neutron optics. c) The third case $|\mathbf{K}+\mathbf{g}| = K$ corresponds to the neutron diffraction, when the both kinds of wave excited in the crystal. Neutrons in the crystal are propagating along the planes in this case, and there are two beams direct and reflected after the crystal

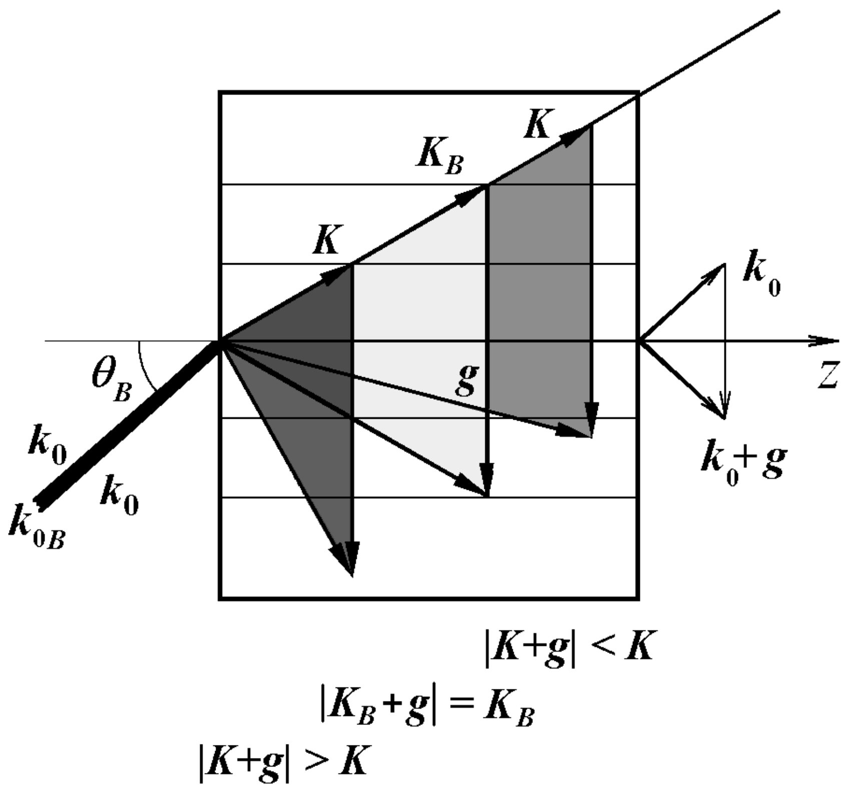

Figure 9: Scheme of the neutron movement in the crystal with the wave vectors $\mathbf{K}$ of given direction but of different absolute values (different wave lengths). The same three cases as in the Fig. 8 $|\mathbf{K}+\mathbf{g}| > K$, $|\mathbf{K}+\mathbf{g}| < K$ and $|\mathbf{K}+\mathbf{g}| = K$

For the centrosymmetric crystal $\Delta\phi_g \equiv 0$ and therefore $\mathbf{E}_{sum} \equiv 0$.

For noncentrosymmetric crystal $\Delta\phi_g \neq 0$ and the electric field acting on a neutron can be nonzero $\mathbf{E}_{sum} \neq 0$. Therefore a spin dependence arises for the neutron-crystal interaction potential, which will result in a neutron spin rotation around the direction $\mathbf{H}_{sum} = [\mathbf{E}_{sum} \times \mathbf{v}]/c$. The rotation angle for the crystal length $L = 1$ cm will be

$$\Delta\varphi = \frac{2\mu}{\hbar v} \frac{\boldsymbol{\sigma}[\mathbf{E}_{sum} \times \mathbf{v}]}{c}. \tag{15}$$

To describe the absorbing crystal one should add an image part into the nuclear potential of crystal:

$$V_g = v_g^N e^{i\phi_g^N} + i v_g^{N'} e^{i\phi_g^{N'}} + i v_g^E e^{i\phi_g^E} \mu \frac{\boldsymbol{\sigma}[\mathbf{g} \times \mathbf{v}]}{c}, \tag{16}$$

where $v_g^{N'}, \phi_g^{N'}$ is the amplitude and phase of g-harmonic of the image part of nuclear potential.

Then $\tilde{E}_k$ becomes equal to:

$$\tilde{E}_k = E - V_0 - V_{\langle g \rangle} - i(V_0' + V_{\langle g \rangle}') - \mu \frac{\boldsymbol{\sigma}[(\mathbf{E}_{sum} + i\mathbf{E'}_{sum}) \times \mathbf{v}]}{c}, \tag{17}$$

where

$$V_{\langle g \rangle} = \sum_g \frac{(v_g^N)^2 - (v_g^{N'})^2}{E_k - E_{k_g}}, \tag{18}$$

$$V_{\langle g \rangle}' = \sum_g \frac{2 v_g^N v_g^{N'} \cos(\phi_g^N - \phi_g^{N'})}{E_k - E_{k_g}}, \tag{19}$$

$$\mathbf{E'}_{sum} = \sum_g \frac{2 v_g^{N'}}{E_k - E_{k_g}} v_g^E \sin(\phi_g^{N'} - \phi_g^E)\mathbf{g}. \tag{20}$$

The estimations give that the values of the diffraction corrections to a mean potential for α-quartz crystal are $V_{\langle g \rangle} + iV_{\langle g \rangle}' \approx 10^{-3}(V_0 + iV_0')$,
$\mu\boldsymbol{\sigma}[(\mathbf{E}_{sum} + i\mathbf{E'}_{sum}) \times \mathbf{v}]/c \approx 10^{-6}(V_0 + iV_0')$ for the wide range of the incident neutron wavelengths and sharply increase near the Bragg conditions.

6 Observation of neutron spin rotation

Scheme of the experiment is shown in a Fig. 10. Initially the neutron spin was directed along the neutron velocity (axis Y). The X-component of the polarization was measured after neutron passage through the crystal. This component should be equal to zero, if the spin rotation effect is absent. Time of flight technique was used for measuring the spectral dependence of polarization. The crystal was overturned around Z axis to eliminate the false effect due to nonzero value of the X-component of polarization for real setup. It is equivalent to replacement of $\mathbf{v}$ to $-\mathbf{v}$. The effect changes its sign in this case (see (15)).

The measurement was carried out using the α-quartz crystal with the dimensions $14 \times 14 \times 3.5$ cm^3. The direction of the neutron velocity in the laboratory coordinate system (X,Y,Z) and the crystallographic one (Z',X_1,X_2,X_3) is shown in Fig. 11. The crystallographic

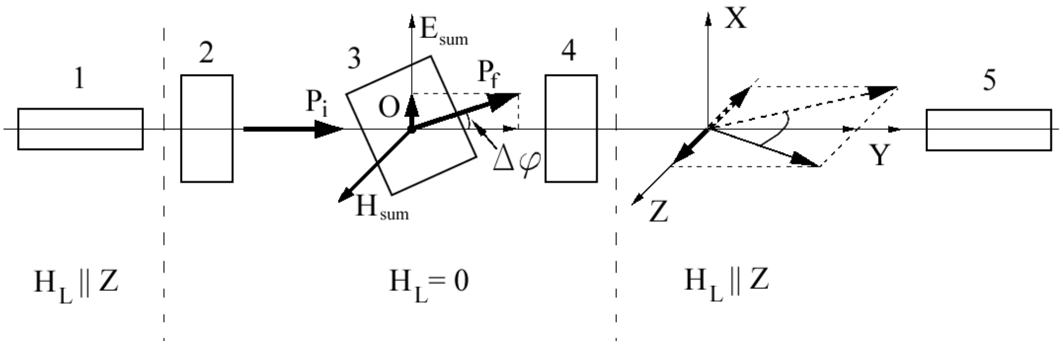

Figure 10: Scheme of the experiment. 1 is a polarizer; 2 is $\pi/2$ coil around X axis; 3 is α-quartz monocrystal with sizes $14 \times 14 \times 3.5$ cm^3; 4 is $\pm\pi/2$ coil around Y axis; 5 is an analyzer. $\mathbf{H}_L$ is a guiding magnetic field; $O \| Z$ is an axis of a crystal rotation; $\mathbf{P}_i$ and $\mathbf{P}_f$ are the polarization of neutron beam before and after the crystal correspondingly

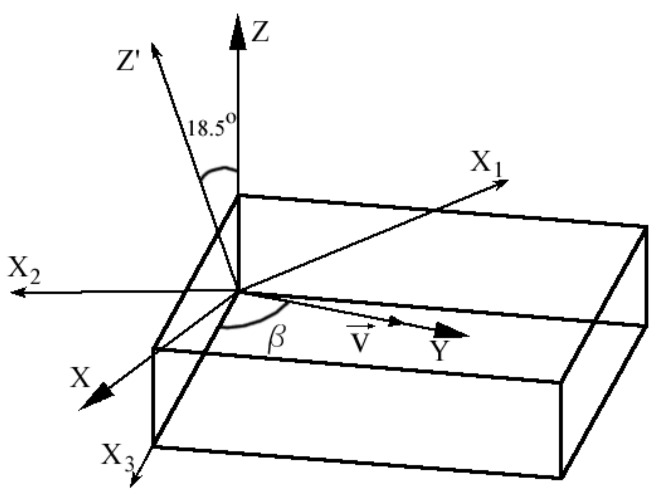

Figure 11: Crystal orientation

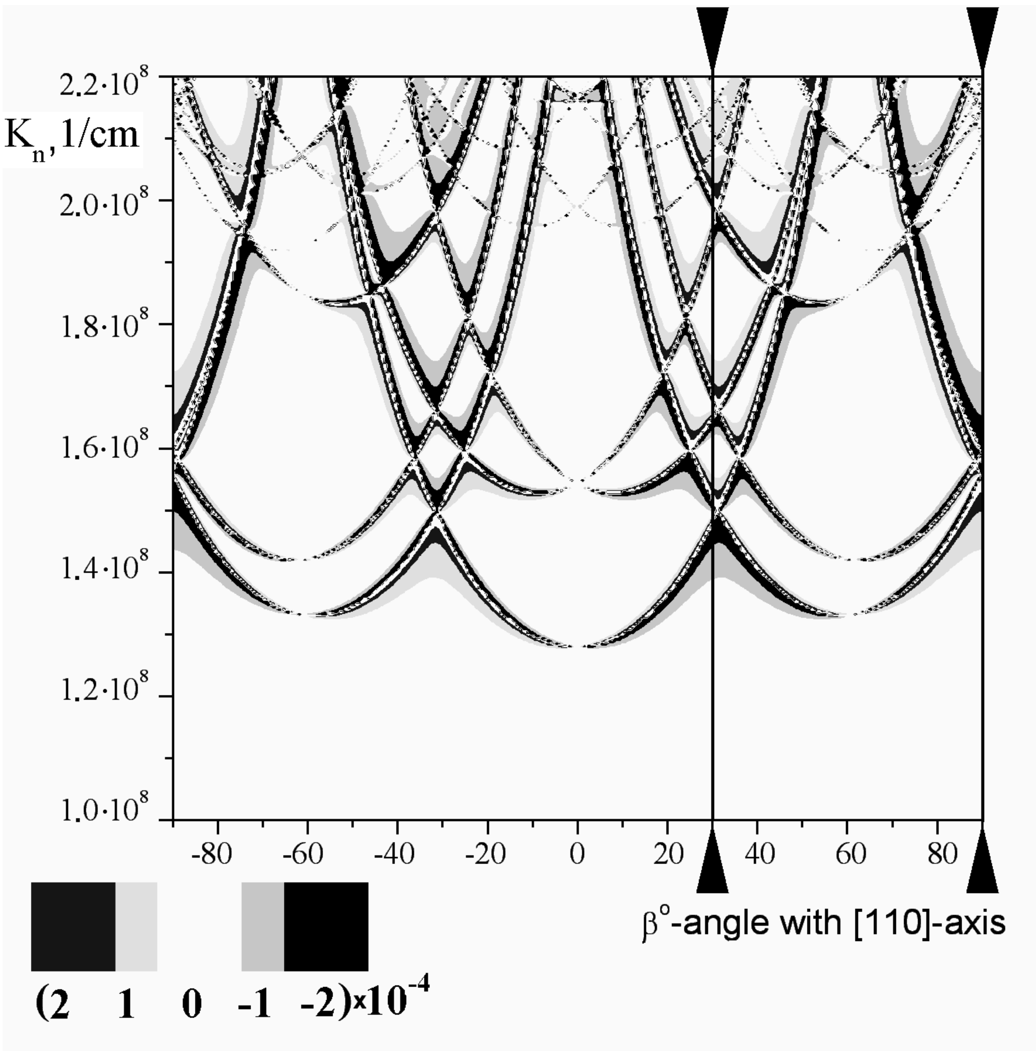

Figure 12: Theoretical dependence of $\Delta\varphi$ on the wavevector and direction of neutron for the α-quartz crystal (see Fig. 2)

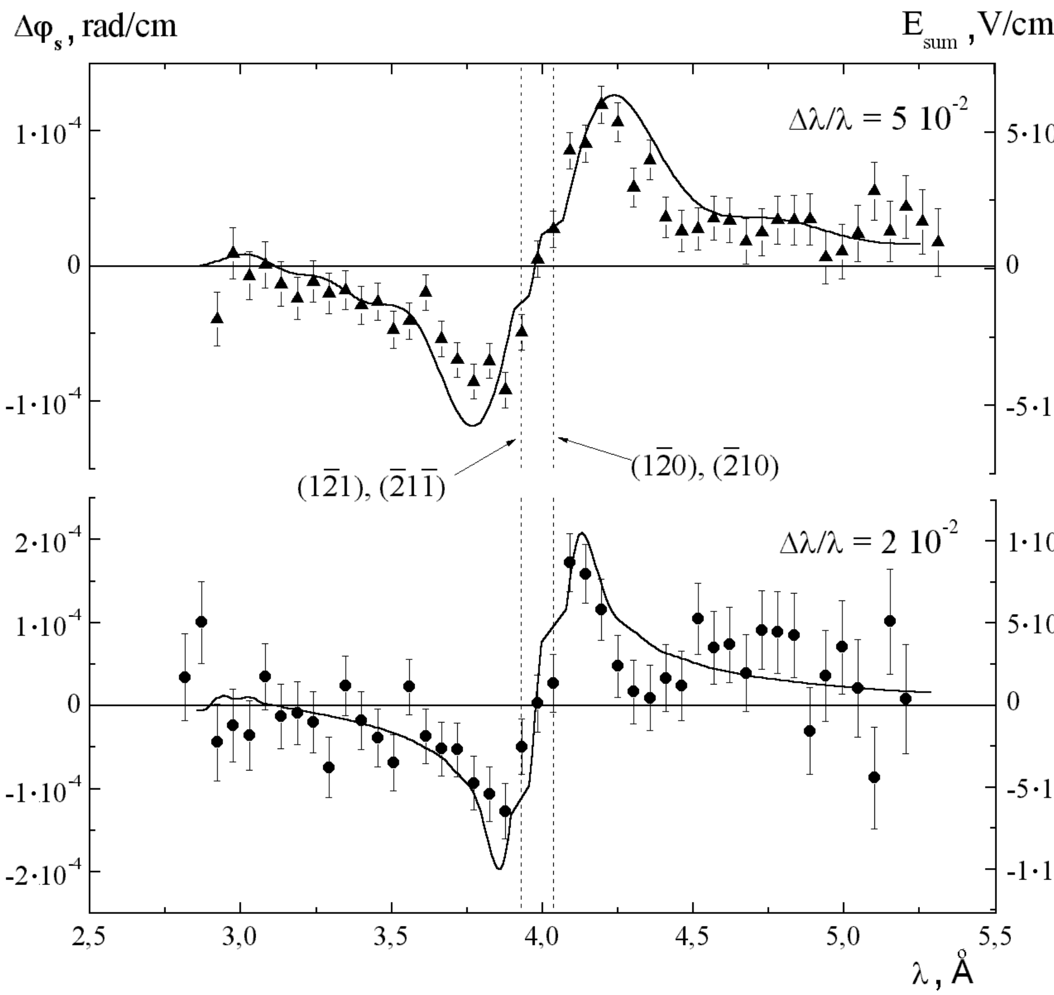

Figure 13: Energy dependence of $\Delta\varphi$ for $\beta = 90°$

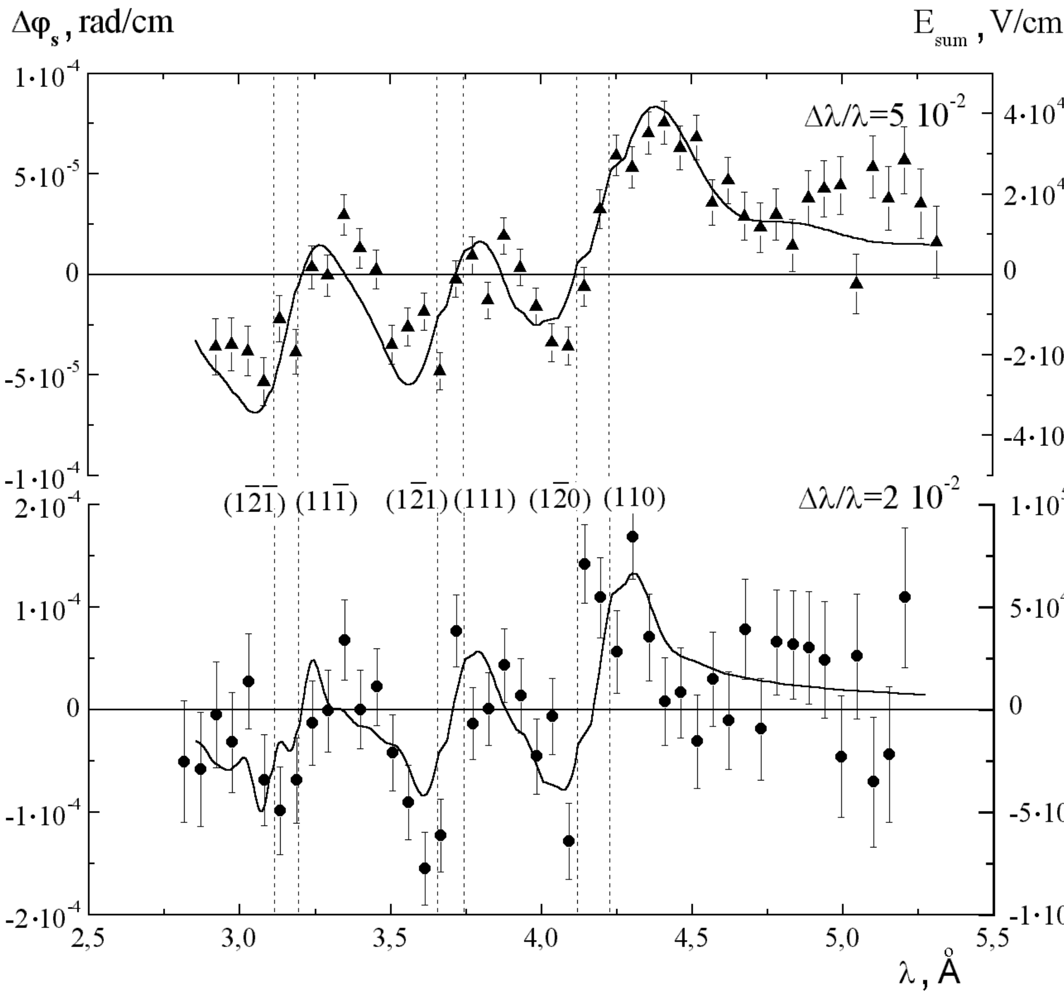

Figure 14: Energy dependence of $\Delta\varphi$ for $\beta = 30°$

system was turned relative to the laboratory one by 18.5°. The angle of crystal orientation β was measured from the [110] axis (X_3) direction.

The theoretical dependence of the angle of neutron spin rotation $\Delta\varphi$ on the value and direction of neutron wavevector is shown in Fig. 12.

The experiment was carried out for two crystal positions with $\beta = 90°$ and 30° pointed by arrows in Fig. 12. The results are shown in Fig. 13, 14. Two plots at the figures correspond to different energy resolution of the experiment ($\Delta\lambda/\lambda = 5 \cdot 10^{-2}$ and $= 2 \cdot 10^{-2}$). The solid curves reproduce the theoretical dependencies (15) averaged over energy resolution. The dotted lines indicate the positions of the crystallographic planes with nonzero value of $\Delta\phi_g$ (see (14)). One can see a well agreement between theoretical and experimental results. The resultant electric field $|\mathbf{E}_{sum}|$ is shown on the right ordinates axis. Its value $|\mathbf{E}_{sum}| \approx (1 - 10) \cdot 10^4$ V/cm for any point of spectrum and accordingly $\Delta\varphi$ may achieve $\pm 2 \cdot 10^{-4}$ rad/cm.

7 Conclusions

The first experimental study of some new phenomena for neutron diffraction and optics in the noncentrosymmetric crystal was carried out, using the set-up created for a search for a neutron electric dipole moment (EDM) by crystal-diffraction method.

For the first time the neutron dynamical Laue diffraction for the Bragg angles close to the right one (up to 87°) was studied, using the direct diffraction beam and the thick (~ 3.5 cm) crystal.

The effect of an essential time delay of the diffracting neutrons inside the crystal for Bragg angles close to 90° was experimentally observed. For (110)-plane of α-quartz and $\theta_B = 87°$ we have got $\tau_L = (0.90 \pm 0.02)$ ms that corresponds to $v_{\|} = (40 \pm 1)$ m/s, while $v = 808$ m/s.

The predicted earlier phenomenon of the neutron beam depolarization was first experimentally observed for the case of Laue diffraction in noncentrosymmetric α-quartz crystal. It is experimentally proved that the interplanar electric field, affecting the neutron in crystal, maintains its value up to Bragg angles equal to 87°.

It is shown experimentally that the value $E\tau$ determining the sensitivity of the method in our case can be $\sim 2 \cdot 10^5$ V s/cm that is comparable with that for the UCN method ($\sim 6 \cdot 10^5$ V s/cm)[13] and much more than the value obtained by Shull and Nathans ($\sim 2 \cdot 10^2$ V s/cm)[18] and also than that of [39] ($\sim 1.2 \cdot 10^3$ V s/cm)[8].

These results give the opportunity to propose the Laue diffraction method for a neutron EDM search with the sensitivity $\sim 10^{-25}$e·cm per day for really existing α-quartz crystal (see Table 1). The use of the other crystals may allow to improve the sensitivity of the method by about one order of magnitude and to reach $\sim 10^{-26}$e· cm per day.

The effect of the spin rotation due to Shwinger interaction of the magnetic moment of moving neutron with an interplanar electric field of the noncentrosymmetric crystal was experimentally observed for neutron, passing through the crystal far from any Bragg condition.

[8] One can consider the measurements of the depolarization as a first preliminary and rough measurements of a neutron EDM, which gives the result $D < 10^{-22}$ e·cm that is some better than the old Shull's and Nathans's result [18]. The result obtained in magnetic resonance method using cold neutrons [39] was $D < 3 \cdot 10^{-24}$ e·cm.

For α-quartz crystal the value of the spin rotation angle can reach $\pm(1-2)\cdot 10^{-4}$ rad/cm that corresponds to the value of resultant electric field equal to $\pm(0.5-1)\cdot 10^5$ V/cm.

We note also that the presence of the terms (19) and (20) in equation (17) should result in dependence of an imaginary part of nuclear interaction (absorption) on direction and value of a neutron wave vector as well as on a neutron spin orientation.

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