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Measurement of the neutron electric dipole moment by crystal diffraction

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ABSTRACT

An experiment using a prototype setup to search for the neutron electric dipole moment by measuring spin rotation in a non-centrosymmetric crystal (quartz) was carried out to investigate statistical sensitivity and systematic effects of the method. It has been demonstrated that the concept of the method works. The preliminary result of the experiment is $d_n = (2.5 \pm 6.5) \times 10^{-24}$ e cm. The experiment showed that an accuracy of $\sim 2.5 \times 10^{-26}$ e cm can be obtained in 100 days data taking, using available quartz crystals and neutron beams.

1. Introduction

The electric dipole moment of the neutron (nEDM) is a very sensitive probe for CP violation beyond the Standard Model of particle physics [1,2]. The most precise experiments today use Ramsey's resonance method and ultra-cold neutrons (UCNs) [3,4]. Further progress is presently limited by systematics [5] and the low density of UCNs available. Here we discuss an alternative approach based on spin rotation in non-centrosymmetric crystals.

The statistical sensitivity of any experiment to measure the nEDM is determined by the product $E\tau\sqrt{N}$, where τ is the duration of the neutron interaction with the electric field E and N the number of the counted neutrons. New projects to measure the nEDM with UCNs aim to increase the UCN density and thus N by orders of magnitude (see Ref. [6] for a recent overview). In contrast, experiments with crystals exploit the electric field inside matter, which for some crystals can be by a few orders of magnitude higher than the electric field achievable in vacuum.

EDM experiments with absorbing crystals were pioneered by Shull and Nathans [7]. Their experiment was based on the interference of the electromagnetic amplitude with the imaginary part of the nuclear one. Abov with his colleagues [8] were the first who paid attention to the presence of a spin dependent term due to the interference of nuclear and spin–orbit parts of the scattering amplitude in the interaction of neutrons with a non-centrosymmetric non-absorptive crystal. Spin rotation in non-centrosymmetric crystals due to such interference effects as a way to search for a nEDM was first discussed by Forte [9]. The corresponding spin rotation effect due to spin–orbit interaction was experimentally tested by Forte and Zeyen [10]. The authors of Refs. [11,12] have shown that the interference of the nuclear and the electromagnetic parts of the scattering amplitude leads to a constant strong electric field, acting on a neutron during all time of its movement in the non-centrosymmetric crystal. This field was measured in a Laue geometry diffraction experiment [12], in agreement with the calculated value.

The spin rotation can be measured in Bragg [9,10,13] and Laue [14–17] diffraction geometry. In this paper, we compare both geometries and present preliminary results of a test experiment in Bragg geometry. We show that the sensitivity of an optimized experiment in Bragg geometry can compete with the most sensitive published UCN nEDM measurements.

2. Comparison of Laue and Bragg diffraction geometry

A detailed recent study of a nEDM measurement in Laue geometry can be found in Ref. [18]. The main advantage of this scheme is the possibility to increase the time τ of neutron passage through the crystal using Bragg angles θ_B close to $\pi/2$ [14]. In this way, times close to the time of neutron absorption $\tau_a \approx 1$ ms were obtained in short crystals [16,19]. However, in order to suppress systematic effects due to the Schwinger interaction (spin–orbit coupling), the method relies on an effective depolarization of the neutron beam by Schwinger-rotating the two components of the neutron wave by $\pm\pi/2$. This fixes the thickness of the crystal to [17]

$$L_0 = \frac{\pi m_p c^2}{2\mu_n e E_{\mathbf{g}}}. \quad (1)$$

$E_{\mathbf{g}}$ is the electric field affecting the neutron for the exact Bragg condition for the crystallographic plane $\mathbf{g}$ ($\mathbf{g}$ is a reciprocal lattice

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vector) and m_p the proton mass [12]. Therefore the sensitivity of the method cannot be increased by using crystals with a higher electric field $E_{\mathbf{g}}$ since the crystal length and thus the time τ would need to be reduced. On the other hand, it is impossible to increase the sensitivity using Bragg angles extremely close to $\pi/2$, because of a resulting decrease of the neutron count rate for such angles [18]. In the experiment [18], also a strong sensitivity of the method to crystal deformations was found.

The main advantage of the Bragg diffraction scheme [9,13] is that the electric field acting on the neutron depends on the deviation of the neutron trajectory from the Bragg condition. This allows us to control value and even sign of the electric field and makes new tests of systematic effects possible. On the other hand, the time τ that the neutron spends in the crystal cannot be increased by using Bragg angles close to $\pi/2$ as it depends on the total neutron velocity v and not on the velocity component parallel to the crystallographic planes as in the Laue case. However, this disadvantage can be obviated by increasing the crystal thickness, in principle.

A first experiment in Bragg geometry was reported in Ref. [10], measuring the neutron spin rotation due to Schwinger interaction in quartz. The experimental value of the spin rotation angle was a few times less than the theoretical expectation [10]. The main experimental difficulty was to obtain monoenergetic neutrons with a well-defined small deviation from the Bragg condition. This was solved by placing the monochromator in a strong magnetic field, but this field may cause systematic errors.

Here we propose and use a very simple solution of the problem to obtain these monoenergetic neutrons.

3. Two-crystal scheme

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

In this case the neutron wave function inside the crystal in first order of perturbation theory can be written [20]

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

where

$$a = \frac{|V_{\mathbf{g}}|}{E_{\mathbf{k}} - E_{\mathbf{k_g}}} = \frac{|V_{\mathbf{g}}|}{\Delta E_{\mathbf{g}}}. \tag{3}$$

Here $V_{\mathbf{g}}$ is the $\mathbf{g}$-harmonic of the neutron–crystal interaction potential. For simplicity we consider the case $a \ll 1$, permitting to use perturbation theory.

The electric field acting on the neutron in the crystal is [20]

$$\mathbf{E} = \mathbf{E_g} \cdot a \tag{4}$$

where $\mathbf{E_g}$ is the interplanar electric field for the exact Bragg condition. A nonzero nEDM d_n results in neutron spin rotation by the angle

$$\varphi_{\mathrm{EDM}} = \frac{2E \cdot d_n \cdot L}{\hbar v_\perp} \tag{5}$$

where L is the length of the crystal and $v_\perp$ the component of the neutron velocity perpendicular to the crystallographic plane. Obviously, sign and value of the electric field (4) are determined by sign and value of the deviation from the exact Bragg condition $\Delta E_{\mathbf{g}}$. This is illustrated in Fig. 1.

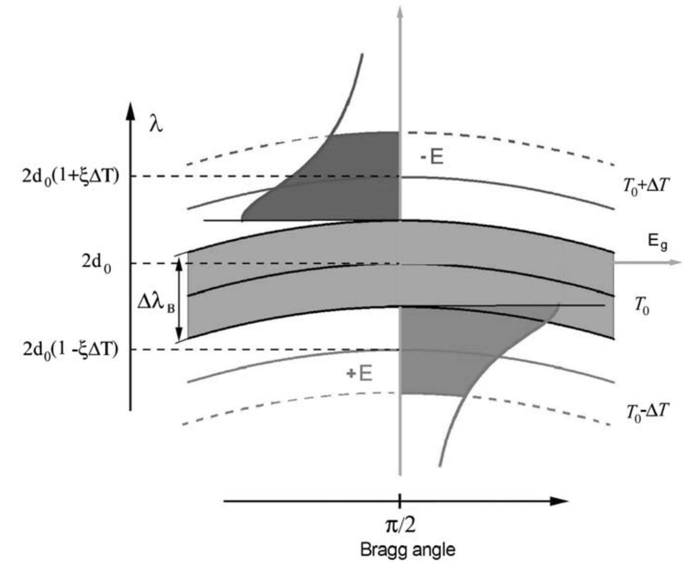

Fig. 1. Electric field for neutrons close to the Bragg condition (Bragg angle $\pi/2$ and $\lambda = 2d_0$) in a non-centrosymmetric crystal: the electric field has a pole for neutrons exactly fulfilling the Bragg condition. By choosing the deviation from the Bragg condition, value and sign of the electric field can be selected. We use Bragg reflection in a second crystal with a different temperature $T_0 \pm \Delta T$ to select neutrons with a certain deviation.

The presence of the electric field will lead to the appearance of a Schwinger magnetic field

$$\mathbf{H}_S = [\mathbf{E} \times \mathbf{v}]/c \tag{6}$$

where $\mathbf{v}$ is the neutron velocity. The corresponding spin rotation angle is [16]

$$\varphi_S = \frac{2\mu H_S L}{\hbar v_\perp}. \tag{7}$$

Note that the Schwinger effect disappears for Bragg angles of $\pi/2$ as $\mathbf{E} \parallel \mathbf{v}$ in this case

$$\varphi_S = \frac{2E\mu L v_\parallel}{c\hbar v_\perp} = \frac{2E\mu L}{c\hbar} \cot\theta_B \underset{\theta_B \to \pi/2}{\longrightarrow} 0 \tag{8}$$

where $v_\parallel$ is the component of the neutron velocity parallel to the crystallographic plane. This can be used in the nEDM experiment to suppress systematic effects due to Schwinger interaction.

In the experiment [21] the effect of neutron spin rotation in neutron optics for large ($\sim 10^3 - 10^4$ Bragg widths) deviations from the exact Bragg condition has been observed. The measured effect has coincided with the theoretical expectation.

In order to tune the electric field $\mathbf{E}$, we have to select neutrons with a well-defined deviation $\Delta E_{\mathbf{g}}$ from the Bragg condition. For this purpose, we use two separate crystals in parallel orientation (see Fig. 2). By heating or cooling the second (small) crystal the interplanar distance Δd changes and, therefore, the energy of the reflected neutrons. The second crystal selects only the neutrons corresponding to its own Bragg condition from the whole beam passing through the first crystal. The deviation parameter and, accordingly, value and sign of the electric field having affected these neutrons in the first crystal depend directly on the temperature difference between the two crystals (see Fig. 1).

The value of the Bragg width $\Delta\lambda_B$ for the (110) quartz plane ($d = 2.45$ Å) is $\Delta\lambda_B/\lambda \approx 10^{-5}$. To shift the reflected wavelength by one Bragg width, $\Delta d/d$ should have the same value, corresponding to a temperature difference of $\Delta T \approx \pm 1$ K (linear coefficient of thermal expansion for quartz $\xi \equiv \Delta L/L \approx 10^{-5}$ K^{-1}). Note that a common variation of the two crystals' temperatures in itself does