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Measurement of the neutron electric dipole moment via spin rotation in a non-centrosymmetric crystal

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ABSTRACT

We have measured the neutron electric dipole moment using spin rotation in a non-centrosymmetric crystal. Our result is $d_n = (2.5 \pm 6.5^{stat} \pm 5.5^{syst}) \cdot 10^{-24}$ $e\,$cm. The dominating contribution to the systematic uncertainty is statistical in nature and will reduce with improved statistics. The statistical sensitivity can be increased to $2 \cdot 10^{-26}$ $e\,$cm in 100 days data taking with an improved setup. We state technical requirements for a systematic uncertainty at the same level.

1. Introduction

Electric dipole moments (EDMs) of elementary particles belong to the most sensitive probes for CP violation beyond the Standard Model of Particle Physics [1]. Constraining or detecting EDMs of different systems allows to gather experimental information about models for new physics that is complementary to high energy physics data.

For the neutron EDM (nEDM), the most sensitive results [2,3] were obtained using ultracold neutrons and Ramsey's resonance method. See [4] for a recent review of measurements using free neutrons. Measurements using the interaction of neutrons with the atomic electric field in absorbing matter were pioneered by Shull and Nathans [5]. Abov and colleagues [6] first discussed a spin-dependent term in the scattering amplitude for neutrons in non-centrosymmetric non-absorptive crystals. This term is caused by the interference of nuclear and spin–orbit structure amplitudes. Forte [7] proposed to search for nEDM related spin rotation in non-centrosymmetric crystals due to such interference. In [8] it was pointed out that such interference leads to a constant interplanar electric field affecting the neutron during all time of its passage through the crystal. This field was measured first in [9]. The interference of nuclear and spin–orbit structure amplitudes was tested by Forte and Zeyen [10] by spin rotation in a non-centrosymmetric crystal.

Here we present the first measurement of the nEDM based on an improved version of this method. Preliminary results and a detailed description of our method with references to earlier work have been published in conference proceedings [11,12].

The statistical sensitivity of any experiment to measure the nEDM is determined by the product $E\tau\sqrt{N}$, where E is the value of the electric field, τ the duration of the neutron's interaction with the field and N the number of counted neutrons. New projects to measure the nEDM with UCNs aim to increase the UCN density and thus N by orders of magnitude and exploit in some cases the higher electric field obtainable in liquid helium compared to vacuum [13,14]. In contrast, experiments with non-centrosymmetric crystals exploit the interplanar electric field. For quartz, this field was measured to be $E \approx 2 \cdot 10^8$ V/cm [9], several orders of magnitude higher than the electric field achievable in vacuum or liquid helium. Furthermore, the statistical sensitivity of the method profits from the higher flux of the used cold neutrons, compared to UCNs available today. These factors compensate the shorter interaction time of the neutrons with the electric field, ultimately limited by the absorption in the crystal. In [15] we have

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demonstrated that a statistical sensitivity of $\sim 6 \cdot 10^{-25}$ $e\,$cm/day can be obtained, comparable to the most sensitive published UCN experiments [2,3].

The results in [15] were obtained in Laue geometry that is limited by systematics [16]. Here we exploit the Bragg geometry first proposed by Forte [7]. See [11] for a detailed comparison of the two schemes.

2. Method

We consider spin rotation for neutrons close to the Bragg condition for the crystallographic plane $\boldsymbol{g}$ in a non-centrosymmetric crystal. These neutrons are exposed to an electric field $\boldsymbol{E} = \boldsymbol{E_g} \cdot a$ where $\boldsymbol{E_g}$ is the interplanar electric field for plane $\boldsymbol{g}$ and a describes the deviation of the neutron from the exact Bragg condition (see [11] for details). A nonzero nEDM d_n results in neutron spin rotation by the angle

$$\varphi_\mathrm{EDM} = \frac{2Ed_\mathrm{n}L}{\hbar v_\perp}, \tag{1}$$

where L is the length of the crystal and $v_\perp$ the component of the neutron velocity perpendicular to the crystallographic plane ($L/v_\perp$ is the time the neutron interacts with the field). By changing the deviation from the exact Bragg condition, a, value and even sign of the effective electric field and the resulting spin rotation φ_EDM can be selected.

On the other hand, the electric field causes a Schwinger magnetic field in the rest frame of the neutron, $\boldsymbol{H}_\mathrm{S} = [\boldsymbol{E} \times \boldsymbol{v}]/c$, resulting in the spin rotation angle

$$\varphi_\mathrm{S} = \frac{2\mu_\mathrm{n} H_\mathrm{S} L}{\hbar v_\perp} = \frac{2E\mu_\mathrm{n} L v_\parallel}{c\hbar v_\perp}, \tag{2}$$

where μ_n is the neutron magnetic moment and $v_\parallel$ the neutron velocity component parallel to the crystallographic plane.

As $\boldsymbol{E}$ and $\boldsymbol{H}_\mathrm{S}$ are perpendicular to each other, φ_EDM and φ_S can be separated by three-dimensional (3D) polarisation analysis. Furthermore, φ_S vanishes for Bragg angles of $\pi/2$ ($v_\parallel = 0$ in Eq. (2)). This is used to suppress the effect due to Schwinger interaction: The crystal is aligned such that the interplanar electric field is parallel to the central neutron velocity, defining the Z direction of a coordinate system. The incident neutron polarisation is aligned in X (or Y) direction. φ_EDM is measured in the X–Y plane. A residual Schwinger magnetic field (for neutron trajectories deviating from the Z direction or in case of a slight misalignment of the crystal) has its largest component in the X–Y plane, thus creating a polarisation component in Z direction. Thus, φ_S can be derived from the Z component of the outgoing polarisation vector. In summary, we measure φ_EDM from the component P_{XY} of the polarisation tensor and the residual Schwinger effect from the components P_{XZ} and P_{YZ}. P_{YX}, P_{ZX} and P_{ZY} serve for control purposes.

In first order, the difference of the polarisation tensors for positive and negative effective electric fields is:

$$\Delta \boldsymbol{P} = g_\mathrm{n}\tau_0 \begin{pmatrix} 0 & -(H^z \frac{\Delta\tau}{\tau_0} + H_\mathrm{EDM}) & (H^y \frac{\Delta\tau}{\tau_0} + H_\mathrm{S}^y) \\ (H^z \frac{\Delta\tau}{\tau_0} + H_\mathrm{EDM}) & 0 & -(H^x \frac{\Delta\tau}{\tau_0} + H_\mathrm{S}^x) \\ -(H^y \frac{\Delta\tau}{\tau_0} + H_\mathrm{S}^y) & (H^x \frac{\Delta\tau}{\tau_0} + H_\mathrm{S}^x) & 0 \end{pmatrix}, \tag{3}$$

where $\tau_0 = (\tau_+ + \tau_-)/2$, $\Delta\tau = (\tau_+ - \tau_-)/2$, and τ_+ and τ_- are the times the neutrons stay in the crystal for the positive and the negative electric field, respectively (the neutron velocity is slightly different for $\pm a$). H^i are the components of the residual magnetic field and H_S^i the components of the Schwinger magnetic field $\boldsymbol{H}_\mathrm{S}$. $g_n = 2\mu_\mathrm{n}/\hbar = 1.8 \cdot 10^4$ G^{-1} s^{-1} is the neutron gyromagnetic ratio, $H_\mathrm{EDM} = Ed_\mathrm{n}/\mu_\mathrm{n}$ the effective magnetic field corresponding to the electric field E. For $E = 1 \cdot 10^8$ V/cm and $d_n = 10^{-26}$ $e\,$cm, $H_\mathrm{EDM} = 1.7 \cdot 10^{-7}$ G.

3. Experimental setup and procedure

The experiment was carried out at the cold neutron beam facility PF1B [17] of the Institut Laue–Langevin. A scheme of the setup is shown in Fig. 1. Neutrons were wavelength-preselected by a pyrolytic graphite monochromator (adjusted to 4.91 Å, resolution about 1%) and spin polarised to about 98% by a super mirror polariser. A resonance spin flipper permitted to flip the neutron polarisation. Cryopad [18,19] was used for 3D polarisation analysis. The direction of the incident beam polarisation was oriented and the measured projection of the outgoing polarisation vector selected by nutators (in the X–Y plane) and precession coils (inside the Meissner screen, for the Z component). The polarisation of the transmitted beam was analysed by a ^{3}He spin filter cell [20] (measured polarisation value of the unperturbed beam between 75% and 87%, depending on the ^{3}He cell). The currents in the precession coils were optimised experimentally for the wavelength of the used neutrons.

We used the (110) reflection of a perfect quartz crystal of 14 cm length. The effective angular mosaic spread of the crystal was $\omega_\mathrm{m} \sim 1''$. The neutrons with a well-defined deviation from the Bragg condition for this crystal were selected behind the ^{3}He spin filter cell by back-reflection at a second quartz crystal oriented parallel to the first one and at a slightly different temperature. A shift of the neutrons by one Bragg width ($\Delta\lambda_B/\lambda \approx 10^{-5}$ for the (110) plane of quartz) corresponds to a temperature difference $\Delta T \approx \pm 1$ K (linear coefficient of thermal expansion for quartz $\xi = \Delta L/L \approx 10^{-5}$/K). Note that the absolute temperature of the

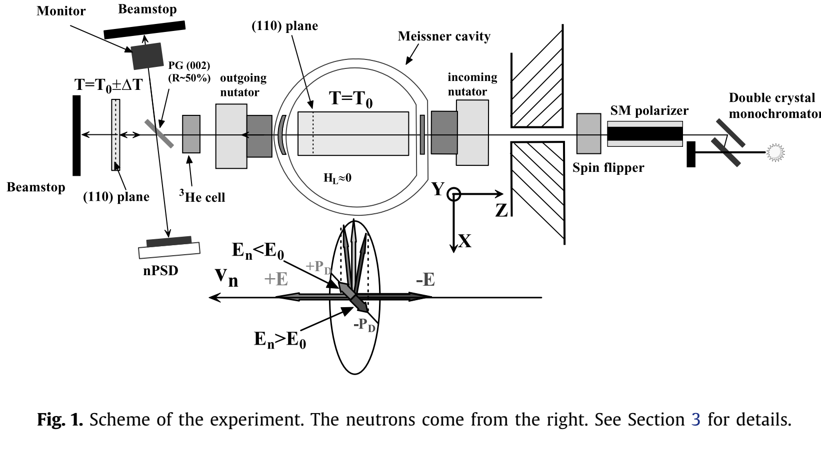

Fig. 1. Scheme of the experiment. The neutrons come from the right. See Section 3 for details.