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SEARCH FOR A NEUTRON ELECTRIC DIPOLE MOMENT BY A SCATTERING EXPERIMENT*

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The recent interest in questions of time-reversal invariance has spurred experimentalists to investigate more closely the possibility of the existence of an intrinsic electric dipole moment (EDM) on single particles. Landau[1] has shown that such an EDM must vanish unless both space-reflection and time-reversal invariances are violated simultaneously. Up to the present time, the most stringent experimental test on this has been the Ramsey resonance-beam experiment on neutrons reported by Smith, Purcell, and Ramsey[2] in which an upper limit of 2.4×10^{-20} e cm was established for the neutron dipole moment. Within the last two years, however, a whole host of theoretical estimates for this dipole length have appeared in the literature and this has encouraged several experimental groups to repeat the original Ramsey-type resonance-beam experiment with slow neutrons with increased sensitivity.[3] We wish to report results of a different type of neutron experiment, namely a polarized-beam scattering experiment, which has yielded a considerable refinement in the possible upper limit for the neutron EDM.

The experiment exploits the fact that a neutron carrying an intrinsic EDM will experience an extra interaction with the atomic Coulomb field in passing through a scattering atom. It can be shown that this will produce a scattering amplitude term b'' given by

$$b'' = i\frac{Ze(1-f)}{\hbar}\mu_e\frac{\csc\theta}{v}\vec{P}\cdot\vec{e},$$

where Ze is the nuclear charge, $1-f$ is an electronic screening factor with f being the charge distribution form factor, μ_e the EDM of the neutron moving with speed v, 2θ the scattering angle, $\vec{P}$ the unit neutron polarization vector, and $\vec{e}$ the unit scattering vector defined as

$$\vec{e} = (2k\sin\theta)^{-1}(\vec{k}-\vec{k}_0)$$

with $\vec{k}$ and $\vec{k}_0$ being the scattered and incident neutron wave vectors.

The amplitude is imaginary, i.e., with phase

90° removed from that of the real nuclear scattering amplitude, and it is seen to be maximized when $\vec{P}$ is coincident with $\vec{e}$ and reversed in algebraic sign with a reversal of neutron polarization direction. We have searched for the presence of this imaginary amplitude term in a Bragg reflection from CdS crystals where an intensity effect upon neutron polarization reversal is to be expected because of coherence with other imaginary terms. The (004) CdS reflection has been found useful for this and the crystal structure factor characterizing the Bragg reflected intensity becomes

$$F_{(004)}^{\ 2} = (a_{\rm Cd} - a_{\rm S})^2,$$

where $a_{\rm Cd}$ and $a_{\rm S}$ are the scattering amplitudes for the two atoms. The nuclear scattering by either atom has both real and imaginary terms which are independent of neutron polarization and so

$$a = b + ib' \pm ib''$$

with b and b' being the nuclear scattering amplitudes. The alternative sign on the EDM amplitude corresponds to neutron polarization reversal. Using the known nuclear scattering amplitudes for Cd and S and calculated values for b'' based upon the early EDM limit, an intensity change (polarization ratio) upon neutron polarization reversal of 0.60 % is to be expected. Such an effect is easily measurable with present polarized-beam technology since intensity ratios can be measured very accurately. Preliminary measurements on this Bragg reflection at Massachusetts Institute of Technology had shown an intensity effect no larger than 0.11 % (hence an EDM limit five times smaller than the above) and further measurements at Brookhaven National Laboratory with much higher intensity have further refined this to a much lower possible value.

Figure 1 shows schematically the salient features of the experiment. Polarized monochromatic neutrons are first obtained from a polarizing crystal on the spectrometer and then passed through a radiofrequency resonance inverter where the polarization may be inverted from the normally down sense (spin vector). In practice this switching is done automatically 10 times per second. In performing the EDM experiment the polarization must be brought parallel to the scattering vector in the horizontal plane of scattering and this is done by adiabatic 90° rotation in the magnetic field produced within a pair of twisted magnetic-pole pieces. The test crystal is supported within a flat pole-piece assembly providing a uniform magnetic field and neutron polarization parallel to the scattering vector.

In searching for very small intensity effects in this reflection, it is imperative that the neutron polarization be precisely aligned along the scattering vector of the crystal. The presence of a transverse polarization component perpendicular to the plane of scattering will produce an intensity effect through interaction of the neutron magnetic moment with its orbital motion within the scattering atom (Schwinger scattering) as discussed by Shull.[4] This type of scattering has been measured experimentally for the CdS (004) reflection and found to yield a polarization ratio of 1.060 for neutrons of wavelength 1.05 Å in excellent agreement with the calculated value. Since this is much larger than the EDM intensity effects, we have collected data in such a fashion that a transverse polarization effect will be canceled with proper data analysis. The polarization direction of the neutrons being scattered by the crystal is along the field produced by magnetic pole plates activated by permanent magnets, with the crystal being supported from the pole plates. By rotation of the whole magnet-crystal assembly about an axis approximately along the scattering vector, the transverse polarization component arising from mistipping of the permanent magnetic field relative to the scattering vector is inverted and this changes the sign of the Schwinger scattering.

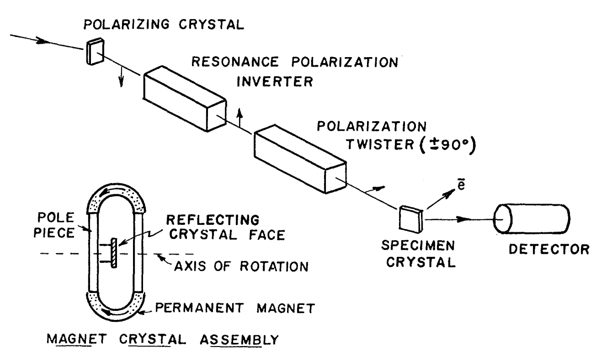

FIG. 1. Schematic diagram of polarized-neutron spectrometer used in searching for a neutron electric dipole moment. Magnetic fields of controlled direction are present throughout the neutron trajectory. The inset diagram shows the magnet assembly surrounding the specimen crystal and its axis of rotation as used in removing transverse neutron polarization effects.

Table I. Summary of total neutron count from (004) CdS Bragg reflection for different experimental configurations.

Configuration	Neutrons counted Normal polarization	Neutrons counted Inverted polarization	r (parts per 10^5)
α	98 845 878	98 841 057	$+4.9 \pm 14.2$
β	105 415 987	105 397 603	$+17.3 \pm 13.8$

Thus equal quantities of data accumulated in the two orientations of the magnet-crystal assembly will show zero Schwinger scattering when averaged.

This inversion procedure does not, however, remove contaminant effects arising from vertical components of fixed stray magnetic fields such as the earth's magnetic field. To surmount this problem the neutron polarization is twisted alternatively clockwise and counterclockwise in the necessary 90° twist from vertical to horizontal polarization sense. This serves to invert the sought-for EDM intensity effect and leaves unchanged all transverse polarization effects and electronic-channel differences associated with counting in the normal and inverted polarization states.

With this scheme of data collection, approximately 400 million neutrons have been counted in the (004) CdS reflection over a 3-month period with results summarized in Table I. Here are shown the total neutron count N in α configuration (counter-clockwise twist of polarization through 90°) and β configuration (clockwise twist) with normal spectrometer beam polarization and with inverted neutron polarization. In either configuration, half of the neutrons were counted in each of the two magnet-crystal assembly orientations. Defining the residual polarization ratio r as

$$r = \frac{N(\text{normal polarization})}{N(\text{inverted polarization})} - 1,$$

it can be shown that $r_\alpha + r_\beta$ should be twice the residual polarization ratio contributed to (1) by fixed stray fields present at the crystal site and (2) by electronic circuit differences in counting during the normal and inverted polarization intervals. On the other hand, $r_\beta - r_\alpha$ should be twice the residual EDM polarization ratio uncontaminated by instrumental effects. For the former, we obtain $+11.1 \pm 9.9$ parts in 10^5 as the instrumental asymmetry and this has been compared with independent measurements of this quantity. The fixed stray magnetic field at the crystal site has been determined as 0.50 G downward and this leads to a residual Schwinger effect of +8.0 units and the electronic channel differences have been assessed as contributing less than +2.0 units. In essence this test is equivalent to the introduction of a signal known in both magnitude and direction into the experiment and the agreement with the experimental data is comfortably within the statistical error of the results.

For the EDM residual polarization ratio we obtain $+6.2 \pm 9.9$ parts in 10^5 and when translated into a dipole length with electronic charges this becomes

$$D = +(2.4 \pm 3.9) \times 10^{-22} \text{ cm}.$$

The positive sign here denotes an EDM vector parallel to the spin vector. Thus the experimental results do not support a finite, nonvanishing value for the neutron EDM but they do serve to establish a refined value for the upper limit magnitude of this quantity. The above errors are all given as standard errors and confidence in their reality is gained from the above test on the over-all data. Further experimentation with other possibly more sensitive Bragg reflections is being explored.

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