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*SEARCH FOR AN ELECTRIC DIPOLE MOMENT OF THE NEUTRON**

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THE discovery by Christenson, et al.[1] of a time-reversal violating mode in the decay of the long-lived neutral K meson into two charged pions, was followed immediately by a suggestion from N. F. Ramsey that a new search be made for a nucleon electric dipole moment. The planning of the present experiment was begun, and early in 1965, two of Professor Ramsey's students, W. B. Dress and J. K. Baird went from Harvard to Oak Ridge to collaborate on such an experiment.

In 1950, Purcell and Ramsey[2] pointed out that the arguments then used to prove that particles could not have an electric dipole moment were based on a parity assumption that must rest on an experimental rather than a theoretical basis. As a test of this assumption, Smith, Purcell, and Ramsey[3,4] used a neutron-beam magnetic resonance apparatus to search for a neutron electric dipole moment and concluded that such a moment divided by the proton charge (μ_e/e) was experimentally less than 5×10^{-20} cm. Later, from the work of Lee and Yang[5] and Wu, et al.,[6] it became apparent that the parity assumption was indeed invalid, but Landau pointed out an additional argument against the existence of a particle electric dipole moment based on time-reversal invariance,[7] although Ramsey[8] emphasized that this invariance was merely assumed and must also rest on experiment.

An electric dipole moment of a neutron would be observed as an interaction with an electric field of the form

$$\mathcal{H} = -\mu_e \mathbf{E} = -\gamma_e \sigma \mathbf{E}. \tag{1}$$

Such an interaction would be even under charge conjugation (since both $\gamma_e \sigma$ and $\mathbf{E}$ are separately odd). It would be odd under parity due to the polar-vector character of electric fields; and it would be odd under time reversal due to σ. Thus such an interaction is allowed under the requirement of being even under CPT.

A neutron-beam magnetic-resonance spectrometer with separated oscillatory fields[9] was used. A strong electrostatic field was applied parallel to the static magnetic field in the region between the rf coils. The resulting energy levels are shown in Fig. 1 for the two cases where the electric field is parallel and antiparallel to the magnetic field. A shift in resonant frequency due to an electric dipole moment would manifest itself as a change in polarization of the beam. The polarization of the beam was observed by analyzing the neutrons leaving the apparatus so that only those with the spins unchanged are detected. As shown in Fig. 1, the electric dipole moment divided by the proton charge is given by

$$\frac{\mu_e}{e} = \frac{h}{2e} \frac{\Delta N}{(E_{\uparrow\uparrow} + E_{\uparrow\downarrow})\, dN/d\nu_{\text{osc}}}, \tag{2}$$

where ΔN is the shift in counting rate due to changing the electric field from $E_{\uparrow\uparrow}$ to $E_{\uparrow\downarrow}$, and $E_{\uparrow\uparrow}$ and $E_{\uparrow\downarrow}$ are the magnitudes of the electric field parallel, and antiparallel, respectively, to the uniform magnetic field. $dN/d\nu_{\text{osc}}$ is the slope of the counting rate with respect to the oscillator frequency. Thus the sensitivity can be enhanced by a high intensity, large electric fields, and a steep resonance.

The requirement that the resonance be steep is equivalent to requiring that the resonance line be narrow. The width of the resonance line, in turn, is determined by the uncertainty principle; a narrow line results from a long neutron transit time through the spectrometer.

An intense beam of slow neutrons was obtained by using the large angular acceptance and the velocity selection of a bent neutron conducting tube whose effectiveness depends on total reflections of the neutrons at the inner surface of the tube. Such neutron conducting tubes were first developed by Maier-Leibnitz[10] but, in the present experiment, they were used for much

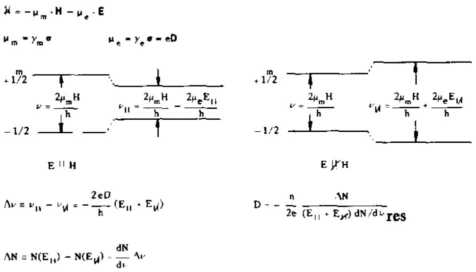

FIG. 1. Energy levels of a neutron with magnetic moment μ_m, and electric dipole moment μ_e, in parallel electric and magnetic fields.

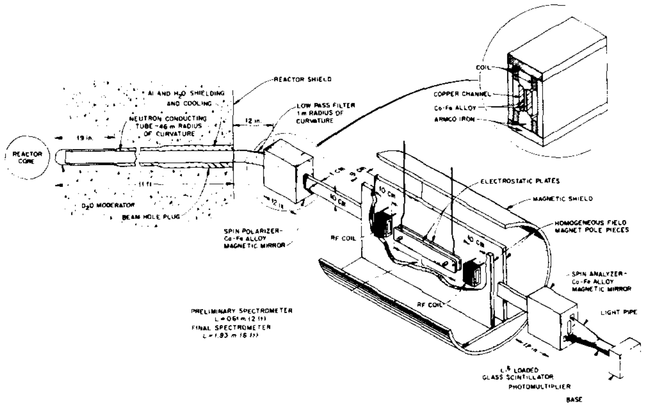

FIG. 2. Schematic drawing of polarized neutron source and magnetic resonance spectrometer.

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slower neutrons than in any previous studies.[11, 12]

The neutron source and the magnetic resonance spectrometer are shown in Fig. 2. The Low-Intensity Test Reactor at the Oak Ridge National Laboratory provided a thermal flux at the entrance of the tube of 1.4×10^{13} neutrons $\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}$. A small D_2O moderator at the end of the beam hole provided an additionally thermalized flux illuminating the entrance of the bent neutron-conducting tube. The portion of the neutron tube lying inside the reactor shield was constructed from polished nickel plates and has a 46 m radius of curvature to attenuate the fast neutrons and gamma rays. The entire neutron path was evacuated to $\sim 10^{-4}$ Torr in order to maximize both the slow-neutron intensity and the attainable electric field. The section of the neutron tube with a 1-m radius of curvature reduced the average velocity of the spectrum. The neutrons were polarized and analyzed by total reflection from 94% Co, 6% magnetized mirrors. The measured polarization was about 70%. The magnetic resonance spectrometer, operating with a uniform field of 9 G, had a reversible electric field of 120 kV/cm applied between the oscillatory field coils over a region 61 cm in length. The neutrons were detected with a 1-cm × 10-cm Li^6-loaded glass scintillator inside the vacuum system. The average neutron velocity determined from the resonance width has been varied from 60 to 150 m/sec. A summary of the operating parameters for the experiment is shown in Fig. 3.

Numerous checks for, and precautions against, possible systematic errors have been made. Electric field reversals were made at intervals of about 5 min, and neutrons were counted relative to a monitor counter so as to eliminate the effect of reactor power fluctuations. Resonance drifts amounted to less than 5 Hz per 10 h of measuring. The apparent electric dipole moment has been measured on opposite slopes of the resonance curve in order to eliminate one type of systematic error and the result reported below is the average of such measurements. A second source of systematic error could result from the fact that a magnetic moment moving in an electric field will experience an effective magnetic field $(\mathbf{v}/c) \times \mathbf{E}$. This will be negligible if the uniform electric and magnetic fields are parallel. Otherwise it is proportional to the velocity and to the sine of the angle between the fields. Since the publication of our preliminary report,[13] the apparatus has been made more rigid, and measurements have been made with the apparatus turned end for end so as to reverse the $(\mathbf{v}/c) \times \mathbf{E}$ effect. Approximately 17 000 field reversals have been made, and 7×10^9 neutrons have been counted.

One analysis of the data gives the results $D = (0.02 \pm 0.85) \times 10^{-22}$ cm, and indicates that the angle between the electrostatic and uniform magnetic fields was about $4 \pm 1/2°$. The exact result and its error, however, depends upon how the 17 000 data points are grouped, and upon what assumptions are made regarding the constancy of the two systematic effects indicated above.

Separation of RF Coils	= 0.75 meters.
Neutron Velocity	= 90 meters/sec.
Polarization	= 70%
Intensity at Detector	= 8000 neutrons/sec.
Sensitivity	= 43 counts/cycle
Electric Field	= 120 kv DC/cm.
Magnetic Field	= 10 Gauss
Reactor Flux	= 1.4×10^{13} neutrons/cm^2 sec.

FIG. 3. Essential parameters associated with the neutron electric-dipole moment experiment at ORNL.

Each of the methods of analysis resulted in numbers not significantly different from that given above, and our conclusion is that the upper limit on the electric dipole moment of the neutron is

$$|\mu_e/e| < 3 \cdot 10^{-22}\,\mathrm{cm}. \tag{3}$$

Two similar experiments on the electric dipole moment of the neutron are being done at Aldermaston and the University of Sussex by J. M. Pendlebury and K. F. Smith[14] and at Brookhaven by V. W. Cohen et al.[15] The sensitivity of both experiments should be similar to the one given above. Another entirely different type of experiment to measure the neutron electric dipole moment has been done at Brookhaven.[16] This experiment exploits the fact that a neutron carrying an intrinsic electric dipole moment 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

$$b = i\,\frac{Ze\,(1-f)}{h}\,\mu_e\,\frac{\operatorname{cosec}\theta}{v}\,\mathbf{pe}, \tag{4}$$

where Ze is the nuclear charge, $(1 - f)$ is an electronic screening factor with f being the charge distribution form factor, μ_e the electric dipole moment of the neutron moving with speed v, 2θ the scattering angle, **P** the unit neutron polarization vector, and **e** the unit scattering vector defined as

$$\mathbf{e} = \frac{1}{2k\sin\theta}(\mathbf{k} - \mathbf{k}_0), \tag{5}$$

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

This 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 **P** is coincident with **e** and reversed in algebraic sign with a reversal of neutron polarization direction. Shull and Nathans searched for the presence of this imaginary amplitude term in a Bragg reflection from CdS crystals where an intensity effect upon neutron polarization re-

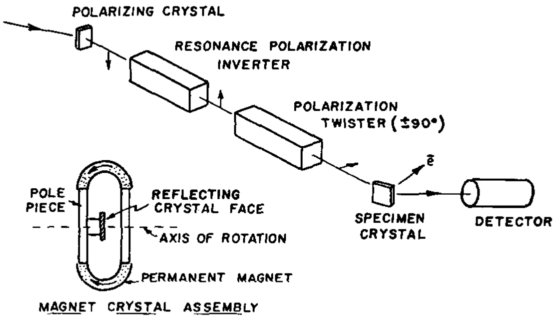

FIG. 4. Schematic diagram of polarized neutron spectrometer used in searching for a neutron electric dipole moment by a scattering experiment. Magnetic fields of controlled direction are present throughout the neutron trajectory. The inset diagram shows the magnet assembly surrounding the specimen crystal and its axis of rotation as used in removing transverse neutron polarization effects.

	10^{-22} cm X e
G. Feinberg Phys. Rev. **140,** B1402 (1965)	1000
G. Salzman and F. Salzman, Phys. Letters **15**, 91 (1965); E. P. Shabalin, Inst. for Theoretical and Experimental Physics, Moscow, No. 367 (1965)	100
N. T. Meister and T. K. Radha, Phys. Rev. **135**, B769 (1964)	20
G. Feinberg and H. S. Mani, Phys. Rev. **137,** 637 (1965); H. Nieh and S. J. Chang (Ph. D. Thesis of H. Nieh), Harvard University, S. L. Glashow, Phys. Rev. Letters **14,** 35 (1965)	10
K. Nishijima and L. Swank (Private Communication)	9
P. Babu and M. Suzuki, Phys. Rev. **162**, 1359 (1967)	>2.2
N. Cabibbo, Phys. Letters **12,** 137 (1964)	1.5 – 3.5
J. Schwinger, Phys. Rev. **136**, B821 (1964)	0.36 – 1.4
M. Peshkin and L. Bollinger (Private Communication)	10^{-3}
D. G. Boulware, Nuovo Cimento, Vol. XLA, No. 4, 1041 (1965)	10^{-5}

FIG. 5. Theoretical estimates of the neutron electric dipole moment.

versal is to be expected because of coherence with other imaginary terms. The (004) CdS reflection was found useful for this measurement. A schematic drawing of their apparatus is shown in Fig. 4. Approximately 4×10^8 neutrons were counted, and great care was taken to compensate for misalignments which would produce an intensity variation with polarization reversal due to Schwinger scattering. The final result of the Brookhaven scattering experiment is

$$\frac{\mu_e}{e} = (+2.4 \pm 3.9)\cdot 10^{-22}\,\text{cm}. \tag{6}$$

Within the last two years a number of theoretical estimates of the neutron electric dipole moment have appeared in the literature. These estimates are summarized in Fig. 5. The largest estimates, by Feinberg, and by Salzman and Salzman, are based upon the assumption of failure of time reversal invariance in the electromagnetic interactions. The present upper limit of 3×10^{-22} cm eliminates this possibility. The estimates which lie in the neighborhood of 10^{-22} cm are based on an assumption of the failure of time reversal invariance in the weak interaction. It would be very desirable, as can be seen from an inspection of Fig. 5, to improve the sensitivity of the measurement of a neutron electric dipole moment by perhaps a factor of ten.

We have constructed a new resonance spectrometer at Oak Ridge which has three times greater separation between the rf coils. The magnetic shielding is much improved which should provide better stability. New magnets have been constructed to improve the polarization and an increased electric field has been attained. These improvements should allow us to achieve a sensitivity of approximately 0.5×10^{-22} cm. Shull[17] has estimated that with new and improved crystals, his scattering measurement might be improved by a factor of four; i.e., to a sensitivity of about 1×10^{-22} cm.

A possible experiment to measure the proton electric dipole moment has been proposed by Sandars.[18] He plans to detect the electric dipole moment of the unpaired proton in a Tl nucleus in a molecular-beam magnetic-resonance experiment. He estimates a sensitivity of $\sim 1 \times 10^{-22}$ cm.

If we ask ourselves what the ultimate limit of the neutron magnetic-resonance technique might be, then we envision:

1) A high flux reactor $\sim 10^{15}$ neutrons/cm^2 sec.
2) A cryogenic moderator with a neutron conducting pipe.
3) A spectrometer with a separation of perhaps 10 meters between the rf coils.
4) An electric field of perhaps 200–300 kV/cm.

Such an experiment would be very difficult, quite expensive, and quite lengthy, but the sensitivity could be $\sim 10^{-25}$–10^{-24} cm.

DISCUSSION

V. M. Lobashov:

What fraction of the error is connected with fluctuations of the magnetic field? By how much is it necessary to decrease the fluctuation of the magnetic field in order to obtain an accuracy of $\sim 10^{-24}$–10^{-25} cm?

P. Miller:

Only a small fraction of our errors is connected with fluctuations. A much larger error is the result of the systematic errors discussed above. The magnetic-shielding factor for our apparatus was only 43. For our new apparatus it will be 1000. With one more shielding layer, it can be increased to 10 000. In addition, the

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[17] C. G. Shull, private communication (1968).

[18] P. G. H. Sandars, Phys. Rev. Lett. **19**, 1396 (1967).

time interval between the reversals of the sign of the field was about 2 minutes, and it can be decreased to 10 sec.

V. M. Lobashov:

Among the results of your experiment there is one differing from the others by 3–4 standard deviations. What can be its cause?

P. Miller:

I don't know.

P. A. Krupchitskiĭ:

Write down, please, two quantities: the values of the dipole moment of the neutron for two branches of the resonance curve, corresponding to the phase shifts +90° and −90°.

P. Miller:

These quantities can be obtained from the tables of our article to be published in Physical Review. I do not recall now the exact values.

C. Rubbia:

a) What will be the change in the neutron count if the dipole moment is 10^{-22} cm?

b) How large are the geometric shifts necessary to explain the observed discrepancies?

P. Miller:

a) A dipole moment on the order of 10^{-22} cm corresponds to a change of 5 in a counting rate of 10^5.

b) If our hypothesis concerning the small geometric changes is correct, then the required shift is on the order of 10^{-4}. But this is only an assumption.

F. L. Shapiro:

What mechanical shifts can appear as the result of a change in the sign of the electric field, and how do they influence the measured results?

P. Miller:

Our apparatus is connected with the electric-field switch by a heavy rigid cable. The switch has an air compensator and certain vibrations could be transmitted to the spectrometer. I must emphasize that this mechanism is only a proposal.