LIMIT TO THE ELECTRIC DIPOLE MOMENT OF THE NEUTRON*

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A neutron-beam magnetic resonance experiment with very slow neutrons (as low as 60 m/sec) has been used to set a limit to the neutron electric dipole moment that is more than 100 times lower than the previous limit set by Smith, Purcell, and Ramsey. The value found for the neutron electric dipole moment divided by the proton charge is $\mu_e/e = (-2 \pm 3) \times 10^{-22}$ cm. This value is lower than the predictions of many of the time-reversal-noninvariant theories which account for the K_2^0 decay.

In 1950, Purcell and Ramsey[1] pointed out that the arguments then used to prove that particles could not have an electric dipole moment (EDM) 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[2] used a neutron-beam magnetic resonance apparatus to search for a neutron EDM 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[3] and Wu et al.[4] it became apparent that the parity assumption was indeed invalid, but the parity argument against the existence of a particle EDM was soon replaced by one based on time-reversal invariance,[5] although Ramsey[6] emphasized that this invariance was merely assumed and must rest on an experimental basis. Schiff[7] and Meister and Rhada[8] made early calculations as to possible magnitudes for a nucleon EDM based upon an assumed small violation of T invariance consistent with the upper limit set by polarized-neutron decay experiments. The experimental search for a proton EDM[1,9] has been much less sensitive than that for the neutron, and although a low limit to the electron EDM has recently[10] been established most theories predict a much smaller EDM for electrons than for nucleons.

The discovery by Christenson et al.[11] of a time-reversal-noninvariant mode in the decay of the K_2^0 meson into two charged pions provided a new incentive to again begin searching for a nucleon EDM and led to the start of the present experiment. Since then a number of theoretical predictions[12-21] have been made for nucleon electric dipole moments on the basis of theories developed to account for the nature of the K_2^0 decay.

The neutron-beam magnetic-resonance spectrometer with separated oscillatory fields[22] shown in Fig. 1 was used for the present experiment. The neutron EDM is observed as a shift in the magnetic-resonance frequency resulting from a reversal of a strong electric field. The sensitivity is enhanced over that of the previous experiment, in accordance with the uncertainty principle, by using very slow neutrons to provide a long transit time through the spectrometer.

An intense beam of slow neutrons is 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[23] but, in the present experiment, they are used for much slower neutrons than in any previous studies.[24]

The low-intensity test reactor at the Oak Ridge National Laboratory provides a thermal flux at the core of 3×10^{13} neutrons cm^{-2} sec^{-1}. A small D_2O moderator at the end of the beam hole provides an additionally thermalized flux illuminating the entrance of the bent neutron-conducting tube. The portion of the neutron tube lying inside the reactor shield is constructed from polished nickel plates and has a 32-m radius of curvature to attenuate the fast neutrons and gamma rays. The entire neutron path is evacuated to ~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 reduces the average velocity of the spec-

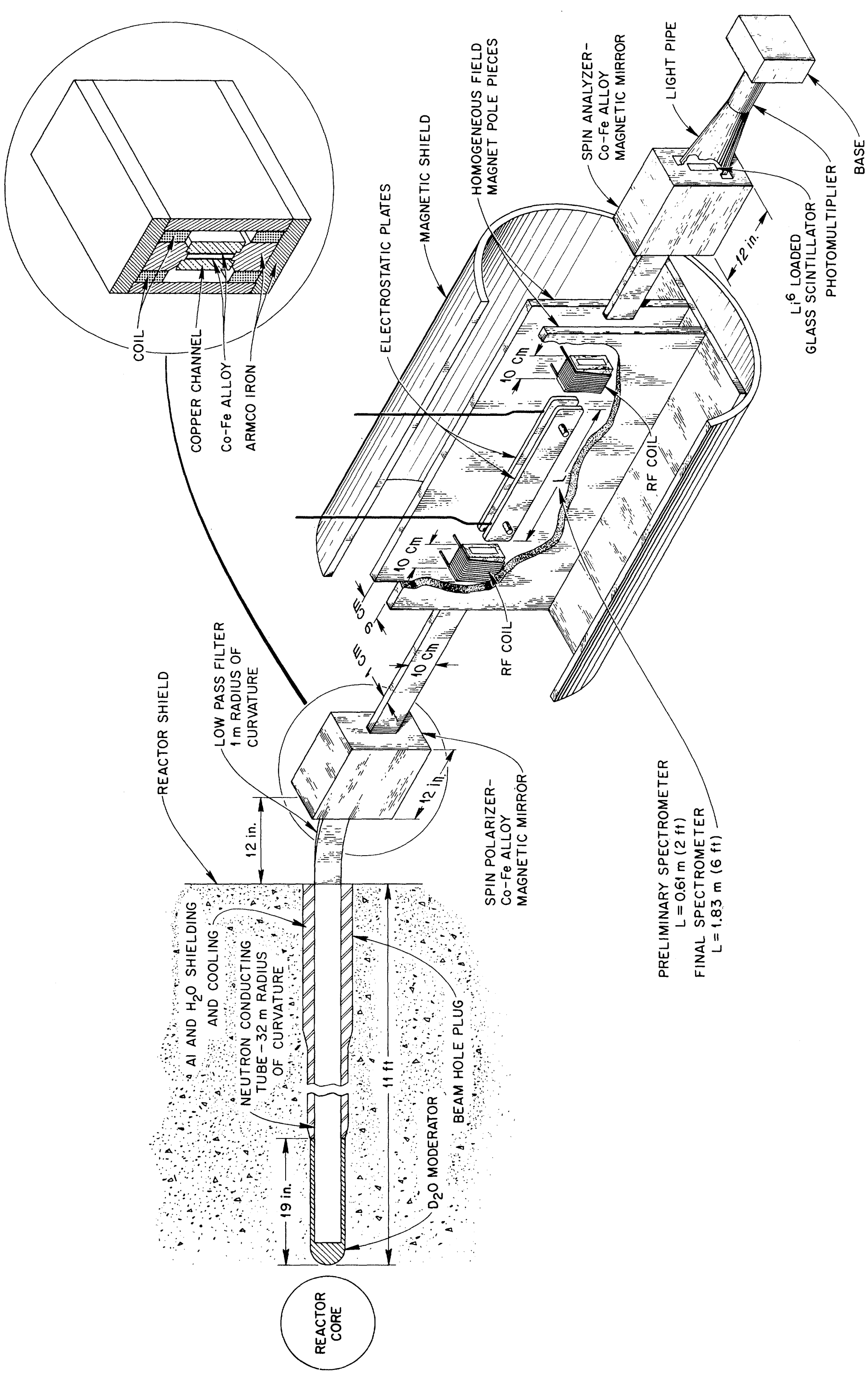

FIG. 1. Schematic drawing of apparatus.

trum. The neutrons are polarized and analyzed by total reflection from 94% Co, 6% Fe magnetized mirrors. The measured polarization is about 55%. The magnetic resonance spectrometer, operating with a uniform field of 9 G, has a reversible electric field of 140 kV/cm applied between the oscillatory field coils over a region 61 cm in length. The neutrons are detected with a 1-cm×10-cm Li^6-loaded glass scintillator inside the vacuum system. The average neutron velocity is 60 m/sec as determined from the resonance width.

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 1 cps per 10 h of measuring. The apparent EDM has been measured on opposite slopes of the resonance curve and the result reported below is the average of such measurements. The apparent EDM measured on one slope differs from the average by three times the standard deviation for reasons not yet fully understood. The averaging of the results from the opposite slopes, however, cancels this effect. Another source of systematic error could result from the fact that a magnetic moment moving in an electric field will experience an effective magnetic field $(\vec{v}/c)\times\vec{E}$. 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. The average angle between the electric and magnetic fields is measured by removing the 1-m radius of curvature section of the neutron tube, thus doubling the average velocity, and observing no change, within statistics, of the apparent neutron EDM. This implies in turn that the angle between the electric and magnetic fields is $\frac{1}{2}° \pm 1\frac{1}{2}°$.

So far observations have been made with 2000 successive field reversals comprising the measurement of some 2×10^9 neutrons. The value of the neutron EDM from these measurements is

$$\mu_e/e = (-2\pm3)\times10^{-22}\ \text{cm}$$

or

$$\mu_e = (-2\pm3)\times10^{-8}\ \text{nuclear magnetons.}$$

This result is consistent with previously reported values,[25] and with the result of a quite different experiment of Shull and Nathans[26] described in an accompanying report and with preliminary observations of a still different experiment by Cohen, Lipworth, Nathans, Ramsey, and Silsbee.[27]

The above limit to the neutron electric dipole is considerably below the maximum values predicted by many of the theories[8,12-21] developed to account for the $K_2{}^0$ decay. To facilitate the comparison between theory and experiment, the maximum value for μ_e/e predicted in each paper is listed in parentheses following each reference. Most theories contain an adjustable parameter which prevents a clear prediction of a minimum value for the electric dipole moment. One frequently discussed theory[20] attributes the T nonconservation to the electromagnetic interaction. On the basis of this theory a μ_e/e of order 10^{-19} cm was expected[15] in contrast to the measurements here reported.

Work on this experiment is continuing and the apparatus will soon be modified to provide a number of improvements including a longer distance between the oscillatory fields. It is hoped that the experimental error can be reduced by at least a factor of 5 with the new apparatus.

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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