PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. SMITH,* E. M. PURCELL, AND N. F. RAMSEY
Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts

(Received May 17, 1957)

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm 2.4)\times 10^{-20}$ cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of D less than 5×10^{-20} cm.

1. INTRODUCTION

SEVERAL years ago Purcell and Ramsey[1] pointed out that the usual parity arguments for the nonexistence of electric dipole moments for nuclei and elementary particles, although appealing from the point of view of symmetry, were not necessarily valid. In particular they pointed out that the validity of the parity assumption must rest on experimental evidence and that the experimental evidence was not as conclusive as then generally supposed in the case of nuclei and elementary particles, even though there was abundant evidence for the assumption in the case of electromagnetic forces. Analysis of the experimental evidence against the existence of electric dipole moments of both nuclei and elementary particles showed[1] that most experiments would not have revealed an electric dipole moment smaller than 5×10^{-23} esu. Such a moment is equal to the charge of the electron multiplied by a distance D of 10^{-13} cm. Henceforth we shall express the nuclear dipole moment in cm, it being understood that the "dipole length" D is to be multiplied by e, the magnitude of the electron charge. Probably the most sensitive experiments at the time were those to measure the neutron-electron interaction[2,3]; it was found that the observed results of these experiments could result from a neutron electric dipole moment with a D of 3×10^{-18} cm. Purcell and Ramsey[1] proposed a sensitive neutron-beam resonance experiment for the detection of an electric dipole moment.

This experiment was successfully completed several years ago. However, the negative results of the experiment were in accordance with the then widely accepted views on parity so the detailed description[4] of the experiment was not published. The upper limit to the electric dipole moment determined in this experiment has occasionally been quoted in other publications.[5,6]

Lee and Yang[6] have analyzed the effects of parity nonconservation on the angular distributions of beta decay, the angular distributions of π-μ-e decays, and existence of electric dipole moments of particles. The effects of the first two of these have been observed by Wu, Ambler, Hayward, Hoppes, and Hudson,[7] and by Garwin, Lederman, and Weinrich.[8] Since electric moments are primarily determined by the strong forces, Lee and Yang[6] showed that the effect of mixed parity should produce an electric dipole moment even smaller than the upper limit set by the experiment described in the present paper. In their most recent theories, Lee and Yang[9] no longer anticipate the existence of an electric dipole moment for the neutron, and arguments involving time-reversal invariance[9,10] can be advanced against its existence. These arguments, however, like the original ones of parity, can be questioned.

Although the negative results of the experiment described here are fully consistent with the current theories, a brief description of the experiment and its results seems appropriate at the present time since the experiment provides the most sensitive experimental upper limit to an electric dipole moment of any elementary particle or nucleus and since the original parity arguments against the existence of such electric dipole moments are now known to be invalid.

2. METHOD AND APPARATUS

The method used in this experiment was similar to that used to measure the magnetic moment of the neutron.[11–14] We might observe that the neutron is the only particle suitable for such an experiment. Any charged particle exposed to an electric field which is not small in the time average will necessarily suffer a large change in momentum. A schematic diagram of the apparatus is shown in Fig. 1. A beam of neutrons 1-cm high and 0.1-cm wide leaves the pile and is polarized by total reflection from a polished, magnetized iron

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* Now at the University of Illinois, Urbana, Illinois.

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mirror[15] at A. The beam then passes into a region of homogeneous magnetic field produced by the magnet B. The polarization of the beam is analyzed by a magnetically saturated iron isthmus[16] in the magnet at A'. The neutrons traversing the apparatus are counted in a BF_3 proportional counter at D. When a radio-frequency magnetic field is applied to the neutron beam in two separated coils[17] C and C' at the average Larmor frequency of the neutrons in the magnetic field between these coils, transitions may be induced to the opposite spin state. The intensity of the beam passing through the analyzer will consequently decrease. If the neutron had an electric dipole moment oriented along its spin, a steady electric field applied parallel to the homogeneous magnetic field in the region between the coils C and C' would alter the torque on the neutron and hence would change its precession frequency. This would result in a shift in the frequency at which a maximum number of spin transitions were induced. Such an electric field was applied between the plates of a condenser E.

The magnetized iron mirror used as the polarizer was polished flat on a pitch lap to one or two wavelengths of light per inch. The mirror was six inches long and one and one-half inches high, though a beam of neutrons only one centimeter high was used. The magnetic field at the surface of the mirror was nearly 2500 oersteds. The intensity of neutrons reflected from this mirror as a function of mirror angle was compared to that theoretically expected from a flux of neutrons with a 500°K Maxwellian velocity distribution and found to agree within experimental error. The polarization theoretically expected at the mirror angles used in the experiment was approximately 85%. The analyzer was a magnetically saturated piece of cold-rolled steel such as other experimenters have used for both polarizer and analyzer.[11–13] A magnetic field of approximately 10 500 oersteds was maintained in the analyzer block. A second mirror would have been preferable, but limited space prevented its use. With the mirror polarizer and steel block analyzer changes of 40% in intensity were observed in varying the frequency through resonance.

The homogeneous field magnet was constructed by clamping two cold-rolled steel pole faces 71-in. long by 5-in. high by 1-in. thick 1.75-in. apart. Sixteen small Alnico magnets bolted between the pole faces along the bottom supplied the magnetomotive force. This construction provided a convenient trough in which the radio-frequency coils and electric-field plates could be suspended. The magnet provided a field of about 250 oersteds which corresponds to a neutron transition frequency of 750 kc/sec. The split rf coil technique does not require a field of high homogeneity, so the homogenizing was done by rubber-cementing suitably cut steel shims to the magnet pole faces. The final field was uniform to within $\frac{1}{3}$ oersted of its mean value over the relevant region traversed by the neutron beam. All magnetic-field measurements were made with a proton-resonance apparatus. The field was not exceedingly stable. It was necessary to enclose the whole apparatus in a box whose temperature was regulated to about 0.2°C. Large steel objects and electromagnets in neighboring laboratories disturbed the field noticeably. Such day to day disturbances are not particularly objectionable because the comparisons involved in any one measurement extend over a relatively short period. Data were discarded, however, when it was discovered that the field was drifting excessively.

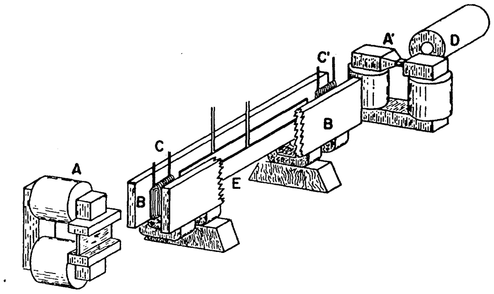

FIG. 1. Schematic diagram of the apparatus. A, the magnetized iron mirror polarizer. A', the magnetized iron transmission analyzer. B, the pole faces of the homogeneous field magnet. Note the horseshoe-like magnets bolted along the bottom. C, C', the coils for the radio-frequency magnetic field. D, the BF_3 neutron counter. The magnetic fields in the polarizing magnet and the homogeneous field magnet are at right angles, and two twisted iron strips were used between them to rotate the neutron spins adiabatically.

The electric field was produced by applying a voltage of approximately 25 000 volts between highly polished nickel-plated copper plates 0.349-cm apart and 135-cm long. This whole structure was enclosed in a vacuum chamber for insulation and suspended in the magnetic field. The nickel disturbed the magnetic field to some extent, but unfortunately the ferromagnetic substances seem to have the best vacuum sparking characteristics.

The radio-frequency magnetic field was produced in two helical coils 5-cm long with their axes along the neutron beam. The coils were spaced 159 cm apart. The radio-frequency current was supplied by a conventional resistance-stabilized electron-coupled Hartley oscillator driving a 1625 beam power tube through two amplifier-buffer stages. The master oscillator was of very rigid construction and was quite stable. During the experimental runs the frequency was monitored on a Bendix Radio LM-18 frequency meter. The average frequency during a run was known to be better than 2 cps per Mc/sec.

All counts were referred to the counts recorded in a thin BF_3 proportional counter used as a monitor, through which the beam passed as it left the pile.

Typical resonance curves are shown in Fig. 2. As the radio-frequency magnetic field is changed in frequency

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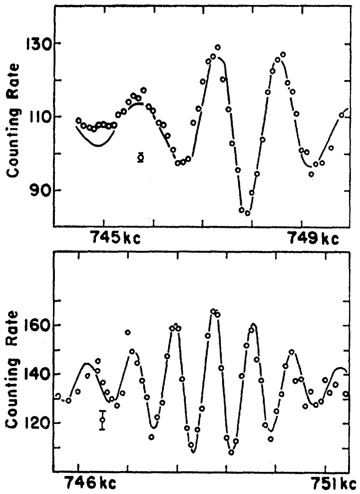

FIG. 2. Resonance curves of the neutron counting rate *versus* the frequency of the radio-frequency magnetic field. The upper curve is for a mirror angle of 3.14×10^{-3} radian, and the lower for 5.77×10^{-3} radian. A typical root-mean-square counting statistical error is shown. The lower curve shows a narrower resonance due to the fact that only slower neutrons are reflected at the larger mirror angles. It also shows more resonance detail since the polarized neutrons are more nearly monochromatic. The central peak is a minimum in the upper curve and a maximum in the lower curve since the phase of one of the coils was reversed.

the intensity varies as the neutrons have their spins flipped by varying amounts. The curves shown are theoretical calculations with the resonant frequency and main peak-to-valley ratio as adjustable parameters. A Maxwellian 500°K spectrum was used for the neutrons. The second curve of Fig. 2 shows the expected narrowing of the resonance curve at large mirror angles where only the slower neutrons are totally reflected. The agreement between theory and experiment is excellent, as shown by the experimental points. A sample probable error is shown for comparison. The upper curve corresponds more closely to the parameters used in the experiment.

3. RESULTS

To find the effect of the electric field on the resonance frequency of the neutrons, the radio-frequency magnetic field was set to a frequency corresponding to a point on one of the steep sides of the central resonance. Counting rates were then recorded as the polarity of the electric field was switched back and forth. The results are shown in Table I. The first column gives the number of the run; the second, the number of readings taken; the third, the average number of counts per reading; the fourth, the difference in the average of the counting rates with the field positive and negative; the fifth, the total change in the potential difference between the condenser plates; the sixth, the slope of the resonance curve in counts per cycle; the seventh, whether the data was taken above or below the resonance frequency. In computing the upper limit for the electric dipole moment, run number 6 has been discarded. Although nothing was found wrong with this particular run, the result looks peculiar and indeed the next day the counting equipment failed completely.

TABLE I. Summary of results.

Run	Number of counting periods	Average number of counts in each counting period	Difference between averages with field + and −	Total difference between + and − voltages	Slope of resonance curve	Run taken above or below resonance
1	16	17 102.3	1.7	47 000	8.28	above
2	16	16 991.3	−52.5	46 000	10.58	below
3	16	18 217.3	68.1	51 000	12.11	below
4	18	17 920.4	−30.7	51 000	11.86	above
5	8	18 447.6	−17.3	51 000	12.11	below
6[a]	8	18 018.5	−248.0	54 000	11.86	above
7	16	17 350.4	−93.3	56 000	12.90	below
8	16	17 987.0	−16.0	56 000	10.35	above
9	8	17 156.4	6.8	56 000	12.90	below
10	16	17 310.3	69.9	56 000	12.33	above
11	16	17 626.8	−29.5	56 000	11.32	above
12	15	16 223.5	39.8	53 000	13.68	below
13	16	16 613.2	47.8	54 000	13.68	below
14	17	16 581.6	−31.5	54 000	13.68	below
15	16	16 615.5	−20.2	54 000	13.14	above
16	14	16 596.2	−18.4	54 000	13.14	above

[a] Run number 6 was discarded.

From the data of Table I, the value of the neutron electric dipole moment is found to be

$$D=(-0.1\pm2.4)\times10^{-20}\ \text{cm},$$

and the indicated error is the root-mean-square deviation from the mean. From this one can conclude that if an electric dipole moment of the neutron exists and is associated with the spin angular momentum it is probably less than the charge of the electron multiplied by 3×10^{-20} cm and it is almost certainly less than 5×10^{-20} cm. As discussed in the first section, this result is consistent both with the dipole moment being very small as would be expected if the only violation of parity conservation were in the weak forces, and with the dipole moment vanishing as would be expected from arguments of time-reversal invariance.