quantum theory is almost exclusively kinematical, the role of dynamics being absorbed in the "stacking" observable $\pi^A(x^s)$. A more customary form of dynamics may be recovered within the quantum theory, if among the conditions used to define $\gamma_A(x^s)$, we include that the space be asymptotically flat at infinity.

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Upper Limit for the Electric Dipole Moment of the Neutron*

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A neutron-beam magnetic-resonance experiment has been used to set an upper limit to the neutron electric dipole moment μ_e of $|\mu_e/e|<3\times10^{-22}$ cm, where e is the charge of the proton. A description of the experimental method using very slow neutrons is given, as well as an analysis of the data for systematic effects.

I. INTRODUCTION

In a preliminary report of the present experiment,[1] we reviewed previous experimental upper limits for the electric dipole moment of elementary particles, and listed some of the theoretical calculations for nucleon electric dipole moments. The experimental number which we reported for the neutron electric dipole moment was $\mu_e/e=(-2\pm3)\times10^{-22}$ cm. This was much below the previous upper limit of 5×10^{-20} cm established by Smith, Purcell, and Ramsey.[2] This was in agreement with an experiment reported at the same time by Shull and Nathans,[3] and with unpublished preliminary observations by Cohen, Lipworth, Nathans, Ramsey, and Silsbee. The magnitude of this experimental result was below the upper limits calculated from some models, and comparable to, or larger than, upper limits of other models.[4–13] An upper limit of this size indicates that it is unlikely that a maximal time-reversal noninvariant term is present in the electromagnetic interaction.[12,13] Since the publication of our earlier paper, we have continued to collect data and have reduced the systematic effect discussed in Ref. 1.

In Sec. II, we review the neutron magnetic-resonance method as it is applied in our experiment, and point out the desirability of obtaining a beam of very slow neutrons. Section III contains a discussion of the method used to obtain the slow-neutron beam, and a description of the design of the polarization mirrors and the magnetic-resonance spectrometer. The experimental results and an analysis of systematic effects are presented in Sec. IV.

II. METHOD

The method used in this experiment is very similar to that of the original experiment on the electric dipole moment of the neutron by Smith, Purcell, and Ramsey.[2] Polarized neutrons pass through a transverse, static magnetic field at each end of which is superimposed an

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‡ Graduate Fellow from Harvard University under appointment by Oak Ridge Associated Universities.

[1] P. D. Miller, W. B. Dress, J. K. Baird, and N. F. Ramsey, Phys. Rev. Letters **19**, 381 (1967).

[2] J. H. Smith, thesis, Harvard University, 1950 (unpublished); J. H. Smith, E. M. Purcell, and N. F. Ramsey, Phys. Rev. **108**, 120 (1957).

[3] C. G. Shull and R. Nathans, Phys. Rev. Letters **19**, 384 (1967).

[4] N. T. Meister and T. K. Radha, Phys. Rev. **135**, B769 (1964); (2×10^{-21} cm), weak. (In Refs. 4–13 the number in parentheses is the maximum value predicted for μ_e/e and the interaction used is given.)

[5] S. L. Glashow, Phys. Rev. Letters **14**, 35 (1965) and private communication; (10^{-21} cm), weak.

[6] D. G. Boulware, Nuovo Cimento **40A**, 1041 (1965); (3.5×10^{-22} cm), weak. See also J. Schwinger, Phys. Rev. **136**, B1821 (1964).

[7] G. Feinberg and H. S. Mani, Phys. Rev. **137**, 637 (1965); (10^{-21} cm), weak.

[8] K. Nishijima and L. Swank (private communication); (9×10^{-22} cm).

[9] H. Nieh and S. J. Chang (Ph.D. thesis of H. Nieh), Harvard University (unpublished); (10^{-22} cm).

[10] E. P. Chabalin, Institute for Theoretical and Experimental Physics, Moscow Report No. 367, 1965 (unpublished); (10^{-20} cm).

[11] P. Babu and M. Suzuki, Phys. Rev. **162**, 1359 (1967); ($>2.2\times10^{-22}$ cm), weak.

[12] G. Salzman and F. Salzman, Phys. Letters **15**, 91 (1965); (10^{-20} cm), electromagnetic.

[13] G. Feinberg, Phys. Rev. **140**, B1402 (1965); (10^{-19} cm), electromagnetic.

oscillating, longitudinal, magnetic field. Spin-flip transitions are induced in the neutron beam when the frequency of the applied oscillatory magnetic field equals the average Larmor frequency of the neutrons in the region between the two rf coils. The resulting change in polarization of the beam is observed by analyzing the neutrons so that only those with their spins unchanged are detected.

A strong electrostatic field is applied parallel to the static magnetic field in the region between the rf coils. If the neutron possesses an electric dipole moment associated with its spin, the neutron moments will interact with the applied fields according to

$$\mathcal{H}=-\boldsymbol{\mu}_m\cdot\mathbf{B}-\boldsymbol{\mu}_e\cdot\mathbf{E}, \quad (1)$$

where μ_m is the magnetic moment and μ_e is the electric moment of the neutron. Upon reversing the direction of the electric field, the resonant frequency will change by

$$\Delta\nu=-2(\mu_e/e)e\Delta E/h, \quad (2)$$

where ΔE is the algebraic difference in the applied electric field in the two directions. The negative sign arises because the magnetic moment of the neutron is directed opposite to the spin. Thus, the presence of a positive μ_e would decrease the resonant frequency. This frequency shift is observed, at a fixed oscillator frequency, as a change in neutron counting rate according to

$$\Delta N=-(dN/d\nu_{\mathrm{osc}})\Delta\nu, \quad (3)$$

where $dN/d\nu_{\mathrm{osc}}$ is the slope of the resonance as shown in Fig. 1. The dipole moment is then given by

$$\mu_e/e=\frac{h}{2e}\frac{\Delta N}{\Delta E(dN/d\nu_{\mathrm{osc}})}. \quad (4)$$

It is apparent from this expression that the sensitivity of the experiment increases with the slope $dN/d\nu_{\mathrm{osc}}$.

According to the uncertainty principle, the slope is proportional to the time which the neutron spends between the rf coils. A measure of this time is L/α, where L is the separation of the rf coils and

$$\alpha=(2kT/m)^{1/2} \quad (5)$$

is the most probable neutron velocity for effective temperature T.[14]

The measurement then requires a long apparatus and slow neutrons. In addition a strong electric field, and high neutron intensity and polarization are necessary for achieving good sensitivity.

III. APPARATUS

An intense beam of slow neutrons is obtained by using a bent neutron-conducting tube whose velocity selection and large angular acceptance depend on total

[14] N. F. Ramsey, *Molecular Beams* (Oxford University Press, London, 1956), Chap. V.

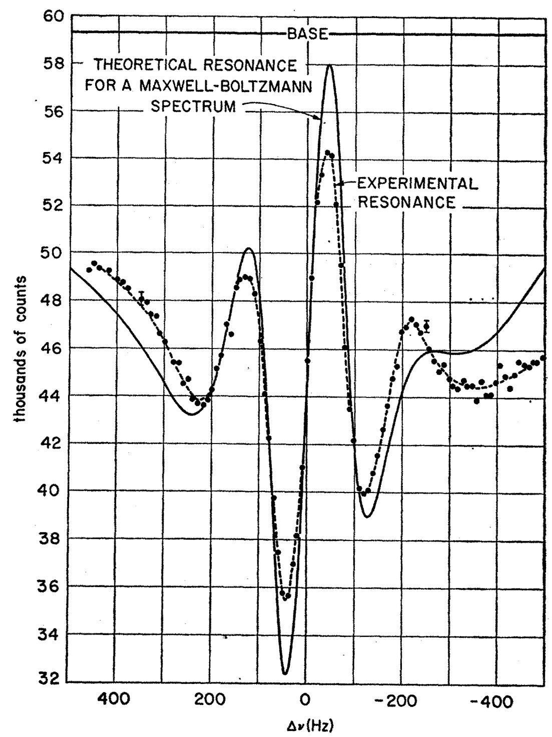

FIG. 1. Comparison of an experimental magnetic resonance with a resonance calculated from the Maxwell-Boltzmann distribution having the same velocity and polarization. The reduction in size of the experimental resonance compared to the theoretical resonance is due to the imperfect homogeneity of the uniform magnetic field. The slope $dN/d\nu_{\mathrm{osc}}$ is 444 counts/cps. Deviations in shape in the resonance wings are due to the non-Maxwell-Boltzmann character of the beam distribution.

external reflections of neutrons at the inner surface of the tube. Such neutron-conducting tubes were first developed by Maier-Leibnitz,[15] but in the present experiment such a tube is used to obtain much slower neutrons than in previous studies. Since the design and construction of the tube has been described elsewhere,[16–18] only a brief description will be given here.

A D_2O moderator is located next to the core of the low-intensity test reactor (LITR) at the Oak Ridge National Laboratory, as shown in Fig. 2. The intensity of neutrons entering the conducting tube was measured by activation methods to be $1.4\times10^{13}/\mathrm{cm}^2$ sec for a reactor power of 3.0 MW. The temperature of these neutrons, estimated to be of the order of 100°C, is higher than the 28°C temperature of the moderator, because of its limited size (13 cm diam) and the presence of nearby neutron absorbers. The D_2O is circulated through a refrigerated heat exchanger and thereby

[15] H. Maier-Leibnitz and T. Springer, J. Nucl. Energy: Pt. A & B 17, 217 (1963).

[16] W. B. Dress, thesis, Harvard University, 1968 (unpublished); Oak Ridge National Laboratory Report No. ORNL-TM-1754, 1967 (unpublished).

[17] P. D. Miller, Oak Ridge National Laboratory Report No. ORNL-TM-11, 1965 (unpublished).

[18] W. B. Dress, P. D. Miller, and J. K. Baird (to be published).

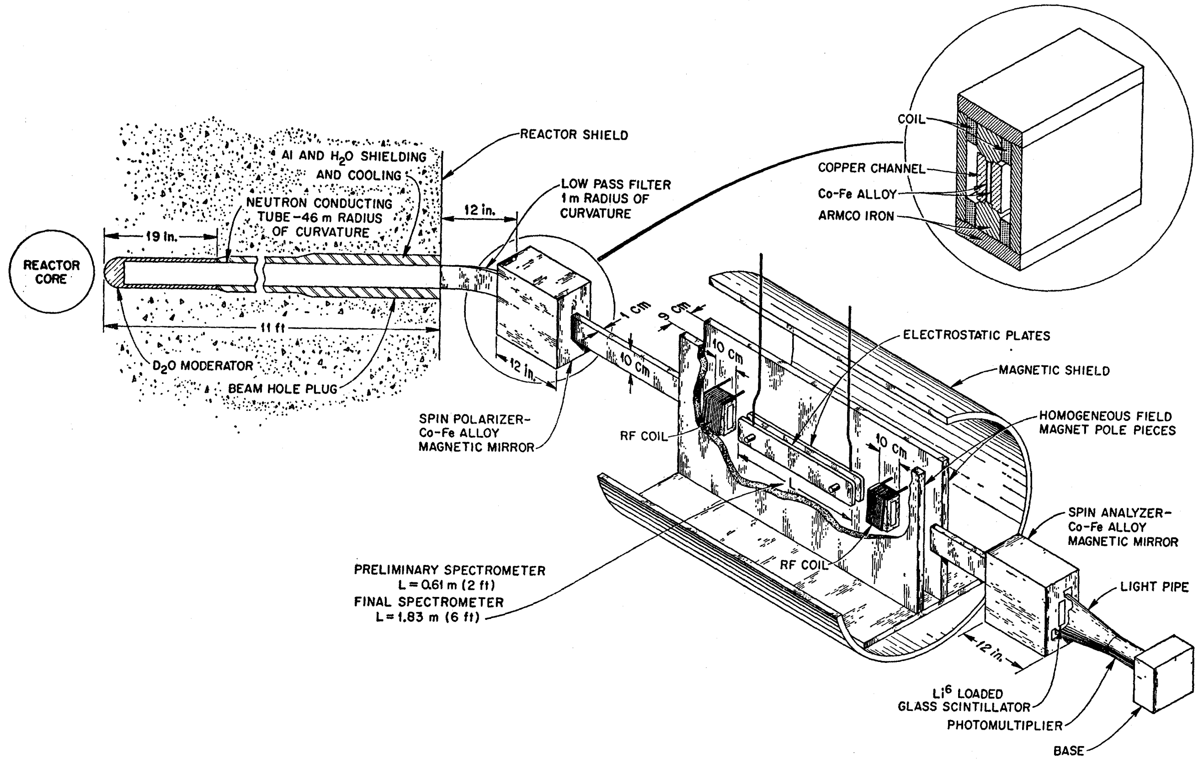

FIG. 2. Sketch of the experimental arrangement of the apparatus.

cooled to 28°C as measured by thermocouples located on the outside wall of the D_2O container. An increase in intensity of very slow neutrons of 31% was obtained by cooling the D_2O from 82 to 28°C. Neutrons enter the conducting tube through a 1×10 cm Al window $\frac{1}{16}$ in. thick. Since natural nickel has a large positive scattering length ($a=10.5\times10^{-13}$ cm), the interior of the tube is made of highly polished nickel. Neutrons of energy E which strike the nickel surface will be totally externally reflected if their grazing angle is smaller than the critical angle γ_c defined by

$$\gamma_c=\arcsin(E_0/E)^{1/2}, \tag{6}$$

where

$$E_0=\hbar^2 Na/2\pi m. \tag{7}$$

N is the number of nuclei per unit volume and m is the neutron mass.[19] The solid angle of acceptance of a straight, rectangular, perfectly reflecting tube is given approximately by[17]

$$\omega=4\gamma_c \sin\gamma_c \tag{8}$$

and is equal to 2π for neutrons with energy below $E_0=2.8\times10^{-8}$ eV as is expected (i.e., for $\gamma_c=\frac{1}{2}\pi$).

If the tube is bent with a radius of curvature ρ so that neutrons can be transmitted only after making collisions with the walls, then only low-energy neutrons will be present at the exit end of the tube. The higher-energy thermal neutrons, fission neutrons, and γ rays will not be totally externally reflected from the nickel walls, and therefore will pass through the nickel and be captured in the surrounding shielding. The bent section of the neutron-conducting path located in the beam hole plug (and thus shielded by Al and water) has a radius of curvature of 46 m. The fast-neutron and γ-ray flux leaving this section is within background when measured at 1% of full reactor power. At full power, the slow neutrons were calculated[16] to have a temperature of 20°K and an intensity of 10^6 neutrons/sec.

The neutron intensity and velocity are further reduced by using a grazing angle of 2° at the polarizing magnet. At the detector, the intensity is about 8000 neutron/sec with $\alpha=130$ m/sec, corresponding to a temperature of about 1.0°K. The velocity was determined both from the width of the resonance (80 Hz between the main peak and valley in Fig. 1) and from the attenuation on passing the neutron beam through a gas cell containing ^{3}He. The velocity inferred from the width of resonance was 130 m/sec and the gas cell gave 125 ± 15 m/sec since the thickness of the cell was not accurately known.[16] Both determinations assume the velocity distribution to be Maxwellian.

Those neutrons transmitted by the low-pass filter enter the polarizer, which consists of a magnetized mirror made from a cobalt-iron alloy as described by Hughes and Burgy.[19] The mirror is placed at an angle

[19] D. J. Hughes and M. T. Burgy, Phys. Rev. 81, 498 (1951).

of 2°–4° to the direction of the neutron beam. Varying this angle provides another means for velocity selection. The polarization mirrors used for obtaining the data previously reported[1] were constructed by brazing 0.025-in. Co-Fe plates to the copper vacuum boxes. The polarization achieved with that arrangement was 55%. We then constructed new vacuum boxes of non-magnetic stainless steel with polished 0.025-in. Co-Fe plates that could be inserted into the magnetic circuit without being brazed to the vacuum box. This resulted in an increase in polarization to 68%.[20] After polarization, the neutron spins are rotated so as to be parallel to the uniform magnetic field in the spectrometer.

The spectrometer operates at a magnetic field of 9 G generated by 45 mA of current in each of two opposing coils of some 1500 turns wound lengthwise along the top and bottom of an Armco iron frame (Fig. 3). The current supply is stable enough so that no resonance drifts have been attributable to it.[21] Soft-anodized Al electrostatic plates[22] are bonded to quartz stand-off insulators which hold the plates parallel to the magnetic-pole pieces. The whole assembly is enclosed in a steel tank which acts both as a magnetic shield (with a shielding factor of 40) and as a vacuum chamber to provide an absorption-free path for the slow neutrons.

The electrostatic field is supplied by two variable 100-kV power supplies of opposite polarities. The field is reversed by means of compressed-air-powered, oil-filled switching tanks. As suggested by Rohrbach,[22] helium at a pressure of about 10^{-3} Torr is introduced into the system to increase the attainable electric field. Without the helium, a maximum field of 80 kV/cm without sparking is attainable; however, with helium this can be made as high as 140 kV/cm.

The oscillating magnetic field is generated by two rf coils, consisting of 10 turns each of $\frac{1}{3}$-in.-wide copper ribbon, and operating at 26 kHz with a current of 150 mA. The coils are excited by a stereo amplifier[23] driven by a stable frequency synthesizer.[24] One input signal to the amplifier is shifted in phase so that the difference in phase of the signal present at the two rf coils is 90°.[25]

The neutrons are detected by a 1×10 cm piece of ^{6}Li-loaded glass scintillator, 1 mm thick, mounted inside the vacuum. The scintillations are conveyed via a light pipe to a phototube outside the vacuum system. The pulses are amplified, pulse-height analyzed, and redundantly scaled.

IV. RESULTS

Although the preliminary report[1] did not indicate the presence of a neutron electric dipole moment, the data

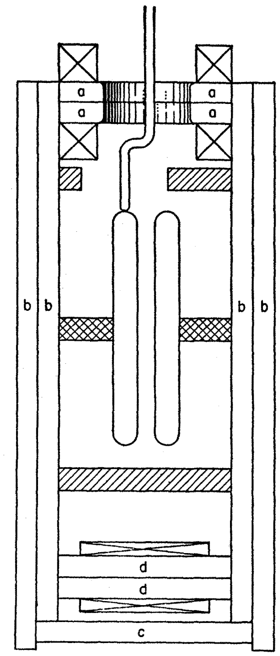

FIG. 3. Cross section of the apparatus. a, b, and d are Armco iron portions of the magnetic circuit. The geometry of the top and bottom coils is indicated. The electrostatic plates with lead-in wire and the quartz stand-off insulators are shown. The gap between the plates is 1 cm.

upon which it was based showed a systematic effect which could not be attributed to a true electric dipole moment since the effect depended upon the relative phase of the oscillatory fields. A phase reversal changes the sign of the slope of the neutron resonance[25] (the resonance in Fig. 1 was taken with a phase lag of +90° of the second rf coil with respect to the first). The apparent dipole moment changed as a result of reversing the phase. With 140-m/sec neutrons and positive slope, the apparent effective dipole length $\mathcal{E}_+$ was equal to -8.14 ± 3.46. The corresponding value obtained for the negative slope was $\mathcal{E}_-=6.74\pm3.01$. The units are 10^{-22} cm unless otherwise stated. Half the difference of these two values is a measure of the phase-dependent effect $\Phi=-7.44\pm3.24$. The value of Φ obtained for the 75 m/sec data was the same within statistical error. With this value of Φ subtracted from each of the results, the corrected numbers were then analyzed to see if there was an effect dependent upon the neutron's velocity. The coefficient κ—defined below in Eq. (9)—resulting from an assumed velocity-dependent effect was found to be $(0.092\pm0.115)\times10^{-22}$ cm sec, which is zero within its error. Consequently, it was assumed in the earlier report[1] that the velocity dependence could be neglected. With this assumption, the value for the neutron's electric dipole moment was -1.9 ± 1.9, which we reported with a larger error in the earlier paper[1] as $\mu_e/e=(-2\pm3)\times10^{-22}$ cm due to the unexplained presence of the term Φ and to the uncertainty of the assumption that the velocity-dependent effect was negligible.

In trying to understand the origin of the term Φ, we observed that the spectrometer was not firmly anchored and hence subject to slight motions due to possible

[20] The authors are indebted to R. Nathans for pointing out the difficulty of magnetically saturating fcc Co-Fe alloy if it is strained.
[21] North Hills Electronics Model CS153. Stability specifications are drift $<\pm10$ ppm of full scale (150 mA) ±10 nA over 100 h.
[22] F. Rohrbach, CERN Report No. 64-50, N.P.A. Division, Meyrin, 1964 (unpublished).
[23] McIntosh Model MC225.
[24] Hewlett Packard Model 5102A.
[25] N. F. Ramsey and H. B. Silsbee, Phys. Rev. 84, 506 (1951).

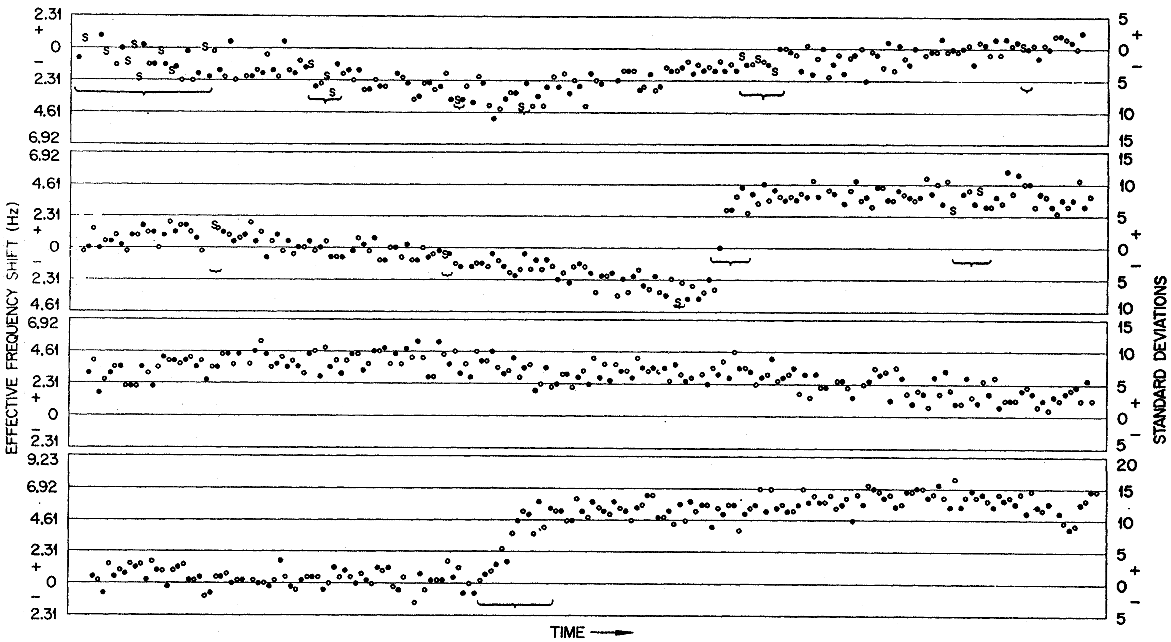

FIG. 4. Typical stability plot. Successive data points are plotted over a period of 24 h. The ordinate on the right shows deviations from the mean measured in expected standard deviations based on counting statistics only; the ordinate on the left expresses the deviation in terms of effective frequency shift, in Hz. The circles represent points taken with the electric field parallel to H_0 and the dots antiparallel. Brackets indicate points thrown out due to shifts in the resonance or due to momentary breakdown of the electric field, which is indicated by a small letter s.

mechanical vibrations or impulses arising, for example, from the remote switching of the direction of the electric field. To correct this, lab jacks were installed to firmly anchor the apparatus within its vacuum tank. Data were taken for six days before a four-day reactor shutdown interrupted the experiment. These data were taken at a velocity such that the width of the resonance (defined by the distance in Hz between the maximum and minimum central loops as in Fig. 1) was 80 Hz, corresponding roughly to an α of 130 m/sec. These six days of 80-Hz data result in a value of Φ of 0.03 ± 1.4 and a value for μ_e/e of 0.6 ± 1.6. Thus it seems that we had corrected the defect leading to the systematic error Φ.

The procedure used in accumulating data was designed to be self-compensating for such effects as variation of reactor power and long-term, linear drift of the magnetic field. The effect on the neutron counting rate due to reactor-power fluctuations was rendered negligible by referring the counts to a detector which monitored the reactor's thermal neutron flux. For added reliability, the monitor and detector counts were double scaled. In order to compensate for possible magnetic-field drifts, each datum point, corresponding to approximately 1-min counting time with the electric field parallel or antiparallel to the static magnetic field, was used twice in computing the dipole moment from Eq. (4) for a pair of field reversals. The error was then multiplied by $\sqrt{2}$ to account for the statistical interdependence introduced in the analysis. When the preset number of monitor counts had been scaled, an automatic mechanism punched the numbers registered by the scalers on paper tape and simultaneously provided a printed record. The electric field was then automatically reversed and the counting process reinitiated.

The punched paper tape was computer-compatible and furnished the input for a program which edited the raw data by rejecting counts where the field failed to switch, the dual-scaled readings differed by more than $\frac{1}{4}$ standard deviation, or the electric field broke down momentarily during a counting period. The data points which passed these tests were then analyzed, as mentioned in the previous paragraph, to give effective dipole lengths denoted by $\mathcal{E}$. These effective dipole lengths were averaged in groups each consisting of a single day's data and are listed in Table I with the standard deviations and the statistically computed errors expected on the basis of the number of counts scaled.

Runs 7–22 clearly indicate the presence of an electric-field-dependent effect. These results were analyzed for the presence of a Φ effect as described above. The phenomenological analysis assumes that the observed effect $\mathcal{E}_\pm$ may be written as

$$\mathcal{E}_\pm = D_r + \kappa\delta\nu \pm \Phi\,, \tag{9}$$

where the $\pm$ refers to data taken on a positive or negative slope. D_r is taken to be the contribution due to the presence of an electric dipole moment of the neutron; $\kappa\delta\nu$ is a term depending on angle between the electric and magnetic fields which will be discussed below.

If the effective dipole lengths $\mathcal{E}$ listed in Table I are now analyzed according to the above prescription, the term Φ appears to change from day to day as seen from Table II. A value for Φ was calculated from each successive reversal of the phase, so some of the values for Φ are repeated in the table. The error in $d=D_r+\kappa\delta\nu$ is the rms error of the error in Φ and the error in $\mathcal{E}$ from Table I.

It is evident by inspection of Table II that the mean value of the effective dipole is different for the $\delta\nu=80$ Hz and $\delta\nu=-72$ Hz cases. Here $\delta\nu$ is the frequency difference between the principal peak and valley of the resonance (see Fig. 1) and is a measure of the neutron velocity. After acquiring the $\delta\nu=80$ Hz data, the direction of the spectrometer with respect to the neutron velocity was reversed, thus changing the sign of the effective velocity. The $\delta\nu=-72$ Hz data were obtained in this manner. A physical explanation for the change in the apparent dipole in the two cases would be the presence of a nonzero angle between the electric and magnetic fields.

TABLE I. Mean effective dipoles averaged and grouped by day. Each run, with the exception of those with statistical errors $>5\times10^{-22}$ cm, contains from 600 to 1100 data points.

Run	Mean effective dipole[a]	Standard deviation[a]	Statistical error[a]	$\delta\nu$ [Hz]	Slope
1	0.54	6.00	4.15	80	+
2	−4.26	3.79	2.35	80	+
3	−0.51	3.41	2.13	80	−
4	0.71	3.97	2.33	80	−
5	4.68	3.63	2.78	80	+
6	2.96	3.95	2.45	80	−
7	−17.26	17.84	9.98	80	−
8	−5.36	3.58	1.83	80	−
9	0.17	4.51	2.25	80	+
10	−2.64	4.29	2.22	80	+
11	−19.97	4.96	2.44	80	−
12	−6.15	5.70	2.97	80	+
13	−6.16	18.08	11.25	80	+
14	−5.87	12.25	6.39	80	+
15	−8.72	4.15	2.37	80	−
16	−22.73	5.73	3.66	80	−
17	−6.69	3.19	2.44	80	+
18	−7.63	3.58	2.18	80	−
19	−10.20	2.59	1.64	80	+
20	−8.33	2.32	1.72	80	−
21	−10.20	3.00	2.41	80	+
22	−9.97	5.91	4.54	80	+
23	−1.62	5.57	4.84	106	+
24	−3.94	4.91	4.51	106	−
25	−2.87	5.39	4.72	106	+
26	−12.23	6.51	5.20	106	−
27	−7.66	5.26	4.47	106	+
28	−10.31	11.18	10.95	106	+
29	9.46	3.36	2.94	−72[b]	+
30	12.65	2.94	2.49	−72	−
31	0.63	3.24	2.97	−72	+
32	11.73	2.88	2.61	−72	−
33	2.73	3.22	2.78	−72	+
34	9.44	2.83	2.42	−72	−
35	2.06	3.19	2.58	−72	+
36	10.47	3.02	2.45	−72	−
37	4.77	2.89	2.67	−72	+

[a] Units are in 10^{-22} cm.
[b] The minus sign indicates that the spectrometer was reversed with respect to the neutron direction, thus changing the sign of the effective velocity of neutrons.

TABLE II. Apparent dipoles averaged by day with the Φ effect (see text) removed. The errors are discussed in the text.

Run	$d=D_r+k\delta\nu$[a]	d error[a]	Φ[a]	Φ error[a]	$\delta\nu$ [Hz]
1	1.06	6.34	−1.61	2.06	80
2	−2.66	4.31	−1.61	2.06	80
3	−2.11	3.98	−1.61	2.06	80
4	2.70	4.79	1.98	2.69	80
5	3.82	4.51	0.86	2.68	80
6	3.82	4.77	0.86	2.68	80
7	−14.26	18.06	3.00	2.86	80
8	−2.36	4.58	3.00	2.86	80
9	−2.82	5.34	3.00	2.86	80
10	−11.31	5.40	8.66	3.28	80
11	−13.06	6.23	6.91	3.78	80
12	−7.46	6.55	1.31	3.24	80
13	−7.47	18.37	1.31	3.24	80
14	−7.17	12.67	1.31	3.24	80
15	−7.41	5.26	1.31	3.24	80
16	−14.71	6.60	8.02	3.28	80
17	−7.16	3.99	0.47	2.40	80
18	−8.91	4.20	−1.29	2.21	80
19	−9.26	3.12	−0.94	1.74	80
20	−9.24	2.92	−0.91	1.77	80
21	−9.29	3.48	−0.91	1.77	80
22	−9.05	6.17	−0.91	1.77	80
23	−2.78	6.70	1.16	3.72	106
24	−3.41	5.56	0.53	3.65	106
25	−7.55	6.85	4.68	4.23	106
26	−10.18	7.66	2.04	4.03	106
27	−9.71	6.63	2.04	4.03	106
28	−12.35	11.89	2.04	4.03	106
29	11.06	4.03	−1.60	2.23	−72[b]
30	6.64	3.66	−6.01	2.19	−72
31	6.18	3.89	−5.55	2.17	−72
32	7.23	3.82	−4.50	2.16	−72
33	6.08	3.86	−3.36	2.14	−72
34	5.75	3.54	−3.69	2.13	−72
35	6.27	3.87	−4.21	2.20	−72
36	7.62	3.68	−2.85	2.09	−72
37	7.62	3.57	−2.85	2.09	−72

[a] Units are in 10^{-22} cm.
[b] The minus sign indicates that the spectrometer was reversed with respect to the neutron direction, thus changing the sign of the effective velocity of neutrons.

From classical electromagnetic theory, the effective magnetic field H_{eff} in a frame of reference moving with a particle at velocity v through an electric field $\mathbf{E}$ is

$$H_{\text{eff}}=-(\mathbf{v}/c)\times\mathbf{E}. \quad (10)$$

If we assume that the neutrons move perpendicular to $\mathbf{E}$, the magnitude of the effective field in gauss will be

$$H_{\text{eff}}=(v/c)E\times10^8/c, \quad (11)$$

where E is measured in V/cm and c is the velocity of light in cm/sec. If θ is the angle between the static magnetic field H_0 and the applied electric field, the magnitude of the resultant of H_{eff} and H_0 will be given to first order as

$$H_r=H_0\pm H_{\text{eff}}\sin\theta. \quad (12)$$

The difference upon reversing the electric field will then be

$$\Delta H_r=2H_{\text{eff}}\sin\theta. \quad (13)$$

Thus the resonant frequency will shift by an amount

$$\Delta\nu_E = \gamma_m \Delta H_r, \quad (14)$$

where γ_m is the gyromagnetic ratio of the neutron in Hz/G. An apparent electric dipole moment of magnitude

$$D_E = \frac{\Delta\nu_E}{\Delta E}\frac{h}{2e} \quad (15)$$

will then be present. This expression may be rewritten as

$$D_E = \tfrac{1}{2}\lambda_c g(M_e/M_p)(v/c)\sin\theta/300, \quad (16)$$

where λ_c is the Compton wavelength of the electron, g is the g factor of the neutron, and M_e/M_p is the electron-proton mass ratio. Substituting the appropriate values in Eq. (16) results in

$$D_E = 0.73\times10^{-24} v \sin\theta \text{ cm}, \quad (17)$$

where v is measured in m/sec. Thus the κ of Eq. (9) is given approximately by (assuming a Maxwell-Boltzmann neutron spectrum)

$$\kappa \approx 0.73\times10^{-24}\sin\theta\times\tfrac{3}{4}(\sqrt{\pi})L/0.464$$
$$=1.57\times10^{-22}\sin\theta \text{ cm sec}, \quad (18)$$

where the conversion factors convert the average velocity of a beam to the most probable velocity α and then convert α to the resonance width as a function of L, the separation between the rf coils.[14,16]

Thus for a width $\delta\nu$ of about 80 Hz, if the effective angle between the electric and magnetic fields were of the order of 1°, we would measure an apparent dipole length μ_e/e of magnitude 2×10^{-22} cm.

If the numbers presented in Table II are fitted in a least-squares manner[26] to the straight line

$$d = D_r + \kappa\delta\nu, \quad (19)$$

the slope of the line κ and the intercept D_r together with their errors are

$$\kappa = (-0.097\pm0.011)\times10^{-22} \text{ cm sec},$$
$$D_r = (0.02\pm0.85)\times10^{-22} \text{ cm}. \quad (20)$$

The first six days of data are not included to obtain the above results for D_r and κ since they seem to indicate that there was a change in the characteristics of the apparatus in the four days between runs 6 and 7. However, the instabilities in the remainder of the data seem to be of the order of the change between the first six runs and the next 16 runs, so this separation may well be artificial. If the first six days are included in the above analysis, the result is

$$\kappa = (-0.084\pm0.010)\times10^{-22} \text{ cm sec},$$
$$D_r = (1.05\pm0.81)\times10^{-22} \text{ cm}. \quad (21)$$

The differences between results (20) and (21) are within their respective errors, so the question is not strictly settled. The value of ϵ, where ϵ is a measure of the fit of the data,[26] is lower for Eq. (20) than for Eq. (21) indicating that the data used in Eq. (20) result in a better fit to Eq. (19). This anomaly, along with the variation of the rest of the data, seems to indicate that the instabilities of the apparatus limit its sensitivity to a small number times 10^{-22} cm.

From Eq. (18), the value of κ in Eq. (21) implies that the effective angle between the electric and magnetic fields is about 4°. Since the electrostatic plates and magnetic-pole pieces were parallel to within $\frac{1}{10}$ of 1°, the large effective angle of 4° is probably due to a residual component of H_0 tangential to the pole pieces.

Other methods of reducing the data were also employed. For example, we plotted the raw data as a function of time, and arbitrarily discarded data near points where electric-field breakdown occurred as well as points showing sudden jumps in the counting rate, and large magnetic drifts over periods less than 20 min. Figure 4 shows a typical plot. Another method was to break the data into arbitrary groups of 100 data points each instead of the equally arbitrary division into days wherein 600–1000 data points were involved.

Each of these methods of analysis resulted in numbers not significantly different from the results in Eqs. (20) and (21). If the value for μ_e/e given by Eq. (20) and the preliminary result[1] (-1.9 ± 1.9) are weighted according to their errors and averaged, the value obtained is

$$\mu_e/e = (-0.3\pm0.8)\times10^{-22} \text{ cm}. \quad (22)$$

However, in view of the fluctuations apparent above and in Table I, we believe that this experiment has set a limit on the magnitude of the electric dipole moment of the neutron of

$$|\mu_e/e| < 3\times10^{-22} \text{ cm}. \quad (23)$$

An apparatus, with an electric-field region three times as long as the one described above, has been installed at the slow polarized neutron facility described in Sec. III. The magnetic field in this new spectrometer is excited by permanent magnets, so that the instabilities noted above should be reduced. It is anticipated that the error will be reduced by at least a factor of 5.

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[26] M. E. Rose, Phys. Rev. 91, 610 (1953).