Electric Dipole Moment of the Neutron*

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An attempt has been made to observe an electric dipole moment of the neutron by performing a neutron-beam magnetic-resonance experiment with a strong electric field superimposed parallel to the uniform magnetic field. Significant limits of error of the measurement based upon probability considerations cannot be assigned because of systematic errors larger than those expected from statistics. The results are not consistent with any absolute value appreciably greater than 10^{-21} e cm and are consistent with other recent measurements.

THE possibility of the neutron possessing an electric dipole moment and its significance as a test of time-reversal invariance has been adequately discussed in the literature.[1–5] Some values for such a moment have been predicted to lie close to the upper limit established experimentally in 1950.[6] We have attempted to observe this moment and, although we cannot report a value as low as those of two other contemporary experiments,[5,7] we feel that this problem is of sufficient importance to justify confirmation. In particular our procedure contains a number of variations from the others so that a number of systematic errors will be treated differently.

The basic principle of the present experiment is the same as in the experiment of Smith, Purcell, and Ramsey in that it seeks an effect linear in the electric field on a neutron magnetic resonance.

The schematic arrangement is shown in Fig. 1. A beam of thermal neutrons from the Brookhaven High Flux Beam Reactor (6×10^{14} neutrons/cm^2 sec at the source) is diffracted by a magnetized CoFe single crystal giving a monochromatic spin-polarized beam of neutrons with a velocity near the peak of the thermal velocity distribution (about 2.2×10^5 cm/sec). The beam then passes through a uniform magnetic field of about $1\frac{1}{2}$ G. A cross section of the magnet is shown in Fig. 2. Magnetic transitions between the $m=+\frac{1}{2}$ and $-\frac{1}{2}$ levels are induced by a pair of rotating magnetic fields, one located at each end of the uniform field. After passing through the magnet the neutrons strike a second magnetized

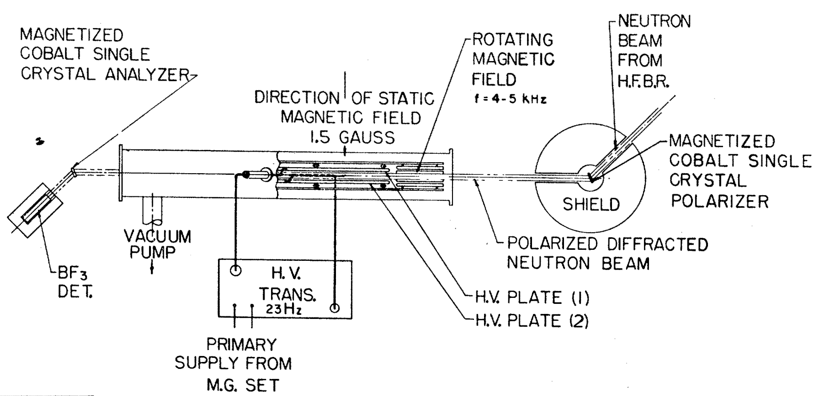

FIG. 1. General schematic arrangement of the Brookhaven neutron resonance spectrometer.

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[1] E. M. Purcell and N. F. Ramsey, Phys. Rev. **78**, 807 (1950).
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[6] For example, G. Feinberg, Phys. Rev. **140B**, 1402 (1965); and other works listed in Ref. 5.
[7] C. G. Shull, and R. Nathans, Phys. Rev. Letters **19**, 384 (1967).

cobalt crystal and are again diffracted only if their spin orientation has been preserved.

A plot of neutron rate as a function of frequency as recorded by the beam detector is illustrated in Fig. 3.

The basic experimental procedure consists of setting the frequency at a point of maximum slope of the resonance curve and looking for a change in neutron intensity correlated with applied electric field.

The apparatus was designed with an intent to suppress some of the principal sources of systematic error. Among these were

(1) the $(\mathbf{V}/c)\times\mathbf{E}$ effect; (2) variations in the neutron flux with time; (3) variation of H in time.

The $(\mathbf{V}/c)\times\mathbf{E}$ effect results from the magnetic field apparent in the system moving with velocity $\mathbf{V}$ in an electric field $\mathbf{E}$. If $\mathbf{E}$ and $\mathbf{H}$ are parallel, then the $\mathbf{V}\times\mathbf{E}$ vector is perpendicular to $\mathbf{H}$ and does not contribute to any observable effect in phase with $\mathbf{E}$. If, however, $\mathbf{E}$ and $\mathbf{H}$ are not parallel, then $\mathbf{V}\times\mathbf{E}$ will have a component along $\mathbf{H}$ and this magnetic interaction with $\mathbf{H}$ will shift the frequency of resonance in a manner indistinguishable from a $\boldsymbol{\mu}_e\cdot\mathbf{E}$ interaction except for its dependence upon $\mathbf{V}$.

By using a source of polarized neutrons derived by Bragg diffraction, it is not feasible to vary $\mathbf{V}$ greatly. However, we attempted to change its sign by rotating the apparatus through 180°. In so doing, however, stray fields due to the reactor building, the monochromator, etc., change also with respect to the apparatus, and thus $\mathbf{H}$ might not remain unchanged. In order to maintain $\mathbf{E}$ and $\mathbf{H}$ as nearly parallel as possible, the magnet pole faces were constructed from 4-79 molybdenum permalloy, to be as close as possible to magnetic equipotentials. They were insulated electrically and served also as the electric field electrodes. Thus, in the central volume of the gap $\mathbf{E}$ and $\mathbf{H}$ were expected to be parallel to a very high degree.

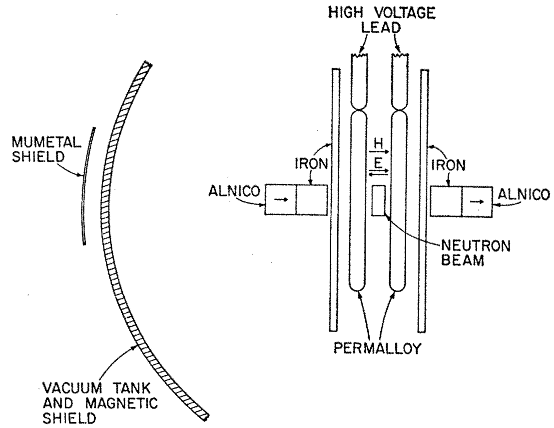

FIG. 2. Cross section through the central section of the spectrometer magnet. The magnetic field was about $1\frac{1}{2}$ G. The applied electric field was about 50 kV/cm peak value.

It has been shown that in the Brookhaven High Flux Beam Reactor that the fluctuations of the neutron intensity in time or "noise" per unit bandwidth increases as the band frequency is reduced below about 15 cps.[8] Therefore, we applied the electric field as an approximate sine wave at 23 Hz. The neutrons were counted in four time channels controlled by 90° intervals of the 23-Hz ac. An accurate measure of the time duration of each channel was made by counting 10-kHz pulses derived from a quartz oscillator. Thus we obtained a neutron rate which could be correlated with the applied voltage. Using this procedure, we avoided using a monitor neutron counter which is susceptible to errors of stability and nonproportionality between the intensity of the beam neutrons and monitored neutrons.

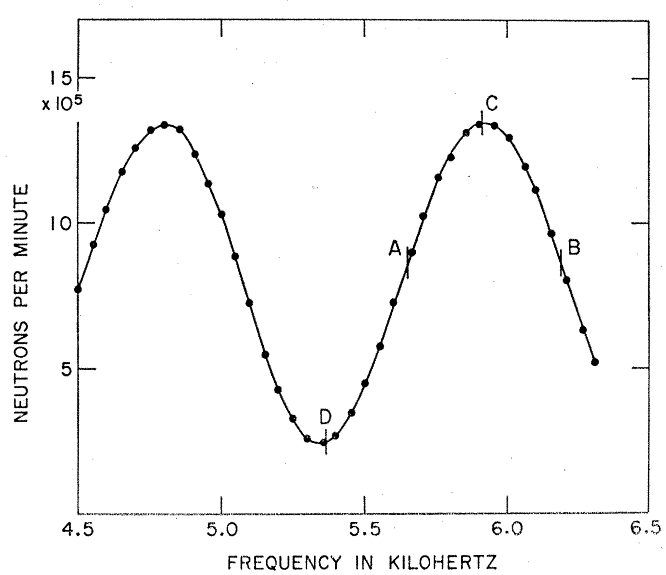

FIG. 3. A plot of the resonance curve, neutron intensity versus applied frequency. Since the velocities all lie within a narrow range, the curve shows repeated minima offset from the central one by multiples of V/L, where V is the neutron velocity and L the length between oscillatory fields. Frequencies A and B were taken for the primary effect. Points C and D were taken to look for systematic spurious effects which could not be due to a dipole interaction.

[8] Caesar Sastre of Brookhaven National Laboratory (private communication).

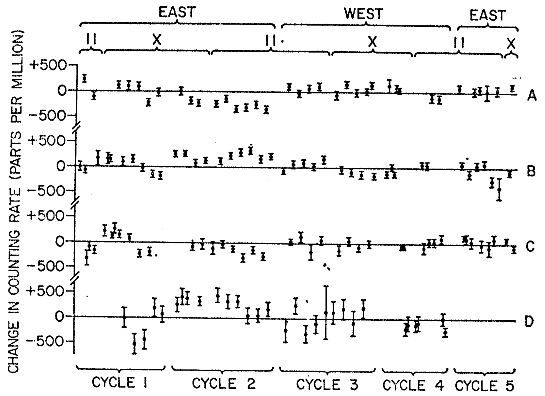

FIG. 4. Incremental change in counting rate correlated with electric field. Each point represents data collected over a period of 4 to 18 h of running time. Lines A to D represent data taken at the corresponding points of Fig. 3. The designation East and West refer to the orientation of the magnet section. The ‖ and X symbols indicate the parallel and crossed configurations of the high-voltage leads.

The apparatus had some magnetic shielding from sources outside of the apparatus. While there is considerable magnetic activity in the reactor experimental area, one would expect that there would be very little which would have frequency components synchronized with the 23-Hz power system. The one exception was the stray field from the high-voltage transformer. This was compensated in two ways: (a) By placing an array of four iron bars inside of solenoids that were wired, two in series with the transformer primary and two in parallel to it. By adjusting currents and orientations of these solenoids it was possible to reduce the stray ac field greatly. (b) During a run it was possible to reverse the direction of this field with respect to the electric field by interchanging the high-voltage leads at the electric-field plates. Half of each run was taken in the "parallel" condition and half in the "crossed" condition.

Data were collected in run periods of approximately 20 days, the normal reactor operating cycle. During this time, points were taken in 6- to 8-h periods:

(1) on one side of the resonance such as A in Fig. 3;
(2) on the opposite side of the resonance such as B in Fig. 3;
(3) at the peak C or valley D of the resonance in order to search for spurious fluctuations in intensity that would not be correlated with a frequency shift. Midway during the run, the high-voltage leads were reversed as described above.

The neutron counting rate for each time quadrant of the 23-Hz Ac was analyzed to search for (a) any effect in phase with E and (b) any quadrature effect (90° out of phase in time with E). The latter might be due to stray magnetic fields from the transformer which would be largely eliminated by reversing the high-voltage leads at the apparatus. Any residual effects due to the charging currents over the electrodes were expected to be very small because of their geometric configuration. Appreciable effects were observed, however, as mentioned below.

TABLE I. Summary of results.

Cycle	Apparent electric dipole moment (10^{-22} e cm)	Remarks
1	+12	Electronics improved and additional shielding added after this cycle.
2	−49	Note the systematic effect at points C and D. The effect out of phase with E was largest for this cycle.
3	− 3	Shielding added after this cycle between the main magnet and the polarizer and analyzer.
4	− 2	
5	+13	Electronic failure caused loss of most data in the crossed-lead configuration.

Figure 4 represents the incremental change in neutron counting rates correlated with electric field. Each point represents the data collected over a period of from four to 18 h of operating time. The error bars are based upon the spread of data collected over 18 min subintervals and are, on the average, about three percent larger than expected from counting statistics. This would indicate that short-term random errors were not serious.

Data for each three-week reactor operating period, during which about 2×10^{10} neutrons were counted, were combined by a least-squares procedure taking into consideration the reversal of transformer leads and the alternating between frequencies A and B of Fig. 3. The resultant apparent electric dipole moments are summarized in Table I.

Each cycle appeared to yield a result with a statistical standard deviation of roughly $\pm4\times10^{-22}$ e cm. However, systematic errors which were not fully understood appeared to be present in varying amounts in each cycle.

If we accept all cycles weighted equally, we obtain a value of -6×10^{-22}. While we do not understand any possible source of systematic error in cycle No. 2, it might be rejected because of (a) its very large effect on the neutron rate correlated with the electric field at the peaks and valleys of the resonance, (b) a quadrature effect which was greater in this run than in the others, and (c) its very large departure from the average obtained from the other cycles. Averaging all cycles except No. 2, we get $+5\times10^{-22}$. Cycle 4, the one in which we have the greatest confidence, gives -2×10^{-22}.

Between operating cycles 2 and 3, and between cycles 4 and 5, the apparatus was rotated end for end, the purpose being to average out the $\mathbf{V}\times\mathbf{E}$ effect. The results showed variations between cycles greater than those expected solely from statistical considerations. Some effort was spent in attempting to analyze the cause of these systematic errors. It is possible that a weak remnant magnetization in the pole faces in a vertical direction might produce a $\mathbf{V}\times\mathbf{E}$ effect that would be influenced by stray magnetic fields of neighboring equipment. After the conclusion of the experiment, tests were made with a search coil to measure the vertical component of the magnetic field within the magnet. There did appear to be a change over a period of several weeks which would change the orientation of the magnetic field with respect to the pole faces by a few milliradians.

Since the fluctuations in the value of μ_e as evaluated in each run cannot be explained on the basis of counting statistics, we feel that exact limits cannot be specified for an upper limit to a possible electric dipole moment. One can say, however, that these results are consistent with those of Shull and Nathans[7] [$(+2.4\pm3.9)\times10^{-22}$ e cm] diffraction experiment and Dress *et al.*[5] ($|\mu_e| < 3\times10^{-22}$ e cm) and not consistent with theoretical predictions appreciably greater than 10^{-21} e cm.[6]

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Search for (Σ^-n) and (Σ^-nn) Bound States*

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In an experiment involving K^- capture in helium, a search was made for (Σ^-n) and (Σ^-nn) bound states as produced by the following reactions: $K^-+\mathrm{He}^4\to(\Sigma^-n)+\pi^++d$; $K^-+\mathrm{He}^4\to(\Sigma^-nn)+\pi^++p$. We did not find any unambiguous examples of these reactions among the interactions of 8370 stopping K^- mesons. Upper limits on the rates for the production of these bound hyperon states are determined, relative to various K^- capture reactions. With respect to stopping K^- mesons, an upper limit on the bound-state production rate is $\leqslant 0.02\%$, using one ambiguous bound-state event for calculational purposes. In addition, for these data, we do not find evidence for a maximally strong (Σ^-n) final-state interaction.

I. INTRODUCTION

PREVIOUSLY, there have been a number of searches for bound states of hyperons in nuclear emulsions with inconclusive results.[1–3] A bubble-chamber experiment, involving K^--deuterium capture at rest,[4] searched for the (Σ^-n) bound state as produced by the two-body reaction

$$K^-+d\to(\Sigma^-n)+\pi^+. \tag{1}$$

By angular momentum and parity-conservation selection rules, only the triplet state can be produced. The result of this experiment was to set a limit of $\lesssim 1\%$ to the fraction of Σ^- hyperons forming a triplet (Σ^-n) bound state. This deuterium capture experiment could not detect a singlet (Σ^-n) bound state.

Recent experiments on Σ-proton scattering indicate a weak triplet Σ-nucleon interaction.[5] So if there is a Σ-nucleon bound state, it could be expected to occur as a singlet (Σ^-n) bound state. In helium, in contrast to deuterium, there are no selection rule restrictions, since there is a three-body final state, and, therefore, K^- capture can produce a singlet (Σ^-n) bound state.[6] In this paper, we report on a search for the (Σ^-n) and the (Σ^-nn) bound states from K^- capture in helium.

II. EXPERIMENTAL PROCEDURE

A two-stage, electrostatically separated beam was designed and built at the Argonne zero-gradient synchrotron (ZGS) to provide 600–850 MeV/c K mesons. The details and parameters of the beam are described elsewhere.[7] In this experiment the K^- beam was transported at 650 MeV/c, then slowed down by a moderator and the copper surrounding the Argonne National

* Work supported in part by the Research Corporation and the National Science Foundation.

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