EXPERIMENTAL SEARCH FOR AN ELECTRIC DIPOLE MOMENT OF THE NEUTRON

RESULTS AND PROSPECTS FOR IMPROVEMENTS

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The discovery of the CP violating mode of decay of the long-lived neutral K meson into two pions is now six years old [1]. We are still faced with the unpleasant fact that the existence of the decays $K_2^0 \to \pi^+ + \pi^-$ and $K_2^0 \to 2\pi^0$ are the only experiments which have shown a CP violation. These K_2^0 transition probabilities are now well established and the experiments have been repeated many times over. The search for an electric dipole moment (EDM) of the neutron is a very sensitive attempt to observe a time reversal or CP violation in a system other than K_2^0.

Many theoretical estimates of the size of the neutron EDM have been made, and these estimates fall into three size groups:

1) The largest predicted neutron EDM results from the assumption of the failure of time reversal invariance in the first-order electromagnetic interaction. Examples of these calculations are those of Feinberg [2] and of Salzman and Salzman [3], and the predicted sizes were $\mu_e/e \sim 10^{-20}$–10^{-19} cm. This type of theory has been eliminated by the present EDM results.

2) If the assumption is made that the CP violating decay of the K_2^0 is due to a small CP violating impurity in the strong or weak interaction, then these milli-strong or milli-weak theories predict an EDM of order $\mu_e/e \sim 10^{-24}$–10^{-22} cm. If time reversal violation occurs in a second-order electromagnetic interaction, similar numbers are obtained [4]. This size range is exactly where our present experimental limit of $\mu_e/e < 5 \cdot 10^{-23}$ cm lies. Consequently, we are strongly motivated to seek an improvement in the sensitivity of the search for a neutron EDM by a factor of 10 or more.

3) The other type of theoretical estimate of the neutron EDM is based on Wolfenstein's superweak theory, and these estimates lie around $\mu_e/e \sim 0$–10^{-28} cm [5]. This size range is probably inaccessible to experiment for all practical purposes.

Our experiments at ORNL have been done by a group consisting of N. F. Ramsey, W. B. Dress, J. K. Baird, and myself. A magnetic-resonance spectrometer with separated oscillatory fields was used with a polarized neutron beam. A strong static-electric field was applied parallel to the magnetic field in the region between the coils. The energy levels for a neutral, spin 1/2 particle possessing both an electric and a magnetic moment are shown in Fig. 1. If the oscillatory fields are excited near the Larmor frequency, spin flip transitions are induced. The resulting resonance pattern is shown in Fig. 2. According to the uncertainty principle, the slope of the resonance is proportional to the time which the neutron spends between the oscillatory coils. A measure of this time is L/α, where L is the separation between the oscillatory coils, and α is a measure of the neutron velocity. The sensitivity to a neutron EDM is enhanced by the following features: 1) long apparatus; 2) large polarizations; 3) high electric field; 4) high-intensity beam of very slow neutrons. The parameters which we used are shown in Table 1. The beam of very cold neutrons was achieved by the use of a bent, neutron-conducting tube whose effectiveness depends upon total external reflections of slow neutrons from the polished nickel inner surfaces. The use of such neutron-conducting tubes was pioneered by Maier-Leibnitz [6].

Oak Ridge National Laboratory, Oak Ridge, Tennessee, USA. Published in Problemy Fiziki Élementarnykh Chastits i Atomnogo Yadra, Vol. 2, No. 4, pp. 959-971, 1972.

TABLE 1

Length of static electric field region	1.96 m
Magnitude of static electric field	120 kV/cm
Magnitude of static magnetic field	17 G
Polarization	70%
Average neutron velocity in the beam	115 m/sec
Slope of resonance	80 counts/cycle
Width of resonance	34 Hz
Intensity at resonance	2800 sec^{-1}
Thermal flux at tube entrance	$1.3 \cdot 10^{13}$ $n/cm^2 \cdot sec$

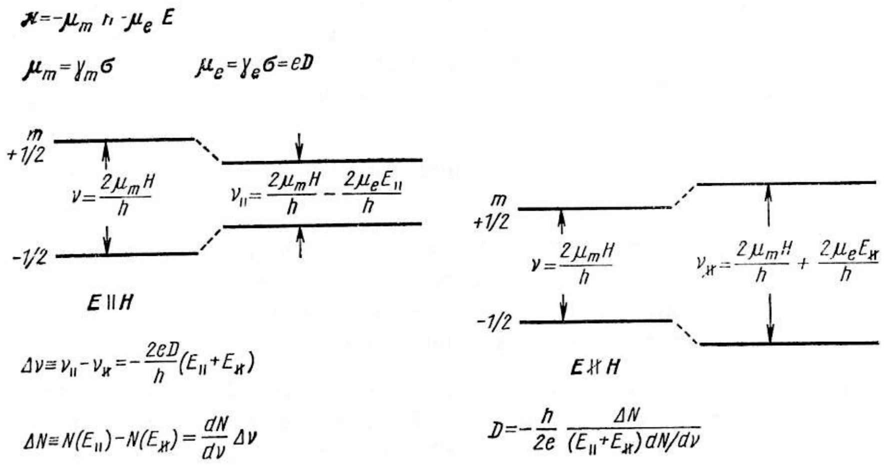

Fig. 1. Energy levels for a neutral, spin-1/2 particle with magnetic and electric moments μ_m and μ_e, respectively, in parallel and antiparallel electric and magnetic fields.

The spectrometer itself was designed to satisfy three requirements. These relate to the homogeneity of the magnetic field, the stability of the magnetic field, and the parallelism of the static magnetic and electric fields.

Each particle passing through the spectrometer averages over the static magnetic field between the oscillatory-field coils. If all particles followed the same path, then the resonant frequency for each would be the same. In the case of this experiment the beam was 1 cm wide × 10 cm high, and the resonance line width was expected to be ~30 Hz. It was therefore necessary to select a magnetic field and design the magnetic pole pieces to assure that the variation of the average magnetic field for neutrons following different paths through the spectrometer would be

$$\Delta H \ll h\Delta\nu/\mu_m \approx 10^{-2}\ \text{Oe}. \tag{1}$$

The time stability of the magnetic field should be such as not to introduce an error comparable to the error to be expected from the Poisson distribution of the counts reaching the detector. This error was estimated, for a counting time of approximately 2 min, to be of the order of $D = 10^{-21}$ cm, corresponding to a shift in resonance frequency of the order of 0.1 Hz. For a resonant frequency of 50 kHz, this implies a stability requirement of

$$\frac{\Delta H_t}{H} \ll 2\cdot 10^{-6}\ \text{per 2 min}. \tag{2}$$

An apparent EDM results from the motion of a neutron with velocity v through an electric field and is given by

$$D_E = \frac{\mu_m}{e}\cdot\frac{v}{c}\sin\theta, \tag{3}$$

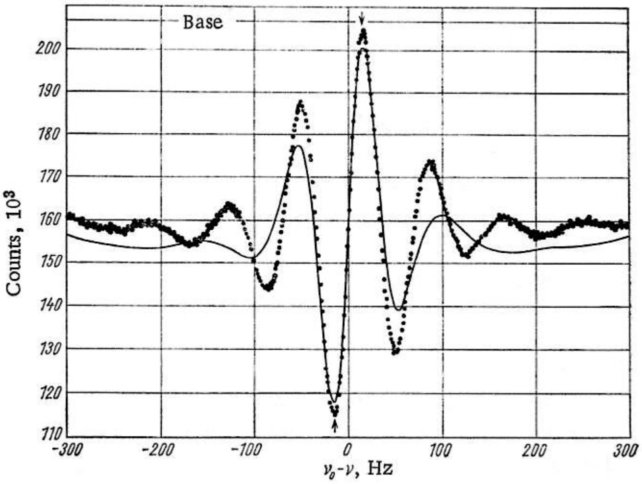

Fig. 2

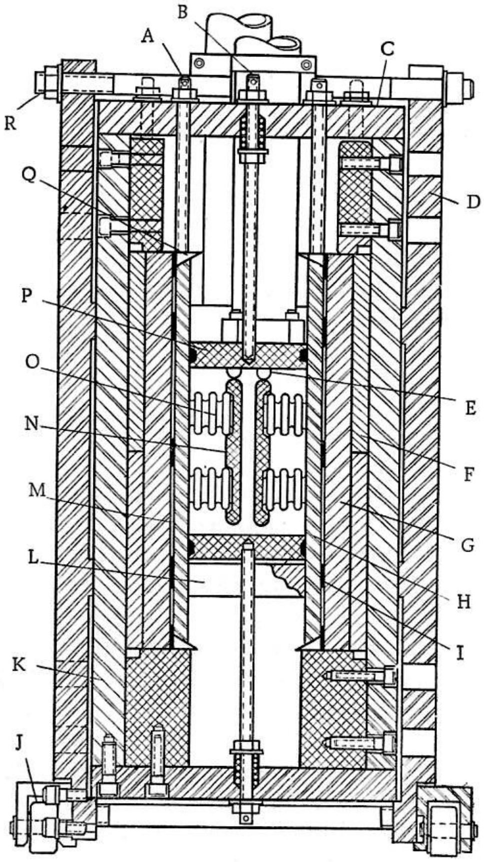

Fig. 3

Fig. 2. Resonance obtained with a 90° phase shift between the currents in the oscillatory-field coils. The line at the top marked "Base" represents the number of counts detected with zero oscillatory field current. We have defined the "width" of the resonance as the frequency difference between the extrema marked by vertical arrows. The calculated transition probability for a Maxwell–Boltzmann distribution characterized by a temperature of 1°K is shown by the solid curve; points indicate experimental data. The close correspondence between the calculated and measured amplitudes reflects the good field homogeneity.

Fig. 3. The magnetic resonance spectrometer. (A) Shim positioning studs. (B) Vacuum box positioning studs. (C) Pure iron. (D) Iron plates. (E) High voltage feed-through. (F) Permanent magnets. (G) Iron plates. (H) Moly Permalloy pole faces. (I) Non-magnetic spacers. (J) Wheels for rolling the spectrometer into the cylindrical magnetic shields. (K) Iron. (L) Quartz spacers. (M) Vacuum gap. (N) Electrostatic plates. (O) Glass stand-off insulators. (P) Vacuum box. (Q) Moly Permalloy triangular shims. (R) Spectrometer clamping studs. In order to maintain the homogeneity of the magnetic field, no bolts are used to join the parts of the pole pieces. Instead, the magnet is bound together by these studs, (R). Studs (A) maintain the alignment of the shims, while studs (B) support the box against air pressure. Stand-off insulators (O) are bounded to electrostatic plates (N) and Moly Permalloy pole faces (H) by epoxy.

where μ_n is the nuclear magneton. Equation (3) allows us to specify the degree of parallelism required between the static magnetic and electric fields in the spectrometer. For a spurious EDM of this nature to be less than $D_E \simeq 10^{-23}$ cm, for a neutron velocity of the order of 100 m/sec, the limit on θ is

$$\theta < 1.5 \cdot 10^{-3} \text{ rad.} \tag{4}$$

This small value of θ need be achieved only on the average over the length of the electric field. Furthermore, as discussed later, the quantity D_E can be experimentally measured and subtracted to give the true EDM.

The achievement of the required homogeneity is best shown by reference to Fig. 3. The magnetic pole pieces (H) and the magnetic shims (Q) were constructed from Moly Permalloy, an alloy of 79% Ni, 17% Fe, and 4% Mo. This alloy has a permeability of ~25,000 at our flux density of 17 G, and hence (H) and (G) quite closely approximate a magnetic equipotential. Each pole piece was 30 cm × 1.25 cm × 2.44 cm, opposite sides of which were ground parallel to within 7 μ. The remainder of the magnetic circuit was constructed from 2.2 cm thick pure iron. Between the iron plate and the Moly Permalloy pole piece was a 0.6-mm vacuum gap maintained uniform to within 7 μ by plastic spacers. The gap served to keep the magnetic field uniform and was evacuated to equalize the pressure on each side of the pole piece, thus preventing bowing of the pole face under the pressure differential of 1 atm. The magnetic shims (Q) were designed following a formalism similar to that of Rose [7], and were calculated to reduce the fringing inhomogeneity to $\sim 10^{-4}$ G. In order that the spacing from top to bottom of the spectrometer be held within the limits set by Eq. (1), the 30 quartz spacers (L) were held uniform in length to 3 μ. All of the materials within the magnetic gap were checked with a Gouy balance and found to have susceptibilities less than $1 \cdot 10^{-5}$. The success in maintaining adequate homogeneity is illustrated by the similarity of the size of the calculated and observed resonance in Fig. 2.

Time instabilities of the magnetic field are from two source: external and internal. To guard against external fluctuations in stray magnetic fields two concentric, cylindrical, Moly Permalloy magnetic shields were used. These were 2.5 mm thick and about 1.0 and 1.1 m in diameter. The end caps for the shields were spun from similar material. The shielding factor of the pair of shields was estimated to be ~800, and the overall shielding factor including the iron magnetic circuit was measured to be $\sim 10^4$. In order to minimize internal fluctuations, it was decided to excite the magnetic field with permanent magnets rather than with coils and a dc supply. The stability of the best dc supplies is about one part in 10^6, while for permanent magnets under closely held isothermal conditions, it is about five parts in 10^8. Alnico IV was chosen as the permanent-magnet material because of its low temperature coefficient of magnetization ($2 \cdot 10^{-4}$ per °C) and since it is not easily affected by shock or vibration. Four permanent-magnet strips were arranged along the back of each pole piece. Each strip extended from the bottom of the pole piece to the top. The magnets were all magnetized to saturation in the same manner and the tolerance on the dimension parallel to direction of magnetization was such that the magnetic field was homogeneous from top to bottom along the pole piece to within the specification set in Eq. (1). Thermal insulation was provided by filling the space between the magnetic shields with poured, expanded styrofoam. The degree of time stability achieved is illustrated in Fig. 4. An additional indication of the time stability was the fact that the final statistical error derived from comparing successive field reversals was very close to that expected from counting statistics.

Each anodized aluminum electrostatic plate was insulated from the corresponding Moly Permalloy pole face by fluted glass insulators. Assuming that the pole face and its attached electrostatic plate are magnetic and electric equipotentials, respectively, then Eq. (4) allows us to establish a limit on their parallelism. Since the electrostatic plate is 11.3 cm high, this implies that the plate and the pole face must be parallel to within 0.2 mm. In actual practice, the electrostatic plate, insulator, and pole face could be bonded together such that the out-of-parallelism was no greater than 0.05 mm.

With the careful attention given to geometrical accuracy, the dominant contribution to nonparallelism of **E** and **H** was probably residual tangential components of the magnetic field due to incomplete demagnetization of the pole pieces.

The data were collected by reversing the electric field automatically about once each minute, and the counts accumulated during that time were recorded on punched paper tape. The punched tape was edited and analyzed by computer; this method allowed a total of about 44,000 field reversals to be made, and the corresponding editing and analysis to be updated daily over the 2-month period of data collection.

Other experimental parameters, besides the direction of the electric field, were varied in systematic manner. The sign of the slope of the resonance was reversed prior to each day's run. This was effected by reversing the 90°-phase shift introduced between the two rf coils. A shift in frequency due to a reversal of the electric field appears as a change in counting rate, ΔN. If the slope of the resonance is reversed, ΔN changes sign for the same shift in frequency. Thus, the expression shown in Fig. 1 should be independent of the slope change if ΔN is due to a neutron EDM. Any significant difference in the results of data taken with opposite slopes of the resonance must be interpreted as due to defects in the measuring device rather than to an inherent property of the neutron. No effect of the sign of the slope of the resonance was found.

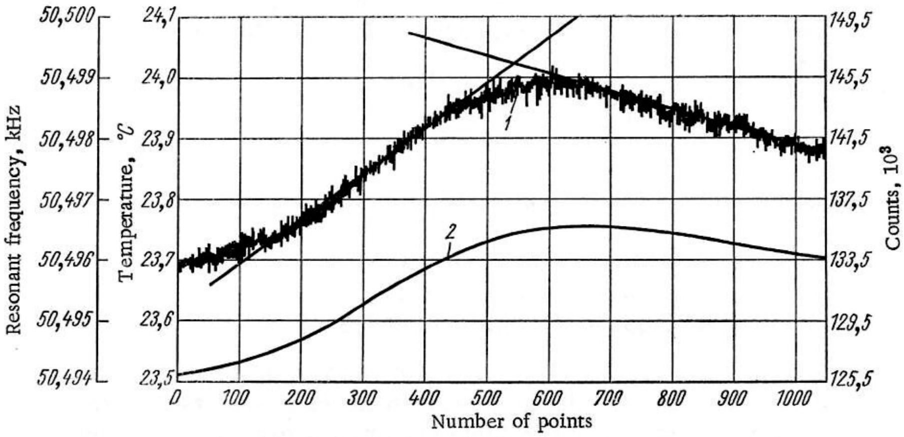

Fig. 4. A plot of the neutron counts (jagged curve) detected during a fixed counting period and spectrometer temperature (smooth curve) as a function of the number of counting periods. The second axis on the left gives the resonant frequency. The correlation between the two curves is evidence of the effect of the drifting temperature on the static magnetic field in the spectrometer. The straight lines were used to estimate the size of the effect of linear and quadratic drifts.

The third parameter subjected to systematic variation was the neutron velocity – or, more specifically, the orientation of the spectrometer with respect to the direction of the neutron beam. The size of the (v/c)E effect as given by Eq. (3) could be checked by a set of measurements made with +v alternating with a set with neutron velocity −v. After 15 days of collecting data the spectrometer was reversed, end for end, and 17 more days of data were collected. The spectrometer was then returned to its original orientation, and 21 more days of data were collected. A fourth set of data was to have provided a check against the second set, but an experimental failure (an electrostatic plate fell off), together with the permanent demise of the reactor concluded the present measurements.

If we denote a real dipole length by D_r and we parametrize the (v/c)E effect by a dipole length, D_E, the averaged results of the three sets of data are given by the following:

$$\left.\begin{array}{ll} \text{I} & D_r + 34.0 D_E/34 = +0.22 \pm 2.19 \\ \text{II} & D_r - 35.5 D_E/34 = +3.56 \pm 1.87 \\ \text{III} & D_r + 31.5 D_E/34 = -0.65 \pm 1.57, \end{array}\right\} \quad (5)$$

where the units are 10^{-23} cm. The coefficients of D_E normalize the neutron velocity, to the value corresponding to an average $\delta\nu$ of +34 Hz (about 115 m/sec). The errors are the larger of the standard deviation from the mean and the error derived from the number of counts obtained. These two errors always agreed to within 10%.

When these three sets of data are combined, the final results are:

$$\begin{array}{l} D_r = \mu_e/e = 1.5 \pm 1.1; \\ D_E = -1.9 \pm 1.1. \end{array} \quad (6)$$

This value of D_E corresponds to an angle θ of

$$\theta = (2.7 \pm 1.6) \cdot 10^{-3} \text{ rad.} \quad (7)$$

Thus we see that the angle between the fields sets a critical limitation on the experiment even though we can correct for its effect on the result.

Since we were able to obtain only three sets of data, we have preferred to state our result as

$$|\mu_e/e| < 5 \cdot 10^{-23} \text{ cm.}$$

These results together with more complete data tables have been reported in the literature [8]. Other experiments have given similar, but not quite so sensitive, results. A measurement at Brookhaven was based on a possible contribution to the imaginary part of the scattering length due to an interaction of a neutron EDM with the Coulomb field of a nucleus [9]. Their result was

$$\mu_e/e = (+2.4 \pm 3.9) \cdot 10^{-22} \text{ cm.} \tag{8}$$

Other magnetic resonance measurements have given the following results:

Brookhaven $< 10^{-21}$ cm [10]
Aldermaston $< 10^{-21}$ cm [11]
Romania $(0.2 \pm 3.9) \cdot 10^{-22}$ [12].

The prospects for improving the sensitivity of the search for a neutron EDM are good. In the near future we should have results from the Oak Ridge Research Reactor with its thermal flux of $3 \cdot 10^{14}$. Our present spectrometer has been mounted on a turntable such that it can easily be reversed end for end. We should be able to achieve a sensitivity of about $5 \cdot 10^{-24}$ cm within the next six months.

The next order of magnitude will be considerably more difficult. We do not think it is feasible to attain much improvement in sensitivity by building a longer spectrometer similar to ours. An increase in length would require even greater field homogeneity and, consequently, more severe requirements on parallelism of the pole pieces.

A more promising approach is the use of a storage box for neutrons of such low velocities that there is total reflection of the neutrons even at normal incidence. The possibility of such boxes was first suggested by Zeldovitch [13], and we have already heard of Lushchikov, Shapiro, Groshev, and co-worker's results [14], [15], with ultracold neutrons. They have achieved containment times in excess of 10 sec, and containment times in excess of 100 sec are theoretically possible. Steyerl at Munich [16] has calculated that it may be possible, with a neutron reflecting turbine, to achieve a flux of ultracold neutrons of 10^4 $n/cm^2 \cdot sec \cdot sr$ from a reactor with a thermal flux of 10^{15} $n/cm^2 \cdot sec$, and using a liquid D_2 moderator. It should be realized that a neutron turbine is only useful for shifting the velocity origin in phase space. Were it not for the strong absorption of ultracold neutrons in the walls of the liquid D_2 moderator, the turbine would be of no value. If then, an electric field of 10^5 V/cm is assumed, and a total measuring time of 10^6 sec is assumed, and neutrons are accepted from 1 $cm^2 \cdot sr$, then the ultimate sensitivity with a containment time of 100 sec might be

$$D = \frac{h}{4eE\sqrt{N}\,\dfrac{dP}{d\nu}} \approx 10^{-27} \text{ cm.} \tag{9}$$

If we inquire as to the construction requirements of such a spectrometer we find that the task is formidable, but perhaps not quite impossible.

The magnetic resonance linewidth would be $\sim 10^{-2}$ Hz so that the field would have to be homogeneous to

$$\Delta H \ll \frac{10^{-2}}{3 \cdot 10^{3}} \approx 3 \cdot 10^{-6} \text{ G.} \tag{10}$$

If one assumes a field reversal period of 100 sec, then the time stability requirement would be

$$\Delta H_t \ll \frac{1}{\sqrt{N_t}\,\mu_m \dfrac{dP}{d\nu}} \approx 10^{-9} \text{ G/100 sec.} \tag{11}$$

The parallelism requirement on **E** and **H** is the only bright spot. If the entrance and exit coils are made to be the same coil, then the vector velocity from entrance to exit is 0 and the (v/c)E effect vanishes identically. In any case, the velocity involved is the distance from entrance to exit divided by the containment time and is vanishingly small.

The requirement on homogeneity (10) is reduced by the long containment times during which each neutron averages over the magnetic field. The dimensional tolerances can be eased by using a small static magnetic field, perhaps 10^{-2} to 10^{-1} G. The most difficult problem is whether high permeability materials can be obtained with the required uniformity.

If the magnetic field of 0.1 G is supplied by a current supply, then a stability requirement of much better than one part in 10^8/100 sec is rather difficult. Multiple layers of very well demagnetized, high permeability magnetic shields have been used in maser experiments with similar, but not quite so severe, requirements for shielding from magnetic fluctuations.

If a containment time of 10 sec is assumed, then the homogeneity and time stability requirements are both relaxed by one order of magnitude and the sensitivity is reduced by one order of magnitude. It seems clear that this condition can be achieved, so that, in conclusion, 10^{-26} cm seems quite possible, but 10^{-27} cm would stretch the limits of technology.

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