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ELECTRIC DIPOLE MOMENT OF THE NEUTRON

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CONTENTS

INTRODUCTION

Although the total electric charge of the neutron is zero, its charge density need not be zero everywhere. In particular, if the density for one sign of electric charge were greater near one pole of the neutron than near the other, the neutron would be said to have an electric dipole moment.

In general, the electric dipole moment of a particle is defined as follows. Let the coordinate z be measured from the center of mass of a particle and let ρ_{JJ} be the electric charge density inside the particle, whose angular momentum is $\mathbf{J}$ with quantum number J and whose orientation state is given by $m = J$ relative to the z axis. The scalar magnitude d_n of the vector dipole moment $\mathbf{d}_n$ is then defined by

$$d_n = \int \rho_{JJ} z \, d\tau, \qquad 1.$$

where $d\tau$ is a differential volume element. If the particle is charged, this

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definition implies that the center of charge of the particle is displaced from the center of mass if $d_n \neq 0$. If, on the other hand, the particle has no net charge, the definition implies a greater positive charge in one hemisphere and a correspondingly greater negative charge in the other.

It is easy to see from the following argument that the electric dipole moment must vanish if there is invariance (symmetry) under the parity transformation (P) for which $\mathbf{r} \to -\mathbf{r}$ or under the time-reversal transformation (T) for which $t \to -t$. Since the orientation of the particle can be specified only by the orientation of its angular momentum, the dipole moment $\mathbf{d}_n$ and the angular momentum $\mathbf{J}$ must transform their signs the same way under P and T invariance. But $\mathbf{d}_n$ changes sign under P whereas $\mathbf{J}$ does not, so $\mathbf{d}_n$ must vanish if there is P symmetry. Likewise $\mathbf{d}_n$ does not change sign under T but $\mathbf{J}$ does, so $\mathbf{d}_n$ must vanish if there is T symmetry. More rigorous proofs of the above can be given (1–4). If one makes the usual assumption of CPT invariance (where C is the charge conjugation transformation, $Ze \to -Ze$), the existence of an electric dipole moment would also imply a failure of CP invariance. In molecules, electric dipole moments do exist and are attributed to degenerate states rather than to a failure of T symmetry; but degeneracy for the neutron would contradict the well-established fact that neutrons obey the Pauli exclusion principle.

For many years it was believed that the above P-symmetry argument precluded the existence of an electric dipole moment for elementary particles. Purcell & Ramsey (1) first pointed out that invariance under P could not be a priori assumed but had to be demonstrated experimentally, and few experiments were sensitive to P. They realized that a sensitive test of P symmetry would be a search for an electric dipole moment. This analysis inspired the first experiment on the electric dipole moment of the neutron by Smith, Purcell & Ramsey (5, 6). Their measurement lowered the experimental limit on $|d_n|$ from 10^{-15} to 5×10^{-20} e cm (e is the electric charge of the proton). Subsequently, Lee & Yang (7) and Wu et al (8) showed that there was a failure of P symmetry in the decay of the kaon and in other weak interactions, including the beta decay of nuclei. Despite this breakdown of P symmetry, which removed one argument against the existence of an electric dipole moment, Landau (9, 10) and others (7) showed that the parity proof against an electric dipole moment could be replaced by the above argument based on time-reversal invariance. However, Jackson et al (11) and Ramsey (12) then emphasized that time-reversal invariance, like parity invariance was merely an assumed symmetry that had to rest on an experimental basis; there was little direct experimental evidence at that time that strong and weak interactions were invariant under T. Ramsey (12) further pointed out that, if either real or virtual magnetic poles existed, they would change sign under magnetic pole conjugation (*M*), and the *CPT* theorem would be replaced by a *CPTM* theorem. In such a case, electric dipole moments would be expected to occur, with *TM* being associated just as *CP* was.

In 1964 Christenson et al (13) discovered the *CP*-violating decay of the K_L^0 meson into two charged pions. If one assumes *CPT* symmetry as discussed above, the result implies a violation of *T* symmetry. A direct indication of a violation of *T* symmetry has also been found in the K_L^0 decay by Schubert et al (14) and discussed extensively by others (13–16). Several authors (14, 15) have shown that the observed *CP* violation in K_L decays is predominantly due to a *T*-violating and *CPT*-invariant amplitude. Outside of K decay, no evidence for *CP* or *T* non-invariance has been detected. Within the standard model of weak interactions, large *CP*-violating amplitudes are expected for $\bar{B}$-B^0 decays, but no sufficient data are yet available.

Since the discovery of *CP* violation in the K_L^0 decay, particle electric dipole moments have frequently been predicted on the basis of theories developed to explain the $K_L^0 \rightarrow \pi^+\pi^-$ decay. The different predictions for the d_n of the neutron cover a wide range of values; some are as large as 10^{-19} *e* cm, many are in the range of 10^{-23} *e* cm and some are 10^{-33} cm or smaller. As the experimental limits on d_n have been lowered, theories have been correspondingly changed or abandoned.

If the neutron has a magnetic dipole moment μ_M and an electric dipole moment $\mathbf{d}_n$, then the moments will contribute an additional energy $-\boldsymbol{\mu}_M \cdot \mathbf{B} - \mathbf{d}_n \cdot \mathbf{E}$ if the neutron is in a combined magnetic field **B** and electric field **E**. Therefore, if the neutron makes a transition from a spin orientation state with $m = -1/2$ to $m = +1/2$, the Bohr frequency ν_0 for the transition (which in this case is the neutron Larmor precession frequency) is given by

$$h\nu_0 = 2\boldsymbol{\mu}_M \cdot \mathbf{B} + 2\mathbf{d}_n \cdot \mathbf{E} = 2\mu_M|B| \pm 2d_n|E|, \qquad 2.$$

where the upper sign is for *B* and *E* parallel. Therefore, the neutron electric dipole moment is revealed by the change in the Larmor precession frequency $\Delta\nu_0 = 4d_nE/h$ when the relative directions of the parallel electric and magnetic fields are reversed.

Experimental measurements and theoretical predictions of electric dipole moments are possible for many different particles, including neutrons, protons, electrons, muons, and hyperons, but the neutron tests of theories have been particularly sensitive. The reason for this sensitivity is the neutron's zero electric charge. As first pointed out in this connection by Purcell & Ramsey (1), the electric dipole interaction energy from Equation 2 must be zero for an electrically charged particle in equilibrium, because the electric field on it must vanish since a nonzero field would accelerate the particle. As discussed by Schiff (17) exceptions to this theorem can occur (*a*) if the particle is significantly actcd upon by forces other than electric, (*b*) if the particle or nucleus involved has a finite size and structure, or (*c*) if relativistic spin-dependent effects are included. Although these exceptions permit observations of electric dipolc moments of electrically charged particles, the sensitivities of experiments with charged particles are often much less than those with neutrons. Nevertheless, the electric dipole moments of atoms have been accurately measured and from these measurements a sensitive limit to the electric dipole moment of the electron has been inferred (17a).

MEASUREMENTS USING NEUTRON BEAMS

The earliest searches for a neutron electric dipole moment were made using the neutron beam magnetic resonance method, which is very similar to the method of molecular beam magnetic resonance. The principal differences are that for neutron beams the source is usually replaced by the moderator of a reactor and that the polarizing and analyzing of the spin orientation are usually provided by reflection or transmission with magnetized iron, as discussed in the next section. The neutron beam is in a weak magnetic field such that the neutron magnetic moment precesses around the field; an oscillatory magnetic field near resonance induces transitions of the neutron from one spin orientation to the other. With the oscillatory frequency such that it is on the steep part of the resonance curve, a strong external electric field is applied first parallel and then antiparallel to the magnetic field. If the neutron has a small electric dipole moment, the extra torque from the applied electric field makes the neutron precess either faster or slower, depending on whether the magnetic field is parallel or antiparallel to the magnetic field. If the neutrons have zero electric dipole moments, the change in the electric field will not affect their spin precession or rate. The experiment consists of searching for a slight dependence of the beam intensity upon the relative orientations of the electric and magnetic fields.

A succession of neutron beam magnetic resonance experiments of ever increasing sensitivity has been carried out by Ramsey's students and associates (5, 6, 18–25) and by others (26, 27). These are described in detail in the referenced papers and were discussed at length in an earlier review article (18) so there is no further discussion of them here except to note that the latest and most sensitive of the beam experiments (24) gave

$$d_n = +(40 \pm 150) \times 10^{-26}\, e\,\text{cm}. \qquad 3.$$

EXPERIMENTS USING STORED NEUTRONS

The current and most accurate measurements of the neutron electric dipole moment all utilize neutrons stored for a relatively long time in a neutron storage bottle.

Such long-term bottling of neutrons is possible because neutrons are totally reflected, in a manner analogous to the total internal reflection of light. The motion of a neutron is governed by a quantum-mechanical wave of wavelength $\lambda = h/p$, where h is Planck's constant and p is the neutron momentum. Just as in optics, the passage of slow neutrons through matter can be described in terms of a wave with an index of refraction n. The index of refraction is given (28) by

$$n = \left[1 - \frac{\lambda^2 N a_{\text{coh}}}{\pi} \pm \frac{\mu_{\text{M}} B}{\frac{1}{2} M v^2}\right]^{1/2}, \qquad 4.$$

where λ is the neutron wavelength, N is the number of nuclei per cm^3, a_{coh} is the neutron coherent forward scattering length, μ_{M} is the neutron magnetic moment, B is the magnetic induction, $\frac{1}{2}Mv^2$ is the neutron kinetic energy, and the sign of the third term depends on whether the neutron magnetic moment and B are parallel (+) or antiparallel (−). As in fiber optics, total reflection occurs for a glancing angle θ less than the critical angle θ_{c}, given by

$$\cos\theta_{\text{c}} = n. \qquad 5.$$

Typically, polarized neutrons at 80 ms^{-1} may be totally reflected from a suitable wall material at a 5° glancing angle, and below 6 ms^{-1} they may be totally reflected at all angles of incidence. Since a_{coh} is positive with some surface materials and negative with others, the index of refraction may be less than unity, which makes possible total external as well as total internal reflection. Copper, quartz, beryllium, and beryllia, for example, give total external reflection of neutrons. It is of interest to note that neutrons at 6 ms^{-1} correspond to an energy of 2×10^{-7} eV, a temperature of 0.002 K, and a wavelength of 670 Å. Since a neutron with such a large wavelength interacts coherently with many nuclei of the reflecting material, there is little exchange of energy between the neutrons and the atoms of the containing walls so the neutrons retain their low effective temperature even when the reflecting surface is at room temperature.

Neutron mirrors are used for several purposes in the experiments on the neutron electric dipole moment. The existence of total reflection makes possible low-loss, neutron-conducting pipes, which can be hollow if the surface material is chosen to give total external reflection. The use of such neutron-conducting pipes overcomes the usual fall of intensity with distance and thereby compensates in part the loss of intensity by the selection of only extremely slow neutrons.

The departure of n from unity in Equation 4 is proportional to λ^2, so at very low velocities (less than 6 ms^{-1}) and with suitable wall materials, the neutrons are totally reflected at all angles of incidence. As a result, totally reflecting neutron storage bottles may be made with storage times exceeding 100 s. Such storage bottles are now used in the most sensitive experiments on the neutron electric dipole moment.

In Equation 4 the index of refraction depends on the neutron spin orientation through the second term. Consequently, with suitable materials and an appropriate value of B, neutrons of one spin orientation may be totally reflected while those of opposite orientation are not. This property is used in experiments both to polarize the neutrons and to analyze the extent of their polarization. One way this has been done is by transmitting the neutrons through a hollow pipe, one portion of which has magnetized ferromagnetic walls; this makes the transmission rate through the pipe much greater for one spin orientation than another. A particularly effective means to polarize neutrons of less than 6 ms^{-1} is the insertion of a thin magnetized foil in the beam path. One orientation is reflected and the other transmitted.

Two groups so far have utilized neutron storage bottles in measuring the neutron electric dipole moment. One group (29, 30), working at the Institut Laue-Langevin (ILL) at Grenoble, France, consists of collaborators from Sussex University, Rutherford-Appleton Laboratory, Harvard University, ILL, and the Technical University of Munich. The other group is a collaboration of USSR scientists working at the VVR-M reactor of the B. P. Konstantinov Leningrad Institute of Nuclear Physics (31). Although the experiments by the two groups differ in detail, they are fundamentally quite similar.

The Grenoble group (29, 30) uses the experimental apparatus shown in Figure 1. The ultracold neutrons emerge vertically from the liquid deuterium moderator of the ILL reactor and pass through a curved nickel pipe and a totally reflecting turbine (32), from which a horizontal beam goes to a magnetized 1-μm iron-cobalt polarizing foil. The polarized neutrons transmitted by the foil pass on to the storage bottle. The neutron bottle, which can store neutrons with velocities up to 6.9 ms^{-1}, consists of two beryllium electrodes, 25 cm in diameter, separated by a cylindrical tube of beryllium oxide, 10 cm long with a 1 cm thick wall. The axis of the cylindrical bottle is horizontal and perpendicular to the axis of a five-layer mu-metal shield, which has a shielding factor of about 10^5 against external magnetic field fluctuations.

A 1-μT magnetic field, for which the resonant frequency of the neutron

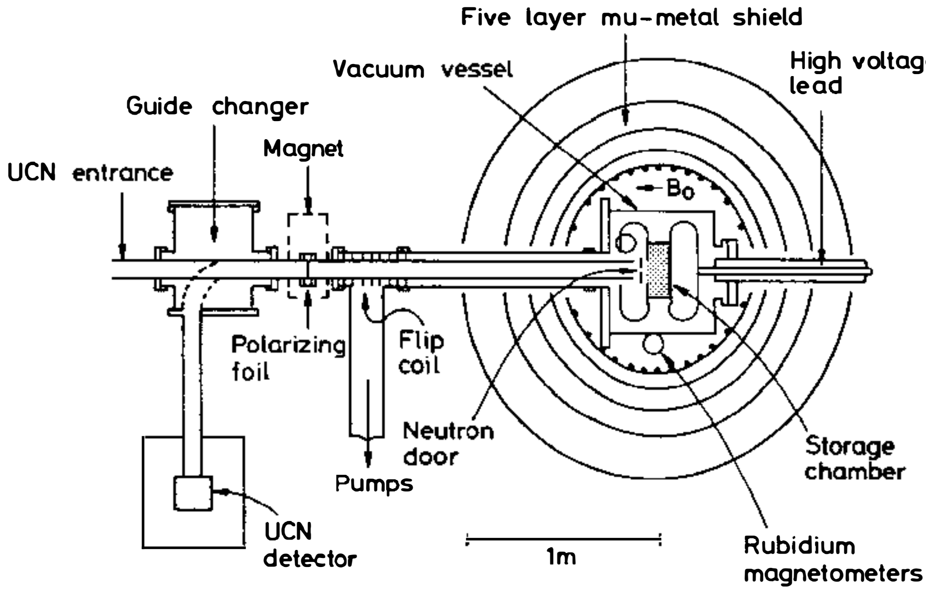


Figure 1 The experimental apparatus used at the Institut Laue-Langevin in Grenoble to measure the electric dipole moment of the neutron. Ultracold neutrons are stored for 70 s in a magnetic field of 1 μT and an electric field of 1 MV m^{-1}.

is 30 Hz, is applied parallel to the axis of the bottle. This field is generated by a coil wound on the inner surface of the mu-metal shield, with a constant number of turns per unit distance along the axis of the bottle. The neutrons enter the bottle through a hole in the center of the grounded electrode, which can be sealed by a beryllium shutter. The five-liter storage volume is filled for 10 s, which corresponds to approximately three filling time constants, and the density of polarized neutrons is about 10 cm^{-3}. The neutrons bounce around in the parallel, uniform, static electric (**E**) and magnetic (**B**) fields for either 0.6 or 6 s to allow their velocities to become isotropic. A resonant 30-Hz oscillating magnetic field is applied perpendicular to B (33, 34) for 4 s, and the neutrons are left to precess about B for 70 s. Then the second oscillating pulse coherent with the first pulse is applied, also for 4 s. The neutron valve is opened and those neutrons in the appropriate spin state pass through the polarizing foil, which now serves as an analyzer, and are counted for 10 s. The last step in the cycle is to energize the spin flip coil, which reverses the spin of the remaining neutrons; as they approach the polarizing foil they are counted for a period of 10 s. The two counting periods give approximately 10,000 and 6000 neutrons. Each measurement cycle takes 124 s, including filling and emptying the bottle.

The electric field **E** of up to 1.6 MV m^{-1} is applied as follows: 8 measurement cycles with the full field parallel to the magnetic field; 4 cycles with zero field; 8 cycles with the full field antiparallel to the magnetic field; and 4 more cycles with zero field. Since 2 additional cycles are needed for each change of state, the complete electric field sequence lasts 32 measurement cycles and takes a little over an hour. The polarity of the electric field is reversed by changing the sign of the voltage applied to the ungrounded electrode. The experiment has been run under vacuum ($\sim 10^{-6}$ torr) and with 10^{-4} torr of either nitrogen or helium, which helps to quench sparking. The leakage current across the bottle is monitored and kept below 30 nA (for most of the data it is less than 5 nA) so that its magnetic fields are negligible.

Three optically pumped rubidium magnetometers (4), which are within 40 cm of the axis of the neutron bottle, provide independent monitors of the magnetic field in the experiment. The output of each magnetometer is integrated over the 70-s neutron storage interval. Readings are also recorded from a flux gate magnetometer placed between the two outermost layers of the mu-metal shield. The direction of the fixed magnetic field is reversed every two weeks, as one of several ways of looking for possible systematic effects.

The resonance frequency of the neutrons is determined by measuring the detected intensity at two points on opposite sides of the central resonance. The resonance frequency ν_0 of the neutron is given by Equation 2 so the electric dipole moment appears as a linear correlation between the resonance frequency of the neutrons and the electric field. A single resonance frequency for the neutrons, for each measurement cycle, is deduced by combining the neutron counts from each spin state in such a way that the result is independent of fluctuations in the initial density.

Occasional jumps in magnetic field have occurred, but only data recorded with stable field were retained. The effects of slow drifts in magnetic field were eliminated by three different algorithms. First, the effects of slow drifts were eliminated by fitting polynomials of various order; second, weighted strings were used; and third, a Fourier transform filter was applied. All three produced results in good agreement with each other.

The three rubidium magnetometers were analyzed in terms of equivalent spurious neutron electric dipole moments. These average to $(2 \pm 2) \times 10^{-26}$ e cm. In onc analysis the spurious dipole moments are subtracted from d_n, reactor cycle by reactor cycle. This method corrects for external magnetic field changes to better than 20% and provides a corrected dipole moment of the neutron of $-(3.4 \pm 2.6) \times 10^{-26}$ e cm with a χ^2 per degree of freedom of 2.2 with 14 degrees. In an alternate analysis multiple linear regression was used to fit the frequency shift of the neutrons as a linear combination of frequency shifts of the three magnetometers and a term linear in electric field. Some significant correlations between the neutron and magnetometer signals have been seen. The corrected value of d_n that is derived from the coefficient of the electric field term is $-(2.3 \pm 3.0) \times 10^{-26} e$ cm with a χ^2 per degree of freedom of 1.6. Combining the results of different analyses of the data, the authors concluded that

$$d_n = -(3 \pm 5) \times 10^{-26} e\,\text{cm}. \quad 6.$$

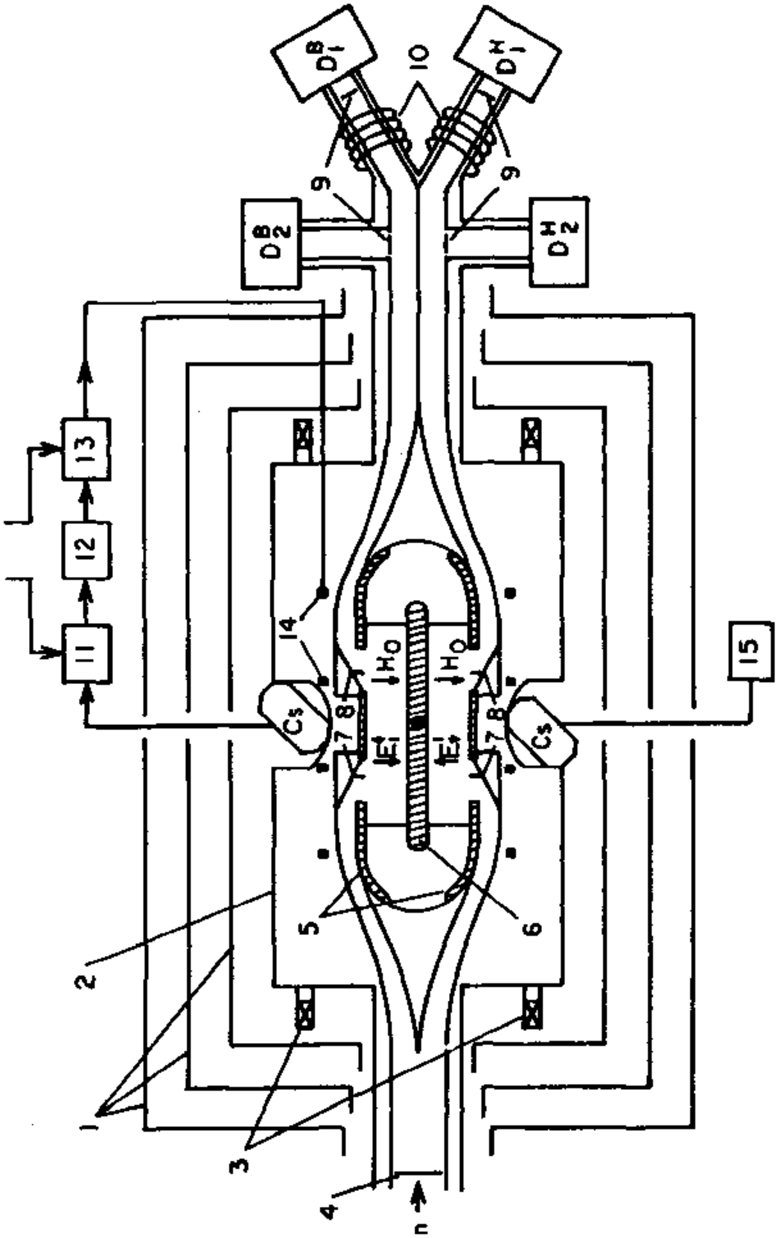
This null result translates to an upper limit of $|d_n| < 12 \times 10^{-26}$ e cm at 95% confidence level.

The Leningrad collaboration (31) uses the apparatus shown in Figure 2. The ultracold neutrons come from the VVR-M reactor and enter the apparatus from the left. Early experiments used a magnetic resonance spectrometer of a continuous-flow type, with the neutrons confined for an average of 5 s. Two chambers with oppositely directed electric fields were used to store the neutrons. The experiments yielded a value of $d_n = -(20 \pm 10) \times 10^{-26}$ e cm.

Since any further improvement in the sensitivity in the continuous-flow version of the spectrometer seemed difficult, prolonged confinement of ultracold neutrons in a closed chamber was introduced. The apparatus was modified by adding entrance and exit shutters (see Figure 2) so the neutrons could be confined to the two chambers for approximately 50 s. The two neutron confinement chambers have oppositely directed electric fields but common static magnetic and radiofrequency fields. The oppositely directed electric fields in the two cavities cancel some of the effects of magnetic field fluctuations and monitor systematic errors. The chamber is designed in such a way that the high voltage electrode separating the two chambers is between two grounded electrodes, which in a sense form a grounded screen around the high-voltage electrode. The average electric field is $\pm(12\text{–}15)$ kV/cm at leakage currents below 30 nA. The chamber walls are quartz rings on which films of BeO and Be_3N_2 have been deposited. The system of shutters can be opened and closed in 0.3 s.

Since the three-layer shield of the Permalloy type does not ensure the stability of the magnetic field for the 50–100-s storage time, the position of the resonance is stabilized by means of cesium quantum magnetometers, positioned above and below the neutron confinement chamber.

The measurement cycle includes filling the chamber with ultracold neutrons (30 s), confinement (50–55 s), and the discharge and counting of the ultracold neutrons (30 s). Coherent radiofrequency signals are applied for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1.2 s at the beginning and end of the confinement time. The polarity of the electric field is reversed in a 40-s interval between measurement cycles.

The authors conclude from a long series of measurements that

$$d_n = -(14 \pm 6) \times 10^{-26} e\,\text{cm}. \qquad 7.$$

Although the value differs from zero by more than two standard deviations, the authors state that they cannot establish the existence of a nonzero electric dipole moment with certainty. Accordingly, they conclude that the most natural interpretation of their result is that it establishes an upper limit of $|d_n| < 26 \times 10^{-26}$ e cm (95% confidence level).

The fact that both results are of negative sign could be used as arguments to suggest a small, nonzero, negative electric dipole moment. However, the result in Equation 6 is closer to zero than to that in Equation 7 and neither group of experimenters has explicitly claimed a nonzero value for the neutron electric dipole moment. As a result the experiments to date can best be described by

$$|d_n| < 12 \times 10^{-26} e\,\text{cm} \qquad 8.$$

at the 95% confidence level.

THEORIES OF NEUTRON ELECTRIC DIPOLE MOMENT

There have been many theoretical calculations of the neutron electric dipole moment. Before 1957 most of the predicted values were exactly zero because parity (P) symmetry was assumed, and from 1957 to 1964 most theories assumed T symmetry and consequently continued to predict zero. Since the discovery of CP violation in the decay of the K_L^0 almost all theories have predicted nonzero values for the neutron electric dipole moment; most of the predicted values range from 10^{-19} to 10^{-33} e cm.

The various theories before 1981 are summarized in the author's earlier review article (18). Many of these early theories attributed the electric dipole moment to CP nonconservation, either in electromagnetism or in

Figure 2 The magnetic resonance spectrometer for ultracold neutrons used to measure the electric dipole moment of the neutron at the B. P. Konstantinov Leningrad Institute of Nuclear Physics. *1*—magnetic shields; *2*—vacuum chamber; *3*—Helmholtz coils for producing static magnetic field; *4*—polarizer for the neutrons; *5*—grounded electrodes; *6*—high-voltage electrode; *7*—entrance shutters; *8*—exit shutters; *9*—analyzers; *10*—rf flipper; *11*—computer-controlled Cs magnetometer; *12*—frequency divider; *13*—unit for producing rf pulses; *14*—coils for producing oscillating magnetic field; *15*—Cs magnetometer; and *D*—neutron detectors.

a milliweak force. Most of these theories predicted values larger than 10^{-23} e cm and were consequently abandoned as the experimental limit dropped below 10^{-24} e cm.

The currently viable theories are well summarized in several excellent review articles (e.g. 35, 36), which provide extensive references. The following paragraphs briefly summarize the predictions of the various types of theories, discussed in greater detail in the excellent review by He, McKellar & Pakvasa (35).

In the standard model with one Higgs doublet, *CP* violation is due to the phase in the quark mixing matrix V_{KM} of the Kobayashi-Maskawa theory (37). There must be at least three generations of quarks to have a nonzero *CP*-violating phase (37). In these models (35, 37) the predicted value of the neutron electric dipole moment is in the range 1.6×10^{-31} to 1.4×10^{-33} e cm, far below the present experimental limit and even far below the best hopes for the next generation of measurements. A fourth family could raise the neutron electric dipole moment by as much as a factor of 20.

The model with two Higgs doublets predicts similar values for d_n as the standard model. In the Weinberg Higgs model (35, 38; S. Weinberg, private communication) of spontaneous *CP* violation with three Higgs doublets, the *CP* violation is due to complex vacuum expectations of the Higgs fields and the predicted value of $|d_n|$ is greater than 10^{-25} e cm. The comparison of this lower limit with the experimental upper limit indicates that *CP* is not maximally violated in neutral Higgs exchange (38).

The left-right symmetric model of Pati, Salam, Mohapatra, and others (35, 39) predicts values of $d_n = 10^{-26\pm 1}$ e cm. This value is just below the present experimental limit. An improvement of the experimental limit should provide crucial information on the validity of left-right symmetric models.

In supersymmetric models, the neutron electric dipole moment is calculated to be $10^{-22}\,\phi\, e$ cm, where ϕ is the possible difference between the phases of the gluino mass and those of the gluino-quark-squark mixing matrix (35). Since there is no bound for the phase ϕ from other experiments, the size of the neutron electric dipole moment cannot be predicted. However, the current limit on the neutron dipole moment indicates a value of $\phi < 10^{-3}$. Such a small value of ϕ cannot reproduce the observed violation in the K^0-$\bar{K}^0$ system, and this implies that the phase ϕ cannot be the only source of *CP* violation (35).

In quantum chromodynamics, the neutron electric dipole moment is predicted to be approximately $d_n \approx 4 \times 10^{-16}\,\theta\, e$ cm, where θ is the strong *CP* violation parameter; the measurements therefore place a limit of $\theta < 10^{-10}$ (35).

In cosmological theories (40), the neutron electric dipole moment can be related to the baryon-antibaryon asymmetry and to the entropy of the universe generated since bariosynthesis.

PROSPECTIVE IMPROVEMENTS

A number of improvements have been made on the Leningrad neutron electric dipole, and experiments with the improved apparatus have recently begun. However, the present limit on the electric dipole moment is already so low that considerable running time will be required to improve it significantly.

The Grenoble experiment on the electric dipole moment has been temporarily discontinued while the apparatus is being rebuilt. The most important improvement will be in the monitoring of the magnetic field. In past experiments, the monitoring has been done with three rubidium magnetometers no closer than 40 cm to the axis of the bottle. This separation led to uncertainties in their use to correct for magnetic field fluctuations in the neutron storage vessel. In the new apparatus, optically pumped ^{199}Hg, or another atom with a ^{1}S ground state such as ^{3}He, will be stored in the neutron bottle along with the neutrons and will monitor the magnetic field in the same position and at the same time as the neutron clcctric dipole moment is measured (30, 41). The neutron storage volume in the new apparatus will be increased from 5 to 60 liters, which should increase the sensitivity. The voltage on the electrodes is also being increased. With these changes the systematic errors should be reduced and the sensitivity of the experiment increased. However, the new apparatus will probably not be in operation before the summer of 1990, and a year or more of measurements will be needed to lower significantly the statistical error.

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