THE ELECTRIC AND MAGNETIC DIPOLE MOMENTS OF THE NEUTRON

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I. INTRODUCTION

In 1950 Purcell and Ramsey¹ pointed out that the parity arguments then used to prove that particles and nuclei could not have electric dipole moments, must be based on an experimental rather than a theoretical basis. As a test of this assumption, Smith, Purcell and Ramsey² used a neutron beam magnetic resonance apparatus to search for a neutron electric dipole moment and concluded that such a moment divided by the proton charge (μ_e/e) was experimentally less than 5×10^{-20} cm. Later, from the work of Lee and Yang³ and Wu, et al,⁴ it became apparent that the parity assumption was indeed invalid, but Landau⁵ and others pointed out that the parity argument against an electric dipole moment could be replaced by one based on time reversal invariance. However, Ramsey⁶ emphasized that time reversal invariance like parity at an earlier time, was merely assumed and must rest on an experimental basis. In 1964 Christenson, Cronin, Fitch, and Turlay⁷ discovered the CP violating mode in the decay of the K_L^0 meson into two charged pions, which strongly suggested a violation of time reversal symmetry.

Since then a number of theoretical predictions⁸ have been made for nucleon electric dipole moments on the basis of theories developed to account for the K_L^0 decay. Although the different predictions cover a wide range of values, some were as large as 10^{-19} cm for μ_e/e and most predicted 10^{-22} cm or

larger.⁸ Since most of the range of predicted values was accessible to experimental search, several different experiments to measure the neutron electric dipole moment were started by Baird, Dress, Miller and Ramsey,^{9,10,13,14} by Nathan and Shull,¹¹ by Cohen, Lipworth, Silsbee, and Ramsey,¹² by Smith and Pendlebury,¹⁵ and by Apostolescu, Ionescu, Bujor, Mecterts and Petrosu.¹⁶ The successive limits of the different experiments is given in Fig. 1. The greatest sensitivity at each time has been provided by the experiments of Dress, Miller, Ramsey and Baird^{9,10,13,14,15} and their most recently published experiment¹³ provides the greatest sensitivity of any experiment so far published. This experiment was based on a neutron beam magnetic resonance study of 80 m/sec neutrons and provided a limit μ_e/e of 10^{-23} cm. It became apparent at the end of this Oak Ridge experiment that a further increase in precision would require a high flux of neutrons at velocities of 100 m/sec or less. For this reason, the apparatus was moved to Grenoble to take advantage of the cryogenic moderator at the Institute Laue-Langevin (ILL) reactor.

The earlier apparatus with considerable modifications has now been operating at the Grenoble reactor and has produced a lower limit for the neutron electric dipole moment than any obtained previously. The experiments were done in collaboration with W. B. Dress and P. D. Miller of Oak Ridge National Laboratory in the United States, Paul Perrin of the CENG in Grenoble and Michael Pendlebury of Sussex University, England.

II. METHOD AND APPARATUS

The apparatus used in this experiment is essentially one to measure with high precision the precessional frequency of the neutron spin in a weak magnetic field with a neutron beam magnetic resonance apparatus similar to that used for measuring the magnetic moment of the neutron. A strong electrostatic field is then applied successively parallel and antiparallel to the magnetic field H . If the neutron had an electric dipole moment the torque due to this dipole moment in the electric field would make the precessional frequency of the neutron spin somewhat greater with the electric field in one direction and somewhat less in the opposite. By setting an experimental limit on the change in the precessional frequency, a limit is thereby set on the electric dipole moment of the neutron. The main requirements in the experiment are to achieve a very high sensitivity and to eliminate spurious effects that might either lead to a false apparent electric dipole moment or might obscure an actual moment.

A schematic view of the apparatus is shown in Fig. 2. The neutron beam comes from the cryogenic moderator at the ILL reactor. The neutrons are conducted from the moderator through a neutron conducting tube of rectangular cross sections on whose surface they are totally reflected at glancing angles of two degrees or less. The use of such neutron conducting pipes which becomes possible with sufficiently slow neutrons, markedly enhances the intensity by overcoming the normal diminution of beam intensity with the inverse square

of the distance from the moderator. This gain of intensity is badly needed to compensate in part for the even greater loss of intensity by the selection of extremely slow neutrons.

As shown in Fig. 2, the neutron beam goes through a portion of the pipe in which the walls consist of magnetized iron. Depending upon the orientation of the neutron spin, there is either a positive or negative magnetic interaction between the neutrons and the magnetic induction of the walls in the magnetized region. The combination of this positive or negative mean magnetic interaction with the coherent forward scattering amplitude of the neutrons by the wall material leads to total reflection at the walls for neutrons of one spin orientation while the neutrons with opposite spins are not reflected by that portion of the pipe and instead penetrate through the walls and are lost. Consequently following the spin polarizing magnetic mirror, the neutrons are mostly polarized. The analyzing device to determine if there has been a change in the neutron spin orientation is a second spin analyzing magnetic mirror. If the neutron spin remains unaltered between the first and the second of these magnetic field regions, most of the neutrons will be transmitted by the second region. If, on the other hand, the neutrons have been reoriented by approximately 180 degrees between the two iron mirror sections, the neutrons whose orientation has changed will not be totally reflected in the second magnetic mirror with a consequent reduction in beam intensity. Therefore, if the oscillatory fields are all in phase, the minimum of detected beam intensity

occurs at the precessional frequency of the neutron. On the other hand, as shown by the author,¹⁷ if the oscillatory magnetic field is provided in two separate segments with a 90 degree phase shift between them, the shape of the resonance curve is that of a dispersion curve with the steepest portion of the slope at the spin precession frequency as shown in Fig. 3. If the frequency of the oscillator is set so that the detected neutron intensity is at the position of the steepest slope, the presence of a neutron electric dipole moment can be detected by successively reversing a strong electrostatic field. If there is an electric dipole moment the torque due to the electric field will increase the precessional frequency of the neutron for one orientation of the field and decrease it for the opposite. At a fixed frequency of the oscillator, this change in the precessional frequency of the neutron spin will then be detectable with high sensitivity as a change in the neutron beam intensity.

The electric field is applied over a length of 196 cm. and typically has a value of about 100 kV/cm. The static magnetic field was about 17G and the neutron beam was 89% polarized.

Great care in the experiment must be taken to avoid spurious effects which could either simulate a non existent electric dipole moment or mask an existing one. Fortunately, a number of things can be done to eliminate or minimize such spurious effects. The relative phase of the two oscillatory fields, can be shifted from +90 degrees to -90 degrees in

which case the slope of the curve at the resonance position is reversed with a consequent reversal of the effect of the electric field on the detected neutron beam intensity. This reversal in the electric dipole moment effect eliminates many possible spurious effects. The phase was reversed once per second. Fortunately, in addition, many of the possible spurious effects cancel themselves due to the parity or time reversal symmetry of the effect. For example, there can be an effect of the electric field upon the frequency due to the force from the electric field pulling the magnets together and thereby changing the magnetic field. However, this effect and many others go as E^2 and consequently cancel on subtracting of results with reversed electric fields. A check on the existence of such E^2 effect can also be obtained from observations at zero electric field. Likewise to detect magnetic effects from the field reversing mechanism, the leads to the source of potential are reversed at intervals. In addition, measurements are made when no potential is present but when the reversing switches are successively changed. The importance of such control measurements is illustrated by the fact that for some months there was a very small residual effect when the switches were reversed in the absence of any potential. This was eventually eliminated by moving the reversing switches still further from the apparatus and by increasing their magnetic shielding.

An important source of a spurious effect has been observed in recent runs of high sensitivity. Whenever there is

a spark across the electric plates, the accompanying current produces a slight magnetic field which in turn produces a very small residual change in the permanent magnetic field due to the hysteresis of the iron. Even if the neutron counts during the period of the spark are excluded, the residual change in the permanent magnetic field can give a false result. This trouble, however, can be eliminated if the existence of sparks are recorded and if care is taken to assure the equal amounts of measurements with fields in opposite directions are utilized in each interval between sparks.

One of the most bothersome spurious effects is that due to the motion of the neutrons with a velocity $\vec{v}$ through the electric field $\vec{E}$ since such motion produces an effective magnetic field $\vec{E} \times \vec{v}/c$. This effective magnetic field can then interact with the known neutron magnetic moment to produce an added precession frequency which will look like that due to an electric dipole moment since it will reverse with the reversal of $\vec{E}$. This effect is drastically reduced by making E parallel to $\vec{H}$. If exact parallelism could be obtained the effect would be completely eliminated since this spurious magnetic field would be perpendicular to the initial magnetic field with the result that the effect would go as E^2 instead of $\vec{E}$. However, due to residual magnetism of ferromagnetic materials and magnetic shields, one can never be absolutely certain as to the direction of the magnetic field with the result that $\vec{E}$ and $\vec{H}$ cannot be made exactly parallel and the perpendicular component of E can produce an apparent electric

dipole effect through the $\vec{E} \times \vec{v}/c$ effective magnetic field. The existence of such an effect, however, can be detected by changing the velocity of the neutrons since the spurious effects should be proportional to the neutron velocity. Consequently, all the data is analyzed in terms of an electric dipole moment and an apparent electric dipole proportional to the neutron velocity. The neutron velocity is altered in either of two ways. In some cases, the velocity is changed by changing the angle of neutron reflection from mirrors and in all cases the measurements are repeated many times with the direction of the neutrons through the apparatus reversed. For this reason, as can be seen in Fig. 2, the basic neutron resonance apparatus is fastened to a turn table which can be rotated to have the neutrons pass through the apparatus in opposite directions. The necessity for experiments at altered velocity greatly increases the running time of the experiment since the $\vec{E} \times \vec{v}/c$ effect must be measured with equal precision to that desired for the neutron electric dipole moment.

III. RESULTS

The results of the present phase of measurements at the Institute Laue-Langevin are

$$\mu_e/e = (0.4 \pm 1.1) \times 10^{-24} \text{ cm.}$$

In other words, the neutron electric dipole moment, if it exists at all, is less than 3×10^{-24} cm. To emphasize the smallness of this result, I should emphasize to nuclear physicists that this is 10^{-24} cm not cm^2 ; it corresponds to

10^{-48} cm^2 . If the neutron were expanded to the size of the earth this asymmetry would correspond to an incremental height of 0.001 cm. in the northern hemisphere.

There have been numerous theoretical predictions as to the value of the neutron electric dipole moment. All theories that account for the CP violating decay of the K_L^0 meson⁷ predict non zero values for the neutron electric dipole moment. The predictions of these theories¹⁸⁻³² are shown in Fig. 4. Each lettered block in the figure corresponds to the prediction of a different theory. One source of interest of the present experimental limit is that it provides extreme difficulties for many of the theoretical predictions and significant difficulty for most of the theories except those which attribute the time reversal asymmetric interaction to a new super weak force.

IV. NEUTRON ELECTRIC DIPOLE MOMENT EXPERIMENTS WITH BOTTLED ULTRA-COLD NEUTRONS

The neutron electric dipole moment experiment so far described depends upon the fact that neutrons at a velocity of 80 m/sec will be totally reflected by many materials at glancing angles of approximately 5 degrees. As the velocity of the neutrons diminish, the glancing angle for total reflection increases until finally at a velocity of 6 m/sec total reflection can be obtained even at normal incidence on many surfaces. Under such circumstances, it is possible in principle to store neutrons in an enclosed bottle. For many years,^{33,34,35} we have been anxious to do such experi-

ments which would provide for the neutrons many of the advantages of the successive oscillatory field experiments with stored atoms^{33,34} including those with the hydrogen maser.³⁴ Up until recently, however, we have had no prospect of obtaining access to such ultra-cold neutrons.

Zeldovitch,³⁶ Vladiminski^{37,38} and the late Dr. F. L. Shapiro have discussed bottled ultra-cold neutrons and Shapiro and his collaborators³⁹ have shown that ultra-cold neutrons can be stored in bottles for up to 20 seconds. Improvements in the techniques with ultra-cold neutrons and storage bottles have been made by Steyerl,⁴⁰ Ageron,⁴¹ Lobashov,⁴² Taran,^{43,44} Pendlebury, Gollub and Smith^{45,46} and Miller, Dress and Ramsey^{46,47} and others. Specific experiments to use neutron bottles to measure the neutron electric dipole moment have been discussed by Ramsey, Miller and Dress,^{33,35,46,47} by Taran^{43,44} and by Pendlebury, Smith and Gollub.^{45,46}

The experiment at ILL now being prepared to use ultra-cold bottled neutrons to set a limit to the neutron electric dipole moment is a collaboration between J. Byrne, R. Gollub, J. M. Pendlebury, K. F. Smith, N. F. Ramsey, W. B. Dress, P. D. Miller, A. Steyerl, P. G. H. Sandars, P. Ageron and P. Perrin of the University of Sussex, Harvard University, Oak Ridge National Laboratory, Munich, Oxford University, ILL and CENG. Ultra-cold neutrons at approximately 6 meters per second will be led by a neutron conducting pipe into the apparatus shown in Fig. 5. The neutrons will be stored in a cylinder approximately 15 centimeters in diameter and 10

centimeters high with the top plates being metallic -- probably beryllium -- and the sides of the cylinder being of beryllia insulator. The oscillatory field is applied to the admission and exit tubes so the resonance can be observed by the previously described successive oscillatory field technique.³³ The resonance will be observed in a similar fashion to our present neutron beam experiment and observation will be at the steepest point of the resonance curve. The change in beam intensity correlated with the application of an electric field will then be examined to set a limit to the neutron electric dipole moment.

The use of stored ultra-cold neutrons possesses two particularly important advantages. The resonance curve for 18 second storage time of the neutron should be approximately 800 times narrower than in the present experiment with a corresponding increase in sensitivity. Furthermore, as mentioned earlier, a large fraction of running time in the present experiment must be devoted to eliminating the $\vec{E} \times \vec{v}/c$ effect. Since it is the average value of $\vec{v}$ that is important, this effect is drastically diminished when the neutrons enter and leave by the same exit hole with an 18 second storage time instead of passing through the apparatus at a velocity of 80 m/sec. As a result of the reduced effective magnetic field from $\vec{E} \times \vec{v}/c$, it should also be possible to use a much weaker static magnetic field with an accompanying reduction in the field stability problem.

Although the new experiment being planned will have the

above marked advantages, it must be recognized that it will still be an extremely difficult one. The limit has by now been pushed to such a low value that care must be taken to avoid all possible systematic effects. Although some of these are intrinsically reduced in an experiment with bottled neutrons, other serious problems will remain. For example, problems due to stray magnetic fields (especially when associated with reversals of the electric field) and to magnetic field changes resulting from electrical sparks can be just as serious with bottled neutrons as with neutron beams. These problems have already caused much difficulty in the beam version of the experiment and should be even more formidable in the bottled neutron experiment which seeks to lower the limit for the neutron electric dipole moment by a factor of 100 to 1000.

The apparatus is planned to be capable of being operated in either of two fashions. In one, pulsed ultra-cold neutrons will be admitted for a few seconds and then stored with the neutron valve closed for approximately 30 seconds before the valve is reopened so the neutrons can escape past the oscillatory field for a second time.

In the second mode of operation, the neutrons will continuously be introduced and permitted continuously to bounce out of the neutron bottle with a mean storage time of approximately 18 seconds. The precision of the two methods of observation are comparable and the two procedures should mutually compliment each other.

With an electric field of 30 kV/cm. and a multilayer Mu-metal or Moly-Permalloy magnetic shield, it should be possible to achieve a limit on the electric dipole moment of 10^{-26} cm. To go to a lower limit will probably require superconducting magnetic shields. These are currently contemplated but decisions on a subsequent phase of the experiment will not be taken until later. With superconducting shields and sufficiently long observation times, it should be possible to lower the limit to 10^{-27} cm. With a larger cell diameter and other improvements, sensitivity of the order of 10^{-28} cm. might ultimately be reached.

V. OTHER NEUTRON BEAM MAGNETIC RESONANCE EXPERIMENTS

Since it will take more than a year before the ultra-cold neutron beam can be available at ILL and before the apparatus for the bottled neutron experiment can be ready and since the new apparatus will be required to achieve a significant improvement in the present limit, the collaborators of the present experiment plan to modify the present apparatus so it can be used during the coming year markedly to improve the accuracy of the measurements of the neutron electric dipole moment. At present, the neutron electric dipole moment is the least accurately known of all the nucleon and lepton magnetic moments. The magnetic moments of the negative electron, the positive muon and the proton are all known to a fractional error less than 3×10^{-8} whereas the fractional error in the neutron moment is 1000 times greater or

3×10^{-5} . Although the present apparatus was designed with the neutron electric dipole moment exclusively in mind, by coincidence it turns out to be an appropriate design for measuring the magnetic moment of the neutron. Although the magnetic field is low and probably cannot easily be raised much above 800 gauss, this disadvantage is more than offset by the large magnetic gap which permits an accurate calibration of the magnetic field because of the smaller inhomogeneities which result from the increased gap. In the previous most accurate experiment⁴⁸ the precision of the result was primarily limited by this field inhomogeneity and the consequent difficulty in calibrating the magnetic field accurately.

The magnetic moment will be measured in an apparatus which is essentially the same as that now being used in the neutron electric dipole moment experiment. Permanent magnets, however, can be added to increase the magnetic field from 15 oerstead to 800 oerstead. The magnetic field can be calibrated in several alternative ways. One is by the use of a proton NMR magnetometer and another is by the use of a rubidium magnetometer. A still different alternate is to pump water at high speed through a high magnetic field storage region to polarize the protons and then to have the water pass through the neutron beam pipe at high velocity, with the resonance being observed by the separated oscillatory field method;¹⁷ in this case the second oscillatory field region has many of the characteristics of a volume filled with molecules in "super radiant" states. The flowing water

method has the advantage of a close similarity between the averagings done by the neutrons and by the protons as each are confined to the neutron pipe. It is anticipated that all three methods will be used. The greatest possible care must be devoted to assuring that the magnetic field at the time of the proton calibration is the same as that during the measurements with the neutron.

With this technique, it appears that it should be relatively easy to improve the accuracy of the measurement of the neutron magnetic moment by at least a factor of 100 and hopefully by a somewhat larger factor.

There are two other interesting neutron beam experiments which we would very much like to do as soon as we can fit in the time without significant interference with the primary priority we attach to the neutron electric dipole moment experiments. From the experimental point of view, the two experiments are closely related. Since both involve the measurement of a small parity violating reorientation of the neutron spin when it passes through matter.

Kabir, Karl and Obryk⁴⁹ have pointed out that when a neutron passes through an optically active medium, (one whose constituents are parity asymmetric as solutions of levulose), the transverse component of the neutrons polarization should precess about the direction of propagation about 10^{-5} radians in traversing a centimeter of a representative optically active medium. Since an electric dipole moment of 10^{-24} cm. provides a precession of only 0.3×10^{-5} radians, there

should be sufficient sensitivity in an adaptation of the apparatus for that experiment to observe such a precession; among the apparatus changes required in such an adaptation would be the provision of a weak longitudinal magnetic field instead of a weak transverse field. If sensitivity alone were the only requirement, the measurement should be relatively easy. Unfortunately, the primary difficulty will arise from the existence of the neutron magnetic moment and the necessity of demonstrating that there is no small magnetic perturbation associated with insertion of the interacting material which produces a comparable or greater recession. This can be seen from the fact that a magnetic field of 3×10^{-8} gauss would produce 10^{-5} radians of precession while a 100 m/sec neutron traversed the 1.9 meter length of our present apparatus. Some benefit could be obtained by making the apparatus as short as possible, but there is still a severe requirement for eliminating any change in magnetic field associated with the change in the sample. A great improvement in this problem can be obtained by simultaneously running neutron beams through the apparatus in opposite directions. The parity violating effect depends on the direction of the neutron velocity while the magnetic precession is independent of the neutron direction so by simultaneously measuring the precession for opposite directions of neutron motion the two effects can be distinguished.

A second experiment of even more fundamental interest is to look for a similar parity violating precession of the

neutron in passing through a medium which is not optically active. Michel⁵⁰ and Stodolsky⁵¹ have pointed out that a precession of 1.4×10^{-6} radians should occur if cold neutrons passed through at about 1 meter of say bismuth. The source of the parity violating rotation in this case would not be the optical activity of the medium but instead would be the parity violating weak interaction of the neutron. It would be of great interest in this way to observe directly the weak interactions of neutrons and the parity violating character of the weak interaction provides a unique signature through the spin precession to distinguish this interaction from the strong forces that usually dominate the interaction of neutrons with matter. The problem of magnetic effects in this case is of course even more severe than in the case of an optically active medium because the precession angles from the desired effects are even smaller. However, as in the previous experiment, great benefit could be obtained in distinguishing the precession due to the weak forces from those due to magnetic fields by simultaneously making observations on neutrons which pass through the apparatus in opposite directions.

Although the possibility of doing these experiments was first discussed as a neutron beam magnetic resonance experiment, they can also be done by Mezei's interesting neutron spin echo technique.⁵² To avoid unnecessary duplication, we have discussed a combined effort with Mezei to observe these two interesting effects probably using a modification of his neutron spin echo technique. The principle problem

is finding time to fit these experiments in to our respective programs, particularly in view of the primary priority attached to further lowering the limit on the electric dipole moment of the neutron.

FIGURE CAPTIONS

- Fig. 1. Experimental results for the electric dipole moment of the neutron.
- Fig. 2. Experimental arrangement of the magnetic resonance spectrometer.
- Fig. 3. Typical magnetic resonance with a phase shift of $\pi/2$ between the two oscillatory fields. The calculated transition probability for a Maxwell-Boltzmann distribution characterized by a temperature of 1°K is shown in the solid curve. The departure of the experimental curve from the theoretical one when far from resonance is to be expected from the known departure of the beam velocity from a Maxwell-Boltzmann distribution.
- Fig. 4. Theoretical predictions of the neutron electric dipole moment. Each lettered block corresponds to a different theory with the references to the different theories given by the corresponding letters in the references.¹⁸⁻³² The basis of the different theories are indicated in square brackets in the references with EM indicating a theory which attributes the time reversal violation to the electromagnetic theory, W attributes it to the weak forces, MW to a milliweak force, SW to a new super weak force. Normally the rectangle indicating each theory is a square spanning one decade; where the authors propose a wider spread the rectangle is adjusted accordingly

but with the same area as for other theories.

Fig. 5. Schematic diagram of apparatus for determining the neutron electric dipole moment by a neutron magnetic resonance experiment with bottled neutrons.

REFERENCES

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1. E. M. Purcell and N. F. Ramsey, Phys. Rev. 78, 807 (1950).
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. T. D. Lee and C. N. Yang, Phys. Rev. 105, 1671 (1957).
4. C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes and R. P. Hudson, Phys. Rev. 105, 1413 (1957).
5. L. Landau, Zh. Eksperim. i Teov. Fiz. 32, 405 (1957
[translation: Soviet Physics - JETP 5, 336 (1971)]).
6. N. F. Ramsey, Phys. Rev. 109, 225 (1958).
7. J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Letters 13, 138 (1964).
8. References to many of the theoretical predictions for nuclear electric dipole moments are given in references 12-21 in reference 9 below.
9. P. D. Miller, W. B. Dress, J. K. Baird and N. F. Ramsey, Phys. Rev. Letters 19, 381 (1967).
10. J. K. Baird, P. D. Miller, W. B. Dress and N. F. Ramsey, Phys. Rev. 179, 1285 (1969).
11. C. Shull and R. Nathan, Phys. Rev. 19, 384 (1967).
12. V. W. Cohen, E. Lipworth, R. Nathan, N. F. Ramsey and H. B. Silsbee, Phys. Rev. 177, 1942 (1969).

13. W. B. Dress, P. D. Miller and N. F. Ramsey, Phys. Rev. D7, 3147 (1973).
14. W. B. Dress, J. K. Baird, P. D. Miller and N. F. Ramsey, Phys. Rev. 170, 1200 (1968).
15. K. Smith and M. Pendlebury, private communication (1968).
16. Apostolescu, Ionescu, Ionescu-Bujor, Meiterts and Petrosu, Rev. Romaine Phys. 15, 343 (1970).
17. N. F. Ramsey, Molecular Beams, Oxford University Press (1956).
- 18.a. G. Feinberg, Phys. Rev. B140, 1402 (1965) [EM1]
- 19.b. F. Salzman and G. Salzman, Phys. Rev. Let. 15, 91 (1965) [EM1]
- 20.c. G. Barton and E. D. White, Phys. Rev. 184, 1660 (1969) [EM2]
- 21.d. D. J. Broadhurst, Nucl. Phys. B20, 603 (1970) [EM2]
- 22.e. Babu and Suzuki, Phys. Rev. 162, 1359 (1967) [MWAS=0]
- 23.f. N. T. Meister and T. K. Rhada, Phys. Rev. B135, 769 (1964) [MWAS=0]
- 24.g. G. R. Gourishankar, Can. Journ. Phys. 46, 1843 (1968) [MWAS=1]
- 25.h. P. McNamee and J. C. Pati, Phys. Rev. 178, 2273 (1969) [MWAS=0,1]
- 26.i. K. Nishijima and L. J. Swank, Nuc. Phys. B3, 565 (1967) [MWAS=0]
- 27.j. K. Nishijima, Prog. Theor. Phys. 41, 739 (1969) [MWAS=0]
- 28.k. D. G. Boulware, Nuovo Cimento 40A, 1041 (1965) [MWAS=0]
- 29.l. L. Wolfenstein, Phys. Rev. Let. 13, 562 (1964) [SWAS=2]

- 30.m. A. Pais and J. Primack, Phys. Rev. D8, 625 and 3036 (1973) [MW]
- 31.n. T. D. Lee, Phys. Rev. D8, 1226 (1973) and Physics Reports 9, 143 (1974) [MW]
- 32.o. L. B. Opun, Comments on Nuclear and Particle Physics III, 135 (1969) [SW]
- 32.p. R. N. Mohapatra, Phys. Rev. D6, 2026 (1972) [MW]
- 32.q. J. Frenkel and M. E. Ebel, Complex Cabbibo Angle and CP Violation in a Class of Gauge Theories, Univ. of Wisconsin Preprint and reference 32.r. below [MW]
- 32.r. L. Wolfenstein, Nuclear Physics B77, 375 (1974) [SW]
- 32.s. R. N. Mohapatra and J. C. Pati, Phys. Rev. D11, 569 (1975) [MW]
- 32.t. S. Pakvasa and S. F. Tuan, Phys. Rev. Letters 34, 553 (1975) [MW]
33. N. F. Ramsey, Rev. Sci. Inst. 28, 57 (1957).
34. D. Kleppner, N. Ramsey, P. Fijilstadt and M. Goldenberg, Phys. Rev. Letters 1, 232 (1958) and 8, 361 (1960).
35. N. F. Ramsey, Proposal to ILL for Neutron Electric Dipole Moment Experiment (1969).
36. Y. B. Zeldovitch, Zh. Eksp. Zero. Fiz. 36, 1952 (1959) [JETP 9, 1389 (1952)].
37. V. Vladimirkii, JETP 12, 740 (1961).
38. A. Droshkevich, JETP 16, 56 (1963).
39. V. I. Luschnikov, Yu N. Pokotilosky, A. V. Stvelkov and F. L. Shapiro, Zh. Eksp. Teov. Fiz., Pis mo v Redaktsiya 9, 40 (1969) Sov. Phys. - JETP Letters 9, 23 (1969).

40. A. Steyerl and W. B. Trustedt, Private Communication, 1973.
41. P. Ageron, J. M. Astruc and J. Verdier, Preliminary Project of an Ultra-Cold Neutron Source at the High Flux Reactor, Institute Laue-Langevin, Grenoble (Unpublished).
42. V. M. Lobastov, G. D. Porsev and A. B. Serebrov, Preprint No. 37, Konstantinov Institute of Nuclear Physics of the Academy of Science of the USSR, Leningrad, 1973.
43. Elementarnaya Teoriya Metoda Elektricheskova Dipolnaya Momenta Neitrona C. Pomoshyn UXN. I Protoshini.
44. Variant. Yu V. Taran, Dubna, Preprint P3-7147, Elementarnaya Teoriya Metoda Opredeleniya Elektricheskova Dipolnaya Momenta Neitrona C. Pomoshyn UXN. II Nakopitelny Variant, Yu V. Taran, Dubna Preprint P3-71479.
45. R. Gollub and J. M. Pendlebury, Contemp Phys. 13, 519 (1972).
46. J. Byrne, R. Gollub, J. M. Pendlebury and K. F. Smith in collaboration with N. F. Ramsey, W. B. Dress, P. D. Miller, A. Steyerl, P. G. H. Sandars, P. Ageron and P. Perrin, A Proposal to Search for the Electric Dipole Moment of the Neutron Using Bottled Neutrons, Institute Laue-Langevin (1974) and Rutherford Laboratory (1975).
47. P. D. Miller, Measurements of the Electric Dipole Moment of the Neutron. P. D. Miller, Second International School on Neutron Physics, Alushta, Crimea, USSR (1974).

48. V. W. Cohen, N. R. Corngold, and N. F. Ramsey, Phys. Rev. 104, 283 (1958).
49. P. K. Kabir, G. Karl and E. Obryk, Phys. Rev. D10, 1471 (1974).
50. F. C. Michel, Phys. Rev. 133, B329 (1964).
51. L. Stodolsky, Max Planck Institute, MPI-PAE/PTh9 (1974).
52. F. Mezei, Z. Physik 255, 146 (1972).

NEUTRON EDM EXPERIMENTAL RESULTS

VALUE D (cm)	LABORATORY (year)	REFERENCE
$< 5 \times 10^{-20}$	ORNL (1951, 1957)	2
$(-2 \pm 3) \times 10^{-22}$	ORNL (1967)	9
$< 3 \times 10^{-22}$	ORNL (1968)	14
$(+2.4 \pm 3.9) \times 10^{-22}$	MIT-BNL (1967)	11
$< 1 \times 10^{-21}$	BNL (1969)	12
$< 1 \times 10^{-21}$	ALDERMASTON (1968)	15
$< 5 \times 10^{-23}$	ORNL (1969-1972)	10
$0.2 \pm 3.9 \times 10^{-22}$	ROMANIA (1970)	16
$< 1 \times 10^{-23}$	ORNL (1973)	13