PHYSICAL REVIEW D VOLUME 15, NUMBER 1 1 JANUARY 1977

Search for an electric dipole moment of the neutron*

W. B. Dress and P. D. Miller
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

J. M. Pendlebury
Institute Max von Laue-Paul Langevin, Grenoble, France and University of Sussex Brighton, United Kingdom BN1 9QH

Paul Perrin
Centre d'Etude Nucléaires 38042 Grenoble, France

Norman F. Ramsey
Harvard University, Cambridge, Massachusetts 02138
(Received 2 September 1976)

The result of a search for the electric dipole moment of the neutron is presented. A short review of past experimental work and theoretical predictions introduces a discussion of the experimental method used in, and the results obtained by, the present work. The weighted mean of three separate groups of data gives $(+0.4 \pm 1.5) \times 10^{-24}$ cm for the neutron's electric dipole moment. We conclude that the electric dipole moment is less than 3×10^{-24} cm.

I. INTRODUCTION

The work reported herein is the continuation of a long line of experiments designed to detect or set an upper limit on the electric dipole moment (EDM) of the neutron. The first investigation in this series was in response to a short note by Purcell and Ramsey[1] in 1950 which pointed out that the arguments then used to prove that electric dipole moments of elementary particles could not exist rested on untested assumptions. J. H. Smith, in collaboration with Purcell and Ramsey, undertook to search for the neutron EDM as a test of parity (P) conservation in the subatomic domain. The result of this first measurement was that[2] $|D| < 5\times10^{-20}$ cm, where eD is the parameterization used for the EDM (D being the dipole length and e the magnitude of the elementary charge). This result is consistent with parity conservation, and consequently little attention was paid to the result until 1957 (Ref. 3), following the publication of the classic paper of Lee and Yang[4] in 1956 proposing parity violation as a possible explanation of the $\tau\theta$ puzzle (a then-current anomaly in the K mesons) with the testable consequences of spatial asymmetry in β decay, π-μ-e decay, and hyperon decay as well as the possible existence of EDM's for elementary particles.

Even as the experiments verifying these predictions were under way,[5-7] Weyl's long-dormant theory of the neutrino was revived by Landau,[8] and independently developed by Lee and Yang[9] and Salam.[10] Landau also revived the earlier notion of Wick, Wightman, and Wigner[11] of "combined parity" or CP as being the "exact symmetry law," where C stands for charge conjugation. C and P separately were then only approximately valid. These developments resulted in a clear path for the universal V-A theory of the weak interaction which was put on firm experimental grounds by Allen *et al.*[12]

The understanding of the nature of the violation of the parity symmetry thus brought about a certain completeness and maturity to the theory of weak interactions, one of the most successful theories of modern physics. The $\tau\theta$ puzzle appeared to be, in essense, solved; and the kaon system seemed to be understood from a theoretical viewpoint. As in any fruitful theory, new avenues of investigation opened up: Lee, Oehme and Yang[13] proceeded to discuss the possible noninvariance of charge conjugation (which, by implication, is violated in those processes violating P) and time reversal (T), and Landau[8] and Zel'dovich[14] pointed out that the time symmetry prohibits elementary particles from exhibiting EDM's. This prohibition is due to the spin being reversed by T, whereas the electric field, whose sources are static charges, its unchanged, Ramsey[15] then pointed out that the validity of all symmetry arguments must rest upon experiment and that a search for a neutron electric dipole moment provided a particularly sensitive test of T. Garwin and Lederman[16] discussed the basic ideas involved and presented the results of a search for the EDM of the electron.

Following the analysis of β decay by Jackson, Treiman, and Wyld,[17] there were a number of tests of T in β decay,[18-20] with the latest and most sensitive by Steinberg, Liaud, Vignon, and Hughes[21] all consistent with T invariance. From the discussions of Gell-Mann and Pais[22] and Lee, Oehme, and Yang[13] and the work of Lande *et al.*[23] verifying the predictions of Ref. 22, it was evident that the most likely place to find a violation of the combined parity, CP, was in the K-meson system. A number of workers examined the kaons[24-26] without any sign of abnormality, whereas Abashian *et al.*[27] reported a null effect to the limits of their experiment with a possible hint of CP noninvariance. In the same issue of that journal, Christenson, Cronin, Fitch, and Turlay[28] reported finding a violation of CP some five standard deviations larger than experimental error.

Since a CP violation, assuming validity of the CPT theorem,[29-31] implies a violation of T, the observed violation of CP stimulated both experimental and theoretical studies of electric dipole moments of elementary particles. Schiff[32] discussed the measurability of EDM's even before the observation of CP violation, and soon thereafter Meister and Radha[37a] made one of the first calculations going beyond dimensional arguments. Even though violation of T has been sought in everything from hyperon decay to detailed balance in nuclear reactions,[33] the most concentrated effort seems to have been in the EDM's of elementary particles, most notably the neutron, electron,[34,35] and the proton.[36]

The neutron has received most attention from theorists and experimentalists alike. Figure 1 summarizes the measurements and calculations over the last 25 years. The theoretical information is displayed as a histogram on a logarithmic scale, the position and range being only approximate; the alphabetic order is roughly the chronological order of the publications which are listed in Refs. 37a–37y. The listed calculations are all based on the representation of the neutron's EDM as a characteristic length associated with the neutron, scaled by the strength of the interaction responsible for the violation of P and T. The characteristic responsible for the broad range of estimates (covering some 13 orders of magnitude) is the choice of the interaction thought to violate T: electromagnetic, strong, or weak, as well as higher-order processes in these interac-

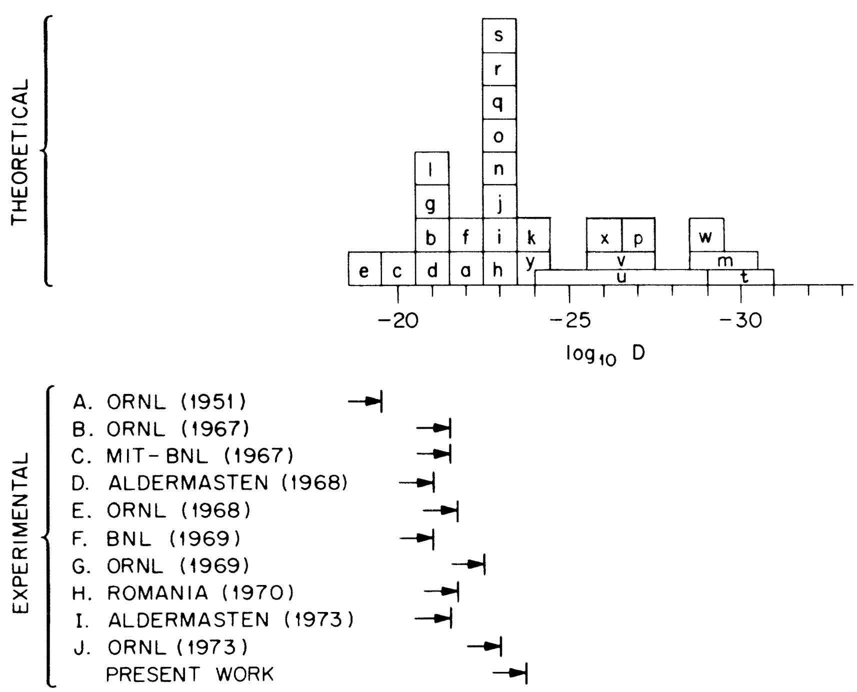

FIG. 1. Summary of theoretical and experimental work on the electric dipole of the neutron. The theoretical predictions are displayed in the histogram which is plotted as a function of $\log_{10} D$, where D is the EDM length in cm. The small letters, a through y, indicate the letters in Refs. 37, which are roughly in chronological order. The experimental results are displayed below by the arrows representing sensitivity down to the place indicated. The limit attained by the present work lies just below the main body of predictions. The capital letters, A through J, refer to Refs. 39 for the experimental work.

tions. The choice is indicated in the references by the letters EM, S, or W, preceeded by the letter M for milli- (thus a millistrong interaction would be denoted by MS, and indicate a violation of T in the second-order strong interaction). The variations within a group depend upon the details assumed for the specific model as well as on specific computational methods. For example, the two main classes of violations appearing in the weak interaction consider a change of strangeness, ΔS, to be either 0 or 1. Other refinements are of course considered in the various publications.

One of the first hypotheses invented to explain the CP violation in the kaons was the superweak theory of Wolfenstein.[38] In this theory the K^0 and $\bar{K}^0$ (antiparticle to the neutral K meson) are coupled by an interaction about a thousand times weaker than the second-order weak interaction so that transitions between particle and antiparticle are allowed. Since the K^0 is in a definite state of CP, such an interaction obviously violates combined parity. Even though all of the parameters of the kaon system are consistent with the predictions of superweak theory, the theory is unsatisfactory in that it is specific to the K mesons and may never be adequately tested outside that system due to the smallness of the effect. There is a real possibility, of course, that the superweak interaction is the correct explanation of T violation, and that the kaon system will exhibit the only manifestation of CP and T invariances, except for extremely small higher-order effects.

The experimental work shown in Fig. 1 has been almost worldwide in extent, and shows a steadily decreasing upper limit for the EDM of the neutron. All experiments known to date (Refs. 39A–39J and the present work) are consistent with time-reversal invariance and superweak theory as well. Overlooking the possibility of a cancellation of effects to produce an anomalously small or zero neutron EDM, the electromagnetic and strong interactions, as the source of the symmetry violation, predict an excessively large EDM. The data also suggest that most theories attributing T violation to the weak interaction and second-order electromagnetic and strong interactions are probably incorrect as well. The figure obviously suggests the need for further experimental work if only to focus theoretical attention on mechanisms consistent with EDM's smaller than the main group.

After eleven years of theoretical and experimental effort, T violation remains a maverick. No comprehensive understanding and predictive power has emerged as in the case of parity violation. Indeed, the only known violations of T and CP to date take place exclusively in the K-meson system. This, then, provides the impetus for the effort which has gone into the search for the electric dipole moment of the neutron, and explains the continuing interest in these results and the desire to continue the search to ever more sensitive levels.

II METHOD AND APPARATUS

In the search for electric dipole moments of elementary particles, the neutron seems to occupy a particularly priviledged position. It is known to participate in the strong, electromagnetic, and weak interactions, so tests of symmetry violation in all three are made in the same experiment. It is electrically neutral so exposure to a large electric field will not change its momentum to any great extent, and consequently the interaction energy for the EDM will contain the full strength of the applied field, not merely a screened value or second-order term (see for example Schiff[32]). The neutron is produced in abundance in nuclear-fission reactors, is easily polarized to produce the necessary alignment in the electric field, and has a relatively long half-life. These features lead to the obvious method of measurement by means of a neutron magnetic-resonance spectrometer of the type used by Cohen, Corngold, and Ramsey[40] to measure the neutron's magnetic moment. Indeed, all of the experiments cited in Fig. 1, with one notable exception,[39C] make use of this method.

Since the apparatus used in this experiment has been described in detail elsewhere[39G] only a brief description will be given here. Essentially, the method of measurement is to let a beam of transversely polarized neutrons traverse a region in which there is a fixed, homogeneous magnetic field $\vec{B}_0$ with a parallel and reversible, static electric field $\vec{E}$. For the present experiment, B_0 had a value of around 17 G and the E-field region was 180 cm long with voltages around 100 kV across a 1-cm gap. In the absence of the electric field, the neutrons precess at the Larmor frequency corresponding to the strength of the magnetic field. This frequency may be accurately measured by introducing oscillating magnetic fields of the same frequency at each end of the homogeneous-field region.[41] These oscillating fields, which are perpendicular to $\vec{B}_0$, introduce spin-flip transition amplitudes into the neutron wave function. The probability of detecting a neutron which traverses the apparatus is dependent on the length, amplitude, frequency, and relative phase of the oscillatory field regions as derived in detail in Ref. 41.

If the neutron had an EDM associated with its spin (the only intrinsic vector possible since the spin is $\frac{1}{2}$), the presence of the electric field would cause a shift in the frequency of the Larmor precession according to the expression for the Hamiltonian:

$$H = -\vec{\mu}\cdot\vec{B} - \vec{p}\cdot\vec{E} \qquad (1)$$

where $\vec{\mu}$ is the magnetic dipole moment, $\vec{B}$ the magnetic field, $\vec{p}$ the presumed EDM, and $\vec{E}$ the applied electric field. The frequency of precession is the transition rate between the upper and lower spin states, and is given by

$$h\nu = -2\mu B - 2pE . \qquad (2)$$

Upon reversing the electric field, the difference in this precession frequency becomes

$$h\Delta\nu = -4pE \qquad (3)$$

or expressing p as a length, D, multiplied by the magnitude of the elementary charge, we have

$$D = -\frac{h\Delta\nu}{4eE} \qquad (4)$$

in terms of the experimental parameter E and the measured value of the frequency difference, $\Delta\nu$. The method, then, is to measure the precession frequency with the electric field parallel and antiparallel to the magnetic field to find the frequency difference introduced by the electric field.

Conceptually, the apparatus is primarily a device to sustain a magnetic field and a reversible electric field over a region where a polarized neutron beam may pass and the precession angle be monitored. The spectrometer used in the earlier experiments[39G,39I] was modified in order to correct some of the faults noted earlier and allow for the expected increase in neutron flux available at the Institute Max von Laue–Paul Langevin (ILL), Grenoble, France, where the measurements were to be done. The principal modifications were the development of a neutron detector capable of counting some 5×10^6 neutrons per sec over an area of 10 cm^2; more extensive use of the turntable allowing rotation of the entire apparatus with the exception of the neutron-guide tube from the reactor, and the detector; and the incorporation of a minicomputer to take advantage of the higher data rate as well as to control the experiment as extensively as possible.

One of the first tasks upon transferring the equipment to the ILL was to develop a detector compatible with the beam geometry of 1 cm width and 10 cm height and capable of counting a neutron flux some 1000 times our previous values. In the past we have used both ^{6}Li-loaded glass scintillators and ^{3}He proportional counters, which exhibited a much higher signal-to-noise ratio than the glass scintillators. With the dramatic increase in neutron flux, it was found that the proportional counters could not recover rapidly enough between events to allow the signal to stand out from the low-level instrumental noise. With some effort spent in acquiring fast phototubes, mounting the ^{6}Li glass directly on the faces of the phototubes to minimize light loss and consequent degradation of the signal, and in designing a voltage-divider network to optimize pulse separation, we were able to count neutrons of the required intensity. It was necessary to employ two phototubes, since a single tube with a 10-cm photocathode would give much poorer resolution than one with half the size. The anodes of the two phototubes were tied together and the resulting signal clipped by means of a terminated cable some 10 cm long. The combined anode signal was amplified by a fast amplifier and passed through a fast discriminator. The signal-to-noise ratio was not very good, but the discriminator proved stable enough so that a reliable measure of the counting rate was obtained. The discriminator fed a 100-Mhz prescaler which divided the counting rate by a factor of 10 and, in turn, drove a CAMAC binary scaler at a rate of about 3×10^5 pulses/sec. A duplicate system (with only one photomultiplier) monitored the neutron beam before polarization. This monitor was placed about 3 cm above the used portion of the 3-cm×20-cm beam coming from the cold source (a 30-cm-diameter sphere of liquid deuterium placed next to the core of the high-flux reactor, ILL). Again, because of the high counting rate, a proportional counter could not be used, so the monitor could not be placed at the polarizing mirror due to the high magnetic field which would render the phototube inoperable. Thus the monitored neutrons did not originate in the same part of the cold source as did the neutrons passing through the spectrometer. The results of a test of the variation of the detected neutrons passing through the spectrometer to the monitored beam did not show any deviation from that expected from statistics except when the reactor changed power by significant amounts.

The turntable, a converted naval gun mount, provided the mechanical support for the spectrometer and its double magnetic shields. Figure 2 shows the assembly of the spectrometer, mounting table, shields, and iron polarizing and analyzing mirrors. This entire assembly could be rotated 180° on the turntable. The alignment of the 3-m-long assembly was such that, upon rotation of the apparatus, changes in intensity, average velocity, and polarization of the neutron beam amounted to only a few percent. The purpose of the mechanical rota-

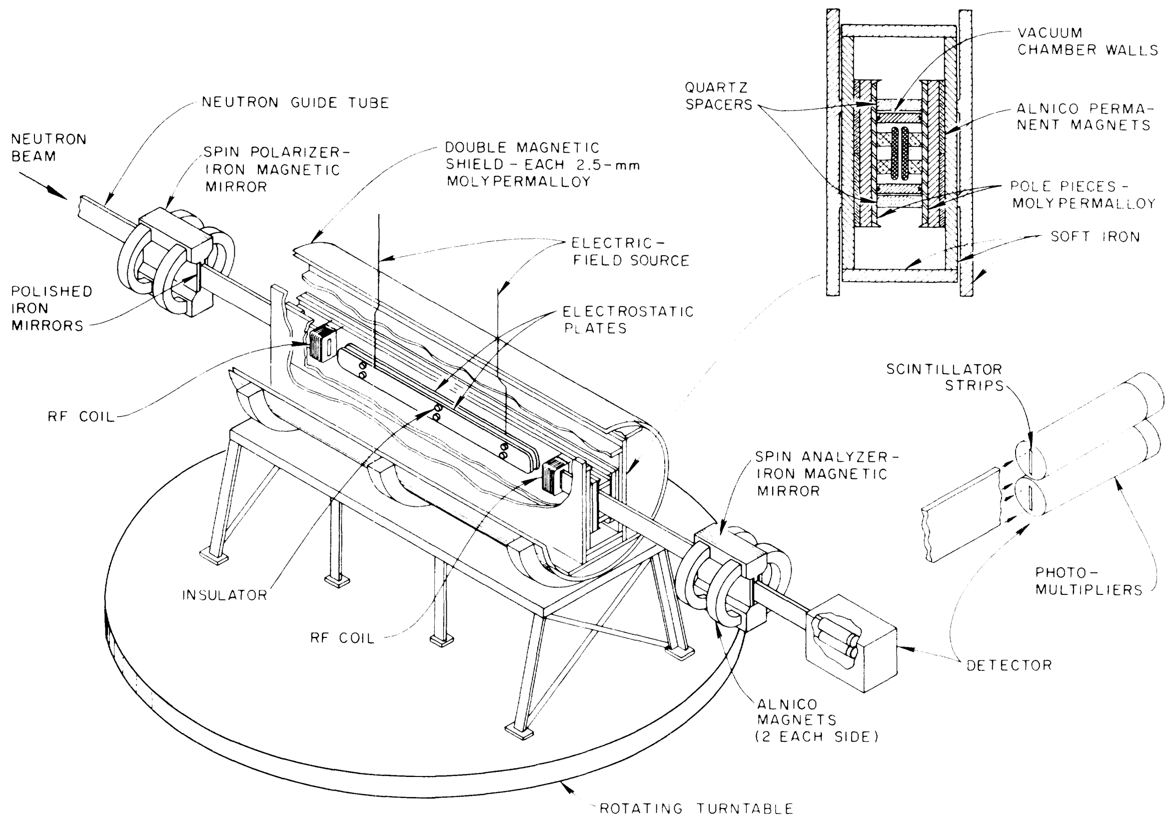

FIG. 2. Pictorial representation of the neutron spectrometer, showing the position of the main components. The inset, upper right, is a cross-sectional view through the midpoint of the apparatus indicating the various materials used in the construction. The gap between the magnetic poles (and thus the length of the quartz spacers) is 9 cm; and the distance between the electrostatic plates (cross-hatched in the figure) is 1 cm. The material between the pole pieces and the Alnico magnets is soft iron with a gap under the pole pieces to provide some homogenizing of the magnetic field.

tion was to reverse the direction of the neutron beam with respect to the apparatus, thus compensating for the most severe systematic effect which could produce a spurious EDM signal: the $\vec{E}\times\vec{v}/c$ effect, which arises from the motion of the neutron through the electric field producing an effective magnetic field according to Maxwell's equations. In order to compensate reliably for this effect, even the magnetic mirrors were rotated with the spectrometer and shield; only the detector and reactor (including the remainder of the environment) remained unaffected. Thus the strongest and closest sources of the magnetic environment reversed direction with respect to the neutron veolocity, thus eliminating a possible fault of an earlier measurement.[39I]

The spectrometer and minicomputer were interfaced by means of a CAMAC electronics system consisting of a set of relays to drive various components of the apparatus; scalers for counting neutron pulses, electric field breakdowns, detector live time, frequency of the rf field, and the internal temperature of the spectrometer; two preset scalers for timing events via a master oscillator; a device for controlling the frequency synthesizer which supplied the rf field; and a system controller for translating signals between the CAMAC modules and the PDP-11 computer. A software system specific to the PDP-11 in conjunction with the system controller was developed at the ILL and made available to the experiment.[42] This system allowed complete data-acquisition and experiment control along with time sharing and program swapping—all on a real-time basis. The actual programs of data acquisition and experiment control, running under the real-time system, were written by the authors so that modifications could be easily effected and a coherent data-handling system could be evolved.

One of the first demonstrations of the power of such a system was an experiment to measure the neutron spectrum actually present at the detector. The program for this measurement was assembled from the phase-reversal, counting, and timing subprograms in the form of a time-of-flight program using the spin flip produced in one rf coil

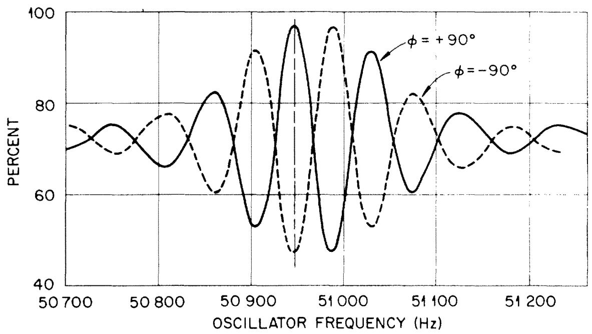

FIG. 3. Neutron resonance, shows the result of an actual measurements for both +90° and −90° (dashed curve) phase shift between the rf coils. The ordinate is the counting rate as a percentage of the rate with no rf (i.e., no spin-flip transitions). The actual data were taken at 2-Hz steps and the smooth curves shown here pass through the measured points. The width of the line is larger than the individual error bars, each point representing some 10^8 counts. The resonant frequency is the point where the two curves cross just to the right of the vertical dashed line. The width of the individual loops reflects the distance between the rf coils (200 cm) and the average neutron velocity; the number of loops before being damped out at the sides of the figure is an indication of the width of the velocity distribution in the neutron beam.

to "chop" the neutron beam. This "chopping" was effected by setting the oscillator frequency to the position in the neutron resonance indicated by the vertical dashed line in Fig. 3, and then reversing the phase of the rf coil farthest from the detector, thus switching the counting rate from the dashed curve ("off" state) to the full curve ("on" state) as shown in the figure. The flip was accomplished over the 10-cm rf-coil length compared to the flight path of some 3.5 m to the detector. The arriving neutrons were counted into a bin of fixed width and variable position along the time axis. The phase was then switched back to the off state, and the bin position changed while waiting for the slowest off neutrons to reach the detector before the cycle was restarted by a flip to the on state. This cycle was repeated many times to build up enough statistics since a typical bin width was less than 1 ms wide, and only one bin collected counts during each cycle. This latter feature noticeably slowed data collection, but allowed accurate determination and reproducibility of bin position, since the use of a 1-Mhz clock to position each bin with a start pulse derived by the phase-flip signal avoided the problems of computer-cycle time and computer-CAMAC time lags which could introduce errors as large as 20% in bin position. Figure 4 shows the resulting spectrum of a time-of-flight measurement. The

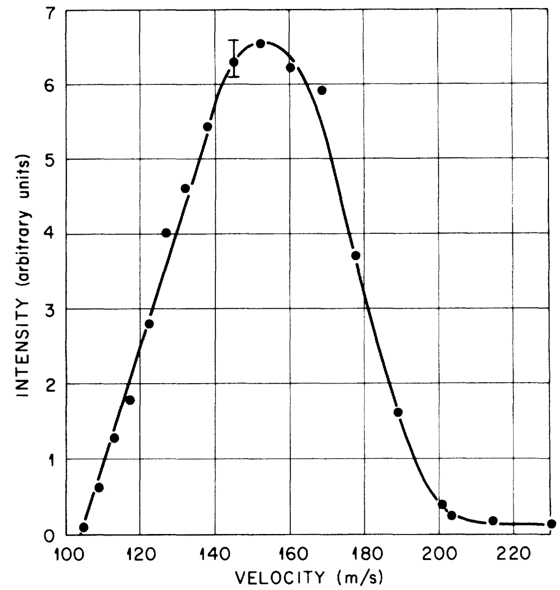

FIG. 4. Neutron velocity spectrum using spin-chopped time-of-flight neutrons. This data is the result of numerical differentiation of a curve obtained by counting neutrons into a movable time bin of fixed width relative to the spin-flip signal, as discussed in the text, and shows the actual velocity distribution present in the spectrometer under normal operating conditions.

velocity spectrum is centered at about 154 m/sec and has a full width at half maximum of about 50 m/sec.

The final method of data taking for the EDM search evolved from this measurement: The phase between the two rf coils was reversed from +90° to −90° at a one-second rate some 200 times for each polarity of the electric field. Appropriate dead times were inserted after each phase reversal to allow those neutrons present in the apparatus during the phase change to escape before counting began again. Since a 90° phase-shifted resonance is antisymmetric about the actual point of resonance as shown in Fig. 3, a measurement of +90° and −90° will, when combined, determine the true resonant frequency, provided no resonance-distorting effects are present. Thus, assuming the oscillator frequency to be set close enough to the true Larmor-precession frequency so that a linear approximation can be used for the counting rate versus the oscillator frequency, the difference in counting rate for phase +90° and −90° divided by the slope of the resonance in counts/Hz is a measure of the actual resonant frequency. Therefore during each 200 sec between high-voltage polarity changes (electric-field reversals) we obtained 100 measures of the resonant frequency which could be least-squares fitted to a straight line or any other curve representing the drift of the magnetic field $\vec{B}_0$. The electric field was then reversed, and the process started over again. The extrapolated value of the straight-line plot of the resonant frequency to the midpoint in time of the high-voltage (HV) reversals was used as the value of resonant frequency with which to form the differences with field parallel and antiparallel to $\vec{B}_0$ [the $\Delta\nu$ of Eq. (3)]. An alternative method was to average the 100 values of the resonant frequency obtaining a 200-sec average for each field reversal. This would, of course, show any effects of temperature and other drifts of the neutron resonance more clearly. Figure 5 illustrates this procedure of phase changes and fitting during a HV point.

This method of chopping the data cycle into many small parts had the advantage that noise and drifts with a period of about one second were averaged out to first order. Also, since the field was reversed every 200 sec, noise with a period comparable to or less than that made only small effects. Thus the only first-order effects left in the data other than induced or real signals due to magnetic or electric field effects in step with the field reversals were long-term drifts such as temperature changes, which showed daily, as well as reactor-cycle variations. The comparison between internal and external errors determined from the least-squares fit indicated that the short-term stability of the data was only a few percent from the value expected on the basis of counting statistics.

At the end of each field-reversal cycle, the computer ran the HV to zero in about two seconds by means of a stepping motor driving a dual variac in the primary of the HV supplies. The polarity was then reversed, and the HV turned up to its full value in a controlled fashion: three fourths of the operating voltage was attained in about two seconds in a linear fashion, whereas the next one fourth was set following a logarithmic curve in time, lasting about three seconds. This was a gentle method of reversing the HV since it was found in earlier tests that field breakdowns (sparks) occurred primarily during the last portion of the voltage run-up, and the sparking incidence could be diminished if the voltage were increased slowly over a few seconds. There was then a pause of some two seconds before continuing with the measurement in order to allow any transients to

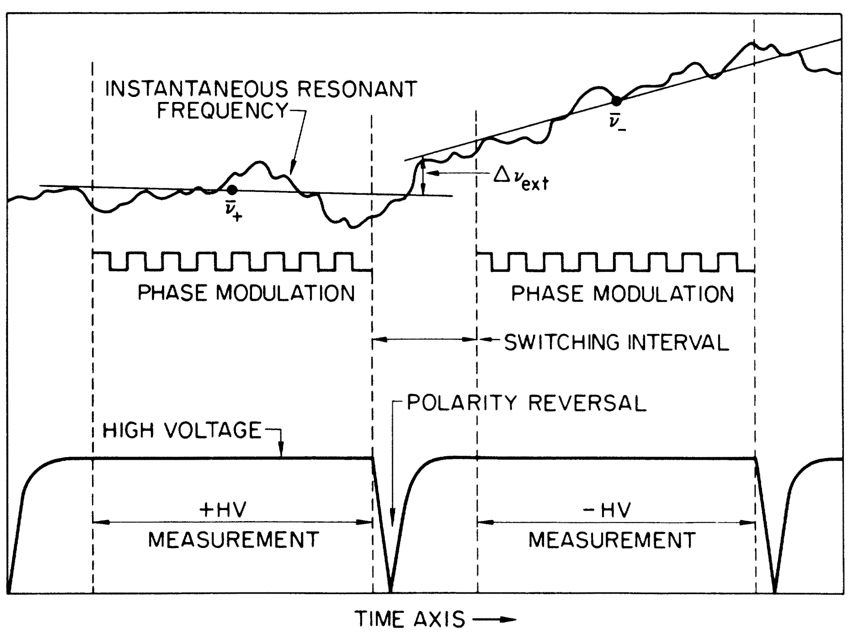

FIG. 5. Data cycle. This is a pictorial representation of the basic measurement cycle. The top curve represents a presumed instaneous resonant frequency which has high- and low-frequency components (noise, short-term instabilities, and temperature drifts). The bottom curve represents the HV cycle starting off with the HV at zero, showing the linear rise in HV turning into the logarithmic approach to the operating value (the horizontal portion between the two pairs of dotted lines). The "square wave" represents the modulation of the phase difference between the two rf coils from +90° to −90° (a 12-msec dead-time at the end of each phase reversal is not shown). The straight lines through the frequency curve represent the least-squares-fitted line during the measurement periods, and indicate the extrapolation to equal times (midway in the switching cycle). $\Delta\nu_{ext}$ is the value of the frequency difference of the extrapolated straight lines (one forward and the other backward in time). The average frequency is represented by the dots labeled "$\bar{\nu}$." The time scale is distorted to enhance the details of the HV switching.

die away. The 9 sec taken for the HV reversal was thus a compromise between very long reversal times and maximizing neutron-counting time.

Since sparks were monitored by means of pick-up loops wrapped around the HV leads to the apparatus, the computer could and did optimize the electric field. When a spark occurred, the field of the following point was lowered 2 kV/cm. If there were no sparks for a period of time, depending upon how many previous points did not contain any sparks, the HV was raised by 1 kV for the following measurement. Thus the field optimization followed a conservative course, and proved its worth over and above the previous method of no optimization, which at times resulted in runs completely lost due to severe sparking or to the HV supplies tripping out due to overload conditions. Overloads could and did occur in the present arrangement in spite of using a helium buffer gas at about 10^{-5} Torr in the electric-field region, but provision was made for resetting the supplies under computer control after waiting an appropriate interval and lowering the voltage to a safe level. Typical ranges of electric field during a run were about ±5 kV/cm about the mean value, which varied from about 80 kV/cm to 130 kV/cm depending upon the condition of the electrostatic plates and the cleanliness of the vacuum system. Some runs showed no fluctuation in HV, while others had such large changes that they were discarded for fear that they would contribute only noise to the data being collected.

In this way, sparking was sufficiently reduced that there was a lifetime of about four months between successive spectrometer disassemblies for reanodizing the 180-cm Al electrostatic plates. Since this was one of the most time-consuming tasks, the automatic feature of controlling the HV saved the experiment several months of down time and allowed higher average operating voltage.

III. SYSTEMATIC EFFECTS

The measurement cycle described in the preceeding section (reversing the phase between the two rf coils many times before reversing the electric field) was repeated several hundred times each day to give a daily result for the EDM, with the various systematic effects such as $\vec{E}\times\vec{v}/c$ still remaining. Every day or so, the spectrometer was rotated 180° to change the sign of v, thus reversing the $\vec{E}\times\vec{v}/c$ effect, and allowing its measurement and removal from the EDM signal. Other periodic changes were made: operating with the HV supplies turned down to zero to measure the effect of the switching mechanism on the EDM signal (defined as the difference in resonant frequency with the electric field parallel and antiparallel to $\vec{B}_0$), as well as operating at lower and higher maximum values of the electric field. One particular set of runs, lasting several weeks, involved a modification of the HV cycle allowing a measurement at zero HV before each polarity reversal. This procedure eliminated any effects due to the reversal mechanism, while allowing a determination of the frequency shift due to the electrostatic force between the two electrostatic plates.

An estimate of the magnitude of systematic magnetic effects correlated with the act of reversing the electric field can be obtained from Eq. (4). It may be seen that a reversible electric field of about 100 kV/cm and a frequency shift of 1 Hz would correspond to an EDM of about 10^{-20} cm. To obtain reliable measurements near or below 10^{-24} cm, the frequency shift must be known to better than $\frac{1}{10}$ mHz. Since the neutron's magnetic interaction is about 3000 Hz/G, the allowable magnetic noise correlated with the field reversals must be below a few hundredths of a μG. This, in turn, demands a limit of a few hundredths of a microampere for any reversible currents flowing through the spectrometer. One of the earliest problems encountered was just such a current effect: rather large EDM signals of varying magnitude appeared, even when the HV was turned to zero. These signals ranged in magnitude from a few mHz to about 50 mHz—corresponding to an apparent EDM of 1 to 50 in 10^{-23}-cm units. Since the error for a 100-sec measurement was about 3 mHz out of a resonant frequency of 50 kHz (corresponding to a value of B_0 of around 17 G), the source of the larger spurious signals was relatively easy to determine. It was found that currents of the order of a few microamperes were present between the spectrometer and the electronics. After complete electrical isolation of the spectrometer from its surroundings, these currents dropped to less than 10 picoamperes, and the spurious effect disappeared into the noise.

Momentary breakdowns in the electric field also caused a problem. A simple model of a spark as an avalanche across the 1-cm gap between the electrostatic plates involving current pulses (as seen on meters at the HV-supply controls) of about 50 μA with a width of a few tens of milliseconds, indicated the production of a magnetic field which could permanently magnetize small portions of the Molypermalloy pole faces. The effects of such sparks were most noticable with new electrostatic plates or poor vacuum and usually involved a frequency shift of 10 to 50 mHz, whose direction depended upon the polarity of the electric field producing the spark. Such jumps in frequency were dealt with during data reduction, and avoided as much as possible by means of a conservative HV-optimization routine. To avoid possible spurious results, data surrounding each spark were rejected in a symmetrical fashion that insured equal amounts of data with the two directions of the electric field.

Once the above two main sources of systematic error were eliminated, smaller effects began to be apparent. The most troublesome one was traceable to the reversing mechanism for the electric field. This mechanism consisted of two air-operated plungers which made contact with a central conductor forming a double-pole, double-throw switch designed for 140 kV. The vertical motion of the plungers was about 10 cm, and was found to act as a magnetic-flux shunt between the spectrometer shield and the turntable mount. The main source of the background magnetic field was a large overhead crane modifying the earth's field. The closest distance of the crane to the experiment was comparable to the dimensions of the crane itself, so the field at the spectrometer was several hundred μG in magnitude. A differential shunting of a few percent of this field through the magnetic shielding was large enough to give a noticeable effect on the EDM signal. This systematic effect was monitored by a magnetometer for correlation with each datum point. In order to reduce this shunting effect, the switching mechanisms were shielded with mumetal, the switch tanks themselves were moved several meters away from the spectrometer, and the HV cables to the electrostatic plates were periodically reversed by disconnecting them close enough to the points where they passed through the magnetic shields into the spectrometer so that any switching effect taking place outside the spectrometer shields would have its sign reversed and could be measured and removed from the EDM signal.

The final effect studied was due to the electrostatic force between the electric-field plates. Such a force would compress the quartz spacers defining the magnet gap and distort the magnetic pole faces slightly. Since this force is quadratic in V, the applied voltage, a reversal of the electric field would not change the resonant frequency. However, not all of the data points had the same HV due to the need for HV optimization, so the resonant frequency could differ between points of unequal HV, reflecting different dimensions of the gap between the magnetic pole faces. The magnitude of this effect was easily obtainable from the data taken with a measurement at zero electric field between each field-up measurement. Thus the data could be paired as a + or − HV point minus its corresponding zero HV point to give the frequency shift due to the V^2 effect. At 100-kV/cm field, the frequency shift was about 4.5 mHz, and corresponds to change of the magnetic gap given by S, where

$$S=(44.0\pm0.7)\times10^{-8}\ \mathrm{Hz/kV^2}. \tag{5}$$

This size of effect is entirely accounted for by the compressibility of the quartz spacers shown in Fig. 2. Such behavior could introduce a bias in the results if there were preferential sparking (and hence a lowering of the HV) on one particular polarity over a long period of data collection. However, knowledge of S allows a correction to be made. Since a datum point containing a spark was rejected, the only change in HV from point to point allowed to remain in the data was a 1-kV change which means a correction of only 0.09 mHz, and was easy to effect during the final data reduction.

There remain two possible systematic effects whose presence we were unable to rule out entirely. The first is related to the V^2 effect in that a difference in impedence to leakage currents through the HV system could, upon HV reversal, mean that the positive and negative values of the electric field were not equal in magnitude. The second effect is possible influence of magnetic fields due to leakage currents inside the spectrometer (along the insulators supporting the electrostatic plates, for example). A limit can be placed on both these effects by observing the current measured by meters placed in the primary circuit of the HV supplies. This current has a magnitude corresponding to about 20 μA, and varied about 10% upon reversal of the electric field. From the value of S given in Eqs. (5) and (4) and the internal impedence of the HV supplies, the estimated influence on the EDM was less than 6×10^{-25} cm. Similarly, the influence due to currents inside the spectrometer can be estimated to be lower than about 5×10^{-25} cm, since all of the current except for perhaps 1 or 2 μA was determined to be leakage outside the spectrometer, and the primary direction of any leakage currents would give rise to magnetic fields perpendicular to $\vec{B}_0$, as may be seen from the geometry of the interior of the spectrometer.

IV. DATA AND RESULTS

Each 200-sec datum point was written on a magnetic tape in sequential order. Interspersed with the data were temperature measurements with the corresponding times taken about every 30 minutes by means of a quartz thermometer whose probe was placed inside the spectrometer adjacent to one of the permanent magnets. A recorded datum point consisted of the slope and intercept of the least-squares fit of the 100 phase-reversed pairs of frequency measurements; the internal error (deviation of the 100 pairs from the fitted straight line); the stability, which is the ratio of the internal error to the external error (that expected on the basis of error propagation from counting statistics); the value of electric field; the magnetometer reading; an experiment-status word; and the number of sparks during that point. Each day's result was then analyzed by a central computer (PDP-10). The basic scheme of analysis was to consider a string of n points, form partial means and errors, then combine the strings to give a result for that day's run. The number, n, varied from 4 to several hundred depending on how long a sequence of points could be found which did not violate one of the selection criteria. A point was deemed acceptable if (1) it had no spark, (2) the magnetometer reading was normal, (3) the experiment-status word was normal, (4) the stability as defined above was not greater than 1.2, (5) the sign of the HV was expected as based on the preceeding point, and (6) if the difference from adjacent points did not exceed three standard deviations for such differences as estimated for the entire run. An acceptable point was included in the current string; an unacceptable one terminated the string—being included or not depending whether the error occurred during the point or during the switching before the next point.

A "dipole" was calculated for each string using a method of alternate differences between succeeding points. This was done in each of two ways: one using the extrapolated value of the frequency as shown in Fig. 5, thus drifts of the order of the length of the datum point itself were automatically compensated; secondly, using the average of the frequency during the 200-sec point. The error in the latter method was a factor of 2 smaller than in the extrapolated method due to different degrees of freedom being used in the two calculations. As was expected, the average-frequency method showed effects of temperature drifts (as determined by correlation of the frequency with the temperature measurements). However, when the long-term drifts were removed by fitting to a polynomial of degree 3 to 7, the two methods resulted in the same final answer within statistics. Since the fitting of the drift involved many points (300–800), the increase in error due to a 7° polynomial fit was negligible, so the average-frequency method, having the smaller statistical error, is the one reported here.

The dipole signals obtained from average-frequency data which had been drift-corrected by subtracting a fitted polynomial were consistent with those obtained from the uncorrected average-frequency data. The insensitivity of the uncorrected data to obvious drifts in the magnetic field is due to the method of forming differences within a data string—the method used eliminated any linear temperature effect and substantially reduced any quadratic term. A more sophisticated method of taking differences of equal-length points within a string could be used to eliminate any order of drift as long as the order was two less than the number of points in the string. A short description of this method is given in the Appendix.

The results of the daily runs were combined into three groups of data each spanning two or three months of running. Between one group and the next, major changes were made in the apparatus or in the structure of the data cycle. Each group had runs with both directions of velocity, with some runs at zero HV. Later data also contained runs with the cables reversed. Thus each of the systematic effects discussed in the preceding section was measured and removed from the EDM signal. The usual methods of error propagation were used in keeping both the internal and external error at each stage of the data reduction. A comparison of the two errors at the end of a day's run or at the end of a set of runs provided a measure of the stability of the results. The errors quoted in the final results are the larger of the two, so errors other than due to counting statistics are included.

Table I displays the reduced data with long-term drifts removed by a fitting procedure, the various systematic effects discussed, and the results for the EDM signal. Group A is data taken after complete electrical isolation of the spectrometer from its surroundings. Group A shows the corresponding zero-field runs. Group B is data taken with a measurement at zero HV

TABLE I. Results of EDM experiment. Units are 10^{-25} cm. The first three columns give the systematic effects. Groups A and C must be corrected by Groups A' and C', respectively, to account for the unexplained effects found with no electric field. Groups A' and C', originally frequency shifts, are presented in EDM units by the artifice of using a fictitious electric field of around 100 kV/cm. The corrections were done on a frequency basis, however, to take into consideration varying values for the electric field.

Data group	Systematic effects $\vec{E}\times\vec{v}/c$	Cable	Switch	EDM	Runs
A	−24.9	···	···	14.9 ± 4.0	29
A'	6.7	···	···	1.3 ± 20.4	8
B	−1.8	−24.1	−24.4	8.6 ± 21.4	21
C	−46.2	−7.9	−3.9	25.3 ± 9.9	38
C'	−33.6	−6.1	38.4	28.1 ± 17.9	9

between each positive or negative HV point. The switch tanks were magnetically shielded before this data was acquired. Group C data was taken after the apparatus was taken apart, and reassembled with reanodized electrostatic plates. The switch tanks were moved a distance of 5 m from the spectrometer, and no longer rotated with it. Group C' is the result of the zero-field runs for Group C.

If μ_n is the neutron's magnetic moment, v the neutron velocity, and θ the angle between the electric field and the component of the magnetic field lying in a plane normal to the velocity vector, then the $\vec{E}\times\vec{v}/c$ systematic effect introduces a spurious EDM given by

$$D_{Exv} = -\frac{\mu_n}{e}\frac{v}{c}\sin\theta \sim 10^{-20}\ \text{cm}\times\sin\theta\,. \qquad (6)$$

When the values of D_{Exv} from Groups A and C are corrected for the zero-field runs, and combined with the value from Group B, the resultant value for D_{Exv} is less than 1.1×10^{-24} cm which indicates that the angle θ is less than 1.1×10^{-4} radians. This shows that $\vec{E}$ and $\vec{B}$ are quite parallel, at least in the plane normal to $\vec{v}$. The systematic effect labeled "cable" is that reversible signal which is measured by reversing the cables from the HV switch tanks to the electrostatic plates. The "switch" effect is any left-over signal which reverses both when the spectrometer is rotated and when the cables are reversed, and may be associated with the physical position of the electronics or the switch tanks with respect to the spectrometer. Both of these effects are seen to vary considerably, and seem to reflect changing environment as well as probable aging in the HV circuit implying an inconstant impedence.

The EDM signal is that portion of the reduced data which has the known systematic effects removed. However, to be able to give a final answer for these measurements, the zero-electric-field runs which contain any other effects that were not measured must be subtracted from the EDM signal. Thus Group A must be corrected by Group A', and Group C by Group C'. This correction was done according to frequency shift, and not the EDM values shown in Table I. This was necessary since the zero-field runs could only be viewed as EDM's if a standard value of the electric field were assumed when none was applied. Group B needs no such correction since the zero-HV points were intermingled with the HV-up points. The combined results of the data presented in Table I give a value of $+0.4\times10^{-24}$ cm for D with a standard error of 1.1×10^{-24} cm. Because of the instabilities of the several systematic effects, including those which produce nonzero values for measurements taken at zero HV, we have arbitrarily increased the experimental error to 1.5×10^{-24} cm and prefer to state our results as

$$D = (+0.4\pm1.5)\times10^{-24}\ \text{cm} \qquad (7)$$

where eD is the neutron electric dipole moment and e the magnitude of the elementary charge. We interpret this result as indicating that, to a 90% confidence limit,

$$|D| < 3\times10^{-24}\ \text{cm}\,. \qquad (8)$$

This limit for D is some four orders of magnitude lower than that set by the first experiment, and lies below the bulk of the theoretical estimates shown in Fig. 1.

This is by no means the last such experiment to seek the neutron's electric dipole moment. In cooperation with scientists from several nations, we are now preparing the initial stages for a highly-sensitive trapped-neutron experiment to take place at the ILL within the next few years.

ACKNOWLEDGMENTS

The authors wish to express their appreciation for help and encouragement given by the director and staff of Institut Max von Laue–Paul Langevin.

APPENDIX

There is a certain class of experiments wherein the effect of interest is to be found in a small change in some measured quantity due to the reversal or presence of an experimental parameter. In the present case, the relevant effect is sought in a small change in counting rate upon reversal of the electric field. The usual technique for the extraction of the desired effect is to take differences of the measured quantity, each pair of differences being taken with opposite conditions of the experimental parameter. An obvious difficulty arises unless any parameter-independent change is much smaller than the parameter-dependent one; that is drifts due to effects such as magnetic field changes, temperature variations, and line-voltage fluctuations must be much smaller than the expected effect. Since this case rarely obtains, a method to reduce or eliminate the effects of any drifts must be used. A general method which is simple in execution and general in application is described below.

Assume the measured quantity (a counting rate corresponding to a frequency in the present case) can be represented by a power series in time. Then a sequence of measurements of that quantity, where each measurement lasts the same period and the times between measurements are also uniform, may be represented by a power series of the same order as the original series. Thus, consider the set of $m+1$ measurements

$$\nu_n = \sum a_i n^i \tag{A1}$$

for $n=0,\ldots,m$, representing the equal-time measurements. It can be shown that the sum,

$$M = \sum (-1)^n \nu_n \, {}_mC_n \tag{A2}$$

where ${}_mC_n$ is the binomial coefficient, and n ranges from 0 to m as above; has zero for the coefficient of each a_i for $i=0,\ldots,m-1$ when the sum in Eq. (A1) is substituted for ν_n. Thus the sum of Eq. (A2) applied to four consecutive points will be unaffected by drift terms up through the quadratic, and five consecutive points will cancel drift terms up through the cubic. At the same time Eq. (A2) gives a nonzero expectation for the quantity sought. In a string of (acceptible) data, each consecutive set of four (say) points is equivalent, so the first through the fourth, the second through the fifth, etc. may be used as a measure of the desired quantity with drifts through second order removed. For example, the data may be combined within a string as

$$M = (\nu_0 - 3\nu_1 + 3\nu_2 - \nu_3) - (\nu_1 - 3\nu_2 + 3\nu_3 - \nu_4) + \cdots , \tag{A3}$$

which can be rewritten as

$$M = \nu_0 - 4\nu_1 + 7\nu_2 - 8\nu_3 + 8\nu_4 - \cdots + 8\nu_{m-3} - 7\nu_{m-2} + 4\nu_{m-1} - \nu_m \tag{A4}$$

in a more convenient fashion for calculation of error propagation due to statistics on the individual ν_n. The sum for M is continued until the end of the string. Since this method exactly compensates for any drift up to the desired order, it is equivalent to fitting a polynomial of that order exactly through the data points in a piece-wise fashion. This is to be contrasted with the usual least-squares method which presupposes a form for the drift to be removed.

A similar method has appeared in the literature[43] which requires the data cycle to be built of unequal measurement periods, whose duration, variation, and repetition is determined by the order of the drift chosen to be removed. The two methods are equivalent in their results (except for a small reduction in statistical error of the latter method due to the smaller number of counting periods and hence time between measurements). The unequal periods, except for the error propagation, correspond to the binomial coefficients described above. However, the use of the equal times with variable weightings at the analysis stage allows the options to be kept open for analysis after data collection so that drifts of different order than anticipated may be eliminated. The principal advantage in an experiment such as the present one, where random points must be rejected to sparking or other external effects, is that an interrupted sequence of equal-time points simply means another string with a minimum number of points (most likely none) lost due to premature truncation. The predetermined-drift method looses the entire current sequence, or if the sequence can be restarted upon error, merely that portion up to the interruption. Also post-analysis for a different drift order would not be an easy task.

In summary, the equal-time method with post-analysis using binomial coefficients as weights allows a simple and flexible means of drift removal. The mechanics of acquiring the data are straightforward, being a simple reversal when a preset time is reached. The choice of drift order is not built in to the mechanics, and the loss of efficiency is very small if the switching time for the experimental parameter is much smaller than the measuring time.

---

*Work jointly supported by the U. S. Energy Research and Development Administration under contract with Union Carbide Corporation, Institute Max von Laue-Paul Langevin, Grenoble, France, Centre d'Etude Nucleaires de Grenoble, Département de Recherche Fondamentale, Grenoble, France, and the National Science Foundation.

[1]E. M. Purcell and N. F. Ramsey, Phys. Rev. 78, 807 (1950).

[2]J. H. Smith, Ph.D. thesis, Harvard Univ., 1951 (unpublished).

[3]J. H. Smith, E. M. Purcell, and N. F. Ramsey, Phys. Rev. 108, 120 (1957).

[4]T. D. Lee and C. N. Yang, Phys. Rev. 104, 254 (1956).

[5]C. S. Wu, E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, Phys. Rev. 105, 1413 (1957).

[6]R. L. Garwin, L. M. Lederman, and M. Weinrich, Phys. Rev. 105, 1415 (1957).

[7]J. I. Friedman and V. L. Telegdi, Phys. Rev. 105, 1681 (1957).

[8]L. Landau, Nucl. Phys. 3, 127 (1957); Zh. Eksp. Teor. Phys. 32, 405 (1957) [Sov. Phys.—JETP 5, 336 (1957)].

[9]T. D. Lee and C. N. Yang, Phys. Rev. 105, 1671 (1957).

[10]A. Salam, Nuovo Cimento 5, 299 (1957).

[11]G. C. Wick, A. S. Wightman, and E. P. Wigner, Phys. Rev. 88, 101 (1952), footnote 9.

[12]J. S. Allen, R. L. Burman, W. B. Herrmannsfeldt, P. Stähelin, and T. H. Braid, Phys. Rev. 116, 134 (1959).

[13]T. D. Lee, Reinhard Oehme, and C. N. Yang, Phys.

Rev. 106, 340 (1957).
[14]Ia. B. Zel'dovich, J. Exp. Theor. Phys. 6, 1488 (1957) [Sov. Phys.–JETP 6, 1148 (1957)].
[15]N. F. Ramsey, Phys. Rev. 109, 225 (1958).
[16]R. L. Garwin and L. M. Lederman, Nuovo Cimento 11, 776 (1959).
[17]J. D. Jackson, S. B. Treiman, and H. W. Wyld, Jr., Phys. Rev. 106, 517 (1957).
[18]M. A. Clark and J. M. Robson, Can. J. Phys. 38, 693 (1960).
[19]M. T. Burgy, V. E. Krohn, T. B. Novey, G. R. Ringo, and V. L. Telegdi, Phys. Rev. 120, 1829 (1960).
[20]B. G. Erozolimskiĭ, L. N. Bonarenko, Yu. A. Mostovoĭ, B. A. Obinyakov, V. P. Zakharova, and V. A. Titov, Yad. Fiz. 11, 1049 (1970), [Sov. J. Nucl. Phys. 11, 583 (1970)].
[21]R. I. Steinberg, P. Liaud, B. Vignon, and V. W. Hughes, Phys. Rev. Lett. 33, 41 (1974).
[22]M. Gell-Mann and A. Pais, Phys. Rev. 97, 1387 (1955).
[23]K. Lande, E. T. Booth, J. Impeduglia. L. M. Lederman, and W. Chinowsky, Phys. Rev. 103, 1901 (1956).
[24]M. Bardon, K. Lande, L. M. Lederman and W. Chinowsky, Ann. Phys. (N.Y.) 5, 156 (1958).
[25]D. Neagu, E. O. Okonov, N. I. Petrov, A. M. Rosanova, and V. A. Rusakov, Phys. Rev. Lett. 6, 552 (1961).
[26]D. Luers, I. S. Mittra, W. J. Willis, and S. S. Yamamoto, Phys. Rev. Lett. 7, 255 (1961).
[27]A. Abashian, R. J. Abrams, D. W. Carpenter, G. P. Fisher, B. M. K. Nefkens, and J. H. Smith, Phys. Rev. Lett. 13, 243 (1964).
[28]J. H. Christenson, J. W. Cronin, V. L. Fitch, and R. Turlay, Phys. Rev. Lett. 13, 138 (1964).
[29]J. Schwinger, Phys. Rev. 82, 914 (1951); and 91, 713 (1953).
[30]W. Pauli, *Neils Bohr and the Development of Physics* (McGraw-Hill, New York, 1955).
[31]Gerhart Lüders and Bruno Zumino, Phys. Rev. 106, 385 (1957).
[32]L. I. Schiff, Phys. Rev. 132, 2194 (1963).
[33]See, for example. Felix Boehm, in *High-Energy Physics and Nuclear Structure– 1975*, edited by D. E. Nagle, R. L. Burman, B. G. Storms, A. S. Goldhaber, C. K. Hargrave (A.I.P., New York, 1975).
[34]M. C. Weisskopf, J. P. Carrico, H. Gould, E. Lipworth, and T. S. Stein, Phys. Rev. Lett. 21, 1645 (1968).
[35]M. A. Player and P. G. H. Sandars, J. Phys. B3, 1620 (1970).
[36]G. E. Harrison, P. G. H. Sandars, and S. J. Wright, Phys. Rev. Lett. 22, 1263 (1969).
[37a]N. T. Meister and T. K. Radha, Phys. Rev. B135, 769 (1964) W $\Delta S=0$.
[37b]F. Salzman and G. Salzmann, Phys. Lett. 15, 91 (1965) EM1.
[37c]G. Feinberg and H. S. Mani, Phys. Rev. B137, 636 (1965) W $\Delta S=1$.
[37d]D. G. Boulware, Nuovo Cimento 40A, 1041 (1965) W $\Delta S=0$.
[37e]G. Feinberg, Phys. Rev. B140, 1402 (1965) EM1.
[37f]P. Babu and M. Suzuki, Phys. Rev. 162, 1359 (1967) W $\Delta S=0$.
[37g]K. Nishijima and L. J. Swank, Nucl. Phys. B3, 565 (1967) MW $\Delta S=0$.
[37h]G. R. Gourishankar, Can. J. Phys. 46, 1843 (1968) MW $\Delta S=1$.
[37i]A. T. Filippov, Z. Oziewicz and A. Pikulski, Joint Inst. for Nuclear Research, Dubna report, 1968 (unpublished) EM.
[37j]P. McNamee and J. C. Pati, Phys. Rev. 178, 2273 (1969) MW $\Delta S=0,1$.
[37k]G. Barton and E. D. White, Phys. Rev. 184, 1660 (1969) EM2, MW $\Delta S=0,1$.
[37l]K. Nishijima, Prog. Theor. Phys. 41, 739 (1969) MW $\Delta S=0$.
[37m]L. B. Okun, Comments Nucl. Part. Phys. III, 133 (1969) SW.
[37n]E. R. McCliment and W. D. Teeters, Nuovo Cimento 68A, 657 (1970) MW.
[37o]D. J. Broadhurst, Nucl. Phys. B20, 603 (1970) EM2.
[37p]A. Chodos and K. Lane, Phys. Rev. D 6, 596 (1972) MW3.
[37q]R. N. Mohapatra, Phys. Rev. D 6, 2023 (1972) MW.
[37r]A. Pais and J. R. Primack, Phys. Rev. D 8, 3063 (1973), MW.
[37s]T. D. Lee, Phys. Rev. D 8, 1226 (1973); Phys. Rep. 9C, 143 (1974) MW.
[37t]L. Wolfenstein, CERN Report No. Ref. TH. 1837-CERN (unpublished); Nucl. Phys. B77, 375 (1974) SW (see also Ref. 38).
[37u]R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 566 (1975) MW.
[37v]S. Pakvasa and S. F. Tuan, Phys. Lett. 34, 552 (1975) MW.
[37w]J. Frenkel and M. E. Ebel, Univ. of Wisconsin report, 1974 (unpublished); Nucl. Phys. B83, 177 (1974) MW.
[37x]R. B. Clark and J. Randa, Phys. Rev. D 12, 3564 (1975) MS.
[37y]Steven Weinberg, Phys. Rev. Lett. 37, 657 (1976) MW.
[38]L. Wolfenstein, Phys. Rev. Lett. 13, 562 (1964).
[39A]See Refs. 2 and 3.
[39B]P. D. Miller, W. B. Dress, J. K. Baird, and N. F. Ramsey, Phys. Rev. Lett. 19, 381 (1967).
[39C]C. G. Shull and R. Nathans, Phys. Rev. Lett. 19, 384 (1967).
[39D]K. Smith and J. M. Pendelbury, private communication (1968).
[39E]W. B. Dress, J. K. Baird, P. D. Miller, and N. F. Ramsey, Phys. Rev. 170, 1200 (1968).
[39F]V. W. Cohen, R. Nathans, H. B. Silsbee, E. Lipworth, and N. F. Ramsey, Phys. Rev. 177, 1942 (1969).
[39G]J. K. Baird, P. D. Miller, W. B. Dress, and N. F. Ramsey, Phys. Rev. 179, 1285 (1969).
[39H]S. Apostolescu, D. R. Ionescu, M. Ionescu-Bujor, S. Meitert, and M. Petroscu, Rev. Roum. Phys. 15, 343 (1970).
[39I]K. N. Baird, D. Phil. Thesis, Univ. of Sussex, 1973 (unpublished).
[39J]W. B. Dress, P. D. Miller, and N. F. Ramsey, Phys. Rev. D 7, 3147 (1973).
[40]V. W. Cohen, N. R. Corngold, and N. F. Ramsey, Phys. Rev. 104, 283 (1956).
[41]N. F. Ramsey, *Molecular Beams* (Oxford Univ. Press, Oxford, England, 1956).
[42]P. Ledebt, RTS11 System, Institute Max von Laue-Paul Langevin Internal Report (unpublished).
[43]J. C. Vanderleeden and F. Boehm, Phys. Rev. C 2, 748 (1970).