New Experimental Limit on the Electric Dipole Moment of the Neutron

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The latest neutron electric dipole moment (EDM) experiment has been collecting data at the Institut Laue-Langevin (ILL), Grenoble, since 1996. It uses an atomic-mercury magnetometer to compensate for the magnetic field fluctuations that were the principal source of systematic errors in previous experiments. The first results, in combination with the previous ILL measurement, yield a possible range of values of $(-7.0 < d_n < 5.0) \times 10^{-26} e$ cm (90% C.L.). This may be interpreted as an upper limit on the absolute value of the neutron EDM of $|d_n| < 6.3 \times 10^{-26} e$ cm (90% C.L.). [S0031-9007(99)08421-5]

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In order for particles to have electric dipole moments, the forces concerned in their structure must violate both space parity (P) and time reversal (T) symmetries [1]. P violation is a well-known feature of the weak interaction, but CP (and hence T) violation has thus far been found only in the neutral kaon system [2]. This leaves open a wide range of possibilities for competing theories that attempt to explain its origin. Extensions to the standard model, such as additional Higgs fields, right-handed currents, or supersymmetric partners typically give rise to neutron electric dipole moment (EDM) contributions which are of order $(10^{-25}$ to $10^{-27})e$ cm [3]; dipole moments of this size might also come from CP violation in QCD. Experimental measurements of particle EDMs, and in particular that of the neutron, are providing some of the strongest additional constraints on these theories.

The RAL/Sussex experiment at ILL.—This EDM experiment uses the Ramsey resonance technique to measure with very high precision the precession frequency of ultracold neutrons in a weak magnetic field. The precession frequency will change in the presence of an electric field if the neutron has an EDM. Systematic errors in the most recent of these measurements, both those carried out at the Institut Laue Langevin (ILL) in Grenoble [4] and those at PNPI in Russia [5], were dominated by fluctuations in the magnetic field, for which it was impossible to compensate adequately with the external magnetometers in use at the time. Following an idea of Ramsey [6], the current EDM experiment incorporates for the first time a "comagnetometer" based upon the storage of polarized atoms simultaneously with and in the same cell as the neutrons. However, instead of the ^{3}He atoms originally proposed by Ramsey, ^{199}Hg was used in this case; this was suggested by the University of Washington group, following its own measurement of its EDM [7]. The presence of the comagnetometer reduces by about a factor of 20 what was thought to be the dominant systematic error of the previous experiment, by measuring the magnetic field in much more nearly the same volume as that occupied by the neutrons. It should be noted that, although the experiment was substantially rebuilt to allow for the inclusion of the magnetometer, the environment (magnetic shielding, ambient temperature stability, high-voltage generation, etc.) remains similar. Here an outline of the experimental technique is presented; full details will be published in an upcoming archival paper.

EDM measurement principle.—The measurement is made with neutrons stored in a cell permeated by uniform **E** and **B** fields. The terms $-\boldsymbol{\mu}_n \cdot \mathbf{B}$ and $-\mathbf{d}_n \cdot \mathbf{E}$ are added to the Hamiltonian determining the states of the neutron. Given parallel **E** and **B** fields, the Larmor frequency $\nu_{\uparrow\uparrow}$ with which the neutron spin polarization precesses about the field direction is

$$h\nu_{\uparrow\uparrow} = 2\boldsymbol{\mu}_n \cdot \mathbf{B} + 2\mathbf{d}_n \cdot \mathbf{E}\,. \qquad (1)$$

For antiparallel fields, $h\nu_{\uparrow\downarrow} = 2\boldsymbol{\mu}_n \cdot \mathbf{B} - 2\mathbf{d}_n \cdot \mathbf{E}$.

Thus the goal is to measure, with the highest possible precision, any shift in the transition frequency ν as an applied **E** field alternates between being parallel and then antiparallel to **B**.

A schematic of the apparatus is shown in Fig. 1. The neutrons are prepared in a spin-polarized state by transmission through a thin, magnetized iron foil, and enter a 20-liter storage cell, composed of a hollow upright quartz cylinder closed at each end by aluminum electrodes that are coated with a thin layer of diamondlike hard carbon [8]. The storage volume is situated within four layers of mu metal, giving a shielding factor of about 10 000 to external magnetic field fluctuations. A highly uniform 1 μT vertical magnetic field is generated by a coil wound around

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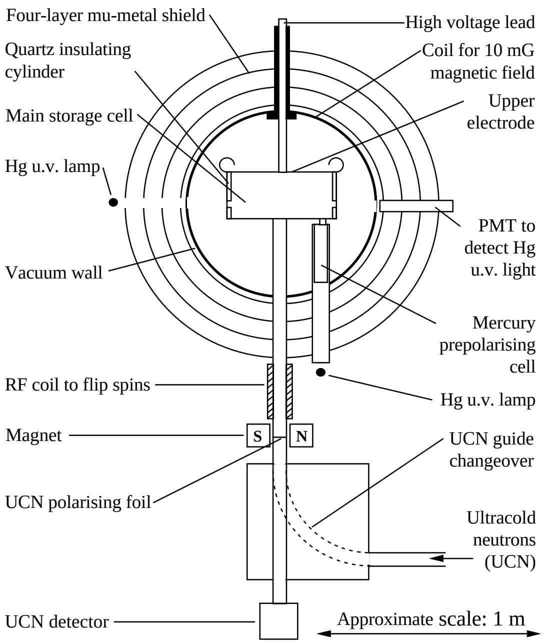

FIG. 1. The neutron EDM experimental apparatus.

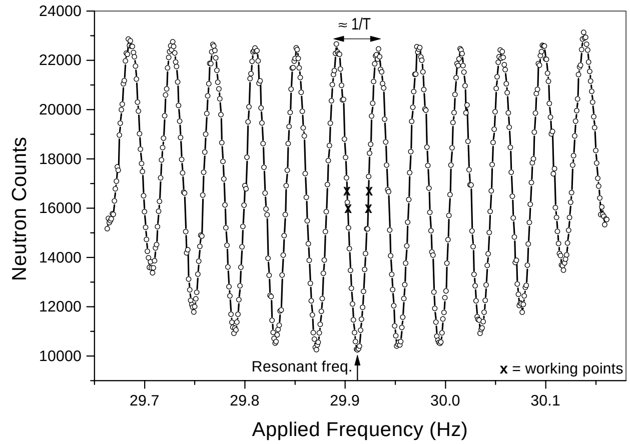

FIG. 2. The Ramsey resonance curve for spin-up neutrons, $N_\uparrow$. The corresponding pattern for $N_\downarrow$ is inverted but otherwise identical.

the vacuum tank with a uniform pitch in z, the vertical diameter of the cylinder. Approximately 20 s are needed to fill the storage cell with neutrons, after which the entrance door is closed pneumatically. The electric field is generated by applying high voltage to the upper electrode while keeping the lower electrode grounded.

The transition frequency ν of the neutrons is measured using the Ramsey separated oscillatory field magnetic resonance method. During the storage period, the neutrons interact coherently with two short ($\approx$2 s) intervals of oscillating magnetic field having a chosen frequency close to the Larmor frequency. The two intervals are separated by a long period $T \approx 120-150$ s of free precession. The last step is to count the number of neutrons $N_\uparrow$ and $N_\downarrow$ which finish in each of the two polarization states. This is achieved by opening the entrance door to the storage cell and allowing the neutrons to fall down onto the polarizing foil, which now acts as a spin analyzer. Only those in the initial spin state can pass through to the detector, which is a proportional counter in which neutrons are detected via the reaction $n + {}^3\mathrm{He} \rightarrow {}^3\mathrm{H} + p$. During one-half of the counting period, an rf field is applied in the region above the polarizing foil; this flips the spins of the neutrons, thereby also allowing those in the opposite spin state to be counted.

Figure 2 shows $N_\uparrow$ from a succession of batch cycles, each with a slightly different offset between the precession frequency and the oscillating field frequency. The normal data-taking procedure entails choosing a working point at a half-height position close to the center of the resonance pattern in Fig. 2, where the slope of the curve is greatest. The batches are cycled continuously for 1–2 days, while about once per hour the direction of **E** is reversed. The data are fitted to a cosine curve to yield the resonant frequency. It can be shown that the uncertainty σ_{d_n} on the dipole moment due to neutron counting statistics noise alone is then

$$\sigma_{d_n} \approx \frac{\hbar}{2\alpha E T \sqrt{N}}, \qquad (2)$$

where N is the total number of neutrons counted and α is the visibility of the central resonance fringe:

$$\alpha = \frac{(N_{\uparrow\max} - N_{\uparrow\min})}{(N_{\uparrow\max} + N_{\uparrow\min})}, \qquad (3)$$

with a similar value for $N_\downarrow$. For the data involved in this analysis, approximate average values of the variables in Eq. (2) were $\alpha = 0.5$, $E = 4.5$ kV/cm, $T = 130$ s, and $N = 13\,000$ neutrons per batch, with each batch cycle taking about 210 s. From one day of data, therefore (and allowing for pauses between runs and control measurements at zero voltage), σ_{d_n} was about $6 \times 10^{-25} e$ cm.

The mercury magnetometer.—Under normal running conditions, small changes in B (at the level of a few nG) cannot be avoided, and they invariably produce shifts in the neutron precession frequency that far exceed those from the $\mathbf{d}_n \cdot \mathbf{E}$ interaction. A high-precision magnetometer is therefore essential. The current experiment uses atoms of ^{199}Hg (with 3×10^{10} atoms/cm^3) stored simultaneously in the same cell as the neutrons. Gravity causes the center of mass of the (ultracold) neutrons to be about 0.5 cm lower than that of the (hot) Hg atoms; this may crudely be compared with the 30-cm separation of the magnetometers in the previous ILL experiment [4] and the 10-cm separation between the pair of cells used in the measurement at PNPI [5].

The ^{199}Hg is polarized by optical pumping in a one-liter antechamber. Once the main storage cell has been filled with neutrons and the entrance door closed, the polarized mercury is allowed in to join the neutrons. The spins, first of the mercury and then of the neutrons, are rotated into the xy plane (i.e., perpendicular to **B**) by magnetic resonance. They both precess freely for 130–150 s. The magnetic field has a strength of 10^{-2} G, and the precession frequencies are therefore about 30 Hz and 8 Hz for neutrons and mercury, respectively. The mercury spin precession is monitored continuously with a circularly polarized beam of 254 nm resonance radiation which passes through the main storage cell in the x direction. This light suffers an absorption proportional to the x component of the Hg spin vector. It is detected in a photomultiplier tube; the ac component of the tube output, which has the form of an exponentially decaying sinusoidal oscillation corresponding to the precession and slow depolarization of the mercury atoms, is digitized at 100 Hz by a 16-bit analog-to-digital converter. With a typical ^{199}Hg spin relaxation time of 70 s, a storage time of 130 s, and an initial signal-to-noise ratio of 1000, the magnetic field can be measured by one batch with an rms error of about 2 nG. For comparison, the neutron counting statistics rms error per batch currently corresponds to an uncertainty in B of nearly 10 nG. It should be noted that the EDM of ^{199}Hg itself has been shown to be less than $8.7 \times 10^{-28} e$ cm [7], which is far smaller than the neutron EDM sensitivity of this experiment.

The successful performance of the mercury magnetometer [9] has essentially eliminated magnetic field drift as a source of systematic uncertainty. This is demonstrated in Fig. 3, in which the measured neutron precession frequency is plotted as a function of time over a period of one day; data are shown both before and after correction by the mercury frequency measurements. In searching for frequency shifts corresponding to the hourly polarity reversals in the raw signal, it is difficult to eliminate the drift noise entirely; however, the corrected signal (or, equivalently, the ratio of neutron to mercury atom precession frequencies) may simply be plotted as a function of the applied electric field, and a linear fit yields a slope which is directly proportional to the electric dipole moment.

Results.—There have been ten reactor cycles of 50 days' length since data taking with the mercury magnetometer in place began in 1996, during which time 322 measurement runs have been completed. Analysis of the data obtained yields a value for the EDM of

$$d_n = 1.9 \pm 5.4 \times 10^{-26} e \text{ cm}, \tag{4}$$

with a χ^2/ν of 0.97 for 321 degrees of freedom, corresponding to a confidence level of 62%. Grouping the runs by reactor cycle, as shown in Fig. 4, the χ^2/ν is 0.37 for 9 degrees of freedom (giving a confidence level of 95%). Systematic effects are judged to be negligible in comparison with the uncertainty due to counting statistics. This result by itself yields an upper limit on the neutron EDM of $|d_n| < 9.4 \times 10^{-26} e$ cm (90% C.L.).

The data obtained prior to the installation of the internal mercury cohabiting magnetometer yielded $d_n = -3.4 \pm 2.6 \times 10^{-26} e$ cm [4], with $\chi^2/\nu = 2.2$ for 14 degrees of freedom. The large χ^2 reflected the overall scatter in the data from random shifts in the magnetic field that were not fully compensated by the rubidium magnetometers. This time-varying systematic effect had a spread which may be accommodated by multiplying the uncertainty obtained from neutron counting statistics by $\sqrt{\chi^2/\nu}$, giving an overall statistical uncertainty of $3.9 \times 10^{-26} e$ cm. In addition, it may have caused an overall offset due to incomplete cancellation in the long-term average. As a conservative estimate, this should certainly be less than $3.1 \times 10^{-26} e$ cm, which would have been the false EDM signal obtained (with an uncertainty of $2.5 \times 10^{-26} e$ cm) if the average frequency shift observed in the three magnetometers had been applied to the neutrons instead. Thus, the final result was

$$d_n = [-3.4 \pm 3.9 \text{ (stat)} \pm 3.1 \text{ (syst)} \times 10^{-26}] e \text{ cm}, \tag{5}$$

thereby giving a net uncertainty of $4.9 \times 10^{-26} e$ cm. This was published as $(-3 \pm 5) \times 10^{-26} e$ cm [4]. The new data support the previous analysis: it now seems clear that the observed scatter was due to magnetic field fluctuations rather than to other, unknown, systematic effects.

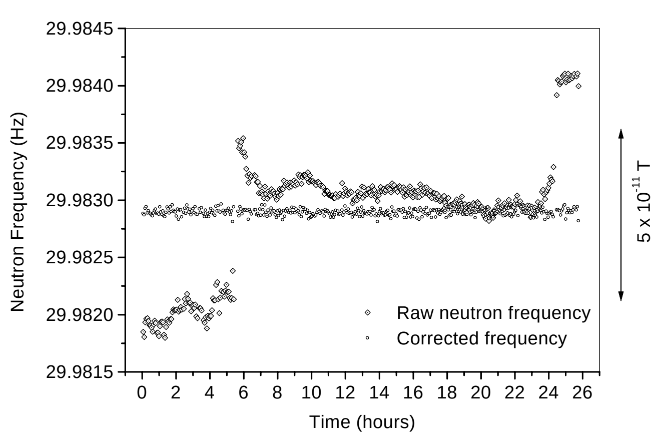

FIG. 3. Neutron resonant frequency measurements, showing both the raw and the mercury-corrected measurements.

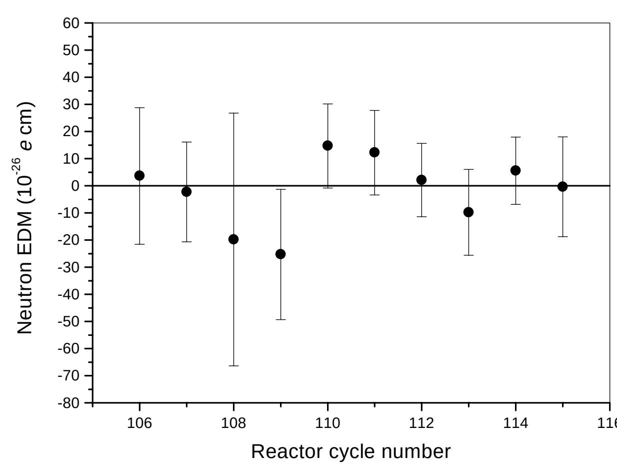

FIG. 4. Results of the neutron EDM measurements, grouped by reactor cycle.

Combining the results of the two sets of data, an overall value of

$$d_n = -1.0 \pm 3.6 \times 10^{-26} e \text{ cm} \quad (6)$$

is obtained, corresponding to a 90% confidence interval of

$$(-7.0 < d_n < 5.0) \times 10^{-26} e \text{ cm} . \quad (7)$$

Placing limits that are symmetric about zero, the upper limit on the absolute value of $|d_n|$ is therefore found to be

$$|d_n| < 6.3 \times 10^{-26} e \text{ cm (90\% C.L.)} . \quad (8)$$

Although concerns frequently arise about the combining of different data sets in this manner, the authors are of the opinion that in this case the systematic errors of the earlier data set are sufficiently well understood to warrant its inclusion.

Systematic errors.—Although the result obtained is consistent with a neutron EDM of zero, it is important to evaluate possible systematic effects that might nonetheless contribute to the generation of an artificial signal or mask a real EDM. Such effects, discussed briefly here, will be covered in some detail in the upcoming archival paper.

Leakage currents and sparks.—Any azimuthal component of leakage current around the storage cell will result in a small additional magnetic field either parallel or antiparallel to **B**, which will reverse polarity with the electric field and thus give rise to a spurious EDM signal. However, as our leakage currents are typically $\sim$1 nA, even the extreme case of a complete circulation around the bottle would result in an apparent EDM of less than $1 \times 10^{-26} e$ cm. In confirmation of this, we have studied the measured EDM as a function of leakage current and have found no measurable effect.

Any electrical activity that occurs during a measurement cycle will normally disturb the mercury to such an extent that a reliable frequency estimate is impossible to obtain, and the cycle is therefore automatically rejected. A number of other possible processes, e.g., spark-induced changes in the residual magnetization of the mu-metal shields or shifts in the storage cell position in response to high-voltage induced forces, might produce systematic shifts in the magnetic field; however, the mercury magnetometer provides more than adequate compensation for any such effects.

The $\mathbf{v} \times \mathbf{E}$ *effect.*—If the neutrons have a net rotational motion, any radial component of the electric field will be seen in their rest frame as a combination of electric and magnetic fields. However, any such flow of neutrons is expected to be destroyed by wall collisions before the first Ramsey pulse is applied. We calculate that the maximum error to be expected from this source and from higher-order $\mathbf{v} \times \mathbf{E}$ effects is below $1 \times 10^{-26} e$ cm.

Other high-voltage induced effects.—The high-voltage stack is a source of ac as well as dc currents which might affect the precession frequencies of mercury and neutrons. For a real EDM, the frequency shift between positive and negative polarities changes sign as the magnetic field reverses; the frequency shift from an ac magnetic field does not. Roughly half of the data were taken for each direction of the magnetic field, and the difference between the measured EDMs for the two subsets is $(0.3 \pm 5.4) \times 10^{-26} e$ cm, which gives no evidence for the presence of such a systematic effect.

In conclusion, the inclusion within the experimental apparatus of a cohabiting magnetometer has enabled the neutron EDM to be measured with a statistical accuracy comparable to previous measurements, and with systematic uncertainties reduced to a negligible level. The similar nature of the neutron frequency fluctuations in the two sets of data discussed above supports the hypothesis that the fluctuating systematic errors limiting the previous measurement at the ILL were due to slowly varying systematic shifts in the magnetic field. It therefore seems reasonable to assume that there were no larger unknown systematic errors conspiring, by chance, to mask a true EDM signal in the earlier data set. Under this assumption, the two sets of data combine to yield an overall limit on the absolute value of the neutron EDM of $|d_n| < 6.3 \times 10^{-26} e$ cm.

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