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The neutron EDM experiment at the ILL

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Abstract

The latest-generation neutron electric dipole moment (EDM) experiment has been collecting data at the ILL since 1996. It uses a "cohabiting" atomic-mercury magnetometer to measure and compensate for the magnetic field fluctuations that were the principal source of systematic errors in previous experiments. The first results, which are soon to be published, essentially verify the existing limit on the dipole moment d_n; however, this new measurement is clearly limited by statistical rather than systematic uncertainties. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

For particles to have electric dipole moments, the forces concerned in their structure must be asymmetric with regard to space-parity (P) and time reversal (T). P violation is a well-known intrinsic feature of the weak interaction, but CP (and hence T) violation, which is believed to be responsible for the baryon asymmetry of the universe, has thus far been found only in the neutral kaon system. Such limited information leaves open a wide range of possibilities for competing theories attempting to explain the origin of CP violation. Extensions to the Standard Model of the electroweak interaction, such as additional Higgs fields, right-handed currents or supersymmetric partners typically give rise to dipole contributions which are of order 10^{-25}–$10^{-27}e$ cm. Dipole moments of this size might also come from CP violation in the QCD sector of the strong interaction. Experimental measurements of particle EDMs, and in particular that of the neutron, are providing some of the strongest additional constraints on these theories.

2. The RAL/Sussex/ILL experiment

This EDM experiment uses the Ramsey resonance technique to measure with very high precision

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the precession frequency of ultracold neutrons (UCN) in a weak magnetic field. The precession frequency will change in the presence of an electric field if the neutron has an EDM. The most recent result from our collaboration, published in 1990, was $d_n = (-3 \pm 2 \pm 4) \times 10^{-26} e$ cm [1]; that of PNPI in Russia was $d_n = (+3 \pm 4 \pm 2) \times 10^{-26} e$ cm [2], with a recent reanalysis of the data yielding $(+2.6 \pm 4 \pm 1.6) \times 10^{-26} e$ cm [3]. The systematic errors in each of these measurements 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. In contrast, the current EDM experiment incorporates a new type of magnetometer based for the first time on atomic ^{199}Hg stored simultaneously in the same cell as the neutrons. This 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. A schematic of the apparatus is shown in Fig. 1.

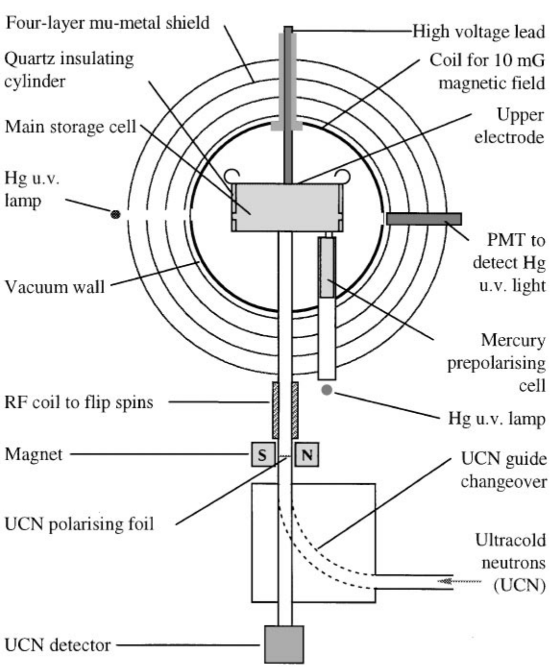

Fig. 1. The neutron EDM experimental apparatus.

2.1. EDM measurement principle

The measurement is made with neutrons stored in a cell permeated by uniform $\boldsymbol{E}$- and $\boldsymbol{B}$-fields. The terms $-\boldsymbol{\mu}_n \cdot \boldsymbol{B}$ and $-\boldsymbol{d}_n \cdot \boldsymbol{E}$ are added to the Hamiltonian determining the states of the neutron. Given parallel $\boldsymbol{E}$ and $\boldsymbol{B}$ fields, the Larmor frequency $\nu_{\uparrow\uparrow}$ corresponding to the separation between the $M_J = \pm\frac{1}{2}$ energy levels is given by

$$h\nu_{\uparrow\uparrow} = 2\boldsymbol{\mu}_n \cdot \boldsymbol{B} + 2\boldsymbol{d}_n \cdot \boldsymbol{E}. \tag{1}$$

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

Thus the goal is to measure, with the highest possible precision, any shift in the transition frequency ν as a strong applied $\boldsymbol{E}$ field alternates between being parallel and then antiparallel to $\boldsymbol{B}$.

The neutrons are prepared in a spin-polarised state (e.g., mostly with $M_J = -\frac{1}{2}$), and the transition frequency ν is then measured using the Ramsey separated oscillatory field magnetic resonance method. The neutrons interact coherently with two short (≈ 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_1 and N_2 which finish in the $M_J = \pm\frac{1}{2}$ states. Fig. 2 shows N_1 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 centre of the resonance pattern of Fig. 2, where the slope of the curve is greatest. The batches are cycled continuously, while about once per hour the direction of $\boldsymbol{E}$ 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

$$\sigma_{d_n} = \frac{\hbar}{2\alpha E T \sqrt{N}} \tag{2}$$

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

$$\alpha = \frac{(N_{1\max} - N_{1\min})}{(N_{1\max} + N_{1\min})} \tag{3}$$

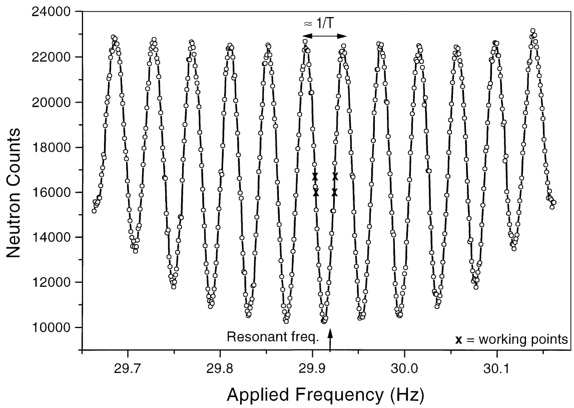

Fig. 2. The Ramsey resonance curve.

with a similar value for N_2. α is also called the polarisation product, and ideally it would be 1.0. In practice, the neutron experiments achieve $\alpha \approx 0.5$.

Currently we have $\alpha = 0.5$, $E = 4.5$ 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} is about $6 \times 10^{-25} e$ cm. A programme of developments is under way which should steadily improve this performance.

2.2. 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 outweigh those from the $\boldsymbol{d}_n \cdot \boldsymbol{E}$ 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 20-l cell as the neutrons. Because of gravity, the centre of mass of the neutrons is about 0.5 cm lower than that of the Hg atoms; this may crudely be compared with the 30 cm separation of the magnetometers in the previous ILL experiment.

The ^{199}Hg is polarised by optical pumping in a one-litre antechamber while a Ramsey NMR measurement is in progress in the main storage cell. The polarised mercury is let into the main cell to join the next batch of neutrons just after they have entered. The spins, first of the mercury and then of the neutrons, are rotated into the xy-plane (i.e., perpendicular to $\boldsymbol{B}$) 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 and 8 Hz for neutrons and mercury, respectively. The mercury spin precession is monitored continuously with a circularly polarised 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 depolarisation of the mercury atoms, is digitised at 100 Hz by a 16-bit ADC. 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.

The successful performance of the mercury magnetometer has been described in some detail in a recently published paper [4]. It 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. Searching for frequency shifts corresponding to the hourly polarity reversals in the raw signal would be an arduous and error-prone task; the corrected signal, on the other hand, 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.

3. Preliminary results

There have been 10 reactor cycles of 50 d length (ILL cycles 106–115) since we began taking data in 1996 (although some of this time has been unavailable

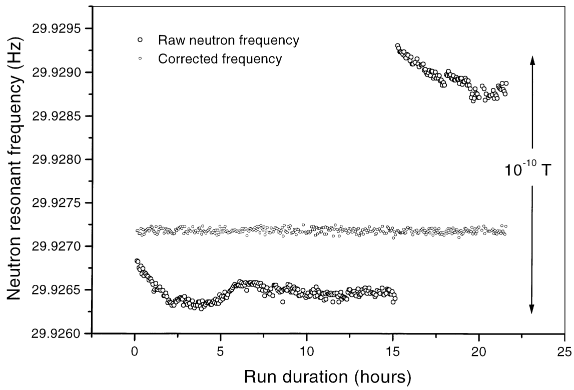

Fig. 3. Neutron resonant frequency measurements, showing both the raw and the mercury-corrected measurements.

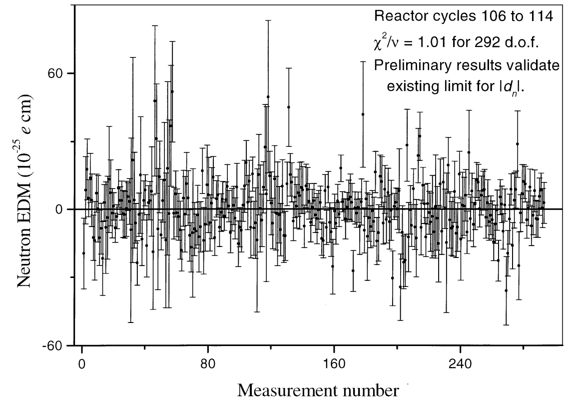

Fig. 4. Preliminary results of neutron EDM measurements for reactor cycles 106–114.

to us due to the needs of other UCN users). Our running efficiency has generally increased throughout this period, and we are now preparing to publish our first results. We have essentially reached the sensitivity of the previous experiment, and so are able to confirm the existing limit on $|d_n|$; but we believe that our new result is much more convincing, because it is very clearly limited by statistical rather than systematic uncertainties. Fig. 4 shows the measurements resulting from 293 individual runs (from reactor cycles 106–114); the χ^2/ν for this set of data is 1.01. The results to be published will also include data from reactor cycle 115.

4. Future plans for the neutron EDM experiment

The present room temperature version of the EDM experiment with mercury magnetometry was recently (October 1997) approved by the ILL to run on the UCN source (PF2) for a further 3 years until 2001. Besides running as intensively as possible during this period, we also plan to carry out a programme of research and development to increase the statistical sensitivity. Potential gains have already been identified, in (a) the number of stored neutrons, through application of various coatings such as a diamond-like form of carbon; (b) a 50% increase in the electric field, through the recently-completed installation of a shorter, but wider, storage cell, and (c) the transfer effiency of the guides used to transport the UCN from the ILL source to the EDM apparatus. The latter has already yielded a 50% increase in flux within the last year, and we believe that further gains of a similar order may be possible.

Overall, therefore, we expect to increase our EDM measurement sensitivity from its current level of $6.0 \times 10^{-25} e$ cm/day to about $2.5 \times 10^{-25} e$ cm/d over the next year. Completion of this programme will leave us well on the way to our goal of reaching an EDM sensitivity of $10^{-26} e$ cm whilst remaining limited by statistical rather than systematic uncertainties.

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