The Electric and Magnetic Moments of the Neutron

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The electric and magnetic moments of the neutron

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It is well known that the free neutron decays spontaneously into a proton, an electron and an antineutrino, that it has a spin of $\frac{1}{2}\hbar$ and a negative magnetic moment, but very careful measurements have failed as yet to reveal any evidence for a finite electric charge or dipole moment. This paper contains a brief discussion of early work and more detail of recent experiments at the Institut Laue–Langevin (I.L.L.), Grenoble, which have shown that the neutron charge is probably less than 4×10^{-20} electron charges (Bayreuth–Munich group), the neutron electric dipole moment (e.d.m.) is less than 1.5×10^{-24} cm times the electron charge (Oak Ridge–Harvard–Sussex group), and the ratio of the neutron and proton magnetic moments is equal to $-0.68497947(17)$, the uncertainty being only $0.25/10^6$ (Harvard–Sussex–Oak Ridge group). The main features of the Leningrad experiments with ultra-cold neutrons, which have reduced the neutron electric dipole length to 7.5×10^{-25} cm, are reported, with some details of the performance of the ultra-cold neutron magnetic resonance spectrometer now working at I.L.L. and the way it will be used to look for a neutron e.d.m. The paper concludes with some comments on the importance of the neutron moments to the development of the theory of fundamental particles.

Measurement of neutron charge

The earliest estimate of the neutron charge was made by Dee (1932), who studied ionization in gases due to neutrons and concluded that $q_n < 1.4 \times 10^{-3}\, q_e$. Twenty years later, Shapiro & Estulin (1957) looked for the sideways deflexion of a thermal neutron beam in an electric field and estimated that $q_n < 6 \times 10^{-12}\, q_e$. A big increase in sensitivity, by a factor of more than 10^6, was obtained by Shull *et al.* (1967) when they measured the effect of an electric field on the direction of the neutron beam passing between silicon crystals. Although they could detect deflexions as small as 5×10^{-6} rad, there was no significant correlation between electric fields as high as 225 kV cm^{-1} and the transmitted neutron intensity. They concluded that $q_n = -(1.9 \pm 3.7) \times 10^{-18}\, q_e$.

A still more sensitive experiment is now being carried out by R. Gähler, J. Kalus & W. Mampe (personal communication) at I.L.L., Grenoble, using the apparatus shown in figure 1. Partly monochromatized neutrons with wavelength 20.6 ± 0.5 Å† that pass the 50 μm entrance slit are focused on to the 30 μm exit slit 10 m away by the quartz lens. The optical bench with a mass of 4 t is water-filled for thermal stabilization, and the flight path, over which an electric field of 200 kV cm^{-1} can be applied, is evacuated to 10^{-4} Torr‡. Results obtained so far indicate that $q_n < 4 \times 10^{-20}\, q_e$ and that the limit is likely to be reduced by another factor of four by the time the calibration experiments have been completed.

Several methods of measuring the neutrality of molecules have been reviewed by Dylla &

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† 1 Å $= 10^{-10}$ m $= 10^{-1}$ nm.

‡ 1 Torr ≈ 133.3 Pa.

King (1973). The lowest limit has been reported by Hillas & Cranshaw (1960), who looked for a change in electric potential when a large mass of gas was allowed to leave a metal container and concluded that the charge on a helium atom is less than 5×10^{-21} electron charges.

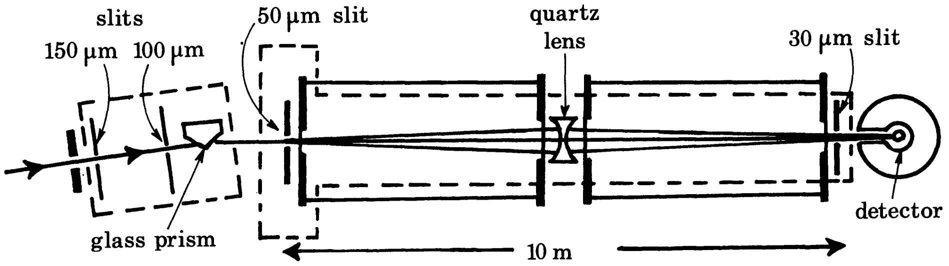

FIGURE 1. Schematic arrangement of the system used by the Bayreuth–Munich group at I.L.L., Grenoble, to obtain an upper limit for the neutron charge.

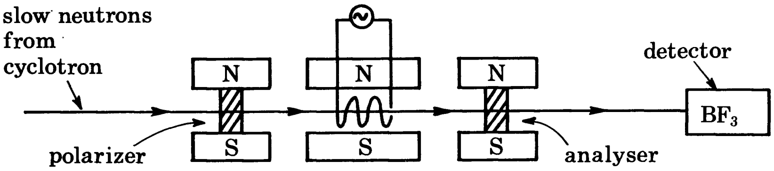

FIGURE 2. Apparatus used by Alvarez & Bloch to make the first measurement of the neutron magnetic moment in 1940.

MEASUREMENT OF THE NEUTRON MAGNETIC DIPOLE MOMENT

The first measurement of the neutron magnetic dipole moment μ_n was carried out by Alvarez & Bloch (1940) using the apparatus shown schematically in figure 2. Neutrons produced by D bombardment of Be in a cyclotron were slowed down and polarized by transmission through magnetized iron, allowed to pass through a few centimetres of steady transverse magnetic field with a perpendicular oscillating field, and then analysed by transmission through a second block of magnetized iron. The oscillating field induced a spin-flip with maximum probability when the rotating component had the same angular frequency and direction as the spin precession in the steady field and the neutron intensity at the detector fell by a small percentage when the resonant condition $h\nu = 2\mu_n B$ was satisfied. The resonance curve obtained had a width roughly equal to $1/T$, where T was the average time spent by the neutrons in the oscillating field. The magnitude of the magnetic moment obtained was $1.93 \pm 0.02\,\mu_N$, the accuracy being limited mainly by the difficulty of measuring the steady magnetic field by pick-up coil techniques. No indication of the sign of the moment was obtained because an oscillating rather than a rotating field was used.

A considerable increase in accuracy was obtained using similar apparatus by Arnold & Roberts in 1947 and, independently, by Bloch *et al.* in 1948, by using nuclear magnetic resonance techniques to measure the steady magnetic field in terms of the proton precession frequency, thereby allowing a measurement of the ratio of the neutron and proton precession frequencies in a given field, and hence the ratio of the magnetic moments, without introducing the errors associated with absolute field measurements. Bloch *et al.* obtained the result $|\mu_n/\mu_p| = 0.685001(30)$. In 1949, Rogers & Staub used a rotating magnetic field in place of the oscillating field, obtained the neutron resonance with only one sense of rotation, and showed that the neutron magnetic moment is negative.

An important technical advance was introduced by Ramsey (1949) who showed that the precision of a beam resonance experiment can be improved by using short oscillating field regions at the beginning and end of the steady field section instead of a single oscillating field over the whole region. The first oscillating field, as shown in figure 3, rotates the spin into the plane perpendicular to the steady field, a $\frac{1}{2}\pi$ spin flip, the spin then precesess about the steady field until the second oscillating field induces a second $\frac{1}{2}\pi$ spin-flip. The overall probability of spin-flip by π is then a damped oscillating function of the oscillating field frequency with a central oscillation width of $1/2T$, where T is the transit time between the oscillating field regions, and an overall envelope of width $1/\tau$, where τ is the duration of each oscillating field. The centre of the pattern comes at a frequency equal to the average of the precession frequency between the oscillating field regions, and the spin-flip probability is unity on resonance when the oscillating field has the optimum value.

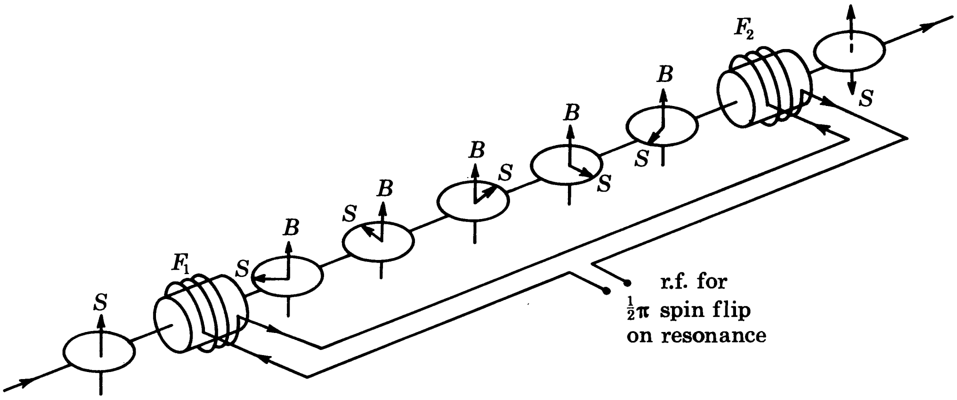

FIGURE 3. The Ramsey separated oscillatory field technique, which results in a resonance with the centre of the pattern at a frequency equal to the average over the transit time between the two oscillating fields.

The double field technique was applied by Ramsey and coworkers in 1954 to the measurement of the neutron magnetic moment with the use of the apparatus shown in figure 4. Reflexion from magnetized iron at glancing incidence was used to polarize the neutrons, and they obtained the resonance curve shown in figure 5 when they plotted against frequency the intensity change when the phase of the second oscillating field was reversed. The magnetic moment ratio obtained after correcting for magnetic shielding of the protons was $|\mu_n/\mu_p| = 0.685039(17)$ with an accuracy of $25/10^6$, which is still limited mainly by the difficulty of averaging effectively the magnetic field between the oscillating field regions.

An experiment recently carried out by Greene *et al.* (1977) at I.L.L., Grenoble, has largely overcome this problem and resulted in a 100-fold improvement in accuracy. A flowing water technique allows the precessing protons to sample almost the same magnetic field as the neutrons and yield a proton resonance curve with the centre at the average of the proton precession frequency over the region between the two oscillating fields. The system used is shown schematically in figure 6. The flowing water, which has a longitudinal relaxation time of several seconds, is polarized nearly to the equilibrium value by taking about 6 s to pass through a baffled container in a field of 2000 G†, it then flows through the oscillating and steady field regions, where the field may well be only a few gauss, into an n.m.r. coil in a field of 2600 G,

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† $1\,\text{G} = 10^{-4}\,\text{T}$.

where the remaining proton polarization is sampled by using a detector tuned to the proton resonance in the strong field. The variation of the n.m.r. detector reading with the frequency of the oscillating field then shows the typical oscillatory shape of the Ramsey system with the frequency of the centre of the pattern at the average of the proton frequency between the two

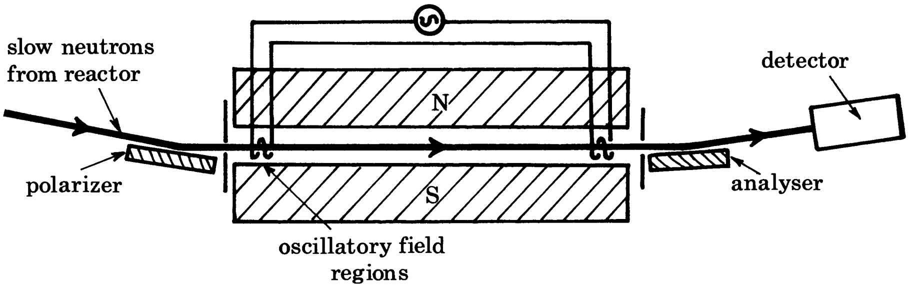

Figure 4. Neutron magnetic resonance apparatus with separated oscillatory fields and magnetized iron–cobalt mirrors as polarizer and analyser.

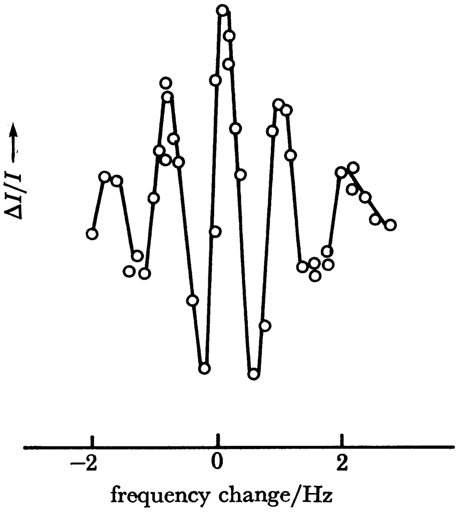

Figure 5. Neutron magnetic resonance obtained by Corngold, Cohen and Ramsey using separated oscillatory fields.

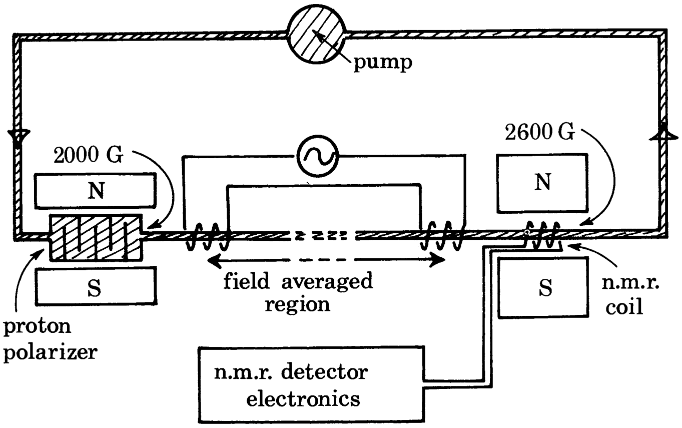

Figure 6. Schematic arrangement of the apparatus used for magnetic field averaging by the flowing water technique.

oscillating field regions. Greene used a neutron system similar to that of figure 4 with the exception that the neutrons passed from the polarizer through the oscillating field regions to the analyser within a 1 cm diameter glass tube acting as a neutron guide, thereby avoiding intensity loss because of beam divergence, and the pipes normally carrying water passed through the same oscillating field coils above and below the neutron guide. Typical proton and neutron resonances are shown in figures 7 and 8 respectively, the line width in each case being roughly $1/2T$ where T is the transit time between the oscillating field coils, the very narrow proton line arising from the slow flow rate of the water. After checking the system by sending water instead of neutrons down the centre tube and taking into account effects due to the Bloch–Siegert effect, oscillatory field phase errors, oscillating field inhomogeneity, neutron velocity distribution and the change in the monitoring tube field by water in the guide tube, the magnetic moment ratio obtained was $|\mu_n/\mu_p| = 0.68497947(17)$, with an error of $0.25/10^6$.

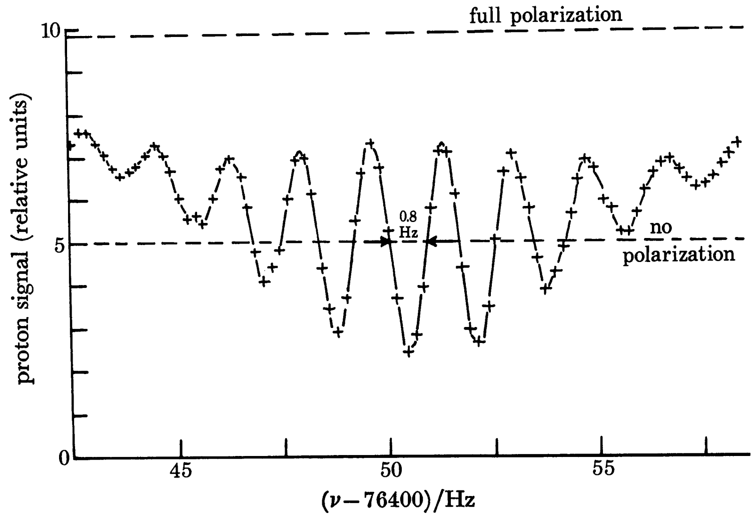

FIGURE 7. Proton resonance signal obtained by the flowing water technique. The line width is approximately $1/2T$ where T is the transit time between the two oscillating fields.

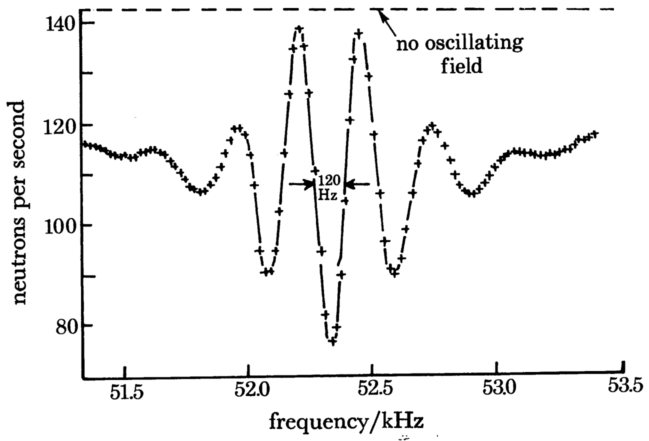

FIGURE 8. Neutron magnetic resonance obtained at the same time as the proton resonance in figure 7 by connecting the oscillating field coils to both signal generators.

Measurement of the neutron electric dipole moment

The Hamiltonian for a neutron with magnetic moment $\boldsymbol{\mu}_n$ and electric dipole moment $\boldsymbol{p}_n$ in a magnetic field $\boldsymbol{B}$ and an electric field $\boldsymbol{E}$ is

$$\mathscr{H} = -\boldsymbol{\mu}_n \cdot \boldsymbol{B} - \boldsymbol{p}_n \cdot \boldsymbol{E},$$

and the frequency, ν, at which resonance would occur in a neutron resonance apparatus such as that shown in figure 4 with parallel $\boldsymbol{E}$ and $\boldsymbol{B}$ fields is given by

$$h\nu = -2\mu_n B - 2p_n E.$$

The change in resonance frequency that results when the direction of the E field is reversed relative to the B field is then independent of the B field, and one obtains

$$h\Delta\nu = -4p_n E = -4q_e DE,$$

where q_e is the electron charge and D is the electric dipole length, thereby allowing a direct measurement of the dipole length in terms of the electric field applied and the frequency shift.

The first attempt to measure the neutron e.d.m. in this way was made by Smith *et al.* (1951), who showed that $D < 5 \times 10^{-20}$ cm, an e.d.m. that would produce a frequency shift of only 10 Hz when the electric field was 200 kV cm^{-1}, a small proportion of the resonance curve line width, which would have been about 1000 Hz. The experiment was therefore carried out by adjusting the steady magnetic field and the frequency of the oscillating field to give a working point on the steepest part of the resonance curve and then looking for correlation between the neutron count rate and the direction of the electric field relative to the magnetic field.

Similar experiments have been carried out since 1951 by several groups in America and Europe, the most recent being that completed at I.L.L., Grenoble, by Dress *et al.* (1977). Using the neutron magnetic resonance apparatus which was subsequently modified for the precision μ_n/μ_p work already mentioned, they obtained neutron resonances similar to figure 8 with a width of 45 Hz. A magnetic shield helped to reduce the sensitivity of the system to external magnetic fields, and a computer was used to run the experiment and reduce to a minimum the effects of magnetic field drifts, reactor power drifts and changes in alignment of the 3 m long apparatus. The most important systematic problem was the effective magnetic field $\boldsymbol{E} \wedge \boldsymbol{v}/c$ seen by neutrons moving with velocity $\boldsymbol{v}$ through the electric field $\boldsymbol{E}$, a magnetic field which produced frequency shifts and associated count rate changes correlated with the direction of the electric field and therefore difficult to distinguish from a real e.d.m. effect. To compensate reliably for this effect, the whole apparatus, including the mirrors and shield, was rotated about a central axis, leaving behind only the reactor and the detector, thereby producing an effective reversal of $\boldsymbol{v}$. The final result of $(0.4 \pm 1.5) \times 10^{-24}$ cm for the dipole length probably represents the limit of the beam experiments, for the electric field cannot be increased significantly above 200 kV cm^{-1}, and the apparatus cannot be made much longer than 3 m so it is unlikely that the line width can be reduced below about 10 Hz. Furthermore, the $\boldsymbol{E} \wedge \boldsymbol{v}/c$ effect will become increasingly important as the limit is reduced, unless there is a corresponding reduction in $\boldsymbol{v}$.

The experimental demonstration by Lushchikov *et al.* (1969) that neutrons with velocities less than 6.5 m s^{-1}, what are now called ultra-cold neutrons (u.c.n.), are reflected at normal incidence by many materials, has led to the possibility of storing polarized neutrons for many seconds and the production of neutron magnetic resonances with a line width $1/2T$, where T is the storage time, of less than 0.1 Hz. Furthermore, because of the small distance between the input and output ports in the storage vessel and the long storage time, the effective velocity in the $\boldsymbol{E} \wedge \boldsymbol{v}/c$ effect is very small and may be neglected.

A first attempt to measure the neutron e.d.m. by using u.c.n. has been made by Altarev *et al.* (1978) at Leningrad with the apparatus shown schematically in figure 9. The u.c.n. from the reactor are polarized by transmission through the magnetized iron foil; they then pass through

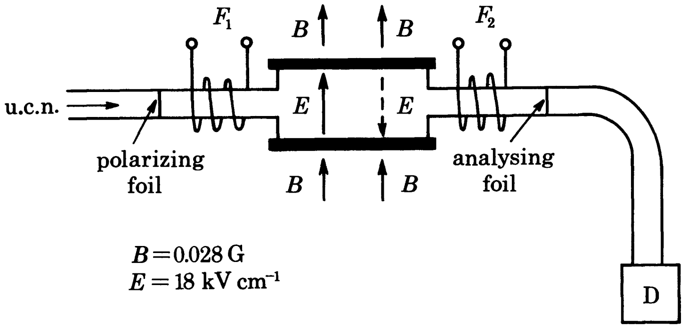

FIGURE 9. Arrangement of apparatus used by the Leningrad group to measure the neutron e.d.m. with stored ultra-cold neutrons. The input and exit apertures in the actual apparatus were at 90° to each other and the u.c.n. took on average about 6 s to bounce on the walls from one aperture to the other.

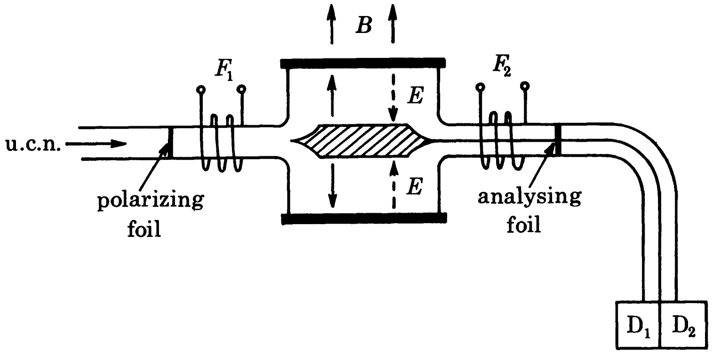

FIGURE 10. The double cavity system used by the Leningrad group to minimize the effects of magnetic field drifts.

the $\frac{1}{2}\pi$ spin-flipper into the storage volume where the magnetic field is 0.028 G and the electric field is 18 kV cm^{-1}. After a storage time, which averages about 6 s, the time needed for incoming neutrons to make collisions with the walls and eventually find the exit port, which is at 90° to the input port in the actual apparatus, the u.c.n. pass through the second $\frac{1}{2}\pi$ spin-flipper and the analysing foil on the way to the detector. The line width obtained is about 0.08 Hz, very much narrower than the resonances obtained in the beam experiments, but the gain is largely offset by the reduction in E by a factor of 10, the very large reduction in neutron count rate and the need to run for long periods to reach an e.d.m. limit due to systematic effects rather than counting statistics. To minimize the effects of external magnetic field changes, which become increasingly difficult to cancel as the line width is reduced, a double cavity spectrometer arranged like the system in figure 10 was used by the Leningrad group with E fields in opposite directions in the two cavities. Significant cancelling of the effect of field changes was obtained by using the difference between the two count rates when looking for correlations with reversals of the electric field. The dipole length reported is $D = (4.0 \pm 7.5) \times 10^{-25}$ cm, the accuracy being limited mainly by the changing magnetic fields owing to leakage currents in the insulating walls of the storage vessel.

A second u.c.n. magnetic resonance spectrometer is now under construction at I.L.L., Grenoble, with the layout shown schematically in figure 11. Polarized u.c.n. entering the storage volume through the neutron valve are stored with the valve closed for times that we hope will be as long as 100 s. Pulses of oscillating field applied perpendicular to the steady field at the beginning and end of the storage period produce the necessary $\frac{1}{2}\pi$ spin flips and the neutrons that leave when the valve is opened at the end of the storage period go through the analysing foil on the way to the detector. A resonance obtained in a magnetic field of 0.01 G with a storage time of 10 s is shown in figure 12. It is hoped that the problem of magnetic field drift and to some extent the leakage current effect can be minimized by monitoring the magnetic field in the cavity while the neutrons are being stored. Professor Ramsey has proposed to do this by storing polarized ^{3}He atoms in the storage volume with the neutrons and by

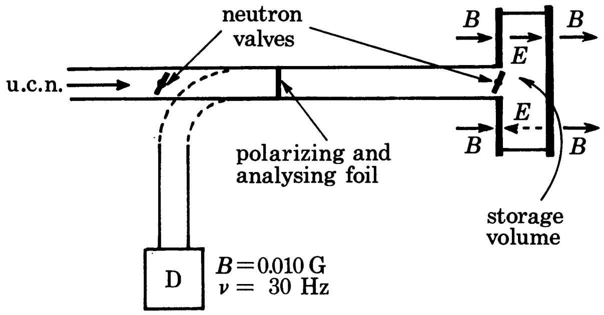

FIGURE 11. The system being used by the Sussex–Harvard–Rutherford group at I.L.L., Grenoble, to study neutron magnetic resonance with stored neutrons.

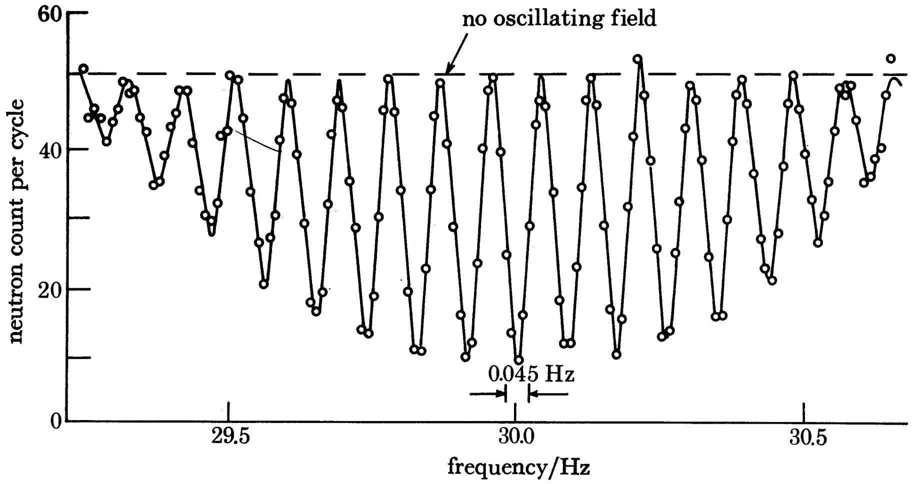

FIGURE 12. Neutron magnetic resonance obtained by applying two 1 s bursts of oscillating field separated by a 10 s period without any oscillating field.

using an n.m.r. technique to analyse the ^{3}He atoms when they emerge with the neutrons at the end of the storage period. It is also hoped that it will be possible to improve the u.c.n. density in the e.d.m. apparatus by a factor of 100 or more by using as the source the u.c.n. that remain and build up in a liquid helium filled storage vessel at 0.8 K after down-scattering from an intense cold neutron beam, the development of a suggestion made by Golub & Pendlebury (1975, 1979).

The neutron moments and nuclear theory

If we assume that the fundamental particles introduced to explain the behaviour of matter are always identical particles, that total electric charge is always conserved in any observable process and that the electric charges of the fundamental particles remain the same when they are in combination, we conclude that the photon must have zero charge and that the charges on the electron and positron must be equal and opposite. We also conclude that the neutron charge must be equal to the sum of the electron, proton and antineutrino charges. Since the atomic charge can be written

$$q(Z, A) = Z(q_p + q_e) + (A - Z)\, q_n,$$

the combination of data for atoms with different $Z/(A-Z)$ ratios allows independent estimates of $q_p + q_e$ and q_n. Akhiezer & Rekalo (1975) conclude in their review on the electric charges of fundamental particles that the atomic neutrality data show that $(q_n + q_p) = (-8 \pm 5) \times 10^{-20}\, q_e$ and $q_n = (7 \pm 6) \times 10^{-20}\, q_e$. The experimental observation that q_n is less than $4 \times 10^{-20}\, q_e$ implies an experimental lower limit on the antineutrino charge of about $10^{-19}\, q_e$, the same as the proton–electron charge difference deduced from atomic neutrality measurements.

Application of the theory of quantum mechanics to fundamental particles shows that no fundamental particle can have an e.d.m. unless there are both simultaneous parity and time-reversal-violating interactions in particle physics. Parity violation in weak interactions such as those responsible for neutron decay has been well established but there is as yet no direct evidence for the violation of time reversal symmetry. The observation of a neutron e.d.m. would provide such evidence and also give important information about the type of interaction. Many calculations of the neutron e.d.m. have been carried out in the last 10 years assuming various types of P and T invariance, predicting neutron dipole lengths from 10^{-20} cm for electromagnetic interactions down to less than 10^{-32} cm for superweak interactions. The results of the theories are reviewed by Golub & Pendlebury (1972), a paper that contains an elementary treatment of P and T reversal, and Dress *et al.* (1977) discuss the recent neutron beam e.d.m. measurement. Extension of the neutron dipole length down to 10^{-26} cm would rule out the proposed electromagnetic and $\Delta S = 0$ weak interactions, and would aid significantly the refinement of existing theories.

Although there is no possibility of predicting the neutron magnetic moment with an accuracy of $0.25/10^6$ from nuclear theory, the existence of the magnetic moment implies circulation of charge within the neutron. Early measurements of the magnetic moments of light nuclei with small percentage accuracy showed that the neutron appears to have an effective magnetic moment of about $-1.91\,\mu_N$ when it forms part of a nuclear system, and a simple single-particle model of the deuteron was able to account for the experimental observation that the deuteron moment is not equal to the sum of the neutron and proton moments. The only significant development in the theory of nucleon moments since 1950 is the proposal by Beg *et al.* (1964), and independently by Sakika (1964), that if quarks have spins and the internal symmetry group SU(3) of the baryons is broken only by electromagnetism, the neutron–proton magnetic moment ratio should be $-\frac{2}{3}$, a result close to but well outside the error in the experimental result $-0.68497945(17)$. The recent experiment at I.L.L. was not carried out to test nuclear theory! The e.d.m. apparatus already existed and could be easily modified, and the experiment was able to demonstrate the effectiveness of the flowing water technique of magnetic field averaging.

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