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DETERMINATION OF THE NEUTRON MAGNETIC MOMENT

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The neutron magnetic moment has been measured with an improvement of a factor of 100 over the previous best measurement. Using a magnetic resonance spectrometer of the separated oscillatory field type capable of determining a resonance signal for both neutrons and protons (in flowing H_2O), we find $\mu_n/\mu_p = 0.68497935(17)$ (0.25 ppm). The neutron magnetic moment can also be expressed without loss of accuracy in a variety of other units.

Key words: Flowing water NMR; magnetic resonance; neutron magnetic moment; particle properties.

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1. Introduction

The realization that the neutron, a neutral particle, possesses a non-zero magnetic moment has been of considerable importance in the development of nuclear and particle physics. Even before any explicit measurement of μ_n had been made, there was a strong indication that $\mu_n \neq 0$ from comparisons of the proton and deuteron magnetic moments μ_p and μ_D. If the neutron and proton combine in a pure $^3S_1$ state to form the deuteron, one would expect $\mu_D = \mu_n + \mu_p$. Early measurements of μ_p and μ_D gave, according to this relation, $\mu_n \approx -1.8\ \mu_N$ where μ_N is the nuclear magneton.

According to Dirac Theory, which assumes structureless, spin 1/2 particles, $\mu_n = 0$ and $\mu_p = \mu_N$. The anomolous moments are defined as the differences between the actual moments and the Dirac moments. The first serious attempt to explain the anomolous moments of the nucleons was made by Frölich, Heitler and Kemmer [1] in 1938. Their "meson exchange theory" predicted equal magnitudes and opposite signs for the anomolous proton and neutron moments [2]. The actual magnitudes of the moments are much more difficult to obtain using this theory. Though subsequently refined by many others [3] the initial conclusions of Frölich, Heitler and Kemmer adequately summarized the state of the theoretical understanding of the neutron magnetic moment until the introduction of the quark model.

The first explicit measurement of the neutron magnetic moment was made by Alverez and Bloch [4] in 1940. Using Rabi's magnetic resonance technique with a neutron beam obtained by deuteron bombardment of Be, they obtained a value of $|\mu_n| = 1.93 \pm 0.02\ \mu_N$. In general, no information about the sign of a magnetic moment is obtainable from a resonance experiment utilizing a purely oscillating magnetic field (In 1949 Rogers and Staub [5] determined the sign of μ_n using a resonance technique that employed a rotating field. As had been thought, the sign was negative.)

The discovery by Kellog, Rabi, Ramsey and Zacharias [6] that the deuteron has an electric quadropole moment implied that the ground state of the deuteron could not, in fact, be accurately described by a pure $^3S_1$ state but must have some admixture of D state. Thus the additivity of neutron and proton moments in the deuteron could not be exact. It was therefore of great interest to determine μ_n more accurately so that it could be compared with the well known values of μ_p and μ_D.

In 1947 Arnold and Roberts [7], using a neutron beam from a reactor, determined μ_n in a resonance experiment with a single oscillatory field. They were able to obtain a more accurate value of $|\mu_n| = 1.9103(12)\ \mu_N$ by using the then novel technique of NMR as a means of field calibration. About the same time, Bloch, Nicodemus and Staub [8] also obtained a more accurate value for μ_n. They reported their result as the ratio of neutron to proton moment $|\mu_n/\mu_p| = 0.685001(30)$.

With these more accurate values for μ_n, it was possible to determine the $^3D_1$ admixture in the deuteron ground state by two independent means, through the deuteron electric quadropole moment, or by comparison between μ_n, μ_p and μ_D. Gratifyingly, these independent values were consistant.

With the introduction of the quark model an appealing explanation for the value of the ratio of the neutron moment to the proton moment emerged. Sakita [9] and Bég, Lee and Pais [10] pointed out that this ratio should be $\mu_n/\mu_p = -2/3$ [11] if the internal symmetry SU(3) is broken <u>only</u> by electromagnetism. In this model, the ratios of all the baryon moments are uniquely determined and easily calculated (Their absolute magnitudes are dependent on the quark magnetic moments. Determining these would require knowledge of the quark masses). The agreement between theory and experiment for μ_n/μ_p is considerably better than for other baryon pairs and is striking for such a simple theory. The approximately 3% discrepancy between theory and experiment should not be viewed as a significant disagreement. SU(3)$\otimes$ SU(2) (i.e 3 similar quarks with spin 1/2) is known to be an incomplete description for strongly interacting particles.

At the initiation of the work reported here, the uncertainty associated with theory far exceeded the experimental error of the best measurement of μ_n[12]. As a result, theoretical considerations did not provide the dominant motivation for the current work. Rather, the possibility of a substantial improvement in our knowledge of a fundamental particle property as well as the opportunity to demonstrate an elegant, new experimental technique prompted our effort.

The most accurate determination of μ_n, prior to the work reported here, was that of Corngold, Cohen and Ramsey [12]. This experiment involved a thermal neutron beam and benefited from the use of the separated oscillatory field method. A result of $|\mu_n/\mu_p| = 0.685039(17)$ was obtained. The major limitation to the accuracy of this measurement arose from the method used to calibrate the magnetic field. An NMR probe of small dimensions was employed to determine the field at a number of discrete locations. This field map was then used to give the appropriate field average by a pointwise integration. The discrete nature of this stepwise integration led to the dominant error in the experimental result.

The current work benefitted from several advances in experimental technique. Access to the high flux reactor of the Institut Laue-Langevin at Grenoble, France, allowed the use of an intense "cold" neutron beam. Such "cold" beams are characterized by low beam velocities. This led to an improvement of a factor of ~5 over the line width obtained by Cohen, Corngold and Ramsey [12]. An additional advantage to the use of "cold" neutrons lies in the ability to employ neutron guides to reduce beam divergence and therefore increase the flux. Such guides also allowed a novel field calibration technique which provided the major improvement in experimental sensitivity.

Following a suggestion of Purcell [13] made some time ago, the field was monitored by obtaining a separated oscillatory field resonance signal with water flowing through the neutron guide. In this fashion, the field average taken by the protons in the water is the same as that taken by the neutrons. Since all the relevant diamagnetic corrections for protons in water are known to high accuracy, a direct measurement of the ratio of the neutron magnetic moment to the proton magnetic moment was obtained. From this result, the magnetic moment of the neutron can be expressed in a variety of other units.

2. Apparatus

The aim of the experimental technique was to measure the Larmor precession frequency for neutrons and protons (in water) in precisely the same volume as nearly simultaneously as possible. With the use of a neutron guide (a glass tube of circular cross-section) it was a straight forward matter to confine neutrons and water in the same volume. One simply let the water flow through the neutron guide. This procedure, however precluded the possibility of determining the resonance frequency for neutrons and protons with exact simultaneity. To insure that no spurious effects resulted from drifts during the time required to make a change-over from neutron beam to flowing water, a second, parallel tube was installed in the spectrometer. Water was continuously sent through this tube to provide a field monitor. By alternating neutrons and protons in the principal tube while protons flowed continuously in the monitor tube, errors due to field drifts could be detected and reduced to an insignificant level. This technique has been discussed in detail elsewhere [14].

The cold source at the high flux reactor of the Institut Laue-Langevin in Grenoble provided the source of neutrons used in this experiment. The flux through the apparatus was typically 1.5×10^6 neutrons/s. The neutrons were polarized by glancing reflection from a magnetized mirror. A similar mirror was used to analyze the neutron polarization at the exit of the spectrometer. The neutrons were detected by a ^{6}Li loaded glass scintillator coupled to a photo-multiplier.

The protons in the flowing water were polarized by passage through a chamber placed in a high (~2kG) pre-polarizing magnet. As the protons spent more than one longitudinal relaxation time in this field, their polarization could be approximated by a simple Boltzman distribution. While the degree of polarization so obtained was very small, the enormous flux (by molecular beam standards) led to an easily detected signal. The proton polarization at exit was detected in a second high field region (~4kG) with slightly modified commercial NMR equipment.

The spectrometer was based on a high stability, high homogeneity, large volume electromagnet. The nominal field in the magnet was 18G. The separated oscillatory field coils (each 3cm long) were mounted in the magnet with a separation of 61 cm. Surrounding each of the separated coils were independently controllable trim coils to adjust the fields at the coils.

The magnet and spectrometer were mounted in a two layer cylindrical Molypermalloy magnetic shield to reduce the effects of time dependent external fields. The entire assembly was mounted on a large rotating platform. This allowed the orientation of the spectrometer with respect to beam velocity to be reversed.

All relevant electronics were interfaced (via CAMAC) to a PDP 11/10 computer. In this way all data collection and experimental control were carried out on line.

3. Results

Figures 1 and 2 show typical neutron and proton resonance lineshapes obtained in this experiment. The dramatic difference in line widths (~120Hz vs ~0.8Hz) for neutrons and protons is due to the great difference in particle velocities for the two cases. The neutron velocity was ~150 m/sec while the proton velocity was ~1 m/sec. The presence of many more side lobes in the proton resonance is indicative of a narrower relative proton velocity distribution.

The actual quantity measured in this experiment was the ratio between the Larmor precession frequencies for neutrons in vacuum and for protons in a cylindrical sample of water at 22°C. To arrive at this quantity, corrections for several shifts and distortions had to be made.

The largest systematic effect resulted from the Bloch-Siegert effect [15]. This effect may be viewed as arising from the counter-rotating component present in an oscillating field. It is a curious feature of the separated oscillatory field technique that the shift resulting from this effect is not strictly linear in oscillating field power [16]. However, this non-linearity is well understood and can be simply accounted for. Figure 3 illustrates the extrapolation technique which was used to account for the Bloch-Seigert Shift.

The data shown in Figure 3 were taken in the two possible machine orientations. These correspond to a reversal of the spectrometer with respect to the beam velocity. The shift seen between the two orientations is presumably due to geometrical imperfections in coil construction. It should be noted that the shifts seen in Figure 3 arise entirely from the distortion of the neutron resonance. The much lower velocity of the protons, and the consequent reduction in oscillating power, implies negligible shifts in the proton resonance frequency.

Table 1 summarizes the significant shifts and errors in the measurement of the ratio of neutron moment to proton moment in a cylindrical sample of H_2O at 22^{o}C, ω_n/ω_p (cyl, H_2O, 22^{o}). The errors quoted (1σ) in Table 1 are independent and are added in quadrature to yield the error on ω_n/ω_p (cyl, H_2O, 22^{o}). Our experimental result is

$$\omega_n/\omega_p \text{ (cyl., } H_2O, 22^o) = 0.68499588(16) \quad (0.24 \text{ ppm}) \tag{1}$$

The value of the magnetic moment of the neutron can be expressed in terms of the Bohr magneton μ_B with little loss of accuracy through the relation

$$\frac{\mu_n}{\mu_B} = \frac{\omega_n}{\omega_p \text{ (cyl, } H_2O, 22^o)} \frac{\omega_p \text{ (cyl, } H_2O, 22^o)}{\omega_p \text{ (sph, } H_2O, 22^o)} \frac{\omega_p \text{ (sph, } H_2O, 22^o)}{\omega_p \text{ (sph, } H_2O, 35^o)} \times \frac{\mu'_p}{\mu_B} \tag{2}$$

where the notation "sph" refers to a spherical sample, and μ'_p is the effective proton moment in a spherical sample of H_2O at 35^{o}C as measured by Philips, Cook and Kleppner [17].

The first ratio in the right hand side of Equation 2 is our experimental result. The second ratio is given by $1 - 2\pi\kappa/3 = 1 + 1.505(2) \times 10^{-6}$ from the data summarized by Pople et al [18] where κ is the volumetric susceptibility of water. The third ratio is taken to be $1 + 1.4(1) \times 10^{-7}$ from the results of Hindman as interpreted in a footnote in Philips et al [17]. The final ratio of μ'_p/μ_B is given by Philips et al [17]. From Equation 2 we conclude

$$\frac{\mu_n}{\mu_B} = -1.04187564(26) \times 10^{-3} \quad (0.25 \text{ ppm}) \tag{3}$$

The slight increase in experimental error arises from the temperature correction in Equation 2.

Using the results of Winkler, Kleppner, Myint and Walther [19], we can express μ_n in terms of the free electron moment μ_e and free proton moment μ_p by

$$\frac{\mu_n}{\mu_e} = 1.04066884\ (26)\ \times 10^{-3}\quad (0.25\ \text{ppm})$$

$$\frac{\mu_n}{\mu_p} = -\,0.68497935\ (17)\quad (0.25\ \text{ppm}) \tag{4}$$

Our result can also be expressed in terms of the nuclear magneton μ_N. In this case, however, the accuracy is slightly degraded by the uncertainty in the electron to proton mass ratio. Using the value of m/M obtained by combining results from Philips et al [17] and Cohen and Taylor [18] we have

$$\frac{\mu_n}{\mu_N} = -\,1.91304184\ (88)\quad (0.45\ \text{ppm}) \tag{5}$$

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TABLE 1

Effect	Proportion Shift	Proportional Error
Bloch-Siegert effect	$+4.94 \times 10^{-6}$	13×10^{-8}
Coil phase errors	$\sim 1.6 \times 10^{-6}$	
Field inhomogeneity	$\lesssim 3 \times 10^{-7}$	$<4 \times 10^{-8}$
Effects of finite velocity distribution	$\sim 10^{-7}$	$\sim 10 \times 10^{-8}$
External diamagnetic effects of water	-4.8×10^{-7}	$\leq 3 \times 10^{-8}$

Figure and Table Captions

Figure 1 Typical Neutron Resonance

Figure 2 Typical Proton Resonance

Figure 3 Plot of neutron to proton resonance frequencies. The quantity $\kappa(\pi I/4I_o)$ (I/I_o) is an appropriately scaled oscillating power which yields a linear fit. (See references in footnote 16 for a full description). The two orientations correspond to reversals of the machine axis with respect to the beam velocity.

Table 1 Significant shifts and errors on ω_n/ω_p (cyl, H_2O, 22^o). Statistical error is included in the error assigned to the Bloch-Siegert effect and Coil Phase errors.

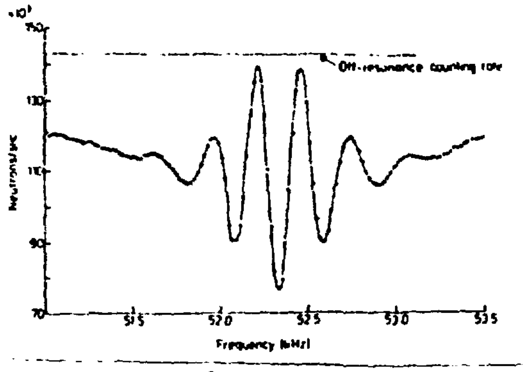

fig 1

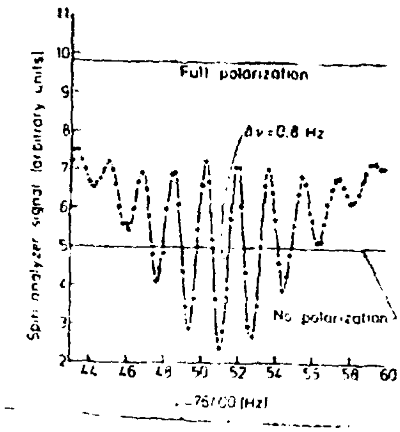

fig 2

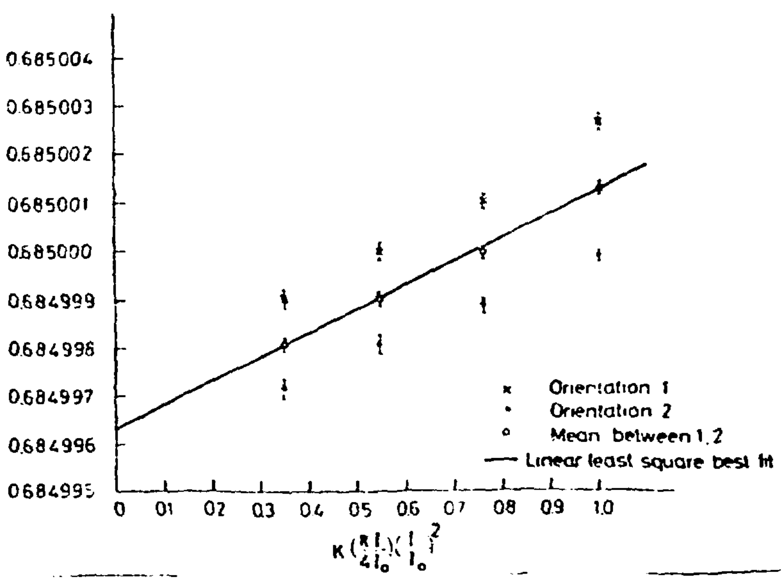

fig 3