A Quantitative Determination of the Neutron Moment in Absolute Nuclear Magnetons

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The magnetic resonance method of determinng nuclear magnetic moments in molecular beams, recently described by Rabi and his collaborators, has been extended to allow the determination of the neutron moment. In place of deflection by inhomogeneous magnetic fields, magnetic scattering is used to produce and analyze the polarized beam of neutrons. Partial depolarization of the neutron beam is observed when the Larmor precessional frequency of the neutrons in a strong field is in resonance with a weak oscillating magnetic field normal to the strong field. A knowledge of the frequency and field when the resonance is observed, plus the assumption that the neutron spin is $\frac{1}{2}$, yields the moment directly. The theory of the experiment is developed in some detail, and a description of the apparatus is given. A new method of evaluating magnetic moments in all experiments using the resonance method is described. It is shown that the magnetic moment of any nucleus may be determined directly in absolute nuclear magnetons merely by a measurement of the *ratio* of two magnetic fields. These two fields are (*a*) that at which resonance occurs in a Rabi type experiment for a certain frequency, and (*b*) that at which protons are accelerated in a cyclotron operated on the *n*th harmonic of that frequency. The magnetic moment is then (for $J=\frac{1}{2}$), $\mu=H_b/nH_a$. n is an integer and H_b/H_a may be determined by null methods with arbitrary precision. The final result of a long series of experiments during which 200 million neutrons were counted is that the magnetic moment of the neutron, $\mu_n=1.93_5\pm0.02$ absolute nuclear magnetons. A brief discussion of the significance of this result is presented.

INTRODUCTION

THE study of hyperfine structure in atomic spectra has shown that a large number of atomic nuclei possess an angular momentum and a magnetic moment. Since, according to the theories of Heisenberg and Majorana, protons and neutrons are recognized as the elementary constituents of nuclear matter, their intrinsic properties and particularly their magnetic moments have become of considerable interest. The fundamental experiments of Stern and his collaborators[1] in which they determined the magnetic moments of the proton and the deuteron by deflections of molecular beams in inhomogeneous fields gave the first quantitative data of this sort. The approximate values which they gave for the two moments,[2]

$$\mu_p=2.5, \tag{1}$$

$$\mu_d=0.8, \tag{2}$$

suggested that in all likelihood, one would have to ascribe to the neutron a magnetic moment of the approximate value

$$\mu_n=-2. \tag{3}$$

The negative sign in formula (3) indicates that the relative orientation of their magnetic moments with respect to their angular momenta is opposite in the case of the neutron to that of the proton and the deuteron.

The technique of molecular beams has been greatly developed during the last few years by Rabi and his collaborators;[3] their ingenious methods have allowed them to determine the magnetic moments of many light nuclei with high precision, and to establish the existence of an electric quadrupole moment of the deuteron. Their values for the magnetic moments of the proton and deuteron are

$$\mu_p=2.785\pm0.02, \tag{4}$$

$$\mu_d=0.855\pm0.006. \tag{5}$$

They have also demonstrated that both moments

[1] R. Frisch and O. Stern, Zeits. f. Physik **85**, 4 (1933); I. Estermann and O. Stern, Zeits. f. Physik **85**, 17 (1933); O. Stern, Zeits. f. Physik **89**, 665 (1934); I. Estermann and O. Stern, Phys. Rev. **45**, 761 (1934).

[2] We shall throughout this paper give magnetic moments in units of the nuclear magneton $eh/4\pi Mc$ (e and M = charge and mass of the proton, c = velocity of light), and angular momenta in units $\hbar=h/2\pi$. The angular momentum of the deuteron is taken to be 1, that of the proton and the neutron to be $\frac{1}{2}$; the last is an assumption for which a direct experimental proof is still lacking, but which is generally accepted.

[3] I. I. Rabi, Phys. Rev. **51**, 652 (1937); I. I. Rabi, J. R. Zacharias, S. Millman and P. Kusch, Phys. Rev. **55**, 526 (1939).

are positive with respect to the direction of the angular momentum.

An experimental proof that a free neutron possesses a magnetic moment, and a measure of its strength, could also be achieved in principle by deflection of neutron beams in an inhomogeneous magnetic field. But while the great collimation required for this type of experiment may easily be obtained with molecular beams, it would be almost impossible with the neutron sources available at present. Better suited for the purpose is the method of magnetic scattering, which was suggested a few years ago by one of us.[4] It is based upon the principle that a noticeable part of the scattering of slow neutrons can be due to the interaction of their magnetic moments with that of the extranuclear electrons of the scattering atom. In the case of a magnetized scatterer this will cause a difference in the scattering cross section, dependent upon the orientation of the neutron moment with respect to the magnetization, and particularly in the case of ferromagnetics, it will cause a partial polarization of the transmitted neutron beam. The magnetic scattering of neutrons, and thereby the existence of the neutron moment, has been proved experimentally by several investigators, particularly by Dunning and his collaborators.[5] The magnetic scattering, however, can yield only a qualitative determination of the neutron moment since the interpretation of the effect is largely obscured by features involving the nature of the scattering substance.

Frisch, v. Halban and Koch[6] were the first to attempt to use the polarization of neutrons merely as a tool, and to determine the neutron moment by a change of the polarization, produced by a magnetic field between the polarizer and the analyzer. Such a change should indeed occur, because of the fact that the moment will precess in a magnetic field; by varying the field strength, one can reach a point where the time spent by the neutrons in the field is comparable to the Larmor period. In this way, one could obtain at least the order of magnitude of the moment. Although these investigators have reported an effect of the expected type, yielding the order of magnitude 2 for the neutron moment, we have serious doubts that their results are significant. Their polarizer and analyzer consisted of rings of Swedish iron, carrying only their remanent magnetism ($B=10{,}000$ gauss), while in agreement with Powers' results, we were never able to detect any noticeable polarization effects, independent of the kind of iron used, until it was magnetized between the poles of a strong electromagnet with an induction well above 20,000 gauss. Although we cannot deny the possibility that, due to unknown reasons, their iron was far more effective for polarization at low values of the induction than that used by other investigators, we think it more likely that in view of their rather large statistical errors the apparent effect was merely the result of fluctuations.

Although most valuable as a new method of approach, the experiment of Frisch, v. Halban and Koch could in any event give only qualitative results. The slow neutrons which one is forced to use emerge from paraffin with a complicated and none too well-known velocity distribution. The time during which they precess in the magnetic field will therefore be different for different neutrons and vary over a rather large range. Since it is that time which together with the field of precession determines the value of the moment, the latter will be known only approximately. A quantitative determination of the neutron moment therefore requires an arrangement which does not contain such features.

Method

Sometime ago, we conceived of an experimental method which could yield quantitative data of this sort. The method was independently proposed by Gorter and Rabi,[7] and most successfully used by the latter in his precision determinations

[4] F. Bloch, Phys. Rev. **50**, 259 (1936); **51**, 994 (1937); Ann. Inst. H. Poincaré **8**, 63 (1938); J. Schwinger, Phys. Rev. **51**, 544 (1937).

[5] P. N. Powers, H. Carroll and J. R. Dunning, Phys. Rev. **51**, 1112 (1937); P. N. Powers, H. Carroll, H. Beyer and J. R. Dunning, Phys. Rev. **52**, 38 (1937); P. N. Powers, Phys. Rev. **54**, 827 (1938).

[6] R. Frisch, H. v. Halban and J. Koch, Phys. Rev. **53**, 719 (1938).

[7] I. I. Rabi, J. R. Zacharias, S. Millman and P. Kusch, Phys. Rev. **53**, 318 (1938). During the summer of 1938 a first attempt to measure the neutron moment with such an arrangement was made at Stanford by Bloch, Bradbury and Tatel, using a 200-mg Ra-Be source of neutrons. However, it was unsuccessful due to instrumental effects which were hard to discover with the small intensity available.

of nuclear moments. Its principle consists in the variation of a magnetic field H_0 to the point where the Larmor precession of the neutrons is in resonance with the frequency of an oscillating magnetic field. The ratio of the resonance value of H_0 to the known frequency of the oscillating field gives immediately the value of the magnetic moment.[8]

The observation of the resonance point is based upon the fact that in its neighborhood there will be a finite probability P for a change of the orientation of the neutron moment with respect to the direction of the field H_0. Let this field be oriented in the z direction and let there be perpendicular to it, say in the x direction, an oscillating field with amplitude H_1 and circular frequency[9] ω, so that the total field in which a neutron is forced to move, is given by its components

$$H_x = H_1 \cos(\omega t + \delta); \quad H_y = 0; \quad H_z = H_0. \quad (6)$$

The solution of the Schroedinger equation for a neutron with angular momentum $\frac{1}{2}$ and magnetic moment μ gives the probability that a neutron, which at time $t=0$ in such a field had a z component $m=\frac{1}{2}$ of its angular momentum, will be found at the time $t=T$ with a value $m=-\frac{1}{2}$, in the form

$$P = \sin^2 [(\mu H_1 T/2\hbar) \times (1+\{2\Delta H/H_1\}^2)^{\frac{1}{2}}]/[1+(2\Delta H/H_1)^2], \quad (7)$$

where

$$\Delta H = H_0 - H_0^* = H_0 - \hbar\omega/2\mu \quad (8)$$

is the difference between the constant field H_0 and its value at resonance,

$$H_0^* = \hbar\omega/2\mu, \quad (9)$$

for which the Larmor frequency $2H_0\mu/\hbar$ is equal to the frequency ω of the oscillating field. Since the time T which the neutrons spend in the oscillating field will, for different neutrons, vary over a wide range, it will be a good approximation to substitute for the $\sin^2$ in the numerator of (7) its average value $\frac{1}{2}$. This means that, at resonance, complete depolarization of an originally polarized neutron beam will occur, and leads to the simplified formula

$$P = \tfrac{1}{2}[1+(2\Delta H/H_1)^2]^{-1}. \quad (7a)$$

Formulae (7) and (7a) have been derived by neglecting in the differential equation under consideration certain rapidly oscillating terms with respect to slowly varying ones; this neglect is justified as long as the condition

$$H_1/H_0 \ll 1 \quad (10)$$

holds. In our final experiments, H_1/H_0 was less than 2 percent; so we felt justified in applying formulae (7) and (7a).*

The dependence of P upon ΔH, and particularly its maximum value for which the field H_0 has its resonance value H_0^* given by Eq. (9), is detected by a polarizer-analyzer arrangement, similar to that used by Frisch, v. Halban and Koch. We shall show that a beam of neutrons passing through two successive plates of magnetized material will change its transmitted intensity by an amount proportional to P. Consider two plates F_1 and F_2 both magnetized in the $+z$ direction and call f_i^+ and f_i^- $(i=1,2)$ the fraction of neutrons with $m=+\frac{1}{2}$ and $m=-\frac{1}{2}$, respectively, transmitted by F_i. f_i^+ will be different from f_i^- since the magnetic scattering will be preferential for one of the two values of m, thus giving rise to a partial polarization of the neutrons. If there does not occur any change of polarization between F_1 and F_2, the fraction of the neutrons transmitted by both will be given by

$$f = f_1^+f_2^+ + f_1^-f_2^-. \quad (11)$$

If, on the other hand, there is a probability P of a change of polarization between F_1 and F_2, the transmitted fraction will be

$$f' = (1-P)(f_1^+f_2^+ + f_1^-f_2^-) + P(f_1^+f_2^- + f_1^-f_2^+). \quad (12)$$

One will thus observe a relative change ΔI of the intensity I of the transmitted neutrons, given by

$$\Delta I/I = (f'-f)/f = -\alpha P, \quad (13)$$

[8] P. N. Powers, reference 5, has employed a modification of this method to determine the sign of the neutron moment. Instead of encountering an oscillating field between polarizer and analyzer, his neutrons were acted upon by a field which appeared to them, in consequence of their velocity, to be rotating with approximately their Larmor precession frequency. The sign of the moment was found to be negative, in agreement with theory.

[9] We shall always use circular frequencies although we sometimes refer to them merely as "frequencies."

* The corrections, introduced by this neglect are by no means of the order of 2 percent, but very much smaller, since they are essentially given by $(H_1/H_0)^2$. The mathematical theory of these corrections will soon be published.

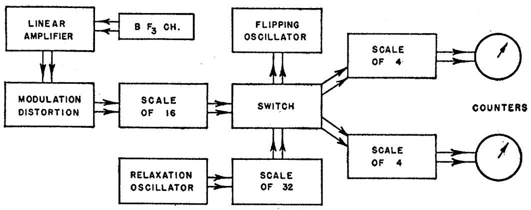

FIG. 1. Schematic drawing of electrical circuits.

with

$$\alpha=[(f_1^+-f_1^-)(f_2^+-f_2^-)]/(f_1^+f_2^++f_1^-f_2^-), \quad (14)$$

where α is a constant, characteristic of the magnetic and geometric conditions of F_1 and F_2 only. We see that this constant α can also be determined independently of any possible changes of polarization. For two identical plates F_1 and F_2 with common thickness a and with the values $f_1^\pm=f_2^\pm=e^{-(\sigma\pm\Delta\sigma)a}(\Delta\sigma=0$ for unmagnetized material) as they follow from the theory of magnetic scattering, one can see that α also has the significance of the relative increase of the total transmitted intensity which one observes by magnetizing F_1 and F_2 to the stage in which the fractions f_i have the values assumed in formula (14). Thus under ideal conditions, and if P assumes its maximum value $\frac{1}{2}$ at resonance, the relative change in intensity will just be $\frac{1}{2}$ of that observed when demagnetizing F_1 and F_2 in an experiment similar to that of Dunning and his collaborators.

Once the maximum value of (13) has been experimentally established, i.e., the value of H_0 has been found for which $\Delta H=0$, or where according to (8) and (9)

$$H_0=H_0^*=\hbar\omega/2\mu, \quad (15)$$

one will know the magnetic moment μ in the form

$$\mu=\hbar\omega/2H_0^*, \quad (15a)$$

provided that the values of H_0^* and the frequency ω of the oscillating field are known.

One can of course measure the latter by means of an ordinary standardized wavemeter and the former by the usual method of flipping a coil in the magnetic field and comparing the ballistic throw of a galvanometer with that produced by breaking the current in the primary of a known mutual inductance. We have, however, thought of an alternative method, which not only can be carried to almost unlimited accuracy, but also has the highly desirable feature of yielding the moment to be determined directly in units of the nuclear magneton. It consists in comparing the frequency $\omega=\omega_n$ and the field $H_0^*=H_n$ with the values ω_p and H_p, where ω_p is the circular frequency of an oscillator driving a cyclotron which accelerates protons in a magnetic field H_p. We have them from (15)

$$\omega_n=(2H_n\mu_n/\hbar)(e\hbar/2Mc)=(eH_n/Mc)\mu_n, \quad (16)$$

if instead of using absolute units as in (15), we express the neutron moment in units of the nuclear magneton, i.e., if we write

$$\mu=\mu_n(e\hbar/2Mc). \quad (17)$$

On the other hand, for the ideal resonance of protons in a cyclotron, we have the relation

$$\omega_p=eH_p/Mc. \quad (18)$$

Dividing (16) by (18), we now obtain

$$\mu_n=(\omega_n/\omega_p)(H_p/H_n). \quad (19)$$

This means that in order to determine the moment in absolute nuclear magnetons one has merely to determine the *ratio* of two frequencies and the *ratio* of two fields instead of determining ω_n and H_n absolutely. In addition to this great experimental advantage, we see that no knowledge of the universal constants of physics is required. The value of Planck's constant does not enter since the moment is expressed in nuclear magnetons and the value of e/Mc is eliminated by use of the cyclotron.

If the radiofrequency generator for the cyclotron were a power amplifier driven by a harmonic of the "neutron oscillator," the ratio ω_n/ω_p would be simply an integer. In this case one would merely have to measure the ratio H_p/H_n, in order to know μ_n. This measurement can be reduced to the determination of the ratio of the wound areas (area × turns) of two flip coils, which can in turn be reduced to that of two currents. If the two coils, located in the same position in a current system and both connected through the same galvanometer circuit give the same ballistic throw, then the ratio of the currents for which this condition is reached gives the ratio of their wound areas. Once that ratio is known, one also has that of any two fields which, using the two coils, give the same ballistic throw in the galvanometer. Gehrcke and v. Wogau[10] have developed this technique, by the use of null indicator methods, to a point where the ratio of two fields may be determined to five significant figures. Although we have determined the ratios of the frequencies and the fields by essentially these methods the errors, entering from elsewhere did not justify the application of all their refinements described above.

Description of Apparatus

Up to the present time, almost all of the precision measurements of neutron intensity have been made using Rn-Be, or similar sources not subject to the erratic fluctuations occurring with artificial sources. Although it is possible to keep the cyclotron ion beam constant to one or two percent for long periods of time, this is not sufficient for the present work, where an accuracy of the order of 0.1 percent is needed. Also, one cannot assume that the neutron intensity is proportional to the beam current, since the distribution of the latter over the target, and the proportion of stray ions striking the insides of the dees are both important in this respect. This rules out the possibility of using an integrating beam meter, or auxiliary BF_3 chamber, as a monitor. The counting-monitoring circuit which was finally adopted for this experiment is shown schematically in Fig. 1.

The neutrons were detected in a BF_3 chamber operated at 5000 volts. Its diameter and length were 9 cm and 15 cm, respectively, and the gas pressure was 50 cm of Hg. The arrangement of electrodes is quite similar to that of a chamber recently described by Powers.[3] A conventional linear amplifier of 4 stages fed the pulses into the modulation-distortion circuit, where all pulses of magnitude greater than a certain value were amplified to uniform size, and all below this height were suppressed. This circuit has been described in detail before, in connection with the production of monochromatic neutron beams,[11] but was not essential for most of this work, since modulated beams were not used in the final experiment. The uniform pulses from this stage were fed to a scale-of-16 of the type described by Reich,[12] which uses hard tubes. After passing through the scale, the pulses entered a switching circuit which fed them to either of two scales of 4 plus a Cenco counter. The switching was carried out automatically at regular intervals of from 2–10 seconds, depending upon the adjustment. At the same time, the switching circuit turned a magnet on and off (from magnetic scattering experiments), or keyed the oscillator (for the resonance experiment).

The first circuits designed to carry out the switching used relays; these were found to be unsatisfactory due to differences in spring adjustments, so an all electronic switching circuit was devised. This is shown in Fig. 2. Negative pulses were fed to the grids of the two right-hand 6K7's, each of which had another 6K7 connected to it in the familiar Rossi coincidence circuit. If the grids of either of these left-hand 6K7's were negative, the plate current of its partner would be cut off, delivering a positive pulse to the corresponding scale-of-4. But if the grid was positive, the voltage pulse at the common plate connection would be too small to affect the scale. The circuit at the left is merely a device for making one grid positive and the other negative, and reversing this condition instantaneously at will. The two 885's are arranged in a conventional inverter, or scale-of-2 circuit. When current flows through the upper Thyratron and is blocked in the lower, pulses will pass through the switch into the upper scale-of-4. If a positive pulse is now applied to the grids of the 885's, the scale-of-2 will invert, and the lower scale-of-4 will receive the neutron pulses. The positive pulse which flips the scale-of-2 originates in a relaxation oscillator of the type used in cathode-ray oscillograph sweep circuits. It was found that the interval between

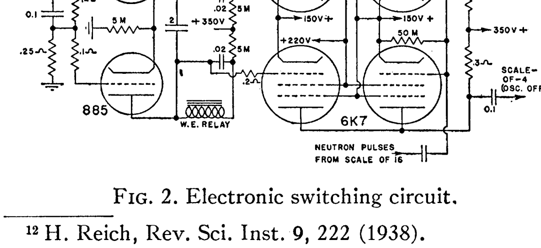

Fig. 2. Electronic switching circuit.

[10] E. Gehrcke and M. v. Wogau, Verh. d. D. Phys. Ges. 11, 664 (1909).

[11] L. W. Alvarez, Phys. Rev. 54, 609 (1938).

[12] H. Reich, Rev. Sci. Inst. 9, 222 (1938).

pulses was not constant when R and C were large enough to make the time constant 5 seconds; so the frequency was increased, and the pulses from the oscillator were fed through a scale of 32 into the switching circuit. Fluctuations in the time interval were reduced to a negligible amount by this procedure. The length of the interval could be varied by means of a variable resistance in the oscillator circuit. Small relays in the plate circuits of the Thyratrons made it possible to control the magnets or R.F. oscillator in phase with the counter switching. A lag in these operations merely reduced slightly any real effect, while a lag in the counter switching would introduce a spurious effect of the same magnitude.

On first thought it would seem that the statistical errors would be considerably increased by the method of switching a scale-of-16 from one scale-of-4 to another. But calculation of the effect shows that it is of no importance, and our experimental fluctuations have always checked with those to be expected on the assumption that this arrangement is equivalent to two separate scales-of-64. We have also made runs to test the equality of the counting time under the two conditions, by feeding the output of a beat frequency oscillator into the distortion amplifier. It was always found that the two Cenco counters recorded equal numbers of counts per cycle of the switching.

We spent several months developing our polarizer-analyzer equipment. Our first attempts were along lines similar to those used by Frisch, v. Halban and Koch. Flat rings of iron with a diameter of 1 meter, a thickness of 1 cm, and a width of 10 cm were wound with copper wire in toroidal fashion to minimize the stray field. We were unable to observe any difference in the transmitted neutron intensity, which depended upon the magnetization of the iron. This is in agreement with the Columbia school which has shown that this iron (Armco) has a sharp magnetic effect threshold very near the saturation value, which most likely was not reached with our low magnetizing currents.

Since they also report that Swedish iron shows neutron magnetic effects at lower fields, we next wound bars of Swedish iron with flat copper strip through which 120 amperes could be passed. The bars were 1.5 meters long, 10 cm wide, and 1.5 cm thick. Although the H in the iron was 250 gauss ($B=20{,}000$), we were still unable to observe a difference in neutron transmission. We finally cut a piece from one of the Swedish iron bars, and magnetized it strongly between the pole pieces of a Weiss magnet and observed the magnetic effect. With an iron piece 4 cm thick, we obtained differences of about 6 percent in transmission. With half of the iron in the Weiss magnet, and the other half in a similar strong magnet, we confirmed Powers' results on double transmission, i.e., that the change in intensity was about the same for the pieces in one magnet, as when they were separated in two, at some distance. Many experiments were made to determine

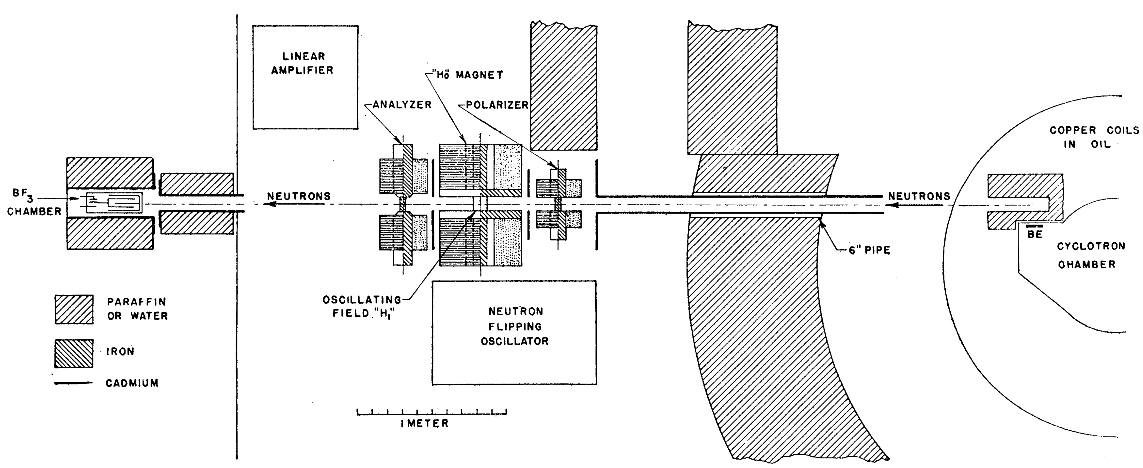

FIG. 3. Plan of the apparatus. Section taken 85 cm above floor of cyclotron room.

the optimum thickness of iron, and the magnetizing currents needed to obtain the maximum effects.

It was then possible to consider the construction of the precessing field, and the oscillator system. A plan of the apparatus is given in Fig. 3. Neutrons from the Be+D reaction were slowed to thermal velocities in the simple howitzer, and diffused down a cadmium-lined tube through the water tank to the polarizer. After passing through the precessing and flipping field, and the analyzer magnet, they were recorded in the BF_3 chamber. The large blocks of paraffin which defined the beam made the fast neutron background quite small. The iron plates reduced the thermal neutron intensity to about 5 percent, but the fast neutron background, as measured by covering one of the plates with Cd, was still only 25 percent of the total counting rate. This small background made it unnecessary to use the backgroundless modulated beam, as was originally planned. The somewhat increased magnetic effect at low neutron velocities was not enough to offset the decrease in intensity which attended the use of the modulation. In the earlier stages of the experiment, and actually in one of the resonance experiments, 120-cycle modulation was used successfully, but it was abandoned in favor of the greater intensity available without modulation.

The oscillator was of the conventional Hartley type, using an Eimac 150*T*, self-excited. The frequency was found to remain constant to better than 0.05 percent for days. The solenoid which produced the oscillating magnetic field was wound with a 9-cm square cross section and 15 cm height. The conductor was flat copper strip 0.50″×0.010″ wound so that adjacent turns almost touched. Neutrons passed through the strip on entering and leaving the region of the oscillating field H_1. The solenoid was connected in parallel with a section of the tank coil chosen to give 11 amperes magnetizing current as measured on an R.F. ammeter in the solenoid circuit ($H_1 \approx 10$ gauss). The oscillator was keyed by means of a relay in the primaries of the plate supply transformers.

The steady precessing field H_0 was at first produced by a pair of Helmholtz coils plus a pair of cylindrical bars of iron to concentrate the flux. This field was quite inhomogeneous, and was used for the first two resonance dips only. For the later measurements, we used a pair of large coils which had energized the magnet of the original 1-mv cyclotron of Lawrence and Livingston. These magnet coils were loaned to us by Professor R. B. Brode, who had been using them in connection with a cosmic-ray cloud chamber. An arrangement of iron was found which produced a field of about 600 gauss ±1 gauss throughout the volume occupied by the R.F. solenoid. The fluctuations in the laboratory d.c. supply were too great to allow its use in the coil circuit, so we utilized the constant current supply of the cyclotron magnet. This automatic stabilizer keeps the voltage fluctuations across the cyclotron magnet coils to less than 0.1 percent and gradually increases the value of the stabilized voltage to compensate for the heating of the coils. The magnet coils were then connected in parallel with the cyclotron coils through a variable resistance. The current was watched constantly, and the resistance was varied slightly when necessary, to allow for the differential heating of the two sets of coils.

A pair of large grounded copper plates were placed against the polepieces, so that the magnet coils were shielded from the R.F. fields of the solenoid. If this shield was not grounded, radiofrequency currents were induced in the d.c. lines and fed back into the stabilizer. A partial rectification of these currents would cause the stabilizer to change the magnet current, and therefore throw the cyclotron out of resonance. The resulting drop in the neutron intensity would be in phase with the switching cycle, and would therefore produce an apparent effect of the same sign and magnitude of that to be expected. Another cause of apparent effects was the interaction of the R.F. oscillator with the relaxation oscillator in the timing circuit. When the scale-of-32 was not properly grounded, it would count an extra pulse whenever the oscillator was turned on. This gave a 3 percent apparent effect of the correct sign and magnitude, due to the change in switching period. Several other spurious effects were encountered at various times during the experiment; it is due to the large intensities of neutrons available that we were able to trace down and eliminate them after comparatively short counting times.

The test for reliability of the apparatus in which we placed most faith was the following: A series of observations was taken at 20μa of deuterons, and it was desired to know whether the effect, e.g., difference in neutron counts with and without the oscillator on, was real. The current was then increased to 80 amperes, and the analyzer was covered with a cadmium sheet. The counting rate in all parts of the amplifier, from the BF_3 chamber to the final mechanical counters remained the same as before, and all relays, magnetic and electric fields were operating in the same manner. The only difference was that the counted neutrons did not for the most part pass through the polarizer and analyzer, and that part of high velocity which did could not exhibit any magnetic effects. Any difference between the relative counting rates under these two conditions was ascribed to magnetic effects of the thermal neutrons. It was also possible in this way to eliminate causes of systematic effects. The closing of relays would occasionally jar the BF_3 chamber, and the resulting noise would introduce extra counts in synchronism with the timing cycle. Several effects of this nature were discovered and eliminated after long blank runs. It was also important at these high counting rates to guard against saturation in the BF_3 chamber. The intensity was always adjusted so that the counting rate was still a linear function of the deuteron current.

These sources of trouble are mentioned to emphasize the great desirability of powerful neutron sources in experiments of this sort. In the final set of experiments, in which all these spurious effects were eliminated and on which our value of the neutron moment is based, only about 4 million neutrons were counted. This number of counts could be taken with Rn-Be sources of moderate strength in a reasonable length of time, but it would be almost impossible to track down obscure systematic effects in the manner outlined above. We counted more than 200 million neutrons in test runs before we felt sure enough of the apparatus to have confidence in the results outlined below. Perhaps the most convincing proof of the reality of the effect was that we varied H_0 and ω over a factor of almost 10, and *each time the frequency was increased, the magnetic field setting for the center of the new dip was found within the accuracy, to be expected at the value calculated from the previously determined value of* H_0^*/ω.

Measurements

In the first experiments with the small Helmholtz coils, the magnetic field was measured with the aid of a fluxmeter-search coil combination. Although somewhat crude, the measurements did show that H_0^*/ω was constant for two frequencies differing by about 20 percent, and that the effect could therefore be attributed to the magnetic moment of the neutron, as outlined above. The shallowness of the resonance dip observed in these first experiments ($\Delta I/I=0.6$ percent) could be attributed to the inhomogeneity of the field H_0.

When the large magnet coils were installed, it was clear that a more accurate method of measuring the field would be necessary. A brass flip coil was therefore constructed in such a way that it could be alternately lowered into a standard position within the R.F. solenoid, or withdrawn to allow the neutrons to pass through. Stops were placed so that the coil turned through exactly 180°, as determined by optical means. The coil was turned by spring tension, after being cocked by hand. The leads from the coil were connected in series with a ballistic galvanometer of very long period, a Hibbert magnetic standard, and a search coil at the center of a standard solenoid. A knowledge of the constant of the standard solenoid plus the wound area of the flip coil and the search coil allowed the strength of the field to be ascertained. The current through the standard solenoid was measured by means of a standard resistance, standard cell, and potentiometer.

Before and after each counting period, the relation between the current through the coils, and the magnetic field was determined. This consisted in noting the ratio of the throws of the ballistic galvanometer d/s, where d was the deflection due to the turning of the flip coil, and s was the throw of the magnetic standard. Effects due to any nonlinearity of the galvanometer were minimized by adjusting this ratio close to one by rewinding the standard. d/s was determined as a

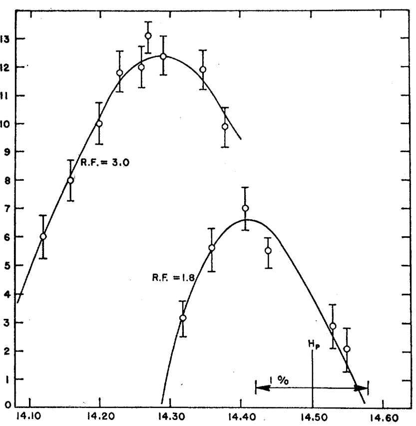

FIG. 4. Proton resonance curves. The potential drop in millivolts across the magnet current shunt is plotted as abscissa against the electromotive force in millivolts of the thermocouple used in the probe on which the proton current fell.

function of the magnetizing current, and the neutron intensity was also measured as a function of this current. The resonant field was then found from a comparison of these two curves.

The frequency of the oscillator was measured on a General Radio precision wavemeter. A knowledge of the field and frequency yielded the magnetic moment of the neutron by substitution in Eq. (15a).

The most trustworthy value of the moment is, however, given in absolute nuclear magnetons by the comparison method, outlined above. Although we ultimately trusted more this method it was gratifying to obtain well within the experimental error the same value for μ_n by the two entirely different methods of calibration. For this purpose it was necessary to construct a new flip coil which when turned through 180° in the proton resonance field of the 60-inch cyclotron would give a d/s almost equal to that obtained in the measurement of H_0^*. From a knowledge of the approximate values of the two magnetic fields involved, and the wound area of the original coil, it was a simple matter to construct such a coil. This coil was wound on a hard rubber form to ascertain the absence of magnetic impurities in it or in the brass used for the first coil.

It was then necessary to determine the ratio of the wound areas of the two flip coils. This measurement was carried out in the following manner: The two coils were mounted near the center of a pair of carefully constructed Helmholtz coils, which were designed for accurate cloud-chamber beta-ray curvature measurements. The constant of the coils did not enter the calculation; it was merely assumed that the field was directly proportional to the current through the coils. This current was measured in terms of the potential drop across a standard resistance in the circuit, on a Wolff potentiometer standardized with a Weston cell. The small coil was flipped in the strongest field available, and the current was then reduced until the large coil gave the same ballistic throw as the small one in the higher field. (The effect of the earth's field was subtracted from all readings.) The ratio of the wound areas of the two coils was then given by the ratio of the currents as determined on the potentiometer. The two coils were connected in series with the galvanometer; so the total resistance of the circuit remained constant. The current ratio was found to be constant for many values of the fields. To test for magnetic impurities in the search coil, the coil was connected in series opposition, and the large coil was turned through such an angle that when a current was broken in the Helmholtz coils no kick was observed on the galvanometer. This condition prevailed for a wide range of magnetizing currents. A very sensitive galvanometer was used in these measurements; so this zero method gave us confidence that no appreciable ferromagnetic contamination existed in the flip coils, one of brass and the other of hard rubber.

The new coil, ballistic galvanometer, and magnetic standard were then carried to the Crocker Radiation Laboratory, where the magnetic calibration was made in terms of the 60-inch cyclotron field. The rod carrying the flip coil projected into the cyclotron chamber through a window so that the coil could rotate in the gap at a point about 25 cm from the center of the cyclotron. Tests with a large search coil connected to a fluxmeter showed the field to be constant throughout this central region to better than 0.1 percent. The magnetization curve of the cyclotron magnet was then measured in the region around the known proton field. The measurements consisted in a determination of d/s against the potential drop across the magnet current shunt, as measured on the Wolff potentiometer.

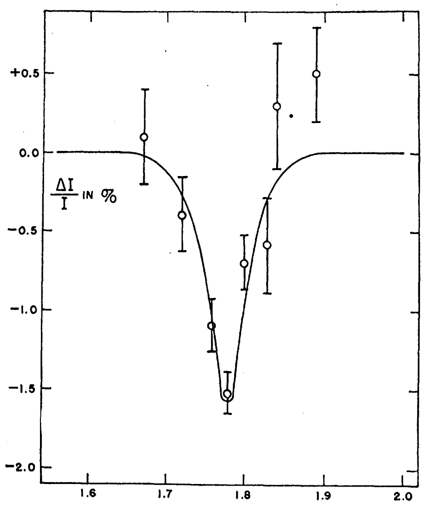

FIG. 5. Neutron resonance dip. The magnet current in arbitrary used is plotted against the fractional change ($\Delta I/I$) of the intensity of the neutron beam.

The cyclotron was then evacuated and hydrogen let into the chamber. The heating effect of the proton current to a probe placed at the point occupied by the flip coil was then measured as a function of the potential drop across the magnet current shunt. A comparison of these two curves gave the d/s value for the acceleration of protons at the frequency in use at the time. The effects of hysteresis on the resonance curve were found to be negligible, by observing it when the magnet current had been increased from zero to the proton value, and also when it had been carried through the cycle—zero, deuteron-field, proton-field.

The proton resonance curve, Fig. 4, was meassured at two values of the dee voltage, and the center of gravity of the curve was found to move toward higher fields as the voltage was reduced. This was shown not to be caused by a change in the cyclotron frequency, by measurements taken during each run. The increase in width of the curves with voltage is due to the fact that at higher voltage, the protons have to circulate fewer times. The shift of the peaks is due mainly to the focusing properties of the cyclotron. Since the magnetic field was uniform out to the probe, the focusing was entirely electrostatic, and this is known to be dependent upon the phase of the protons with respect to that of the oscillator.[13]

[13] M. E. Rose, Phys. Rev. **53**, 392 (1938); R. R. Wilson, Phys. Rev. **53**, 408 (1938).

Professor E. McMillan and Mr. R. Wilson have made a study of these effects in this laboratory, and they agree that the proper method of choosing the magnetic field, H_p, would be to run a large series of resonance curves with decreasing dee voltage, and extrapolate the resonance field to zero dee voltage. Changes in the apparatus made this impossible, so they have suggested that we choose a point midway between the maximum of the curve taken at lower dee voltage and its high field intercept. Since we have seen both experimentally and theoretically that the extrapolated resonance curve will lie somewhere between these two points, separated in field by 1 percent, the maximum error introduced in this way could be only 0.5 percent.

The ratio of the cyclotron frequency to the neutron frequency was determined with the aid of a Super-Pro short wave radio receiver. The second harmonic of the cyclotron oscillator was tuned in on this receiver in the same frequency range as the sixth to tenth harmonics of the neutron oscillator. The agreement between the various values of the frequency of the neutron oscillator as determined from these measurements attests to the linearity of the frequency scale of the receiver. The receiver was thus used merely as an uncalibrated, linear wavemeter.

RESULTS

Since the width of the resonance dip in gauss is constant for all values of the precessing field (Eq. (7a)), it is obvious that it is desirable to

TABLE I. *Data for neutron resonance curve (Fig. 5). Each reading is based on 120,000 counts. Magnetic field for neutron resonance, 622 gauss; frequency of oscillator, 1843 kilocycles; magnetic moment of the neutron, 1.94 nuclear magnetons; d/s for coil 1 in neutron field, 0.866; d/s for coil 2 in proton field, 0.844.*

CURRENT	PERCENTAGE EFFECT	MEAN EFFECT
1.67	−0.8, +1.0	+0.1 ±0.3
1.72	+0.6, −0.9, −0.8	−0.4 ±0.23
1.76	−0.5, −0.9, −2.1, −1.1, −1.2, −0.8	−1.1 ±0.16
1.78	−2.0, −2.2, −1.6, −1.5, −1.4, −0.5, −1.7, −1.2, −1.6, −1.5	−1.52±0.13
1.79	−1.7, −1.7	−1.7 ±0.3
1.80	−1.4, −0.5, −0.7, −1.5, +0.1, −0.3	−0.71±0.16
1.81	−1.5	−1.5 ±0.4
1.83	−0.8, −0.4	−0.6 ±0.3
1.84	+0.3	+0.3 ±0.4
1.89	+1.0, +0.0	+0.5 ±0.3

perform exploratory experiments at low precessing fields, to find an approximate value of the magnetic moment. After the relatively wide dip has been found at low fields, it is possible to increase the precision of the determination by raising the field and the frequency in the same ratio. Our first measurements were made at 260 and 315 kc, and merely served to show that the value of the moment was close to 2 nuclear magnetons. When the large homogeneous field was installed, we repeated the measurement at 315 kc; after observing the dip again at 810 kc, we increased the frequency to 1843 kc, where the field calibrations were made. Since the resonance dips at all the lower frequencies were consistent with that at 1843 kc, we will not describe those measurements in detail. The curve at 1843 kc is shown in Fig. 5.

The experimental data from which this curve is plotted are given in Tables I, II and III. It will be noticed that two of the points were not plotted in the curve. These are the values at 1.79 and 1.81 amperes, which have very large probable errors, due to the small numbers of neutrons counted. These two points have no appreciable effect upon the position of the minimum, and although they lie far off the curve, their positions are quite consistent with their probable errors. The curve was obtained on two separate days a week apart, and since no systematic difference could be noted between the two sets of data, they have been plotted together. The value of the magnetic moment is then given from Eq. (19),

$$\mu_n = (1.856/9.685)\times(10.60\times0.844/0.886) = 1.935 \text{ nuclear magnetons.}$$

The *probable errors* entering from various sources are: position of dip, 0.5 percent; galvanometer readings, 0.2 percent; coil calibration, 0.2 percent; frequency calibration, 0.2 percent; and cyclotron calibration, 0.6 percent. The final result may then be expressed as

$$\mu_n = 1.93_5 \pm 0.02$$

absolute nuclear magnetons.

TABLE II. *Current ratios in cloud-chamber Helmholtz coils for equal galvanometer throws.*

Current	Ratio	Current	Ratio
2.20	10.61	1.60	10.63
2.19	10.61	1.30	10.58
2.18	10.58	Ave.	10.60
2.10	10.60		

TABLE III. *Frequency calibration: reading, R, on radio receiver for nth harmonic.*

Neutron Oscillator			Cyclotron Oscillator		
n	*R*	*R/n*	*n*	*R*	*R/n*
6	11.14	1.856	2	19.37	9.685
7	12.99	1.856	All values in megacycles.		
8	14.83	1.854			
9	16.70	1.856			
10	18.56	1.856			

Discussion

The now rather accurately known values

$$\mu_p = 2.78_5 \pm 0.02 \quad \mu_n = -1.93_5 \pm 0.02$$
$$\mu_d = 0.855 \pm 0.006$$

of the magnetic moments of proton, neutron and deuteron are of considerable interest for nuclear theory. The fact alone that μ_p differs from unity and μ_n differs from zero indicates that, unlike the electron, these particles are not sufficiently described by the relativistic wave equation of *Dirac* and that other causes underly their magnetic properties.

Whatever these causes may turn out to be one has to notice that there holds to well within the experimental error the simple empirical relation

$$\mu_d = \mu_p + \mu_n. \quad (20)$$

This relation is far from being obvious and it would in fact seem rather surprising if it were rigorously satisfied. To explain it in simple terms one would have to make both the following assumptions:

(*a*) The fundamental state of the deuteron is a ^3S state so that there are no contributions to μ_d arising from orbital motion of the particles.

(*b*) The moments μ_p and μ_n are "additive," i.e., their intrinsic values are not changed by the interaction of the proton and the neutron, forming a deuteron.

The first assumption has been disproved by the recent discovery[14] that the deuteron possesses a finite electric quadrupole moment which is

[14] J. M. B. Kellogg, I. I. Rabi, N. F. Ramsey and J. R. Zacharias, Phys. Rev. 55, 318 (1939).

incompatible with the symmetry character of a pure ^3S state. The second cannot be discarded on an experimental basis but it ceases to be plausible if one admits the possibility, that ultimately the same causes may underly both the magnetic properties and the mutual binding forces of the proton and the neutron.

It is conceivable that the departure from any one of the two assumptions (*a*) and (*b*) would separately cause a considerable deviation from (20) but that for unknown reasons both together cancel each other very closely. Until reliable estimates of these deviations can be obtained we consider it, however, more likely that neither of them amounts to more than a few percents.

ACKNOWLEDGMENT

We are indebted to Professor E. O. Lawrence for his interest in this experiment, and in particular, one of us is grateful to him for the opportunity to work as a guest in the Radiation Laboratory. Our sincere thanks are due Professor R. B. Brode for the loan of the magnet which made the precision determination of the magnetic moment possible. We also wish to express our appreciation to the members of the laboratory staff for their many hours at the cyclotron controls. The experiment was made possible by grants to the laboratory from the Rockefeller Foundation and the Research Corporation.

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The Contact Difference of Potential Between Barium and Zinc

The External Work Function of Zinc

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The methods of contact potential measurement described in previous reports of this series have been extended to zinc, for which the published work function data are discordant. Measurement was by the retarding potential method with variable anode, in tubes sealed from the pumps and gettered with vaporized barium. Barium was the reference metal and the measured surfaces of both barium and zinc were prepared by fractional distillation followed by revaporization of the middle fractions. In observations on three tubes and fifteen pairs of Ba-Zn surfaces the observed contact P.D., mean value 1.76 v, was reproducible and constant to ± 0.02 v. Combination of this value with the work function of barium, now well established at 2.52 ev, assigns the value 4.28 ± 0.02 ev to the work function of zinc at room temperature. The initial measurement on a surface was taken within 8 seconds of its deposition. As a consequence of this small time lapse it becomes possible to answer the fundamental but neglected question of whether a work function measured under optimum vacuum conditions is characteristic of the clean metal or of a gas-contaminated surface in equilibrium with the residual gas. The rate of deposition of oxygen on zinc is estimated from the behavior of a tungsten "test surface" in a comparable vacuum. Since the regimes of measurement and of equilibrium gas film formation overlap and no change of work function with aging is detectable, it is concluded that the observed work function is characteristic of clean zinc. From the point of view of the adsorption processes involved, the measurements show that the mean time of sojourn of oxygen is much less on zinc than on tungsten.

THIS paper reports further results in a program of study of the external work functions of the pure metals as determined by measurement of their contact differences of potential with respect to a suitable reference metal, barium. Previous work under this program[1] has shown, (1) that the work functions of barium surfaces are reproducible to at least ± 0.01 ev when the surfaces are formed by fractional distillation in a sealed-off tube, and (2) that measurements of work functions by the contact potential method are now capable of the precision and accuracy characteristic of the best photoelectric work. Since the contact potential method, unlike the thermionic, is applicable to all the metals and, unlike the photoelectric, yields measurements of uniformly high sensitivity, it appears to offer the most promising

[1] P. A. Anderson, Phys. Rev. **47**, 958 (1935); **49**, 320 (1936); **54**, 753 (1938).