# The signs of the magnetic moments of neutron and proton*)

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## 1. Introduction.

The magnetic moments of the two elementary particles, neutron and proton, have become of fundamental importance in nuclear physics. The exact knowledge of their magnitude and signs is necessary for the understanding of the magnetic moments of complex nuclei, particularly of the deuteron, the triton and of $He^3$. The actual values of the moments of these complex nuclei, is one of the sources of information on the nature of nuclear forces. If neutron and proton as elementary particles could be described by the relativistic wave equation of Dirac, the question of the magnetic moments of the two particles would be a simple one. Theory would then predict, that the magnetic moment of the proton is one nuclear Bohr magneton

$$\mu_n = \frac{e\hbar}{2\,Mc}$$

where $e$ and $M$ are the charge and mass of the proton. For the neutron as a neutral particle, the Dirac equation would predict zero value of the magnetic moment. The experimental values of the moments

$$\mu_P = (2.79353 \pm .00014)\ \mu_n{}^{1)} \text{ and } \mu_N = (1.91354 \pm .00013)\ \mu_n{}^{1)2)}$$

show clearly that the Dirac equation does not properly represent the heavy nuclear particles. The meson theory of nuclear forces on the other hand indicates a mechanism by which qualitatively the values of these moments could be explained. Accepting the idea that a proton, with an intrinsic moment of one nuclear magneton, decomposes part of the time into a neutron proper, with zero magnetic moment, and a positive meson, and that the neutron likewise decomposes into a proton and a negative meson, the positive excess moment of the proton over a nuclear magneton should be about

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equal to the absolute value of the neutron moment in approximate agreement with the known values. Unfortunately however, calculations using the known values of the mass of mesons and a reasonable value of the so-called coupling constant, lead with any of the current field theories to impossible values of the magnetic moment of the neutron.

The sign of the magnetic moment of the proton is expected to be positive if one accepts the conventional definition that a positive rotating charge has a positive magnetic moment pointing in the direction of the angular momentum. Similarly it follows from the above given picture that the sign of the neutron moment should be negative.

The magnetic moment of the deuteron:

$$\mu_D = (.857648 \pm .00004)^{1)}$$

likewise suggests this situation. The spin of the proton is known to be $\frac{1}{2}$ (in units $\hbar$) and that of the deuteron in its ground state to be 1, from molecular beam experiments as well as from band spectra. The neutron whose spin has never been directly determined has most likely a spin $\frac{1}{2}$. In a crude approximation one might assume that magnetic moments are additive and one can show[3]) that only the assumptions that the neutron spin is $\frac{1}{2}$, that the ground state of the deuteron is an $S$ state and that the magnetic moment of the neutron is negative lead approximately to the measured value of the magnetic moment of the deuteron. It is, however, well known that the rule of additivity of moments does not hold exactly. In the first place the ground state of the deuteron must be partially a $D$ state in order to explain its observed electric quadrupole moment[4]) which requires a charge distribution characteristic for a $D$ state. The admixture of $D$ state contributes through its angular momentum to the resultant magnetic moment. Secondly, additivity cannot hold because relativistic corrections caused by the motion of the constituents in the deuteron have to be considered. Although the deviations from additivity are quite small they are certainly not negligible.

Experimentally the sign of the magnetic moments of the proton and the deuteron have been determined by KELLOGG, RABI, RAMSEY and ZACHARIAS[5]), using the molecular beam method and the so-called MILLMAN[6]) effect. The result was that both these moments are positive. The sign of the neutron magnetic moment was found to be negative by POWERS[7]) who used a variation of the molecular beam resonance method. Partly polarized neutrons were passed through the strongly inhomogenuous field of two wires carrying equal currents in opposite direction at right angles to the direction of propagation of the neutrons and parallel to a steady field $H_0$. Neutrons of the proper velocity encounter an effectively rotating field, whose direction of rotation depends on the direction of the currents. Neutrons may therefore undergo nonadiabatic transitions in which their spin magnetic quantum number changes by unity. The transitions manifest themselves in the usual way. An originally partly polarized beam of neutrons will, after passing through an analyzing magnet show a decrease in intensity, if transitions occur between polarizer and analyzer. There are several reasons why the effects observed by Powers were quite small. The degree of polarization of the neutron beam was small and only a narrow velocity band could be brought to resonance. Nevertheless Powers obtained an unambiguous result. The transmission effect for one direction of the rotating field was 2.1% ± .4% smaller than for the other direction and from the direction of the fields Powers concluded that the moment of the neutron is negative. Bloch, Nicodemus and Staub[2]) were able to infer the sign of the neutron moment in their precision determination of the value of the magnetic moment. In their experiment they also used the molecular beam resonance method. The neutrons, however, passed through a radio frequency field which was slightly asymmetric. They were thereby subjected to a Millman effect, since they encountered an effective frequency of the rotating field slightly larger or smaller than the measured frequency, depending on the direction of the precession field. From the small, but definite shift in the resonance frequency upon inversion of the precession field, they concluded too that the neutron magnetic moment was negative.

In view of the fundamental importance of the signs of the magnetic moments, we have undertaken the present experiments to compare directly in the same experimental arrangement, the signs of the moments of the neutron and the proton and to make at the same time an absolute determination of the sign of these two moments. With the recent advances made in the technique for measuring nuclear magnetic moments such a direct experiment seemed to be feasible.

## 2. Method.

For the determination of the sign of the neutron moment we used the molecular beam resonance method. This method was originally suggested by Rabi[8]) as a means for determining the signs of nuclear magnetic moments and it was only the lack of purely rotating fields that so far this ingenuous method was mostly used for the determination of the magnitude, rather than of the sign of magnetic moments. For the neutron experiment, the arrangement, shown in Fig. 1 is essentially the same as in the experiment of Bloch, Nicodemus and Staub[2]). A beam of thermal neutrons from a paraffin moderator around the target of a cyclotron is partially polarized by passing it through a magnetized slab of iron. The neutrons then enter a static magnetic field $H_0$, the precession field. At right angles to $H_0$ there is a time variable magnetic field $H_1'$ of a magnitude small compared to $H_0$. After leaving the precession field the neutrons pass through an analyzer which consists again

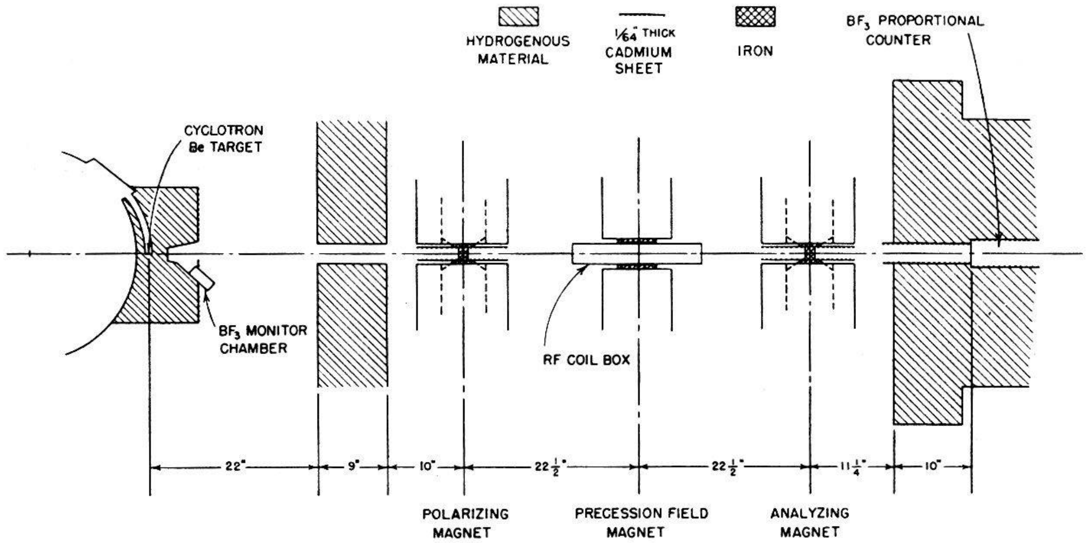



Fig. 1.
Experimental arrangement.

of a slab of iron magnetized in the same direction as the polarizer and enter finally the detector. The time variable field $H_1'$ produces nonadiabatic transitions of the polarized neutrons, if it contains a component $H_1$ rotating around the direction of $H_0$ with the frequency $\omega^*$ and the sense of rotation of the Larmor precession of the neutron about the field $H_0$. The probability of finding at the time $t = T$ a neutron which at the time $t = 0$ had a magnetic spin quantum number $m_s = + \frac{1}{2}$, in a state with $m_s = - \frac{1}{2}$ is given by the well-known relation[8])

$$P_{(\frac{1}{2} \to -\frac{1}{2})} = \frac{\sin^2 (T/_2 \sqrt{\Gamma^2 + \Delta^2})}{1 + (\Delta/\Gamma)^2} \tag{1}$$

where:

$$\Gamma = \gamma_N \overline{H}_1 \text{ and } \Delta = \omega - \gamma_N H_0 = \omega - \omega^*$$

In the derivation of this expression it is assumed, that the amplitude $\bar{H}_1$ of the rotating field $H_1$ is constant. $\gamma_N$ is the gyromagnetic ratio $\mu/J$ of the neutron, $\omega$ the angular frequency of the rotating field and $\omega^* = \gamma_N H_0$ the LARMOR precession frequency of the neutron in the field $H_0$. If $H_1'$ consists actually of a field oscillating in the $x$ direction at right angles to $H_0$ one has:

$$H_x = 2\,H_1 \cos \omega\, t = \bar{H}_1 \cos \omega t + \bar{H}_1 \cos \omega t$$

$$H_y = 0 \qquad\qquad = \bar{H}_1 \sin\, \omega t - \bar{H}_1 \sin \omega t$$

The oscillating field therefore represents effectively two fields of constant and equal amplitude rotating in opposite directions. If $\omega$ approaches $\omega^*$, one or the other of these two components will become resonant with the LARMOR frequency and consequently independent of the sign of $\mu$ or $H_0$, nonadiabatic transitions will take place. This method has been employed in the previous determination of the value of the moment, but unless asymmetries in $H_1$ are introduced as the MILLMAN effect requires, no information on the sign of the moment can be obtained. The component of the field $H_1'$ rotating in a direction opposite to that of the LARMOR precession has practically no effect on the transition probability[9]) as given by eq(1).

We have, for the present experiment, simply modified the arrangement previously used by making the field $H_1'$ as nearly a perfectly rotating field as possible. For this purpose we applied a method well-known to electrical engineering in the construction of alternating current motors to radio frequency fields. The rotating field is obtained by superimposing two fields oscillating perpendicularly to each other at the same frequency in a plane $xy$ perpendicular to $H_0$, but with a relative phase shift of $90^0$. Denoting by $\bar{H}_1$ the equal amplitudes of the two fields parallel to the $x$ and $y$ direction respectively, one has:

$$H_x = \bar{H}_1 \cos \omega t$$

$$H_y = \pm\, \bar{H}_1 \sin \omega t$$

representing a purely rotating field of angular frequency $\omega$. Nonadiabatic transitions can now only be obtained, if $\omega$ approaches $\omega^*$ and if $H_1$ rotates co-directionally with the LARMOR precession of the neutron. While equation (1) predicts that $P$ varies periodically between 0 and 1 with increasing amplitude $\bar{H}_1$, this is only true, if all the neutrons spend the same time in the rotating field. In practice the experiments are carried out with non-monochromatic neutrons and as a result the extrema of the average value of $P$ become less and less pronounced. For sufficiently large values of $H_1$, $P$ will approach asymptotically the value $\frac{1}{2}$. An originally completely polarized beam of non-monochromatic neutrons will thus, at exact resonance become completely depolarized if the product $\Gamma \cdot \bar{T}$ is large compared to unity. $\bar{T}$ is the average time which a neutron spends in the rotating field.

The depolarization can be detected by the so-called transmission effect. As it is well-known, the intensity of a beam of thermal neutrons passing through a slab of iron will increase upon magnetization of the iron, due to the spin dependence of the magnetic scattering cross section. Let $f(v)$ be the velocity distribution of the neutrons after having passed through polarizer and analyzer magnet. The detector in back of the analyzer will record an intensity $I_0 = \int f(v)\, dv$, if both analyzer and polarizer are unmagnetized. If the polarizer alone or the analyzer alone or both together are magnetized in the same direction, the detector will record respectively the increased intensities: $\int f(v)\, C_p(v)\, dv$, $\int f(v)\, C_A(v)\, dv$ and $\int f(v)\, C_D(v)\, dv$. If now both, analyzer and polarizer are magnetized but transitions take place between polarizer and analyzer with a probability $P(T) = P(L/v)$, the intensity will be[2])

$$I_T = \int f\,[(1-2\,P)\,C_D + 2\,P C_P C_A]\,dv$$

If one measures the relative intensity change $E_T$ upon applying the radio frequency field $H_1$, one has:

$$E_T = -2\,\frac{\int f\,(C_D - C_A C_P)\,P dv}{\int f\,C_D dv} \tag{2}$$

In the limiting case of large $\Gamma\,\bar{T}$, $P$ varies rapidly with $v$ at resonance and can therefore be replaced by its average value $\frac{1}{2}$. The transmission effect $E_T$ becomes then:

$$E_T = E_T{}^* = -\frac{E_D - (E_A + E_P)}{1 + E_D} \tag{3}$$

In this relation $E_P, E_A, E_D$ represent respectively the relative intensity increases upon magnetization of the polarizer alone, the analyzer alone and of both together. It is moreover assumed, that the transmission effects $E_A$ and $E_P$ are small compared to unity. The dependence of $E_T$ as given by (2) and (3) has been verified experimentally by Bloch, Nicodemus and Staub[2]).

For the determination of the direction of the Larmor precession of the protons, we used a modified nuclear induction method. As Bloch[10]) has shown in his original work, the nuclear induction effect consists in a change of the orientation of the macroscopic nuclear paramagnetic magnetization vector $\vec{M}$ relative to the static field $\vec{H}_0$, if the frequency of a rotating field $\vec{H}_1$, at right angles to $\vec{H}_0$ is in resonance with the Larmor precession frequency of $\vec{M}$. The resonance condition again requires that frequency and sense of rotation of $H_1$ are the same as for the precessing vector $\vec{M}$. The macros-

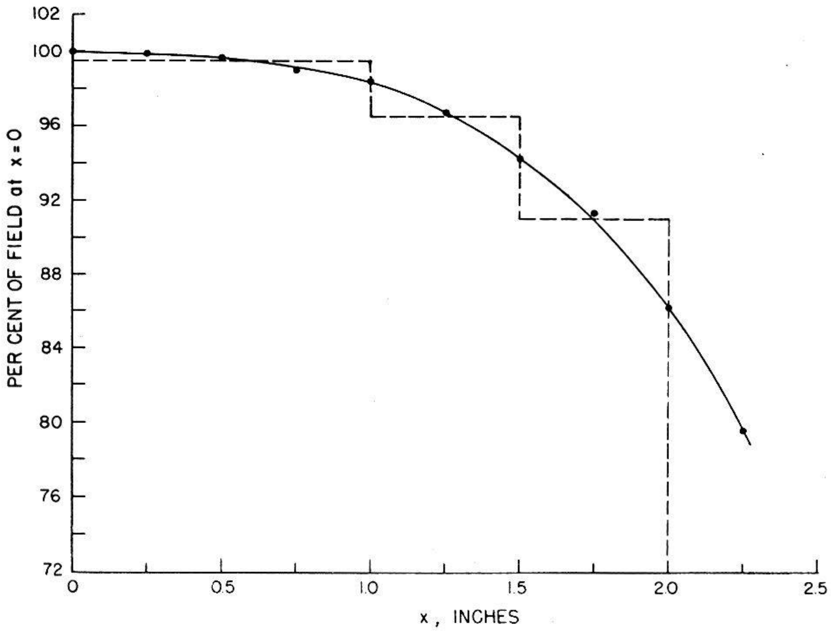



Fig. 2.
Radial distribution of static field.
Abscissa: Distance from center in inches.
Ordinate: Percentage deviation from value of field at center.
Dotted curve: Approximation used in calculating the shape of the neutron resonance dip.

copic angular momentum vector $\vec{A}$ and the magnetization $\vec{M}$ are related in the same manner as for a single nucleus by: $\vec{M} = \gamma \vec{A}$, where $\gamma$ is the gyromagnetic ratio. From this it follows, that the appearance of a nuclear induction signal for a particular direction of rotation of $H_1$ relative to $H_0$ indicates the sign of the magnetic moment of the resonating nuclei. For the exact determination of the magnetic moment, the experiments are carried out with a purely oscillating field $H_1'$, representing again effectively two fields rotating in opposite direction. One of these fields will produce the reorientation of $\vec{M}$, while the other has no effect as long as $H_1' \ll H_0$ except for high order corrections. Under certain circumstances one can, in principle, from the phase of the nuclear induction signal, infer the sign of the magnetic moment. However, this requires among other things a knowledge of the nuclear relaxation time. A purely rotating field, however, will immediately indicate, by its sense of rotation, the sign of the moment of the nuclei.

If nuclear induction signals are observed with rotating fields, one is confronted with a difficulty which in the case of oscillating fields has been circumvented very elegantly by Bloch. In his arrangement, the axis of receiver and transmitter coil, both perpendicular to $H_0$ are placed at right angles. Consequently, the leakage voltage induced in the receiver coil by the field of the transmitter coil is very small and can, by use of a so-called paddle, be reduced to an arbitrarily small amount, so that only the precessing nuclei induce a voltage in the receiver coil. In the case of the rotating field, produced in the above mentioned manner, the receiver coil might be arranged at right angles to one set of transmitter coils and coaxial to the other. Consequently, an enormous leakage voltage will be induced over which the small nuclear signal will be superimposed. While it is true that for the detection of the signal a small amount of leakage is necessary in order to operate the detector in a linear region, the leakage would be much too large and the nuclear induction signal would be drowned in the microphonics and noise of the leakage. In the arrangement of Purcell[11]) and his collaborators, one coil functions as receiver and transmitter, but the voltage, without signal across the coil, is balanced out by a bridgetype network.

For our experiment we have used an arrangement shown in Fig. 3, which in some ways represents a cross-breed between the two methods. The receiver coil with its axis parallel to the $x$ axis transmitter coils is placed in the centre of the four transmitter coils. It is connected in series and opposite to a compensating coil on the $x$ axis placed at a distance from the receiver coil, but within the flux of the $x$ transmitter coils. In this manner, the enormous voltage induced by the $x$ transmitter coils can be completely cancelled. Since there is always present some voltage in phase with the voltage across the $y$ transmitter coils, a third, much smaller coil on the $y$ axis is connected in series with the receiver and compensating coil. It allows the compensation of any amount of $y$ component leakage. For the final balancing of the whole system, paddles for both $x$ and $y$ compensating coils can be used, and a small amount of $x$ or $y$ component leakage can be obtained. The two compensating coils have, of course, to be sufficiently far away from the receiver coil, so that no voltage is induced in them by the precessing nuclei.

The production of a rotating field by two sets of crossed coils sufficiently far apart to allow the unobstructed passage of a rather wide neutron beam through their central region, is an extremely inefficient process. The volume which has to be filled with magnetic flux is many times larger than the volume occupied by the neutron beam or the nuclear induction sample and the field within the transmitter coils is many times larger than in the central region. Consequently one should perform such an experiment with as low a frequency as possible, the lower limit being set by the magnitude of the proton induction signal which decreases quadratically with the frequency and by the decrease of $Q$ with decreasing frequency.

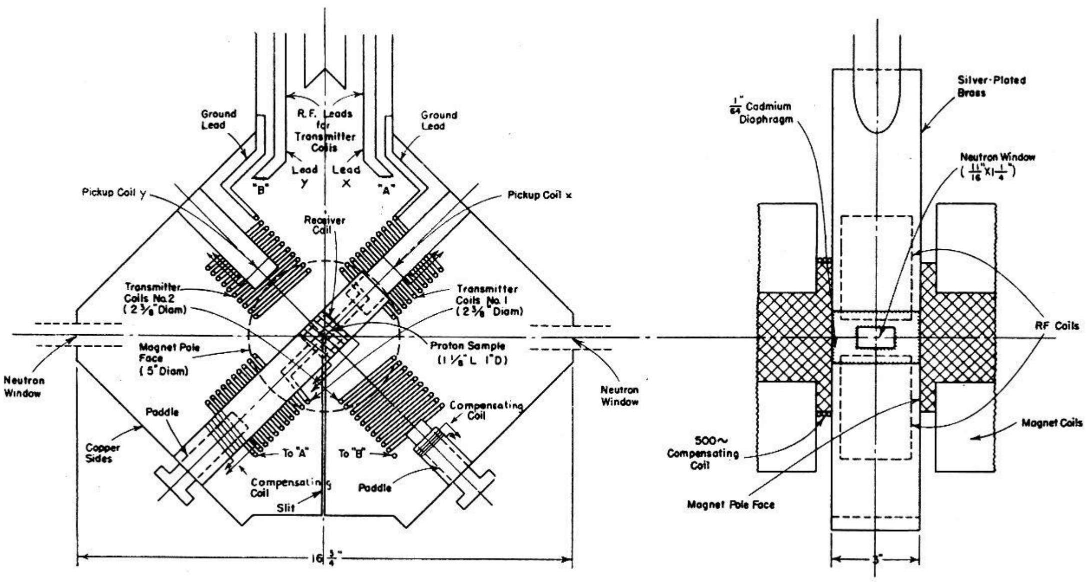



Fig. 3.
Arrangement of transmitter and receiver coils in the gap of the precession field magnet.

In addition, there is a lower limit set by the relative widening of the neutron resonance peak. In order to obtain the maximum value of $E_T$ for a given time $\bar{T}$, one has to apply a field $\bar{H}_1 = \frac{\pi}{\gamma N \bar{T}}$. The absolute width of the resonance dip is then proportional to $\bar{H}_1$ and consequently the relative width inversely proportional to $H_0$. As a specific example consider an arrangement as chosen for the present experiment. The volume occupied by the neutron beam over a length of $L = 5$ cm is about 35 cc. In order to obtain a reasonably uniform rotating field, this requires 2 pairs of coils, each coil of $2^3/_8$ $''$ diameter and $2^3/_4$ $''$ length with a space between the ends of one pair of $3\frac{1}{2}$ $''$. The total volume to be filled with flux is then about 5000 cc. In order to obtain a good neutron resonance curve $L\bar{H}_1$ ought to be about 30 Gauss cm peak rotating field[2]). Under this condition neutrons with a velocity of 2000 m per second have a probability of about unity for undergoing a transition from

$$m_s = + {}^1/_2 \text{ to } m_s = - {}^1/_2$$

The power required for this field increases for constant $Q$ proportionally to the frequency. For a $Q$ of 150, a frequency of 2.3 MC ($H_0 = 790$ G) and a peak r. f. field of $30/5 = 6$ Gauss in the central region, the field inside the coils is about 30 Gauss and the power required of the order of ½ K. W. To obtain the nuclear induction signal of the protons, the water sample can be made as large as possible, the limitation being the inhomogeneity of the static field $H_0$. The number of turns of the receiver coil is limited by the necessity of adding in series two compensating coils which, together with the inevitable distributed capacitance of coils and leads, sets an upper limit to the inductance of the receiver coil. With a cross sectional area of $A = 5\ \mathrm{cm}^2$ (1″ diameter) of the sample and a receiver coil of $N = 50$ turns with a $Q$ of 80, one obtains a signal at resonance of amplitude[10]):

$$V = \frac{A N n}{\pi c} \frac{J(J+1)}{3 k T} \gamma_P h^2 \omega^2 Q = 6.5 \text{ millivolts} \tag{4}$$

which in principle should be sufficiently big to be detected above the rather large background of microphonics which has to be expected in such an arrangement. The amplitude $\bar{H}_1$ for the proton experiment is essentially determined by the inhomogeneity of the $H_0$ field. For the present case it should be about 1 Gauss. The frequency $\omega$ is chosen to be the same for neutrons and protons.

The main difficulty with which one is confronted in a nuclear induction experiment with a purely rotating field as pointed out above, is found in the fact, that it is impossible to orient the receiver coil in such a manner that the direct magnetic flux from the transmitter coil cannot induce a large radio frequency voltage across the receiver coil. For a coil and a field as assumed above, this voltage would be

$$V_0 = \frac{\omega}{c} \bar{H}_1 A N Q = 2900 \text{ Volts.}$$

This voltage has to be balanced down to about 1 Volt by the use of a compensating coil coaxial to the receiver coil.

Since, except for its magnitude, the same rotating r. f. field should be used for observing neutron and proton resonances and since, for reasons of the neutron intensity, this field has to extend over a rather large region, the transmitter coils cannot be very rigidly mounted nor rigidly connected to the proton receiver coil. It was therefore to be expected, that the whole arrangement would be extremely sensitive to microphonic disturbances from extraneous sources, as well as from the $H_0$ field modulation. The present experiment on the other hand does not require a detailed study of the shape of the nuclear induction signal since only its presence or absence for a given sense of rotation has to be ascertained. A very effective means to improve the signal to microphonics ratio consists in filtering out one particular harmonic of the periodically repeated induction signal. The frequency of this harmonic should be such that it does not correspond to one of the natural mechanical frequencies of the apparatus. Its dimensions suggest the use of as high a modulating frequency as possible, the limitation being set by the power necessary to penetrate the metallic shielding of the apparatus. In the present experiment we choose a modulating frequency of 500 c.p.s. and filtered out the second harmonic of the induction signal for amplification. The amplitude of this second harmonic signal is of course considerably smaller than the value computed by equation (4). Its magnitude will depend on the amplitude $\Delta H_0$ of the modulation of the $H_0$ field. At exact resonance the symmetric $v$ component will at first increase with increasing amplitude and then drop slowly, since for large modulation the field passes very rapidly across the signal. Calculation shows, that for a pure $v$ component signal the maximum amplitude of the second harmonic component is reached, if the amplitude of the modulating field is about 2.5 times the width of the signal at half-maximum. The harmonic component then has an amplitude of about $^1/_3$ the size of the signal itself. It appears therefore that the selection of a particular harmonic improves very markedly the signal to microphonics ratio and is a suitable procedure, if merely the presence and not the particular shape of the induction signal has to be investigated.

## 3. Apparatus.

The experimental arrangement is shown in Fig. 1. Neutrons from the Be target of a cyclotron are thermalized in a paraffin moderator. After passing through polarizer, precession field and analyzer, they are recorded by a boron trifluoride chamber as described previously[2]). The fields of polarizer and analyzer magnets had always the same direction as the static field $H_0$ and care was taken that nowhere the magnetic field between polarizer and analyzer was less than about 50 Gauss. The iron blocks inserted in the two magnets were $^3/_4''$ thick and had an area of $1\frac{1}{2}$ by $2''$. They were magnetized by a constant field of about 11000 Gauss. The precession field $H_0$ was produced by a small electromagnet whose core of 3 ″ diameter terminated in pole pieces of 5 ″ diameter with a pole face separation of 3 ″. The radial distribution of the $H_0$ field in the plane of symmetry is shown in Fig. 2. It is very nearly parabolic, such that at a distance of 1 ″ from the center it has dropped by about 1.6%. The current of 1.5 Amps (max.) for this magnet was electronically stabilized. The voltage drop of the magnet current across a resistor was applied to the grid of a tube, whose cathode was held at a constant potential above ground. The plate potential of this tube was directly applied to the grids of a set of $6Y6$ tubes in series with the magnet coils.

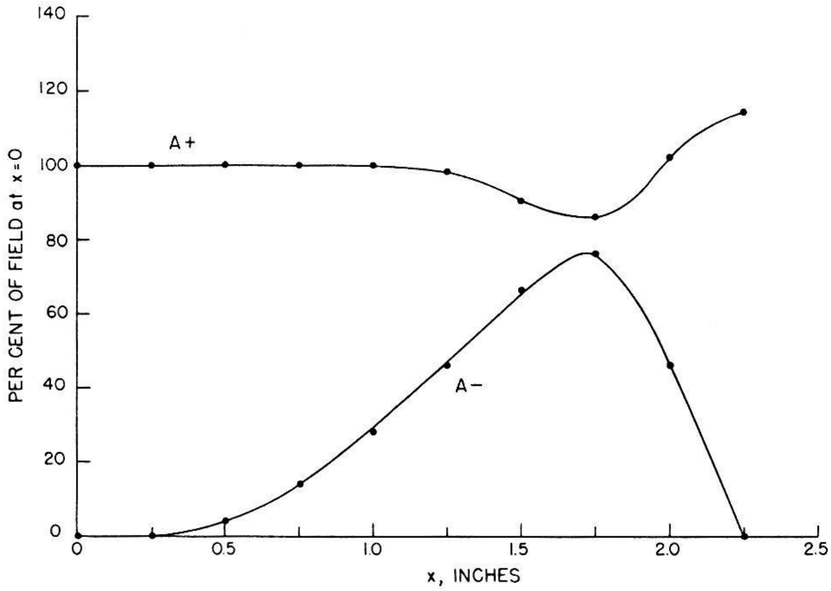



**Fig. 4.**

**Amplitudes of the radio frequency field along the axis of the neutron beam if at the center $x = 0$ the field is purely circular, rotating in the positive direction. $A^+$ and $A^-$ are the amplitudes of two circular fields rotating in opposite directions.**

This arrangement gave a stabilization of about 40 against line voltage fluctuations. Changes of the $H_0$ field were obtained by varying the value of the resistor producing the grid voltage for the shunt tube. The static field for the proton experiment was modulated with 500 c.p.s. with an amplitude up to about 10 Gauss. The modulating voltage was applied to the coils of the magnet through large blocking condensers separating the 500 c.p.s. supply from the D. C. network. The impedance of the two coils connected in series was increased by tuning them with a parallel condenser to 500 c.p.s.

The coil arrangement for the rotating r. f. field is shown in Fig. 3. Two pairs of coils produce the fields in the $x$ and $y$ direction respectively, each coil having a diameter of $2^3/_8$ ″, a length of $2^3/_4$ ″ and 11 turns of $^3/_8$ $''$ diameter copper tubing. The coils were cooled by oil circulated through a heat exchanger. The coil system was mounted as rigidly as possible in a rather tight fitting copper box, whose top and bottom plates were silvered in order to obtain maximum $Q$. Although the arrangement of the leads was made in such a manner as to avoid coupling between the two systems, it appeared that the closed loop of the box represented a considerable coupling link. This was remedied by inserting an insulating strip between the top plate and the sides of the box. The top was then merely connected to the sides at a single point. In this arrangement, the two coil systems could be tuned almost completely independently. Top and bottom

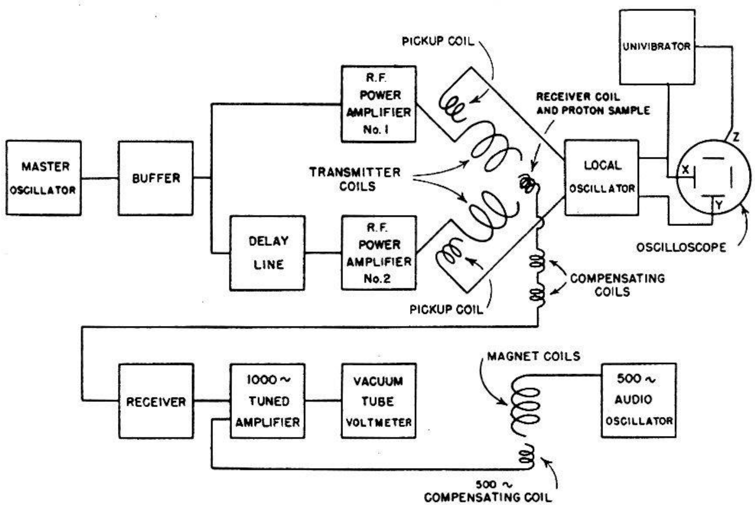



Fig. 5.

Block diagram of circuits for proton experiment.

plates were slotted to allow the modulating 500 c.p.s. field to penetrate to the center.

The two coaxial coils of each system were connected in series and each pair fed by a separate power amplifier. The phase shift of $90^0$ between the two systems was obtained in the following manner (Fig. 5). A self excited electron coupled oscillator whose frequency could be varied from about 1.5 to 3.5 MC delivered power to a buffer stage. Its output was applied to an artificial delay line with pseudo lumped elements. Its inductance consisted of a solenoidal coil of 2 $''$ diameter with 9.5 turns per cm. At regular intervals capacitors of 38 $\mu\,\mu\,F$ were connected to ground. The actual length of the whole line was $4^1/_4$$''$, its electric length $8.2 \cdot 10^3$ cm. A sliding contact permitted one to tap off the desired phase shifted voltage in very small steps. The line was terminated at the far end by its characteristic impedance of 725 $\Omega$, whereby an almost uniform voltage along the line was obtained. From the sending end and the tap point the exciting voltages were fed to the input of two independent intermediate power amplifiers of 25 Watts. Their output was delivered directly to the two coil systems for the proton induction experiment. For the neutron experiment, which required a much higher power output, additional amplifiers of 500 Watts each were inserted into each branch.

In order to obtain in the central region a circularly polarized field, two identical pickup coils were inserted along the $x$ and $y$ axis at the center of one of the $x$ and $y$ coils respectively. Measurements with a separate system of two identical pickup coils at right angles placed at the center of the four coils had shown that equal $x$ and $y$ components at the center of the system were obtained, when the fields at the centers of the individual coils were equal. The output of the $x$ and $y$ pickup coils were each fed to a heterodyning amplifier. This heterodyning circuit converted, by means of a local oscillator of frequency $\omega_0$, two harmonic voltages of frequency $\omega$ into two harmonic voltages of frequency $\omega - \omega_0$. At this frequency it was much simpler to observe phase relations directly with a usual cathode ray oscillograph. Heterodyning two voltages: $V_x = A \cos \omega t$ and $V_y = B \cos (\omega t + \delta)$ yields two voltages $V_x' \sim A \cos (\omega - \omega_0) t$ and $V_y' \sim B \cos [(\omega - \omega_0) t + \delta]$. The heterodyned voltages $V_x'$ and $V_y'$ therefore conserve their amplitudes and relative phase provided that the local oscillator frequency $\omega_0$ is smaller than $\omega$. The two heterodyned voltages $V_x'$ and $V_y'$ with a frequency of 85 Kc were after amplification applied to the deflector plates of a cathode ray tube. Phase shifts introduced by the amplifiers were eliminated by applying the same voltage to both the $V_x'$ and $V_y'$ input. The appearance of a straight line at $45^0$ indicated correct tuning of both amplifiers. If the application of the $V_x$ and $V_y$ pickup voltages to their respective inputs, yielded a circular pattern, the radio frequency field had the desired rotating character. A provision was made to determine at the same time the sense of rotation of the field. The heterodyned voltage $V_x'$ triggered on its ascending part a univibrator producing a square pulse of a duration equal to about $^1/_3$ to $^1/_2$ of the period of the heterodyned oscillation. The duration of this pulse could be varied by varying the RC value of the univibrator, whereby the trailing edge of the square pulse was advanced or retarded. This positive square pulse was applied to the $Z$ axis of the oscilloscope, whose beam intensity was normally biased below visibility. Consequently only part of the closed conic was visible and the beginning and the end of the arc could be distinguished by varying the duration of the square pulse. In the use of this device, care had to be taken that the local oscillator frequency was always lower than that of the signals. Frequent checks were made of the equality of amplification with respect to amplitude and phase of the two systems by applying the same voltage to both inputs and adjusting to a straight line with 45° slope. The device, of course, allowed only to ascertain a certain relative sense of rotation and gave no indication about the true absolute direction of $H_1$.

The radio frequency field $H_1$ was carefully measured over the region, which was to be occupied by the neutrons and protons. If the two transmitter coil pairs carry equal currents phase shifted by $\pi/2$, the field at the center of symmetry of the system will be a purely rotating one, but this is not true at any other point. The phase shift between the two components will still be $\pi/2$, provided that the $Q$ of the system is sufficiently large, so that phase shifts due to energy dissipation are small. At points off the center, however, the resultant oscillation will generally be elliptic, since the two oscillations are not at right angles to each other. The field distribution was measured with two pickup coils of equal wound area perpendicular to each other, with one normal parallel to the direction of propagation of the neutrons, and the other perpendicular to the static field $H_0$. Denoting these two directions by $\xi$ and $\eta$, the components $H_\xi$ and $H_\eta$ contain each components $H_x$ and $H_x'$ caused by the $x$ transmitter coil and components $H_y$ and $H_y'$, caused by the y transmitter coil. If the $x$ and $y$ fields have a phase difference of $\pi/2$, one can decompose the actual field at any point into two purely circular fields of amplitude $A^+$ and $A^-$ rotating in opposite directions according to the relations:

$$H_\xi = H_x \cos \omega t + H_y \sin \omega t = A^+ \cos (\omega t + \delta^+) + A^- \cos (\omega t + \delta^-)$$
$$H_\eta = H_x' \cos \omega t + H_y' \sin \omega t = A^+ \sin (\omega t + \delta^+) - A^- \sin (\omega t + \delta^-) \quad (5)$$

The four components $H_x\ H_x'\ H_y\ H_y'$ can be measured separately by turning off one or the other of the currents flowing in the $x$ or $y$ transmitter coils. The resultant rotating fields are given by:

$$\begin{aligned} A^+ &= \frac{1}{2} \sqrt{(H_x + H_y')^2 + (H_y - H_x')^2} \\ A^- &= \frac{1}{2} \sqrt{(H_x - H_y')^2 + (H_y + H_x')^2} \end{aligned} \quad (5\,\mathrm{a})$$

The field distribution along the axis of the neutron beam obtained in this manner is shown in Fig. 4. While the field $A^+$ rotating in the proper direction remains practically constant up to distances of more than 2″ from the center of the coil system, there is a component, rotating oppositely, whose amplitude increases rather rapidly from $^3/_4$″ on outward. A confinement of the radio frequency field within narrow regions by means of metallic shields appeared to be rather difficult. On the other hand it is obvious that the presence of the $A^-$ component could seriously affect our experiment, unless it is possible to avoid by other means the occurrence of nonadiabatic transitions beyond a certain distance from the center. Fortunately the static field $H_0$ whose distribution is shown in Fig. 2 drops off rapidly from the center, due to the particular size of the pole pieces. With reasonably low radio frequency fields one can thus expect that in the region with large $A^-$ component, the LARMOR frequency of the neutrons differs sufficiently from the frequency of the r. f. field, if the latter resonates with the LARMOR frequency at the center.

For the experiments with protons, a nuclear induction head was inserted in such a manner that the cylindrical sample of 1″ diameter and $1^1/_8$″ length with its axis parallel to the axis of the $x$ transmitter coils was located in a rather uniform constant field $H_0$, as well as in a purely rotating field $H_1$. A lucite rod carried the sample, the receiver coil of 50 turns and a compensating coil of 36 turns. The two coils have different wound area since they are exposed to different fields. The third compensating coil of only 5 turns was placed along the $y$ axis and compensated the out of phase leakage. All three coils were connected in series. Fine adjustment of the compensation to any desired value, usually several volts, was accomplished by two semicircular copper paddles which could be moved in an axial direction and also be rotated. The rotating field for the proton experiment was derived from the same transmitter used for the neutrons except that the last amplifier stage was ommitted since the magnitude of the rotating field was much smaller. With $H_0 = 540$ Gauss, the inhomogeneity of the field across the sample was only about 2 Gauss, requiring an r. f. field amplitude of about .7 Gauss. The power requirement therefore was much smaller than for the neutron experiment. The water sample was a .1 molar solution of manganese sulfate which had a relaxation time corresponding to maximum nuclear induction signal[10]).

Receiver and compensating coils connected in series were tuned to the frequency of the transmitter and the resultant voltage rectified by an electronic diode in connection with an RC network with a time constant which was small compared to $10^{-3}$ sec. The resultant audio frequency voltage was applied to a feedback amplifier tuned to 1000 c.p.s. by means of a twin $T$ network. Fig. 5 shows a block diagram of the various circuits. The output voltage of the amplifier was directly measured with an audio frequency tube voltmeter. The total gain was about 3000 and the breadth of the response curve about 40 c.p.s. A schematic representation of the various voltages is shown in Fig. 6 for the case of the $v$ component. The top curve represents the 500 c.p.s. modulation superimposed on the static field. If $H_A$ is the field value at which proton resonance occurs, the modulated radio frequency voltage of the symmetric com-

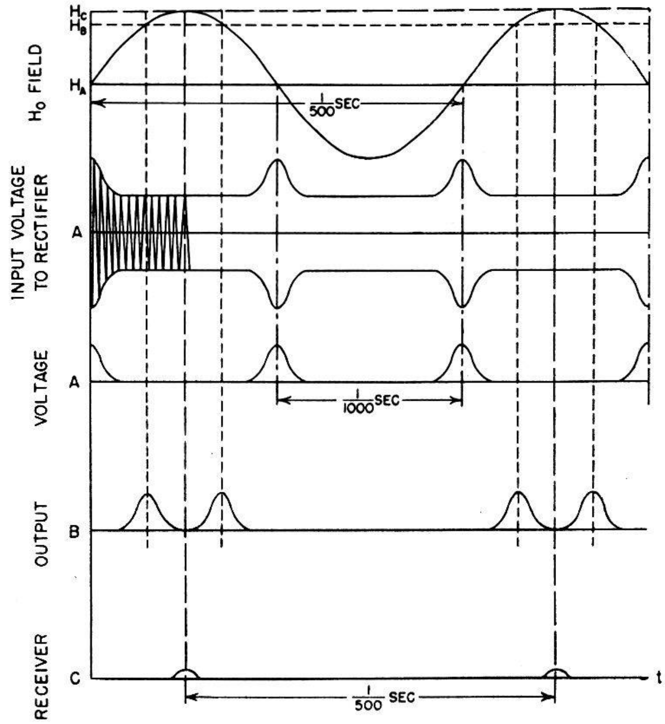



Fig. 6.

Schematic representation of rectifier output for symmetric proton signal with large modulation. $H_A$ $H_B$ $H_C$ represent three different values of $H_0$ for exact resonance. The three lower curves show the corresponding rectifier output voltage.

ponent across the receiver circuit has the appearance shown in the second curve drawn under the assumption of a modulation amplitude which is much larger than the width of the proton resonance. The third curve shows the output of the rectifier and it can be seen that in this case it contains only even harmonics. Shifting the resonance value of $H_0$ to the values $H_B$ or $H_C$ in the uppermost curve, a rectified output is obtained as shown in the two lower curves of Fig. 6. From these curves it is readily seen, that if one measures the amplitude of the second harmonic of the diode circuit output voltage as a function of the $H_0$ field, one obtains a resonance curve with a width approximately equal to the amplitude of the modulation. It also appears, that for a certain value of the modulation, the third curve would be an almost pure harmonic of twice the modulating frequency. This dependence of the second harmonic amplitude on the modulation was indeed observed. The actual signal voltage was always superimposed on a rather large 1000 c.p.s. voltage caused by the mechanical vibration of the receiver-transmitter system, when the static field was modulated. Unfortunately phase and amplitude of this microphonic voltage were extremely dependent on the actual value of $H_0$ and changed markedly even upon changes of $H_0$ of some 20 Gauss. The average microphonic voltage was compensated by adding to the input of the tuned amplifier a voltage of proper amplitude and phase derived from two pickup

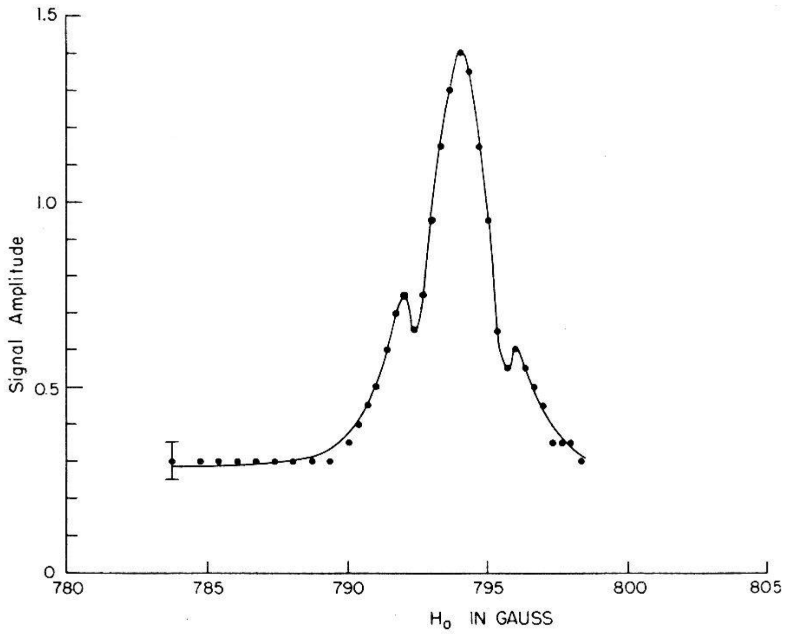



Fig. 7.
Resonance curve obtained with auxiliary nuclear induction apparatus.

coils wound directly on the pole pieces of the magnet. Nevertheless the observed signals were accompanied by a relatively slowly varying background. In principle this could have been avoided by varying the frequency of the rotating field, instead of varying the static field. This however was impractical, since for every frequency it would have required a complete retuning of the receiver system and an adjustment of the r.f. leakage voltage to the same phase and amplitude.

In the measurements of the neutron resonances an additional difficulty arose from the fact that the static field had to be varied over a considerable region. Hysteresis of the iron core of the magnet and temperature variations resulted in different values of the static field for the same value of the magnetizing current. Once a certain current was set, the field remained sufficiently constant to allow the measurements of the neutron transmission effect. The magnetic field was therefore directly measured before and after each transmission measurement by means of an auxiliary proton induction apparatus of conventional design. Its transmitter was a Hartley oscillator, the transmitter coil being the tank coil of a single tube oscillator. The receiver coil was rigidly mounted at right angles to the transmitter coil on the same lucite rod which could be inserted to the center of the static field. The transmitter frequency could be varied over a large region. It was measured accurately by means of a crystal controlled frequency meter. The output of the auxiliary proton induction apparatus was applied to the same tuned audio frequency amplifier used in the proton experiments. The resonance curves of the $v$ component were much narrower than those obtained with the rotating field, since the water sample was much smaller. Consequently the natural width of the signal was smaller and could be measured with less modulation. A sample of a resonance curve obtained with the auxiliary proton apparatus is shown in fig. 7.

## 4. Measurements and results.

The measurements with neutrons were performed in the same manner as described by Bloch, Nicodemus and Staub[2]). The number of neutrons transmitted through the system of polarizer, precession field and analyzer, was measured at a constant frequency of 2.2780 MC of the rotating field for various values of $H_0$ (as measured at the center by the auxiliary nuclear induction apparatus) with the radio frequency field turned on and off, and with the two different directions of rotation as determined by the heterodyning device. Denoting by $I$ the intensity with the rotating field on and by $I_0$ the intensity without, the transmission effect $E_T$ is given by

$$E_T = \frac{I - I_0}{I_0 - I_{cd}}$$

where $I_{cd}$ is the intensity measured with cadmium intercepting the neutron beam. This intensity was always the same irrespective of the presence of the r. f. field. As in the previous work[2]), the change from r. f. field on, to r. f. field off was done by a monitor in short intervals of about 1 minute duration. After twenty intervals with r. f. field on and off, the static field $H_0$ at the center of the precession magnet was checked by the auxiliary nuclear induction apparatus which could be quickly inserted after the rotating field had been turned off. The frequency of the auxiliary induction device at which the resonance maximum occurred was measured, and if it deviated more than a few tenth of one percent from the initial setting, the run was discarded. During the measurements, the current of the precession magnet was constantly checked and, if necessary, kept constant by manual control. Likewise, the frequency was continuously checked by heterodyning with a crystal controlled frequency meter. The r. f. field at the center was always made as perfectly circular as possible with the aid of the heterodyning indicator.

Since the precession field, as well as the rotating field, were strongly inhomogenuous, the most favorable value of the amplitude of the rotating field had to be determined. Denoting by $H_0$ the value of the static field at the center, the resonance dip in the curve of $E_T$ versus $H_0$ showed a sharp decline at low values of $H_0$ and a rather gradual tailing off from the minimum towards high values of $H_0$, if the proper sense of rotation of the r. f. field relative to the direction of the $H_0$ field was present. Reversing either the sense of rotation or the direction of $H_0$ resulted in very broad dips, whose centers were shifted towards high values of the $H_0$ field. The gradual tailing off with the proper sense of rotation, as well as the broad dip with opposite direction of rotation became both more pronounced with increasing amplitude of the rotating field. While it is rather difficult to predict the exact shape of these curves from the expression (1), their general character can be understood qualitatively. Let the r. f. field at the center be perfectly circular with an amplitude $A^+$ and rotating with constant frequency. If the magnitude of the precession field $H_0$ is raised, it will first satisfy the resonance conditions in the central region. If $A^+$ is not too small, neutrons will undergo transitions. If $H_0$ is further increased, regions of the precession field are brought to resonance which are located further away from the center and transitions will still occur, provided that there is still an appreciable rotating field in these regions. This will therefore lead to a gradual drop of the transition probability with increasing value of $H_0$. If the direction of rotation of the r. f. field is inverted, no resonance will occur at the center since the component $A^-$, as shown by Fig. 4, is zero. If, however, $H_0$ is raised so that off center regions satisfy the resonance condition, the presence of the $A^-$ component at these places will produce transitions and, in the case of the "wrong" sense of rotation, a broad and low dip shifted towards higher values of $H_0$ can be expected.

From the above consideration it follows that there must exist a certain rotating field amplitude at which the difference of the resonance dips for the two directions of rotation is most pronounced.

In order to establish this value, the dependence of $E_{T0}$, the resonance value of $E_T$ upon the amplitude of the radio frequency field was measured for the favorable sense of rotation. The result of this measurement is shown in Fig. 8. The errors indicated with the measured points are mean statistical errors. The absolute value of $E_{T0}$ increases first and after passing through a maximum should approach with a damped oscillation a constant value corresponding to a transition probability $P = {}^1/_2$ [2]). The available power was only sufficient to establish the occurrence of the first extremum. Its magnitude is 10.1% ± .7% in good agreement with the previous measurements[2]), where for the same spectral composition of the neutron beam and

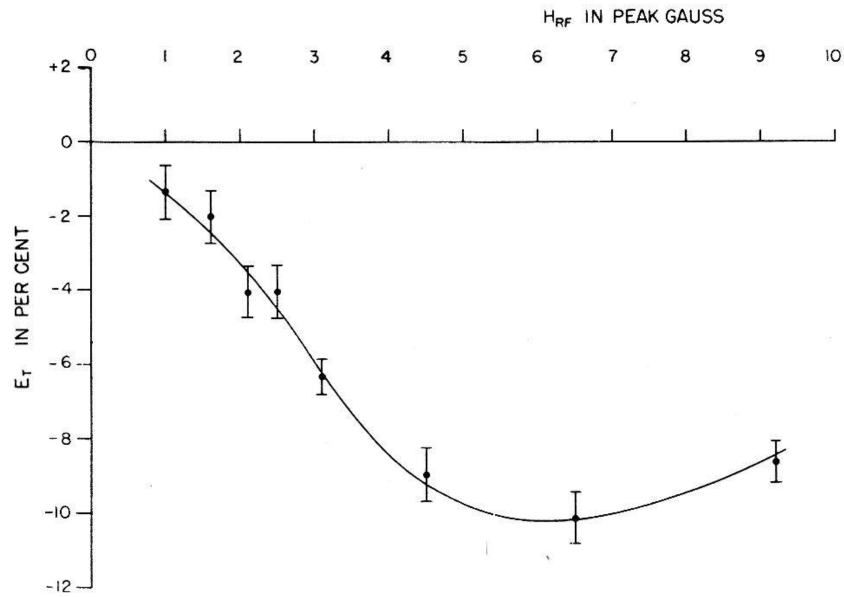



Fig. 8.

$E_{T0}$, the value of the transmission effect at exact resonance in % versus the amplitude of the r. f. field at the center rotating in the favorable direction.

the same polarizer and analyzer arrangement a value of 10.6% ± .7% was found. The value of the r. f. amplitude at which the maximum of $E_{T0}$ occurs is 6.5 Gauss. In the previous measurements the first extremum occurred at a peak oscillating amplitude of 10.0 Gauss or 5 Gauss for one rotating component at the center of the parabolically dropping r. f. field. This corresponds to a value of 33.8 Gauss cm for the expression $\int_0^L \overline{H}(x)\,dx$ of the region over which the r. f. field extends. Since the $A^+$ component in the present experiment is essentially constant over a considerable region, one would therefore conclude that the $H_0$ field was in resonance over a total length of about 2″. Since at $x = \pm 1''$ from the center the

$H_0$ field drops by 1.6%, the average $H_0$ field over this region is about 4 Gauss less than at the center. This is somewhat smaller than the half-width of the resonance dip and it is therefore to be expected that transitions occur over a region of approximately the above mentioned length.

Measurements with a rotating field of 6.5 Gauss at which the largest resonance dips were observed with the proper sense of rotation, showed that the tail of the resonance dip towards higher values of $H_0$ was extremely large. It was therefore to be expected, that a rather large dip would be observed upon reversal of the direction of rotation of the r. f. field. As a consequence, the final measure-

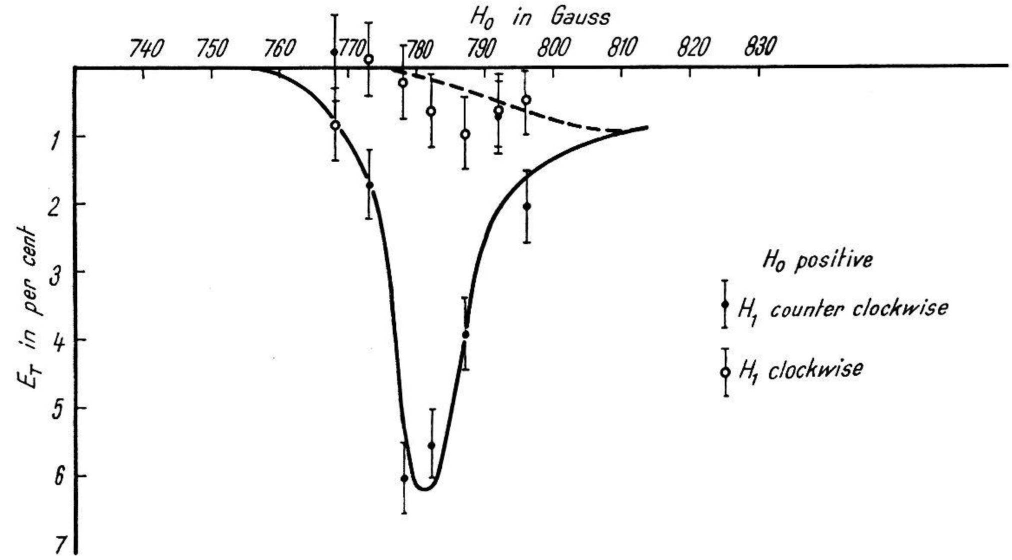



**Fig. 9.**
**Neutron transmission effect $E_T$ in % versus static field $H_0$ for $H_0$ "positive" and the two directions of rotation of $H_1$.**

ments were made at a value of 3.1 Gauss of the rotating field. The magnitude of the resonance dip was thereby reduced to 6.3% but the dip became much more pronounced and upon reversal only a small variation of $E_T$ appeared in the neighborhood of the resonance value of $H_0$.

In order to distinguish the various cases, the two directions of the $H_0$ field were arbitrarily called positive and negative. Similarly the two directions of rotation of the r. f. field were labeled clockwise and counter clockwise, according to the appearance of the trace on the indicator.

The results of the measurements for the four possible combinations of directions, i. e.: clockwise-positive, counter clockwise-positive, clockwise-negative and counter clockwise-negative are shown in Figures 9 and 10. Smooth curves were drawn through the observed points. The errors indicated are again mean statistical errors. The two combinations, $H_0$ positive-$H_1$ counter clockwise, and $H_0$ negative-$H_1$ clockwise show very clearly a pronounced resonance dip at $H_0 = 781$ G with a tailing off towards larger values of the $H_0$ field. From the known value of the neutron magnetic moment, one calculates for a frequency of 2.278 MC a resonant field $H_0 = 778$ G. The two other combinations show the complete absence of the main resonance dip, but a slight hump for values of the $H_0$ field at which the previous curves exhibit a tail of the resonance curve. This is

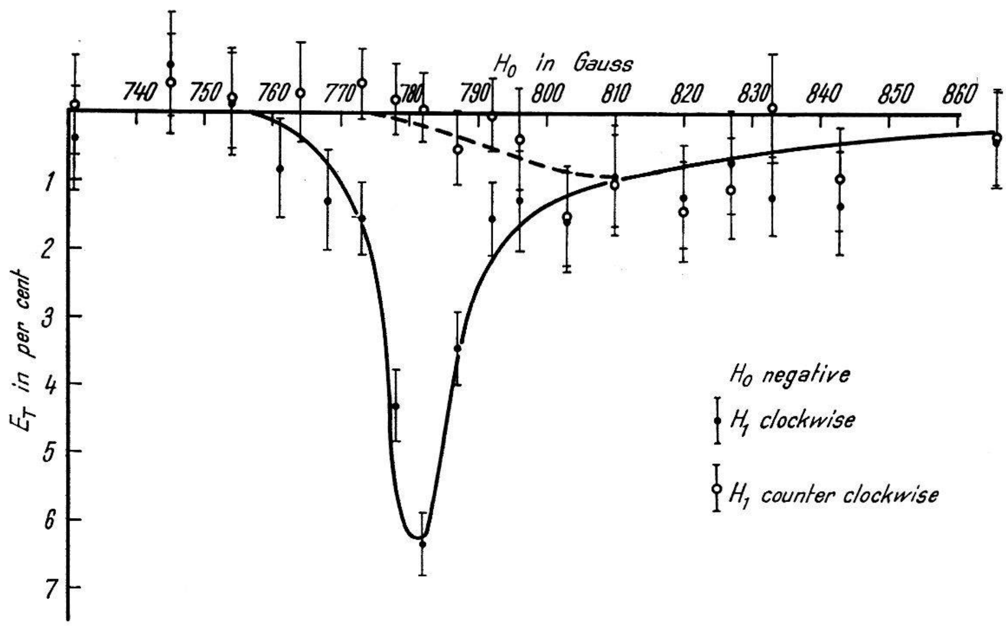



**Fig. 10.**
**Neutron transmission effect $E_T$ in % versus static field $H_0$ for $H_0$ "negative" and the two directions of rotation of $H_1$.**

clearly the result of the presence of a $A^-$ rotating component in regions where the $H_0$ field does not drop sufficiently quickly to prevent transitions of the neutrons. In order to check this point somewhat more quantitatively, an approximate calculation of the shape of the resonance dip for the favorable sense of rotation was performed. It was assumed that the rotating field component $A^+$ was constant over a region of $\pm 2''$ from the center. The parabolic variation of the static field $H_0$ was approximated over a region from $-2$ to $2''$ from the center by six steps of appropriate height and width as indicated in Fig. 2. Assuming, moreover, that the neutrons had a uniform velocity of about 2000 m/sec the quantum mechanical equations for the transition probability $P$ were solved. The result of this calculation together with the corresponding set of measured points is shown in Fig. 11. The calculated curve agrees qualitatively with the observations in as far as it exhibits the sharp drop at low values of $H_0$ and the gradual tailing off towards high values. The calculated minimum of $E_T$ was adjusted to the observed value. The calculated curve, however, shows a resonance dip which is somewhat broader than the observed one. On the other hand its tail decreases more rapidly. In view of the rather crude approximations, the general agreement of the calculation with the actual measurements is considered satisfactory. Particularly it appears that the explanation of the asymmetric drop of the resonance dip as the result of the particular configuration of static and rotating field is

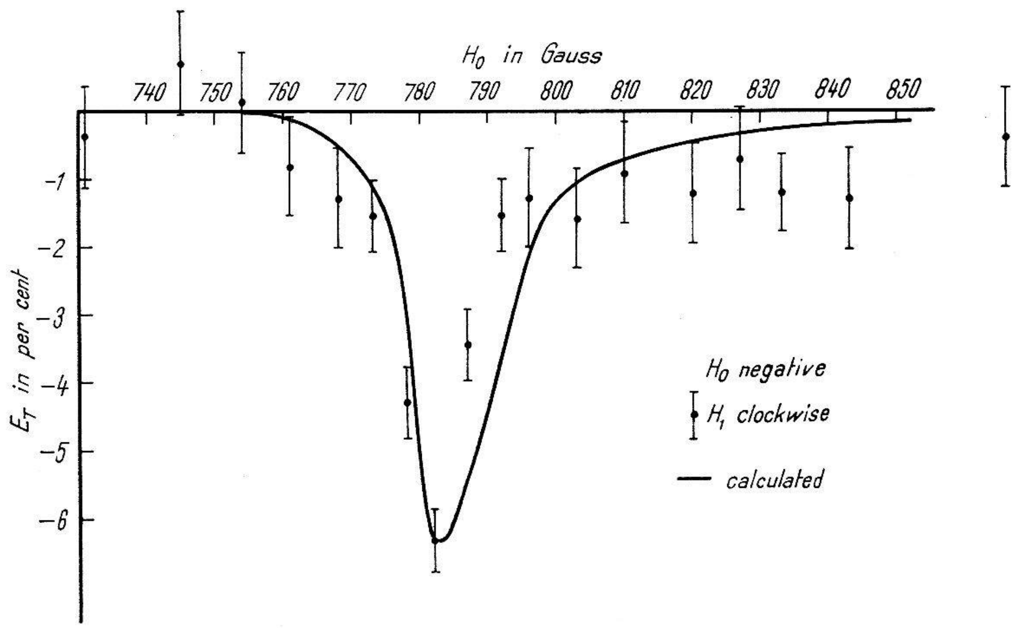



Fig. 11.
Comparison of measurements with calculation of the shape of the resonance dip. $H_0$ "negative"; $H_1$ clockwise. Solid curve calculated.

correct, since the calculation too gives the slow tailing off of the resonance curve towards high values of $H_0$.

In a second series of measurements, the behavior of the proton nuclear induction signal was investigated for the four combinations of directions of rotating and static field. The frequency of the r. f. field was kept at a constant value of 2.3000 MC, corresponding to a resonant static field of 539 Gauss. As indicated in the preceding section, these measurements were rather difficult because variations of the static field $H_0$ even over small regions changed the 1000 cycle leakage caused by microphonics in a rather erratic manner. Consequently the observed resonances were always superimposed on a variable background which, however, in no case exhibited rapid or pronounced variations. For the four combinations, the second harmonic of the $v$ component of the induction signal was measured. The $v$ component was obtained by adjusting first the leakage by means of the paddles to exactly zero and then allowing a small leakage of a few volts by a motion of the $y$ axis paddle. The results of these measurements are shown in Figures 12 and 13, where the audio frequency output voltage of the 1000 c. p. s. tuned amplifier is plotted for the various values of the static field $H_0$. As in the case of the neutrons, the rotating field was made as perfectly circular as possible and its direction infered from the indicator, thus assigning to a particular situation the same signs as

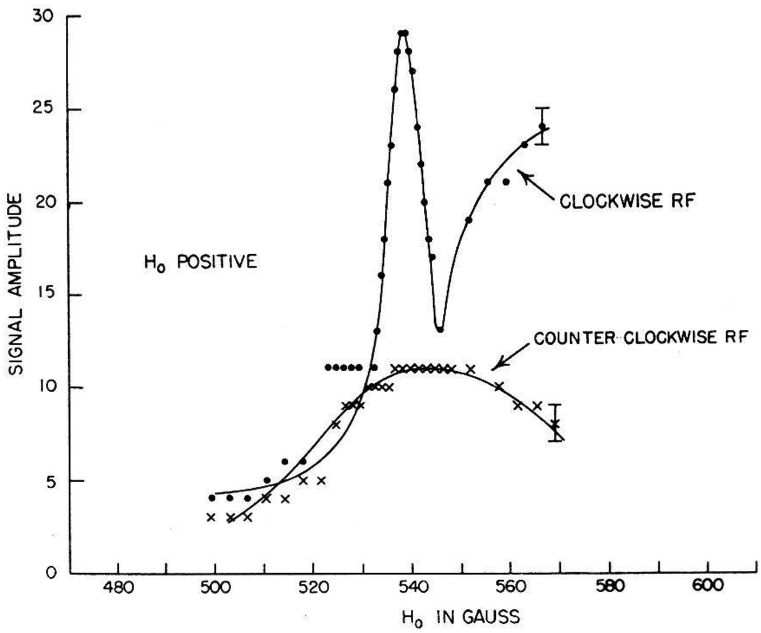



Fig. 12.
Proton nuclear induction signal versus static field $H_0$ for $H_0$ "positive" and the two directions of rotation of $H_1$.

in the neutron experiment. It was, of course, always carefully ascertained that the local oscillator frequency was lower than the frequency of the r. f. field (see section 3). The static field $H_0$ was modulated with an amplitude of a few Gauss and the amplitude of the rotating field in the center was .7 Gauss. The errors indicated at the measured points represent the mean square fluctuation of the meter reading during the short period ( $\sim$ 1 sec.) of observation. Any extended observation time resulted in drifts of the microphonic leakage. Such effects were responsible for the small discontinuities which certain points show in Figures 12 and 13. Since the microphonic leakage could not be compensated to exactly the same value for the different cases, the background differs for the various curves. It should also be noted that the phase of the background, relative to the signal has a definite effect on the particular shape of the resonance curve. If, for instance, the background is in phase with the second harmonic signal at exact resonance, the resonance peak will exhibit two minima on each side which, if the leakage were absent, would appear as maxima. These peaks are the result of the different signs of the curvature of the resonance curve at its center and at its flank. If the microphonic background would be out of phase by $\pi/2$ with the second harmonic of the signal and both voltages were about equal, the observed resonance dip would be considerably decreased. Great care was taken therefore to compensate the micro-

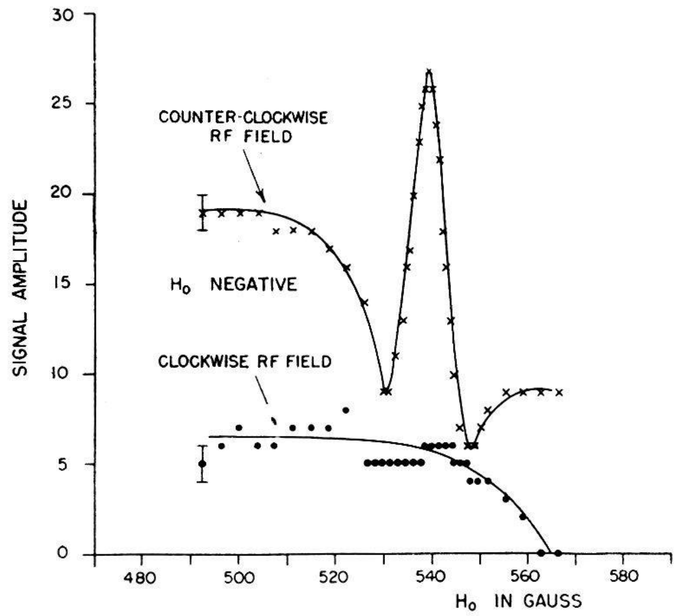



Fig. 13.

**Proton nuclear induction signal versus static field $H_0$ for $H_0$ "negative" and the two directions of rotation of $H_1$.**

phonic voltage at the approximate center of the resonance to as small a value as possible. The curves of Figures 12 and 13 show again very clearly the complete absence of a resonance signal for two combinations (negative clockwise and positive counter clockwise), while the other two exhibit pronounced peaks at a field of 540 Gauss. Their half-width at half-maximum is about 4 Gauss as it should be expected from the values of the amplitude of the modulating and rotating field. As a check on the reliability of the procedure, an antisymmetric $u$ component signal was also investigated. The phase of the r. f. leakage was changed by means of the paddles in such a manner that the leakage was now solely due to the $x$ transmitter coil. The result of this measurement is shown in Fig. 14, which clearly indicates an antisymmetric signal of the expected shape appearing with the combination positive-clockwise at $H_0 = 540$ Gauss.

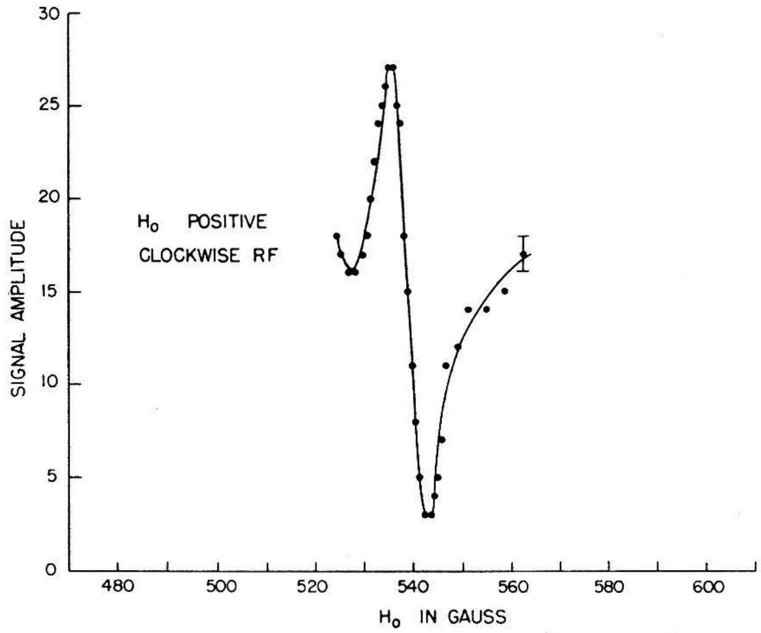



Fig. 14.
Antisymmetric (u component) signal of proton resonance. $H_0$ "positive" $H_1$ "clockwise".

The results of neutron and proton experiments are summarized in table 1.

**Table 1.**

| Direction of precession field | Rotational sense of r. f. field | Proton resonance | Neutron resonance |
|---|---|---|---|
| $H_0$ negative | clockwise | no | yes |
| $H_0$ negative | counter clockwise | yes | no |
| $H_0$ positive | clockwise | yes | no |
| $H_0$ positive | counter clockwise | no | yes |

They clearly show that those combinations which lead to the appearance of a resonance signal in the case of protons, are characterized by the absence of the neutron resonance. One has therefore to conclude that the moments of the two particles are indeed of opposite signs.

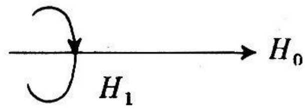
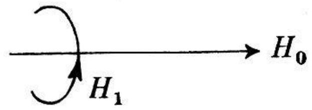
In a last series of measurements, the proper determination of the so far arbitrarily labeled directions of $H_0$ and the sense of $H_1$ was undertaken. The true sign of the direction of a magnetic field is determined by the expression for the LORENTZ force on a moving charge

$$\vec{F} = {}^{e}/_{c} [\vec{v}\ \vec{H}]$$

The true direction of the static field $H_0$ was first determined by comparison with the field of the cyclotron by means of a flip coil. The direction of the cyclotron field is known from the manner in which positive deuteron ions are accelerated and electrostatically deflected to the target. A second determination was made by observing the direction of the force exerted on a current carrying wire in the gap of the precession magnet. Both measurements gave the same absolute direction of the field for the direction previously called $H_0$ positive. They also agreed with a determination made from the direction of the current in the magnetizing coils.

The absolute direction of rotation of the r. f. field, i. e. the calibration of the indicator was also made in two different ways. Two small probe coils were placed at right angles to each other. The directions of the windings were clearly marked on the ends of each coil. The two coils were then placed into the center of the r. f. field, such that the normals to their planes pointed parallel to the $x$ and $y$ transmitter coils respectively. The absolute direction of rotation in space of the r. f. field could therefore be ascertained by determining which of the two induced sinusoidal voltages was leading the other. Since the operation of the available oscilloscope at 2.3 MC was difficult, the voltages of the two coils were heterodyned by a local oscillator, whose frequency was 85 KC less than 2.3 MC. A third pickup coil, whose output was likewise mixed to give a beat frequency of 85 KC, was used to synchronize the linear sweep of the oscilloscope. The heterodyned voltages were alternatingly amplified with the same amplifier and applied to the vertical deflection plates of the oscilloscope. The direction of the linear sweep of the latter was determined by observing the exponential decay of a condenser discharging through a resistor. The phase shift of the two induced voltages could then be directly read by applying these voltages alternatingly to the oscilloscope. A second determination of the direction of rotation was made by inspecting the geometrical arrangement of the two transmitter coil pairs and the direction of their windings and by ascertaining which of the two pairs was fed by the voltage derived from the delay line. If both subsequent amplifiers are tuned at least approximately equally close to resonance, and if all connections are made in a similar way for both systems, the pair of coils fed from the delay line must be lagging in phase by $\pi/2$*. From these facts, the direction of rotation was determined. The consistent results of these determinations are summarized in table 2.

**Table 2.**

| | Arbitrary notation: | True direction of rotation of $H_1$ relative to $H_0$ |
|---|---|---|
| 1. | $H_0$ positive — $H_1$ counter clockwise<br>$H_0$ negative — $H_1$ clockwise | $H_1$ rotates in a right hand direction about $H_0$<br>  |
| 2. | $H_0$ positive $H_1$ clockwise<br>$H_0$ negative — $H_1$ counter clockwise | $H_1$ rotates in a left hand direction about $H_0$<br>  |

The proton signal appears in the two combinations listed under 2. If the moment $\vec{\mu}$ of the proton is positive, it is co-directional with its angular momentum $\vec{J}$. The torque exerted by a field $\vec{H}_0$ will be of the form $\vec{T} = [\vec{\mu}\,\vec{H}_0]$. Consequently the vector $\vec{J}$ will rotate in a left hand direction about $\vec{H}_0$ in the same manner as $\vec{H}_1$ rotates about $\vec{H}_0$ in the combinations listed under 2. It appears therefore from the present experiments, in agreement with the results of Powers[1]), Rabi and his collaborators[5]) and the theoretical considerations discussed in section 1, that the sign of the magnetic moment of the proton is positive, that of the neutron negative.

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*) The fact that the delay was $\pi/2$ rather than $3\,\pi/2$ followed unmistakably from the closeness of the tap point to the sending end of the delay line.

*References.*

[1]) H. Taub and P. Kusch, Phys. Rev. **75**, 1481 (1949).

[2]) F. Bloch, D. B. Nicodemus and H. H. Staub, Phys. Rev. **74**, 1025 (1948).

[3]) H. A. Bethe, Elementary nuclear theory, John Wiley and sons, New York 1947.

[4]) J. M. B. Kellogg, I. I. Rabi, N. F. Ramsey jr. and J. R. Zacharias, Phys. Rev. **57**, 677 (1940).

[5]) J. M. B. Kellogg, I. I. Rabi, N. F. Ramsey jr. and J. R. Zacharias, Phys. Rev. **56**, 728 (1940).

[6]) S. Millman, Phys. Rev. **55**, 628 (1939).

[7]) P. N. Powers, Phys. Rev. **54**, 827 (1938).

[8]) I. I. Rabi, Phys. Rev. **51**, 652 (1937).

[9]) F. Bloch and A. Siegert, Phys. Rev. **57**, 522 (1940).

[10]) F. Bloch, Phys. Rev. **70**, 460 (1946).

[11]) E. M. Purcell, H. C. Torrey and R. V. Pund, Phys. Rev. **69**, 37 (1946).