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Determination and Stabilization of Magnetic Field Strengths by Means of Proton Magnetic Resonance

by

Richard Daniel Jones

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INTRODUCTION

Since the original work on the detection of nuclear magnetic resonance in bulk matter,\textsuperscript{1}\textsuperscript{2} many improvements in technique and method have been introduced by various workers.\textsuperscript{3}\textsuperscript{7} These new techniques have made possible the determination of gyromagnetic ratios of a large number of nuclei. Moreover, these techniques have found wide applications in the study of spin-lattice interactions and, for this reason, are also of interest.

The possibility of utilizing this phenomenon in the stabilization of magnetic fields and the accurate determination of field strength has been suggested in the literature.\textsuperscript{8} Hopkins, Pound, and Knight have described simple instruments employing the absorption method to determine the field strength over a wide range,\textsuperscript{9}\textsuperscript{10} while Packard has used the induction method for the automatic stabilization of magnetic fields at certain fixed field strengths.\textsuperscript{11}

\begin{itemize}
\end{itemize}
This paper contains a discussion of the techniques employed in the observation of proton magnetic resonance absorption and in addition describes a simple instrument capable of stabilizing the magnetic field over a wide range of field strengths. This instrument is more flexible than the one developed by Packard.12

A unique feature of this instrument is the probe which occupies a very small volume and provides its own sweeping field. The physical dimensions are such that the probe can be used in a narrow gap annular magnet used for the determination of particle energies.

THEORY

In observing nuclear magnetic resonance, generally, an equilibrium condition is set up. This steady state results from the competition between an applied r-f magnetic field on one hand and on the other hand the effect of the interactions of the nuclear spin system. The r-f field tends to equalize the populations of the Zeeman levels and thus to demagnetize the system, while the interactions tend always to restore the system to thermal equilibrium as governed by the Boltzmann distribution.

If \( \vec{J} \) is the total angular momentum operator for the nucleus, then its square has the eigenvalues \( J(J+1) \hbar^2 \). The states characteristic of the square of the total angular momentum are also characteristic of the energy. In the absence of a field, these states are \( 2J+1 \) fold degenerate, which means that there are \( 2J+1 \) wave functions corre-

12 Martin E. Packard, Rev. Sci. Inst. 19, 435 (1938)
When the spin system is immersed in a constant magnetic field, the 
$2J+1$ fold degeneracy in the energy is removed. The states 
are now separated from one another by a constant energy difference, $E_0$, 
which is proportional to the strength of the field. Transitions between 
these states allow the absorption (and reradiation) of energy without 
exciting the nucleus or electronic structure. Frequencies corresponding 
to such transitions belong to the short wave region of the radio apac-
trum, each transition carrying with it a small amount of energy:

$$E_0 = \hbar \Delta.$$ 

A perturbing field, of amplitude $2\hbar^2$, applied at right angles 
to the steady field supplies the energy required to effect the desired 
transition. The absorption of energy from this perturbing field may be 
observed if its angular frequency is of the order of the angular fre-
quency of the forced Larmor precession.

For the purpose of this discussion, a classical approach to the 
problem will be sufficient. We shall consider the behavior of the great 
number of nuclei contained in a macroscopic sample of matter and acted 
on by two external fields: a strong constant field and at right angles 
to it a comparatively weak r-f field. In order to simplify the explana-
tion of the principle, we shall omit some of the complicating factors 
and assume:

(1) Changes of orientation of each nucleus are due solely 
to the presence of the external fields.

(2) External fields are uniform throughout the sample.
The second assumption is not serious and can be satisfied by sufficient perfection of the experimental arrangement. The first assumption is very drastic, and the following conditions should be satisfied for its acceptance:

(1) Atomic electrons do not cause appreciable fields to act upon the nuclei.

(2) Interactions between neighboring nuclei can be neglected.

(3) Thermal agitation does not essentially affect the nuclei, i.e., relaxation time is long compared to the considered time intervals.

Accepting these assumptions, the discussion becomes comparatively simple.

Ehrenfest showed that if the probability distribution of the position of a particle is essentially localized in a small volume, the average values of the coordinates will change in a manner very similar to the change of the precisely defined coordinates in the classical theory. In the special case of a system of particles subject to conservative forces, it is shown in works on quantum mechanics that the connection between the average momentum of a particle and the rate of change of its average coordinate is rigorously the same as in classical mechanics and that this relationship is subject to no restriction whatever.\(^{13}\)

Now, if \(\mathbf{A}\) denotes the resultant angular momentum per unit volume of a great number of nuclei contained in a macroscopic sample, we have for the torque

\[
\frac{d\mathbf{A}}{dt} = \mathbf{T}
\]

(1)

\(^{13}\) W. V. Houston, *Quantum Mechanics*, p. 87
Let \( \vec{M} \) represent the nuclear magnetization, i.e., the resultant nuclear moment per unit volume. Then the torque exerted on the nuclei by a field \( \vec{H} \) is given by

\[
\vec{T} = \vec{M} \times \vec{H}
\]

(2)

Since the magnetic moment \( \vec{\mu} \) and the angular momentum \( \vec{\sigma} \) of each nucleus are parallel or antiparallel to each other, we have

\[
\vec{\mu} = \gamma \vec{\sigma}
\]

(3)

where \( \gamma \) is the gyromagnetic ratio. By assigning \( \gamma \) a positive or negative value, we include both cases of \( \vec{\mu} \) and \( \vec{\sigma} \) being parallel and opposite respectively. In the case of a rotating positive charge, they are parallel. Then for the resulting quantities \( \vec{M} \) and \( \vec{A} \),

\[
\vec{M} = \gamma \vec{A}
\]

(4)

From (1) and (2)

\[
\frac{d\vec{A}}{dt} = \vec{M} \times \vec{H}
\]

(5)

then

\[
\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{H}
\]

(6)

Let us suppose that a sample of material with non-vanishing nuclear moments is placed in an applied magnetic field consisting of two components: a steady component of magnitude \( H_0 \) oriented in the \( \Xi \) direction and an oscillating component in the \( \Xi \) direction.
\[
\begin{aligned}
H_x &= 2H_t \cos \omega t \\
H_y &= 0 \\
H_z &= H_o 
\end{aligned}
\]  

(7)

Now the oscillating component can be further decomposed into two circularly polarized components in the \(x-y\) plane rotating in opposite directions about the \(z\) axis. Then the oscillating field can be represented by

\[
\begin{aligned}
H_x &= H_t \cos \omega t \\
H_y &= \mp H_t \sin \omega t 
\end{aligned}
\]  

(8)

The sense of the rotation will be taken as negative or positive, depending upon whether the sign of \(\gamma\) is positive or negative. Only one of the two circularly polarized components, namely, that one rotating in the same sense as the free Larmor precession of the nuclear moment, is effective in disorienting the nuclear moment. The other will be completely ignored since this field has an insignificant effect averaged out over a large number of Larmor periods.

For our purposes, we are interested in a special solution of equation (6) which can be obtained if we make the following assumptions:

1. Both \(H_o\) and \(H_t\) are constant and \(H_t < < H_o\)

2. \(\omega\) of the r-f field is in the neighborhood of the resonance frequency, \(\omega_o\), given by

\[
\omega_o = \gamma H_o
\]  

(9)

Repeating equation (6)

\[
\frac{d\vec{M}}{dt} = \gamma \vec{M} \times \vec{H}
\]
it follows immediately that $\frac{d\vec{M}}{dt}$ is perpendicular to both $\vec{M}$ and $\vec{H}$.

Thus $\vec{M}$ does not change in magnitude but only in direction. Moreover there is a special solution for which $M_x$, the $x$ component of the magnetization, is likewise constant. Introducing the polar angle $\theta$, this solution can be written

$$\begin{cases}
M_x = M \sin \theta \cos \omega t \\
M_y = \mp M \sin \theta \sin \omega t \\
M_z = M \cos \theta
\end{cases} \quad (10)$$

Rewriting (6) in terms of its components and substituting (10), we have

$$\frac{d}{dt} M_x = \chi \left[ M_y H_z - H_y M_z \right]$$

$$-\omega M \sin \theta \sin \omega t = \chi \left[ \mp M H_0 \sin \omega t \sin \theta \pm M \cos \theta H_1 \sin \omega t \right]$$

$$-\omega \sin \theta = \chi \left[ \mp H_0 \sin \theta \pm H_1 \cos \theta \right]$$

$$\pm \chi H_0 - \omega \right) \sin \theta = \pm \chi H_1 \cos \theta$$

$$\tan \theta = \frac{\chi H_1}{\chi H_0 - \omega} \quad (11)$$

Thus we see that (6) is satisfied by (10) if $\theta$ is constant and chosen such that (11) holds. The minus or plus sign depends on whether $\chi$ is positive or negative respectively.

If we let

$$H^* = \frac{\omega}{|\chi|} \quad (12)$$

denote the resonance field at frequency $\omega$, i.e., that field $H$ for which the Larmor frequency,

$$\omega_L = \frac{\chi}{H} \quad (13)$$
is equal to the frequency $\omega$ of the oscillating field, we can write (11) in the form

$$\tan \theta = \frac{H_1}{H_0 - H^*}. \quad (14)$$

Equations (10) represent a solution for which the magnetization rotates around the $z$ direction, i.e., around the strong field $\vec{H}_0$ in such a way that it lies at any instant in the common plane of this field and the effective rotating field (8). The angle $\theta$ between $\vec{H}_0$ and the magnetization follows from (14) to be small, as long as $H_0$ is appreciably larger than the resonance field $H^*$. The direction of $\vec{M}$ starts to deviate noticeably from the $z$ direction as the difference $H_0 - H^*$ becomes comparable or small compared to the magnitude $H_1$ of the effective rotating field.

It is perpendicular to the $z$ axis for $H_0 = H^*$ and for still further decreasing values of $H_0$ turns toward the negative $z$ direction, finally pointing in a direction opposite to $\vec{H}_0$ for $H^* - H_0 < H_1$.

Introducing the difference,

$$\cot \theta = \frac{H_0 - H^*}{H_1} = \Delta, \quad (15)$$

between the actual $z$ field $H_0$ and its resonance value $H^*$ in terms of the magnitude of the effective rotating field (8) or the half amplitude of the actual oscillating field (7) in the $x$ direction, equations (10) may be rewritten

$$M_x = M \sin \theta \cos \omega t = \frac{M \cos \omega t}{\sin \theta} = \frac{M \cos \omega t}{(1 + \cot^2 \theta)^{1/2}}. \quad (16)$$
FIGURE 1
Thus we have

$$\begin{align*}
 M_x &= M \frac{\cos \omega t}{(1 + \delta^2)^{1/2}} \\
 M_y &= \mp M \frac{\sin \omega t}{(1 + \delta^2)^{1/2}} \\
 M_z &= M \frac{\delta}{(1 + \delta^2)^{1/2}}
\end{align*}$$

(16)

This clearly shows the increase of the rotating component of \( \vec{M} \) upon approach to resonance, i.e., at resonance \( H_0 = H^* \) and thus \( \delta = 0 \).

In order to obtain an oscilloscopic presentation of the resonance absorption pattern of a nuclear spin system immersed in a magnetic field, it is necessary that \( \delta \) undergoes a periodic variation. For constant \( H_1 \), variations of \( \delta \) can take place through either of two procedures.

1. \( H_0 \) constant, \( \omega \) slowly varied, i.e., \( H^* \) slowly varied
2. \( \omega \) constant, \( H_0 \) slowly varied

Both procedures have been used; however, the second is accomplished more easily and therefore is generally preferred.

In contrast to the familiar atomic paramagnetism which establishes itself almost immediately upon application of the magnetizing field, there is no assurance for the same thing being true in the nuclear case. The time of establishment or relaxation time can be expected to vary anywhere between fractions of a second and many hours, depending upon the nuclear moments, the electronic structure of the atoms in the sample, their distance and their motion. If the natural relaxation time should turn out to be inconveniently long, the establishment of
thermal equilibrium can be greatly accelerated by the use of paramagnetic catalysts.

For the following purposes we shall assume that the thermal equilibrium between the nuclear moments and their surrounding atoms has been actually established in an external magnetic field of strength $H$. Let $T$ be the equilibrium temperature and $n$ the number of nuclei per unit volume, each having a magnetic moment $\mu$ and an angular momentum $a = \frac{\hbar}{2\pi}$. 

From statistical mechanics we have the nuclear paramagnetic susceptibility

$$\chi = \frac{\hbar^2}{3} \left( \frac{n\mu^2}{kT} \right)$$

in which it is assumed that $H\mu \ll kT$. This condition will always be very well satisfied, except for extraordinarily strong fields or exceedingly low temperatures. Substituting the values given by (3) and (17), equation (24) can be rewritten

$$\chi = n \frac{\hbar^2}{3kT} \left( \frac{kT}{2\pi} \right)^2.$$

In experimental practice, the nuclei occupy a small volume between the poles of a magnet so that the field of the magnet is homogeneous over the sample. The oscillating field is produced by an r-f current passing through a wire wound about the sample in such a way as to give the field a constant amplitude over the sample region. Let us now
consider the change in the r-f voltage across the coil due to nuclear resonance. The induction is given by

$$B_x = 4\pi M_x$$

(20)

and if $N$ turns of the coil surround a cross sectional area $A$ of the sample, we obtain for the effective flux through the coil

$$\phi = 4\pi N A M_x = 4\pi N A M \frac{\cos \omega t}{(1 + \delta^2)^{1/2}}$$

(21)

and for the induced voltage across the terminals of the coil

$$V = -\frac{1}{C} \frac{d\phi}{dt} = \frac{4\pi N A M}{C} \frac{\sin \omega t}{(1 + \delta^2)^{1/2}}$$

(22)

where the variation of $\delta$ has been considered slow enough so that its time derivative can be neglected compared to that of $\cos \omega t$.

The amplitude of the r-f voltage $V$ evidently reaches a maximum at resonance, i.e., for $\delta = 0$, so that here the z field, $H_0$, has, according to (12) and (13), the value

$$H_0 = \frac{\omega}{k_1} = H^*$$

(23)

We shall now assume that the sample has been in a field $H_0 = H > H^*$ for a time long enough that $M$ has reached its thermal equilibrium value, corresponding to that field, and is given by

$$M = \chi H$$

(24)
If now $H_0$ starts to decrease and if our previous assumptions, and particularly that of the constancy of $M$, remain valid, we can substitute this value into (22), thus obtaining

$$V = \frac{4\pi}{c} NAXH \omega \frac{\sin \omega t}{(1 + \delta^2)^{1/2}}.$$  \hspace{1cm} (25)

It is sufficient for the equilibrium field $H$ to be larger than the resonance field $H^\ast$ only by a small percentage, i.e., by several times the relatively weak field $H_0$, in order that thermal equilibrium can be established under non-resonant conditions. If we assume this to be actually the case, we can substitute in (25) the resonance value given by (23). Then applying equation (19), we have finally

$$V = \frac{1}{\pi c} NAX \frac{\omega^2}{3kT} \frac{1}{\delta^2} \frac{\sin \omega t}{(1 + \delta^2)^{1/2}}.$$  \hspace{1cm} (26)

The tuned circuit, of which the coil containing the sample forms a part, will be assumed to have an unloaded quality factor $Q_o$ and an unloaded shunt conductance $g$. The definition of $Q_o$ is given by

$$Q_o = \frac{\omega W}{P_o} \hspace{1cm} (27)$$

where

$$W = \left( \frac{1}{2\pi} \right) H_0^2 V_c \hspace{1cm} (28)$$

is the energy stored in the tuned circuit, $V_c$ is the effective volume of
the coil and

\[ P_0 = \frac{V^2}{2\omega} \]  

\[(29)\]

is the power dissipated in the unloaded circuit. Thus

\[ Q_0 = \frac{\omega a}{\pi V^2} H_1^2 V_c \]  

\[(30)\]

and substituting the value of \( V \) given by \( (26) \) we have

\[ Q_0 = \frac{\pi V_c a}{\omega^3} \left[ \frac{c H_1 kT}{N \pi A i (1+i) \hbar^2 \sqrt{\omega} \sin \omega t} \right]^2 (1+\delta^2) \]  

\[(31)\]

The \( Q_0 \), then, represents the ratio of the energy stored in the r-f field to the energy lost from the r-f field to the system of nuclear spins. The effect of the nuclear resonance on the circuit is to reduce the \( Q \) of the circuit from \( Q_0 \) to a value \( Q_r \). To obtain the largest signal for detection with a circuit of a given \( Q \), it is now apparent that the addition of the loss attributable to \( \delta \) should produce the largest possible change in the voltage across the tuned circuit.

In the absorption method of observing nuclear magnetic resonance, the r-f field is generally produced in the coil by connecting it to an electronic circuit that forms a two terminal negative resistance. In order to just sustain oscillation in the resonating circuit, the magnitude of the negative resistance must be just equal to the positive shunt resistance of the tuned circuit. Because of the curvature of the tube characteristics is small for the small voltage swing when \( \delta = 0 \), the level of oscillation is sensitive to the small changes in shunt resistance.
resulting from passing through a nuclear resonance. Such variations in level are observed as variations in the amplified r-f voltage after rectification. The effective gain of the circuit varies widely with the operating level and is highest at the oscillation threshold.

APPARATUS

The apparatus consists of a probe, r-f oscillator and detector, a-f amplifier, discriminator, and regulator together with their associated power supplies. In addition, an oscilloscope, to monitor the resonance signal, and a variable frequency standard, to check the perturbational frequency, are included.

In order to know that the observed amplifier output is caused by nuclear moments and not by an unknown cause, it is essential that the signal due to nuclear moments be varied or modulated in some known and controllable manner in which case outputs are real or spurious according as they do or do not correspond to the known modulation. Accordingly the steady magnetic field is modulated, at a 60 cycle rate, by sweeping coils mounted coaxially with the steady field direction.

Presentation of the resonance signal is made on a cathode ray oscilloscope with the horizontal plates giving a deflection proportional to the variation in $H$ and the vertical plates giving a deflection proportional to the signal which in turn depends on the $x$ component of the nuclear magnetization. Thus one observes on the screen a plot of $H_x$ versus $H$, the center of the trace corresponding to $H_0$.

The proton magnetic resonance signal beats against the sweep voltage in the discriminator, producing a d.c. frequency-difference volt-
ago. The value of the d.c. voltage is a linear function of the amplitude of the signal, and the sign is determined by the relative phase of the sweep voltage and the signal. This voltage is proportional to the derivative of the absorption curve. Thus the discrimination converts the resonance signal into a usable d.c. voltage suitable for operating a regulator. The regulator is of the degenerative type and changes the current through the magnet in order to maintain the relationship

\[ H_0 = H^* \]

We may summarize by giving, in figure 2, a block diagram of the complete apparatus.

The sample coil and sweeping coils are incorporated in a pill-box-shaped probe which fits into the gap of the magnet. In turn, the probe plugs into a small aluminum chassis containing the 6AK5 regenerative detector together with the tuning condenser and regeneration control. Both these controls are driven by geared verniers designed for minimum backlash. The variable capacitor is of the straight line frequency type, and the plates are triple spaced. All fixed capacitors are zero temperature coefficient ceramics or "silver micas." Connections to the rest of the apparatus are made through short lengths of coaxial cable running from amphenol sockets mounted on the r-f chassis. Referring to figure 3, \( P_1 \) is the r-f input from a variable frequency standard, \( P_2 \) is the input from a 6 volt d.c. filament supply, while \( P_3 \) is the audio output.

The absorption signal is fed directly into a conventional three stage audio amplifier, and from there to the vertical amplifier of the monitoring oscilloscope and the buffer stage preceding the discriminator. This stage consists of a cathode follower and its function is to isolate the discriminator from the audio amplifier.
For convenience a sweep frequency of 60 cycles is used. The sweeping current is obtained from a 6V3 volt filament transformer, and the sweep amplitude is controlled by a variac in the primary circuit of this transformer. Connections are made from the secondary to the sweep coils on the probe and the horizontal monitoring scope. In addition, the same signal is applied across the primary of an audio transformer with a 1:1 ratio between the primary and secondary windings. Referring to figure 4, the secondary of the audio transformer, together with the 100K potentiometer and 0.25 uf capacitor, comprises a phase adjustment circuit. The output of the 6J5 sweep inverter is fed into the sweep section of the discriminator.

The discriminator used in this apparatus consists of a 6SN7 with plates in parallel, cathodes in parallel, and the sweep and resonance signal are applied to the two grids. The condenser across the plate load resistors filters out the 60 cycle so that only a d.c. voltage is left. This voltage will be positive or negative with respect to the zero signal voltage, depending on whether the magnetic field is below or above resonance. The 500 ohm potentiometer in the plate circuit serves as a bias vernier for the regulator stage.

The regulator consists of six 6L6's connected in parallel. A separate 500 volt power supply furnishes the plate current, and the output is taken from the cathode. The d.c. signal from the discriminator is applied to the grids of the regulator through a 160 volt bias battery. Various taps, on a voltage divider across the battery, are chosen by a rotary selector switch so that the regulator is properly biased.
FIGURE 4
The output of the regulator is used to supplement the current supplied the magnet from a d.c. generator. Examination of the regulator circuit reveals that, in itself, the regulator stage provides a small amount of stabilization for line voltage changes. Assuming a zero signal condition, the grids are held essentially constant. Then an increase in the voltage drop across the magnet causes a decrease in the grid to cathode bias, and so decreasing the amount of error current supplied to the magnet.

The probes are approximately two inches in diameter overall and \( \frac{3}{8} \) inch in height. The r-f coils, consisting of 11, 22, 31 and 46 turns of number 19 enameled copper wire, are wound on the outside of \( \frac{1}{8} \) mm glass tubes, 7 mm in diameter and 2.5 cm in length. The tubes are filled with water and sealed with a layer of duo cement directly in contact with the water. For a better signal to noise ratio, a small amount of manganous sulfate is added to the water. A "C" shaped lucite block supports the glass tube, and the ends of the "C" are rounded to fit the curvature of the \( \frac{1}{8} \) inch brass tubing forming the walls of the probe. One end of the r-f coil is soldered to the brass tubing, while the other end passes coaxially through a short length of \( \frac{1}{8} \) inch brass tubing to the amphenol plug.

This apparatus is used to control the magnetic fields produced by an annular magnet for the determination of particle energies. Consequently, sweep fields can not be obtained by 60 cycle coils on the pole pieces. The sweeping coils each consist of 40 turns of 7 strand, number 35, D.S.C., copper wire. These are wound on the outside of the probe shield. Turns are held in place by collodion. A lucite ring is used to separate
1. Amphenol plug
2. Brass coax
3. Brass coax support
4. Lucite coil support
5. Water sample
6. RF coil
7. Brass lid
8. Lucite spacer
9. Sweeping coil slots

FIGURE 5
FIGURE 7

REGULATED POWER SUPPLY
the coils. Top and bottom lids consist of 0.004 inch brass shim stock. One lid is soldered to the shield, while the other is held in place by spring clips.

The power supplies are of conventional type. The 300 volt supply is well regulated by the usual high gain degenerative type regulator. The 500 volt supply consists of four 85's in a full wave bridge, followed by a single \( H \) filter.

**OPERATION**

For a given precessional frequency, the value of the field strength is given by the well-known equation

\[
H = 234.8 f_L
\]  

(32)

where \( H \) is the magnetic field strength in gauss, and \( f_L \) is the Larmor frequency in megacycles per second. (The proton gyromagnetic ratio used is the absolute value quoted by Thomas et al.\(^\text{14}\))

To stabilize a magnetic field at a given field strength, one can obtain the value of the Larmor frequency from equation (32). The variable frequency standard is set at this frequency and the tuning capacitor of the r-f oscillator adjusted to present a Lissajous pattern on the monitor scope. This pattern is the result of the heterodyning action of the r-f oscillator and the frequency standard. Then the regeneration is decreased until oscillations are just maintained. This point is indicated by a noticeable increase in the amplitude of the

\[^{14}\text{2}, 6752 \pm 0.0002 \times 10^4 \text{ rad. per sec. gauss} \]
\[^{14}\text{Thomas, Driscoll and Hippie, Phys. Rev. 75, 902, (1949)} \]
Lissajous pattern. Next the oscillator is tuned for zero beat, determined by the linear base line on the scope. The regulator bias is then adjusted so that the regulator is supplying approximately 250 ma of current to the magnet. Then the current delivered by the generator is changed until the resonance curve appears on the monitor. Regulation is indicated by a decrease in supplementary current for an increase in line voltage or vice versa, meanwhile, the position of the resonance curve remaining constant on the scope base line.

The horizontal width of the oscilloscope trace is just the sweeping amplitude in gauss. For most purposes, a sweep width of 5 gauss is very satisfactory. For more precise stabilization of field strength, the sweep amplitude can be decreased.

The horizontal width of the absorption curve is an indicator of the field homogeneity. Thus the instrument can be used to ascertain the most homogenous regions of the field produced by a given magnet.

CONCLUSION

In comparing the various methods of obtaining nuclear resonance signals, it seems that the method described in this paper achieves very closely the ultimate sensitivity, determined by thermal agitation noise in the resonant circuit, consistent with its band width. The advantage of this technique over the bridge or nuclear induction techniques is the extreme simplicity of the apparatus involved and the ease with which adjustments can be made. No changes in the circuits are necessary to observe resonances for field strengths varying from a few hundred gauss to 20 kilogauss. There are two limitations to the accuracy
obtainable in making absolute measurement of the field strengths. The accuracy depends on the precise determination of the frequency and the value of the gyromagnetic ratio of the proton. The former is almost negligible since one can easily measure the frequency to one part in one million. The latter is more serious, however, but at the present time one can obtain an accuracy of better than ± 0.02 per cent.

It should also be noted here that the field must be homogeneous to one part in one thousand over the volume of the sample if the resonance is to be observed. Moreover the power supply for the oscillator must be extremely stable. Ripple amounting to more than one millivolt is intolerable.

Since the technique described is sensitive only to the absorption phenomenon of nuclear magnetic resonance, this method is particularly applicable to the study of the nature of spin-lattice interactions.
Figure 8

Oscilloscope trace of proton magnetic resonance absorption

\[ f_L = 18 \text{ mc}, \ \Delta H_0 = 4 \text{ gauss} \]
FIGURE 9

DISCRIMINATOR OUTPUT
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