larly with heat flow density. Like results for frictional retardation were observed by Kapitza[11] with regard to a critical superflow velocity.

Only an order of magnitude value for cirtical heat flow density may be given at this time. At 2°K the internal convection appears to have suffered degeneration at a heat flow density of about 0.0025 cal./cm² sec. This is less than used by Lane,[4] thus possibly explaining his detection of first sound by a completely submerged microphone.

Continued measurements in this direction are expected to provide detailed information on the critical relative velocities of the two fluids during the internal convection process.

C-3. Conversion upon Reflection

Finally the faint signals of Fig. 7 show that by some process first sound has been converted to second sound during reflection from the carbon coated Bakelite surface. No explanation for this is attempted; it is not known whether the carbon surface might be sufficiently penetrable to superfluid for the conversion expected at a porous surface[12] to have occurred.

[12] J. Pellam, Phys. Rev. **73**, 608 (1948).

VII. ACKNOWLEDGMENTS

Space does not permit adequate acknowledgment to all those contributing in one way or another to this program. Professor Slater's sincere interest at all times provided an encouraging influence, particularly during the more difficult early phases. Guests at the laboratory prior to this program, Drs. M. Desirent and W. Horvath, introduced and refined many low temperature techniques and developed helium transfer methods. At the suggestion of Professor Tisza, Dr. Horvath and the author undertook an early investigation to measure second sound wave velocities at very low temperatures, using established standing wave methods. Dr. Horvath's work in this connection (plus organizing a program for adiabatic demagnetization) cannot be over-rated.

Following his departure, emphasis was shifted to second sound measurement techniques, and the pulse method developed. The author conducted this program with the technical assistance of R. Cavileer and P. Nicholas. The former furnished liquid helium on repeated occasions, while the continued willing support of P. Nicholas in all phases of the final program contributed markedly to the eventual results.

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The Hyperfine Structure of Tritium

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The hyperfine structure of the ground state of tritium was measured by the atomic beam magnetic resonance method. The frequency of the field independent central Zeeman component of the transition ($F=1\leftrightarrow F=0$) gives the h.f.s. almost exactly with a field correction of less than 0.001 Mc. The mean of three independent determinations of the h.f.s. in different weak magnetic fields is 1516.702±0.010 Mc. The probable error is caused by the uncertainty in the Doppler correction and possible asymmetry in the resonance lines causing a shift in the center of the line. The reproducibility of determining the center of the resonance line was ±0.002 Mc. The theoretical value of the h.f.s. based on the triton-proton moment ratio and the value of the h.f.s. of hydrogen is 1516.709±0.015 Mc. The theoretical and experimental values agree within the probable error of the moment ratio, 1 part in 10^5, which also proves that the spin of the triton is $\frac{1}{2}$.

INTRODUCTION

THE hyperfine structure of the ground state of tritium has been measured by the atomic beam magnetic resonance method[1] previously employed by the authors[2] in the case of H and D. A measurement of the h.f.s. is well suited to test the theory of the h.f.s. of the hydrogens as it has been extended in the light of the results obtained with H and D.

[1] P. Kusch, S. Millman, and I. I. Rabi, Phys. Rev. **57**, 765 (1940).
[2] J. E. Nafe and E. B. Nelson, Phys. Rev. **73**, 718 (1948).

The h.f.s. separation in absolute frequency units for the $^2S_{\frac{1}{2}}$ state of a hydrogenic atom having infinite nuclear mass has been calculated by Fermi[3] and is given by

$$\nu=[8\pi/3h][(2I+1)/I]\mu_N\mu_0\psi^2(0), \qquad (1)$$

where I is the nuclear spin in units of $\hbar$, μ_N and μ_0 the nuclear and electronic magnetic moments, respectively, and $\psi(0)$ the Schrödinger wave function evaluated at $r=0$.

The effect of the relative motion of the nucleus

[3] E. Fermi, Zeits. f. Physik **60**, 320 (1930).

on the h.f.s. of hydrogen has been calculated by Breit and Meyerott,[4] who find that an additional correction factor of $[1+(m/M)]^{-3}$ is to be applied to Eq. (1) where m and M are the electron and nuclear masses, respectively. This is equivalent to replacing the electron mass implicitly contained in $\psi(0)$ by the reduced mass of the electron. Finally, the g factor of the electron has been found experimentally by Kusch and Foley[5] to exceed the value 2, predicted by the Dirac theory, by the factor (1.00119). This correction has been calculated by Schwinger[6] who finds the factor to be $[1+(\alpha/2\pi)]$, where α is the fine structure constant.

The values of the h.f.s. of H and D may be calculated from Eq. (1) using values of the proton and deuteron magnetic moments obtained from the measurement of the proton moment by Millman and Kusch[7] and the ratio of the deuteron to proton moment of Bloch, Levinthal, and Packard.[8] When the above corrections are included, the results agree with the observed values of the hydrogen and deuterium h.f.s. to within the probable errors in the magnetic moments. On the other hand, the ratio of the measured hydrogen h.f.s. to that of deuterium was lower by 0.017 percent than the ratio calculated from Eq. (1). It was shown by Aage Bohr[9] that a correction of 0.018 percent to the ratio of the h.f.s. can be calculated by taking into account the compound structure of the deuteron.

The tritium h.f.s. can be calculated from the known ratio of the magnetic moments of the proton and triton, obtained by Bloch, Graves, Packard, and Spence,[10] and the measurement by the authors of the h.f.s. of hydrogen. Effects of the kind considered by Aage Bohr have been estimated by Fermi and Teller[11] to result in a reduction of the h.f.s. of tritium by about one part in 10^6. In considering explanations of the triton moment (i.e., exchange moment or large orbital moment), Avery and Sachs[12] estimate that in either case the tritium anomaly would be roughly five percent of that in the case of deuterium.

METHOD

The nuclear spin of the triton has been found[13] to be $I=\frac{1}{2}$; consequently, the ground state of tritium is split into two h.f.s. levels corresponding to $F=1$ and $F=0$. The upper state is split in the presence of an external magnetic field into three levels corresponding to $m_F=0$ and ±1. The energies of these magnetic levels and of the $(F=0,\ m_F=0)$ level are given as a function of the magnetic field strength by the Breit-Rabi[14] formula. The field dependence of these levels is shown in Fig. 1. The energies are measured in terms of the h.f.s. splitting, ΔW. The parameter X is proportional to the magnetic field intensity. For tritium the value $X=1$ corresponds to a magnetic field intensity of about 552 gauss.

In very weak fields of the order of a few gauss, the lines resulting from the transitions $F=1,\ m=0$ or $\pm1\leftrightarrow F=0,\ m=0$ are the Zeeman components of the line $F=1\leftrightarrow F=0$. The frequency, f_1, of the central component of the Zeeman pattern is field independent, to the first order, and gives the h.f.s. almost directly. A second-order field correction is obtained from the frequency separation, Δf, of the adjacent Zeeman components and is $-2(\Delta f)^2/f_1$. The external field was sufficiently small that the second-order correction was less than $1:10^6$; thus the h.f.s. splitting is found directly, without any knowledge of the magnetic field or the atomic or nuclear g factors.

APPARATUS

The apparatus used previously in the measurement of the h.f.s. of H and D was modified by the addition of a gas recirculation system so that a small sample of gas would suffice for a run of a few hours' duration and could be recovered after the experiment. A Leybold three-stage mercury diffusion pump provided fore vacuum for the oil diffusion pumps and could discharge the gas at a pressure of 20 mm. The gas was passed through a hot palladium thimble and a liquid air trap before being admitted

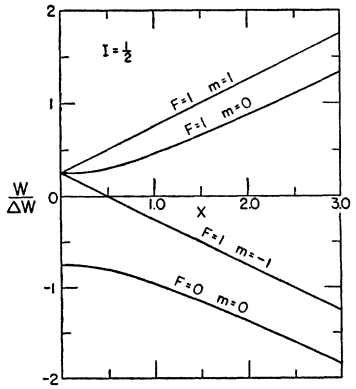

FIG. 1. The magnetic field dependence of the energy of the magnetic components of the h.f.s. multiplet of an atom in the $^2S_{\frac{1}{2}}$ state. The spin of the nucleus is $\frac{1}{2}$.

[4] G. Breit and E. R. Meyerott, Phys. Rev. **72**, 1023 (1947).
[5] P. Kusch and H. M. Foley, Phys. Rev. **74**, 250 (1948).
[6] J. Schwinger, Phys. Rev. **73**, 416 (1948).
[7] S. Millman and P. Kusch, Phys. Rev. **60**, 91 (1941).
[8] F. Bloch, E. C. Levinthal, and M. E. Packard, Phys. Rev. **72**, 1125 (1947).
[9] A. Bohr, Phys. Rev. **73**, 1109 (1948).
[10] F. Bloch, A. C. Graves, M. E. Packard, and R. W. Spence, Phys. Rev. **71**, 551 (1947).
[11] E. Fermi and E. Teller, Notes on Pocono Conference of Physics, sponsored by National Academy of Science, April 1, 1948.
[12] R. Avery and R. G. Sachs, Phys. Rev. **74**, 1320 (1948).
[13] F. Bloch, A. C. Graves, M. Packard, and R. W. Spence, Phys. Rev. **71**, 373 (1947).
[14] G. Breit and I. I. Rabi, Phys. Rev. **38**, 2082 (1931).

to the discharge tube. The gas was recirculated at the rate of about 2 cc at NTP per minute. A Toepler pump was used to recover the gas at the end of the run.

During recirculation of the gas, the tritium was gradually lost by chemical exchange and adsorption and the relative concentration of the tritium was reduced by the evolution of H from the system. The evolution of H was associated with the operation of the discharge tube, the total quantity of H being very constant when molecular gas was recirculated. Prolonged flushing of the discharge tube with He did not retard the evolution of the gas. Preliminary tests on the recirculation system were performed by flushing the system with H for a long period of time and then observing the change in the concentration of the D component of a recirculated H and D mixture. The evolution of H was so fast that the D component was lost within a few hours. The source of this excess gas was not located and the evolution of the foreign gas was the principal experimental difficulty.

The r-f currents which produce the oscillating magnetic field were propagated along a two-wire transmission line which lies in the uniform magnetic field. The beam travels between and parallel to the wires. The plane of the wires is inclined at an angle of 45° to the direction of the uniform magnetic field; thus the r-f field has components both parallel and perpendicular to the uniform field and both σ- and π-transitions may be induced. This was necessary because the polarization requirements are such that the $(1,0\leftrightarrow 0,0)$ transition is induced only by the component parallel to the uniform field and the $(1,1\leftrightarrow 0,0)$ transition by the component perpendicular to the uniform field. In the measurements on H and D, the transmission line was shorted within the uniform field, the beam traveling through the shorting plate. By terminating the transmission line, external to the vacuum system, its frequency sensitivity was reduced and a crystal rectifier could be used to give an indication of the magnitude of the r-f current.

A grounded-grid coaxial line oscillator (Radar Jammer T-85/APT-5) using a 3C22 lighthouse tube supplied the r-f current at 1516 Mc. The frequency could be varied continuously for about 5 Mc by moving a micrometer screw into the grid-plate coaxial line. The precision of the measurement was not limited by the stability of the oscillator. The r-f system was tested, preliminary to the experiment, by studying the $(1,1\leftrightarrow 0,0)$ line in H at frequencies in the neighborhood of the expected h.f.s. of tritium. The power output of the oscillator and the termination of the transmission line were such that the $(1,1\leftrightarrow 0,0)$ line could be located without difficulty when the frequency was within ± 2 Mc of the expected h.f.s. of tritium.

The frequency of the r-f signal was measured by heterodyning the signal from the oscillator with harmonics of the output of a 240-Mc crystal controlled frequency standard. A crystal controlled signal at 1500 Mc was obtained by mixing the harmonics of the 240-Mc signal with harmonics from the lower frequency stages. The difference of about 16 Mc between the frequency of the 1500-Mc standard and that of the unknown signal was measured directly by a General Radio Heterodyne frequency meter, Model 620-A, with an accuracy ± 0.001 Mc. The frequency of the r-f signal could be measured to ± 0.001 Mc at 1516 Mc. The frequency of the 5-Mc stage of the frequency standard was compared frequently with that broadcast by the Bureau of Standards, WWV, and never was found to differ by as much as 1 cycle/sec. (1 part in 5×10^6).

EXPERIMENTAL PROCEDURE

In the measurements on the h.f.s. of H and D, the intensity of the atomic beam was measured as a function of the frequency of the r-f field inducing the transition. The time required to map a single resonance line was about 45 min. The preliminary experiments on the recirculated H and D mixture indicated that the tritium component would probably be lost so rapidly that it would be impossible to map the lines; consequently, the procedure was modified to permit rapid observation, with a possible reduction in precision.

The centers of the spectrum lines were obtained by observing the deflection of the galvanometer in the Pirani detector bridge circuit as a function of the frequency of the r-f field inducing the transition. The frequency was increased from below the resonance frequency, or decreased from above, until a sharp reduction in the deflection of the galvanometer was observed and the mean of these two frequencies was taken to be the center of the line. An attempt was made to approach the line at the same rate and to note symmetrical points on the sides of the resonance lines. The validity of this method is discussed in the following section.

RESULTS

The mean of three independent determinations of the h.f.s. of tritium is 1516.702 ± 0.002 Mc, where ± 0.002 Mc is the average deviation from the mean of the separate determinations of the center of the field independent line, and does not include an estimate of the suspected systematic errors. The errors on account of the Doppler shift and a possible assymmetry of the line are probably less than ± 0.010 Mc. The h.f.s. of tritium is then

$$1516.702\pm 0.010 \text{ Mc}.$$

A detailed discussion of the experimental results and the validity of the measurements is given in this section.

For each of the three runs, a different value of the intensity of the weak magnetic field was used. In each case, the field independent (1,0↔0,0) line and the field dependent (1,1↔0,0) line were observed. The third line of the Zeeman pattern cannot be observed with this apparatus for the change in the atomic moment is too small to cause a measable defocusing of the beam. The results of these measurements are given in Table I. The magnetic field intensity, derived from the frequency separation of the tritium lines, is given in column 1, the frequency of the lines in columns 2 and 3, the number of determinations of the center of the field independent line in column 4, and the h.f.s. of tritium in column 5. The uncertainty listed for the (1,0↔0,0) line and for ν_T is the average deviation from the mean of the individual determinations of the center of the (1,0↔0,0) line.

The identification of the lines whose frequencies are given in Table I was checked carefully. The field independence of the line identified as (1,0↔0,0) is evident from the data of Table I. The field independence was checked in one case by increasing the field from 0.5 gauss to 2.38 gauss. The frequency of the line was observed to increase from 1516.702 Mc to 1516.723 Mc. (The frequency of the field dependent line would have increased by about 3.5 Mc.) The identification of the field dependent (1,1↔0,0) line was checked by comparing the value of the magnetic field, calculated from the separation of adjacent Zeeman components in tritium with that obtained from the Zeeman spectrum of H or D.

The precision of the measurement of the h.f.s. of tritium is limited by the precision of locating the center of the (1,0↔0,0) line. The deflection of the galvanometer caused by the beam of tritium and the other hydrogens was about 18 cm and at best the reduction of this intensity at resonance was expected to be about 2.5 cm. The reduction in beam intensity caused by the (1,0↔0,0) transition was initially about 1.5 cm, decreasing to about 1.0 cm as the beam became contaminated with hydrogen. The reduction in beam intensity caused by the atomic transition was observed against a background drift of the galvanometer spot, caused by thermal drift in the detector, of about 1 cm/min. The time constant of the detector is about 20 sec. The entire detector system was sufficiently stable that in the absence of a beam a frequency variation of ±0.5 Mc about the expected position of the tritium resonances produced spurious effects amounting at most to a few mm. A definite deflection of about 1 cm was observed when the resonance line was approached rapidly so that the drift in the detector did not mask the reduction in intensity.

The theoretical half-width, Δf, of the (1,0↔0,0) line is given by the uncertainty principle

$$\Delta f \Delta t \sim 1,$$

where Δt is the time spent by the beam in the r-f field. Assuming the temperature of the beam, which effused from the water-cooled source to be 300°K, the expected half-width of the line is 0.045 Mc. The apparent width of the line was much less than this, ±0.010 Mc, the reduction being caused by the overshooting of the edge of the line in causing a definite deflection of the galvanometer. The reproducibility of the results is about $\frac{1}{10}$ the theoretical half-width of the line.

The validity of this method of obtaining the center of the spectrum line was demonstrated by measuring the known h.f.s. of H in a field of 0.729 gauss, where the second-order field correction is 0.0014 Mc. The mean of five determinations of the center of the (1,0↔0,0) line was 1420.408±0.001 Mc, from which the value, 1420.407±0.001 Mc, is obtained for the h.f.s. This result agrees very well with the value, 1420.410±0.006, obtained previously by careful mapping of the hydrogen lines.

SYSTEMATIC ERRORS

The important systematic errors in the measurement of the h.f.s. are those involved in the measurement of the frequency of the (1,0↔0,0) line. Natural asymmetry of the line or the asymmetry and shift of the center introduced by a Doppler shift would cause the observed center of the line to differ from the true center.

Inhomogeneities in the uniform magnetic field shound not distort the (1,0↔0,0) line. In the experiments on H, it was observed that, when the field dependent line was broadened by field inhomogeneity to about five times its natural width, the (1,0↔0,0) line was symmetrical and not broadened by a measurable amount. The line might be skewed if the magnitude of the r-f current were less than the optimum and the r-f current were a sensitive function of the frequency. The r-f system was

TABLE I. Results of the weak field measurements of the h.f.s. of tritium.

Magnetic field, gauss	(1,1↔0,0) MC	(1,0↔0,0) MC	No. of obs.	ν_T, MC
0.289	1517.117	1516.703±0.002	5	1516.703±0.002
	1517.103	1516.701±0.001	5	1516.701±0.001
	1517.097			
0.496	1517.400	1516.701±0.002	7	1516.700±0.002
	1517.391			
0.63	1517.575	1516.705±0.004	9	1516.704±0.004

checked by studying the $(1,1\leftrightarrow 0,0)$ field dependent line in H at 1516 Mc. As the current was adequate for the field dependent line, which should be broadened by field inhomogeneities, it was more than adequate for the field independent line.

An upper limit can be set on the systematic error caused by the Doppler shift. This Doppler shift has been observed in repeating the measurement of the h.f.s. of H with this r-f system. The apparent h.f.s., measured when the beam traveled in the direction of propagation of the r-f power, was always larger than when it traveled in the opposite direction. The atomic tritium beam travels in the direction of propagation of the r-f power along the transmission line. A shift of $+0.008$ Mc would be expected for those atoms of the beam whose velocity equals the average velocity of the beam, if the termination of the transmission line were perfect. The error is probably considerably less than this, for reflections are produced by the Micalex spacers which support the line.

In the previous measurements on the h.f.s. of H, the transmission line was shorted within the uniform field, the beam passing through the shorting plate. The standing wave ratio adjacent to the short was probably high and therefore the Doppler shift only a fraction of the theoretical value. (The Doppler shift for H atoms having the average velocity of the beam would be 0.014 Mc.) No error caused by Doppler shift enters the measurement of the h.f.s. of D. The r-f current flows around the beam in a solenoidal manner and the r-f field has the same phase along its length.

DISCUSSION OF RESULTS

The h.f.s. of tritium is related to that of H by

$$\nu_T=\nu_H(\mu_T/\mu_P)(M_T/M_H)^3, \qquad (2)$$

where μ_T/μ_P is the ratio of the triton to proton moment and M_T/M_H is the ratio of the reduced mass of the electron in tritium to that in hydrogen. Using the Bloch, Graves, Packard, and Spence[10] value of the moment ratio, 1.066636 ± 0.000010, and our value of the h.f.s. of H, 1420.410 ± 0.006 Mc, the computed value of the h.f.s. of tritium is 1516.709 ± 0.015 Mc. The theoretical and experimental values agree within the precision of the ratio of the magnetic moments, $1:10^5$. The uncertainty in the value of the reduced mass ratio is too small to affect the precision of the calculated value of the h.f.s.

In calculating the h.f.s. of tritium, relative to hydrogen, no correction for the detailed interaction of the electron with the nucleons of the nucleus was applied. Nevertheless, the agreement between the calculated and experimental values is one part in 10^5. In view of the fact that this was far from true in the case of deuterium where an important correction had to be made for the effect of the structure of the nucleus, this is very surprising. However, by considering the difference in the interaction between a neutron and proton with parallel spins and a neutron and proton with antiparallel spins, Fermi and Teller[11] have calculated the fractional shift in the ratio ν_T/ν_H and find it to be between 0.7×10^{-6} and 2.8×10^{-6}. This effect would reduce the value of the h.f.s. of tritium. The moment ratio μ_T/μ_P and the h.f.s. ratio ν_T/ν_H are both uncertain by an amount larger than the effects calculated by Fermi and Teller and by Avery and Sachs.

The ratio ν_T/ν_H is particularly suited for studying the reduced mass correction since the shift of the h.f.s. of tritium to be expected on account of the structure of the triton is so small. The reduced mass correction for the ratio, ν_T/ν_H, is about 700 times the estimated correction for the interaction of the electron with the individual nucleons, while in the ratio, ν_D/ν_H, the factor is only about 5. The remarkable agreement between the experimental and theoretical values of ν_T/ν_H and ν_D/ν_H offers support to the validity of the reduced mass correction and the nuclear corrections separately.

The agreement between the theoretical and experimental values of the h.f.s. and the complexity of the Zeeman pattern of the transition $(F=1\leftrightarrow F=0)$ verify that the spin of the triton is $\frac{1}{2}$.

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