The magnetic field was provided by an electromagnet with 5-inch diameter pole pieces and with a 1-inch gap. The radiofrequency (r-f) fields for the two samples were produced inside of two equal coils about $\frac{1}{2}$ inch in diameter and about $\frac{1}{2}$ inch long. These were symmetrically disposed about the center of the magnetic field and spaced 1 inch apart. The axes of the coils were at right angles to the direction of the magnetic field. The r-f current for the coils was produced by two generators, one crystal controlled (Set A), while with the other it was possible to vary the frequency continuously (Set B). In each case the coil was in one arm of a "twin T" network which was inserted between the generator and a high frequency receiver (National RHO). The network could be adjusted so that no signal would be transmitted to the receiver from the generator. However, a modulated r-f signal of the same frequency developed in the coil would be detected by the receiver and presented as an audio signal on a cathode-ray oscilloscope screen.

To present the nuclear induction peaks on the cathode-ray screen, a small 60-cycle component was superimposed on the main magnetic field by means of a 60-cycle alternating current flowing through an auxiliary winding on the poles of the magnet. In this way, the magnetic field would give the magnetic moments inside the coil a Larmor precession frequency which varied through the frequency of the generator twice each cycle.

To observe the proton peaks, a drop of ordinary distilled water contained in a Pyrex tube was inserted in one of the coils. Following Bloch, Hansen, and Packard,[1] a small amount of $Fe(NO_3)_3$ was added to the water to speed the establishment of thermal equilibrium. Two peaks per cycle were observed when the frequency of the generator was near 23 megacycles and the magnetic field near 5400 gauss, corresponding to each coincidence of the Larmor with the applied frequency.

With a drop of water made from some tritium gas which was available in this laboratory, and conditioned in the same way, we observed identical peaks at the same frequency and field due to the ordinary hydrogen which was present in this water. In addition, however, we observed the same pattern at a *lower* value of the magnetic field, while keeping the frequency of the generator fixed. These second peaks were not present in the ordinary water sample and we, therefore, identified them with the magnetic moment of the triton.

For a precise determination of the ratio of the nuclear g values of the triton and the proton, the tritium water was put in one coil while the ordinary water was put in the other. The audio outputs of the two receivers were connected to the same oscilloscope through an electronic switch so that the patterns due to both samples could be observed simultaneously. The frequencies of the two generators were then adjusted so that the peaks due to the triton moments in the one sample coincided with those due to the proton moments in the other. The frequencies of the two generators were measured using a Signal Corps BC-221 AE frequency meter. With the samples interchanged, the ratio of the triton frequency to the proton frequency differed by 0.05 percent, this being the difference in the value of the magnetic field at the positions of the two samples. The geometric mean of these two frequency ratios gives directly the ratio of the nuclear g values and cancels any error due to differences in the value of the magnetic field at the two samples. Measurements made at three values of the crystal frequency of Set A, 23.0947, 25.4902, and 22.8301 megacycles, gave the same result within 0.01 percent. Our result gives for the ratio of the nuclear g value of the triton to that of the proton, 1.06666 ± 0.00010.

The fact that the nuclear g value of the triton is larger than that of the proton disagrees with the estimate of Sachs and Schwinger[2] based on the wave function obtained by Gerjuoy and Schwinger.[3] In fact, it shows that the admixture of ${}^4D_{\frac{1}{2}}$ wave functions to the ground state of the triton is not sufficient to account for its magnetic moment.

This work was done under the auspices of the Manhattan District at the Argonne National Laboratory.

* Member of the Institute for Nuclear Studies, University of Chicago.

[1] (a) E. M. Purcell, H. C. Torrey, and R. V. Pound, Phys. Rev. **69**, 37 (1946). (b) F. Bloch, W. W. Hansen, and M. Packard, Phys. Rev. **69**, 127 (1946). (c) F. Bloch, Phys. Rev. **70**, 460 (1946). (d) F. Bloch, W. W. Hansen, and M. Packard, Phys. Rev. **70**, 474 (1946).

[2] R. G. Sachs and J. Schwinger, Phys. Rev. **70**, 41 (1946).

[3] E. Gerjuoy and J. Schwinger, Phys. Rev. **61**, 138 (1942).

Spin and Magnetic Moment of Tritium*

F. Bloch, A. C. Graves, M. Packard, and R. W. Spence
Stanford University, California, and the Los Alamos Scientific Laboratory, Santa Fe, New Mexico

February 17, 1947

NUCLEAR induction[1] has been applied to a small sample containing a 0.3 molar solution of $MnSO_4$ in H_2O, and clearly distinguishable signals have been obtained from both hydrogen isotopes, H_1 (proton), and H_3 (triton) present in the sample. A density determination indicated that about 80 percent of the hydrogen was present in the form of H_3, and about 20 percent in the form of H_1.

A first series of observations was performed by keeping the frequency constant at $\nu = 41.5$ megacycles, and merely varying the magnetic field B_0. The signal originating from H_3 appeared at a field $B_0 = 9160$ gauss, and, except for being about three times larger, had an identical sign and shape as the signal originating from H_1, which appeared at a field $B_0 = 9770$ gauss. It leads to the following conclusions:

(a) The gyromagnetic ratio γ_T of H_3 is about 7 percent larger than γ_P, the gyromagnetic ratio for H_1, as indicated by the ratio of the respective resonance fields B_0.

(b) Within the observational error of about 30 percent, the magnitude of the signals agrees in their ratio with the ratio of the respective amounts of the two isotopes. This shows that the spin of H_3 is the same as that of H_1, which is known to be $\frac{1}{2}$. A spin of $\frac{3}{2}$ or more for H_3 would have resulted in a fivefold[2] larger signal relative to that of H_1 than was observed and could therefore be definitely excluded.

(c) With the signals which originate under identical radio frequency conditions from the two isotopes having the same sign, the relative orientation of their magnetic moments and angular momenta is the same. Since H_1 is

known to have a positive magnetic moment, H_3 has therefore likewise a positive moment.

A second series of observations to obtain a more accurate value for γ_T was performed by keeping the current in the electromagnet constant, and observing the induced signals of the two isotopes for different frequencies. The following table gives the results for the resonance frequencies ν_3 and ν_1 of H_3 and H_1, respectively, in megacycles together with the field B_0 in gauss, at which the observation was carried out and the resulting ratio γ_T/γ_P of the gyromagnetic ratios.

TABLE I. Resonance frequencies ν_3 and ν_1 of triton and proton and the resulting value of γ_T/γ_P. The fourth column represents the result of a repetition for tritium to ascertain that the field stayed constant during the run.

B_0	ν_3	ν_1	ν_3	γ_T/γ_P
9770	44.29	41.51	44.28	1.067
9500	43.08	40.37	43.08	1.067

To summarize we can therefore state that the triton has a spin of $\frac{1}{2}$, and that its magnetic moment is positive, and 1.067 ± 0.001 times larger than that of the proton.

* Work done at Stanford University and at the Los Alamos Scientific Laboratory operated by the University of California under U. S. Government contract.

[1] F. Bloch, Phys. Rev. **70**, 460 (1946). F. Bloch, W. W. Hanson, and M. Packard, Phys. Rev. **70**, 474 (1946).

[2] See Eq. (29) of reference 1.

Transition from Classical to Quantum Statistics in Germanium Semiconductors at Low Temperature

VIVIAN A. JOHNSON AND K. LARK-HOROVITZ
Purdue University, Lafayette, Indiana*
February 8, 1947

ANALYSIS[1] of the experimental results[2] obtained with germanium semiconductors in the temperature range from -180°C to about 600°C has shown that one can account for electrical conductivity and thermoelectric power of these impurity semiconductors by assuming that lattice vibrations and scattering by singly charged impurity centers[3] are responsible for the observed resistivity ρ, where $\rho=\rho_L+\rho_I$.

$$\rho_L=DRT^{3/2},$$
$$\rho_I=\frac{9\cdot10^{11}\pi^{3/2}\epsilon^2m^{1/2}}{2^{7/2}\epsilon^2(kT)^{3/2}}\cdot\ln\left(1+\frac{36\epsilon^2k^2T^2d^2}{e^4}\right),$$

where $R\sim1/n$ is the Hall constant, n the number of conduction electrons per cc, m the electronic mass, ϵ the dielectric constant, $d=0.28n^{-1/3}$=one-half the average distance between impurity centers D determined from experiments.

In both cases it has been assumed that classical statistics can be applied. This is justified in most cases since the number of electrons, as determined from Hall effect measurements, is small.

If the number of electrons is nearly independent of temperature one may apply the well-known criterion for degeneracy and define a degeneracy temperature

$$T_d=\frac{h^2}{8mk}\left(\frac{3n}{\pi}\right)^{2/3}=4.2\times10^{-11}n^{2/3}\ ^\circ\text{K}.$$

Since n varies from sample to sample, one finds that degeneracy temperatures vary from a fraction of a degree K to about 150°K in the germanium samples studied at Purdue. Therefore, at low temperatures, the behavior of these semiconductors should vary widely, depending upon the number of electrons and the activation energy.

Measurements of such semiconductors down to about 10°K have been reported recently.[4] The observations show that three kinds of samples exist:

(1) Very pure samples with a resistance increasing so sharply with decreasing temperature that the material becomes almost non-conducting (Estermann's "pure" germanium and silicon samples).

(2) Samples for which the resistivity increases with decreasing temperature and in some cases seems to reach a "saturation" value.

(3) Samples with constant resistivity from liquid air temperature to liquid hydrogen temperature. All of the samples of type (3) have degeneracy temperatures of about 100°K or higher; calculations using classical statistics, such as have been used at medium temperatures, are not justified for such samples at low temperatures.

We have, therefore, carried out calculations assuming Fermi statistics instead of classical statistics and can summarize our results as follows:

(*a*) Lattice scattering.[5]

above T_d, $\rho_L=DRT^{3/2}$,
below T_d, $\rho_L=D'RTG(\Theta/T)\rightarrow D'RT^5$ at 25°K.

These expressions, calculated for germanium samples, show a smoothly decreasing resistivity with decreasing temperature and, therefore, contribute little to the observed resistivity at low temperatures.

(*b*) Impurity scattering. By calculating the scattering of electrons by randomly distributed, singly-charged impurity centers, one obtains:

$$\frac{1}{\rho_I}=\sigma_I=\frac{32}{3}\frac{\epsilon^2mk^3T^3}{ne^2h^3}\int_0^\infty\frac{x^3\exp(x-\mu^*)dx}{[\exp(x-\mu^*)+1]^2\ln Y'}$$

$$Y=1+\frac{4\epsilon^2k^2T^2d^2x^2}{e^4},\quad x=\frac{mv^2}{2kT},\quad \mu^*=\frac{\mu}{kT}$$

TABLE I.

Sample	Measured by Estermann	Measured at Purdue	Calculated
26 *Z*	0.0051	0.0044	0.0040
11 *R*	0.0040	0.0034	0.0037
26 *E*	0.0037	0.0033	0.0034
27 *L*	0.0034	0.0029	0.0033

(All of the above values represent constant low temperature resistivities measured in ohm-cm.)

Thus the transition from classical to quantum statistics leads to a constant residual resistance due to impurity scattering in degenerate samples in agreement with experiment.