Neutron Spin from Magnetic Resonance Experiment

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The magnetic resonance type of experiment used for the measurement of the gyromagnetic ratio of the neutron has been extended to give a demonstration of the neutron spin. The spin ($\frac{1}{2}$) is demonstrated uniquely by the measured transition probability as a function of the amplitude of the oscillating magnetic field.

THE molecular beam magnetic resonance method was developed by Rabi[1] for the measurement of gyromagnetic ratio. This type of experiment was used by Alvarez and Bloch[2] to measure the gyromagnetic ratio of the neutron. We have used the magnetic resonance method with monochromatic neutrons to give a direct demonstration of the neutron spin.

Two magnetized single crystals of magnetite whose polarizing properties were closely the same[3] were used as neutron polarizer and analyzer, as shown in Fig. 1. The use of Bragg reflection from a single magnetite crystal for the selection of a particular spin state has distinct advantages over the transmission method used by Alvarez and Bloch,[2] in that a monoergic neutron beam is produced which has a high degree of polarization.[3,4] Between these two magnetite crystals a constant field H_1 of several hundred oersteds was maintained parallel to the field applied to the crystals. Transitions between neutron energy levels in the constant field were induced by an oscillating field of amplitude H_0 perpendicular to H_1. The frequency ω_0 of the oscillating field was adjusted so as to satisfy the resonance condition $\omega_0=\omega_1=(\mu/S)H_1$, in which $\mu/S=g$, the gyromagnetic ratio of the neutron. The intensity reflected from the two crystals was measured as a function of the amplitude of the oscillating field. The oscillating magnetic field was produced by a variable frequency oscillator whose output was continuously variable. A maximum oscillating field strength of about 65 oersteds was produced in an oval-shaped 80-turn solenoid of about 6 cm maximum height, 4 cm maximum width, and 8 cm length. Neutrons of energy 0.075 ev were used.

The transition probability in a rotating magnetic field is a function of the frequency ω_r, the strength of the field H_r and the length of time t spent by the particle in the field. It depends also upon the angular momentum j of the particle and upon its initial and final magnetic quantum numbers, m and m'. The transition probability is given by the expression[5,6]:

$$W(j,m,m') = (j+m)!(j-m)!(j+m')!(j-m')!(\sin\tfrac{1}{2}\alpha)^{4j} \times\left|\sum_{\rho=0}^{2j}\frac{(-1)^\rho(\cot\frac{1}{2}\alpha)^{m+m'+2\rho}}{(m+m'+\rho)!(j-m'-\rho)!(j-m-\rho)!\rho!}\right|^2, \quad (1)$$

in which

$$\alpha=2\arcsin[(gH_r/L)\sin(\tfrac{1}{2}Lt)] \quad (2)$$

and

$$L=[(\omega_r-\omega_1)^2+(gH_r)^2]^{\frac{1}{2}}. \quad (3)$$

In the summation, any term containing factorials of negative numbers is to be omitted. The above expressions can be applied with good approximation to the case of the oscillating field if H_r is replaced by one-half the amplitude of the oscillating field H_0.

The magnetic field applied to the magnetite crystals was perpendicular to the scattering plane. Under these conditions, the amplitude of scattering from a single magnetic ion is given by[7]

$$a=C+D, \quad (4)$$

in which C is the nuclear scattering amplitude and D is the magnetic scattering amplitude. The magnetic scattering amplitude is given by

$$D=(2e^2/mc^2)S'fg'jm, \quad (5)$$

in which S' is the effective atomic angular momentum in units of $\hbar$, f is the atomic magnetic form factor, j and m are the neutron spin total and magnetic quantum numbers, (e^2/mc^2) is the classical electron radius, and g' is defined as the ratio of the neutron magnetic moment

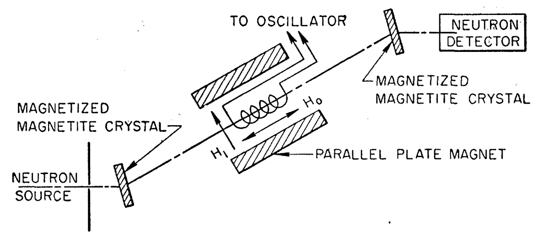

FIG. 1. Schematic diagram of apparatus.

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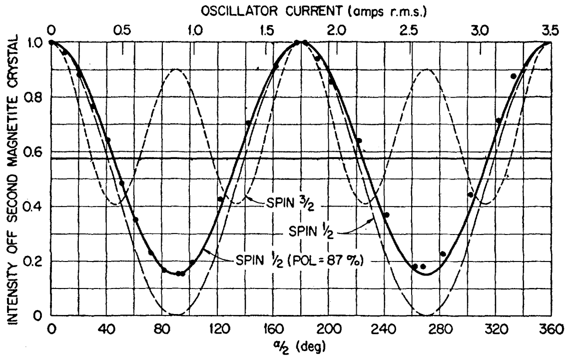

FIG. 2. Relative neutron intensity *vs* amplitude of oscillating field. Points are measured values; long dash curve calculated for neutron spin $\frac{1}{2}$, short dash curve calculated for spin $\frac{3}{2}$; solid curve, calculated for spin $\frac{1}{2}$ and 87 percent polarization.

in nuclear Bohr magnetons to its angular momentum in units of $\hbar$.

In this work we used reflection from the 220 planes of magnetite. The crystal structure of magnetite is such that the amplitude of scattering A from a single unit cell for the 220 reflection depends only upon the eight tetrahedral Fe^{+++} ions in the cell. It is given in centimeters by

$$A_{220}=7.65\times10^{-12}-31.0\times10^{-12}jm. \tag{6}$$

To obtain (6) from (4) and (5) we have used the values[8,9] $C=0.956\times10^{-12}$ cm, $f=0.72$, with $S'=5/2$ and $g'=-3.83$. The intensity of reflection is proportional to $(A_{220})^2$.

Using values of the transition probability calculated from Eq. (1), and values of the magnetite crystal reflectivity calculated from Eq. (6), we have calculated the neutron intensity reflected from the two crystals as a function of the amplitude of the oscillating magnetic field, for different values of the neutron spin. With $\omega_0=\omega_1$, the transition probability for spin $\frac{1}{2}$ is of the form $W=\sin^2(\frac{1}{2}\alpha)$, where α is proportional to the amplitude H_0 of the oscillating field. The intensity I coming off the second crystal is then proportional to $[1-B\sin^2(\frac{1}{2}\alpha)]$, in which B is a function of the polarization P produced by either crystal alone: $B=(2P^2)/(1+P^2)$. The measured and calculated values for neutron intensity as a function of amplitude of oscillating field are compared in Fig. 2. The points of Fig. 2 represent the measured values. The long dash curve represents the calculated intensity *vs* amplitude of oscillating field for spin $\frac{1}{2}$. For purpose of comparison, the calculated intensity for spin $\frac{3}{2}$ is shown by the short dash curve. These curves are based upon numerical values of the nuclear and magnetic scattering amplitudes of Eq. (6). The calculated value of the polarization P of spin $\frac{1}{2}$ neutrons reflected from our magnetite crystal, when these amplitudes are used, is very close to 100 percent. However, we have measured the polarization of the reflected beam[3] and found it to be 87 percent. The solid curve of Fig. 2 has been calculated with $P=87$ percent for spin $\frac{1}{2}$. It fits the measured values very well. The minimum at oscillator current of 0.9 amperes should correspond to $\alpha/2=\pi/2$. For $\omega_0\doteq\omega_1$, $\alpha/2=gH_rt/2$. The value of $\alpha/2$ at this minimum was calculated to be $\pi/2$ from the measured current in the solenoid, the geometrical properties of the solenoid, and the known neutron velocity. Also, the calculated ordinates in the region of the minimum and maximum intensities pass through the measured values. The value of $P=0.87$ corresponds to a value of the amplitude C (or D) different by 50 percent from the value derived from neutron diffraction data. The reason for our low value of P is not known. (Two single crystals of magnetite giving widely different neutron polarizations were found to be closely the same on chemical analysis.)

A similar attempt to fit the data with neutron spin $\frac{3}{2}$, by varying the parameter C, was much less successful. For C up to twice the accepted value, the first minimum occurs at a value of α about $\frac{1}{2}$ of the measured value and at an ordinate a factor of two above the measured value of 0.16; the first maximum occurs at $\alpha/2=90°$ instead of 180°, with an ordinate of only about 0.7 instead of 1. The character of the curve for spin $\frac{3}{2}$ can be forced to approach the measured curve, only by changing C by about a factor of 10. Such a change from the accepted value seems hardly likely. Other neutron spin values are equally unsatisfactory.

The straight line of Fig. 2 is drawn through the measured values of the intensity when the neutron beam is depolarized between the two crystals by the insertion of a thin sheet of iron in a region of near zero field. The fact that the best-fit calculated curve is symmetrical about this line demonstrates that the maximum transition probability was 100 percent.

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