tions can be a convenient means of detecting the "forbidden" $\Delta|M|=2$ transitions.

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Observation of Nuclear Magnetic Resonance in Antiferromagnetic $Mn(F^{19})_2$

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WE have observed F^{19} nuclear magnetic resonances in *antiferromagnetic* MnF_2 at frequencies in the range of 152–168 Mc/sec, external magnetic fields between 300 and 3000 oersteds, and temperatures between 1.3°K and 20.4°K. The resonances were observable at these high frequencies and low fields because of the large internal magnetic fields at the F^{19} sites. These internal fields were previously[1] inferred to exist from the large temperature- and field-dependent displacements of the F^{19} nuclear magnetic resonance in the *paramagnetic* state and were attributed to electron transfer or covalent bonding between the predominantly diamagnetic F^- ion and the paramagnetic Mn^{++} ion. By postulating[2–5] a spin-dependent tensor hyperfine interaction of the form $\mathbf{I}\cdot\mathbf{A}\langle\mathbf{S}\rangle$, the resonance frequency in the paramagnetic state was shown to be displaced, for $H_0\|[001]$ or z direction, by an amount

$$\delta\nu=\frac{1}{h}(2A_z^{\mathrm{I}}+A_z^{\mathrm{II}})\langle S\rangle, \tag{1}$$

where A_z^{I} and A_z^{II} are the relevant principal values of the hyperfine interaction resulting from electron transfer from a given F^- site to the three nearest Mn^{++} neighbors (two of the latter being equivalent) and where $\langle S\rangle$ is the time-averaged spin polarization per ion. The abrupt disappearance of F^{19} nuclear magnetic resonance at the antiferromagnetic transition temperature, T_n, was explained by the sudden rise in $\langle S\rangle$ displacing the resonance beyond the range of the conventional nuclear magnetic resonance spectrometer.

Since below T_n the Mn^{++} spins are antiferromagnetically ordered with the spins, $\pm\frac{5}{2}\hbar$, respectively parallel and antiparallel to [001], the frequency for resonance was expected, with $H_0\|[001]$, to be at

$$\nu=\frac{1}{h}(2A_z^{\mathrm{I}}-A_z^{\mathrm{II}})(\tfrac{5}{2}-\alpha)\frac{M(T)}{M(O)}\pm\frac{\gamma^{19}}{2\pi}H_0 = \nu_0(T)\pm\frac{\gamma^{19}H_0}{2\pi}. \tag{2}$$

Here α represents the expected departure[6] of the antiferromagnetic ground state from the state of complete antiparallel alignment and the Zeeman term reflects the removal of the spatial degeneracy by the application of an external field parallel to a given sublattice magnetization. Assuming $\alpha=0$, Bleaney[3] predicted $\nu_0(0°K)$ to be 179 Mc/sec from Tinkham's paramagnetic resonance data on Mn^{++} in ZnF_2. On the same assumption we expected[7] the essentially identical value of 177 Mc/sec from the nuclear magnetic resonance studies of paramagnetic MnF_2.

The resonances corresponding to the two branches of Eq. (2) have been observed in an annealed single crystal prepared by E. F. Dearborn and J. W. Nielsen. The crystal (~1 cc in volume) was placed in a Dewar which fitted into a re-entrant transmission cavity used in a bolometer single detection scheme. The magnetic field was modulated at 500 cps and phase-sensitive detection was employed following a narrow-band amplifier centered at 1000 cps. Detecting the second harmonic of the modulation frequency minimized spurious effects of amplitude modulation of the carrier and reproduced essentially the second derivative of the absorption. Two recorded traces of the absorption at 1.4°K are shown in Fig. 1. Saturation effects are illustrated by the

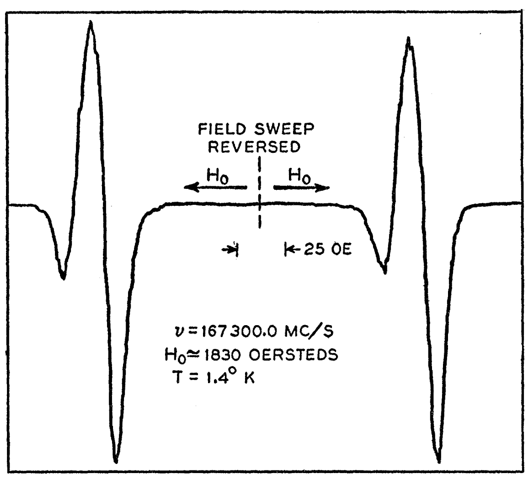

FIG. 1. Reproduction of the recorder trace of the high-frequency line with output time constant of 1 second. At lower rf fields, in the absence of saturation, the pattern is symmetrical. The asymmetry reflects saturation effects.

dependence of the asymmetry upon the sweep direction. From the known rf field in the cavity and behavior of the resonance, we estimate that T_1 is ~ 20 seconds at 4.2°K and several times longer at 1.3°K. More exact measurements of T_1 are in progress including an investigation of the predicted angular dependence.[8]

When not saturated, the resonances were Gaussian in shape with widths of ~14 oe which are comparable to the calculated nuclear-nuclear dipole widths of 10 oe. It has not been determined, however, that the lines are homogeneously broadened.

TABLE I. The temperature dependence of ν_0 extrapolated from the observations of the two branches of Eq. (2). Temperatures were measured by vapor pressures and calibrated carbon resistors.

T°K	ν_0 Mc/sec
1.3 ±0.1	159 985±10
4.22±0.05	159 975±10
10.2 ±0.1	159 640±50
13.95±0.1	158 810±80
16.0 ±0.3	158 280±80
17.0 ±0.3	158 040±80
20.4 ±0.05	156 100±20

The extrapolated value of ν_0 for several temperatures are listed in Table I. The narrow resonances (which were quite remarkable considering the indirect origin of the internal fields) made it possible to measure ν_0 with considerable precision. We have then a measure of a quantity proportional to the sublattice magnetization accurate to one part in 10^4. In the region $T \ll T_n$, spin-wave theory predicts[6] a T^2 departure of the sublattice magnetization, while near T_n the molecular field approximation predicts a modified Brillouin-function dependence. The observed low-temperature behavior suggests a $T^{3.5}$ law.

The field for resonance at a fixed frequency was measured as a function of the angle in the allowed plane of rotation. These results are shown in Fig. 2 where the geometrical relation expected between angle and H_0 is plotted as a dashed curve.

The values of the hyperfine interaction terms determined by these results depend upon the value of α in Eq. (2). Assuming the extreme case of $\alpha=0$, we find

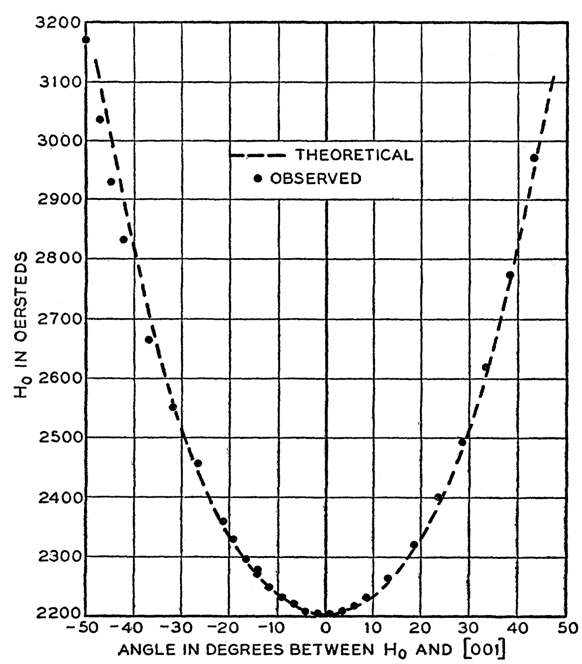

FIG. 2. External field required for resonance of the high-frequency line at 4.2°K. The dashed curve plots the external field necessary for a constant resultant field at these particular F^{19} sites.

$A_z^{\mathrm{I}} = (15.4\pm0.2)\times10^{-4}$ cm^{-1} and $A_z^{\mathrm{II}} = (16.2\pm0.2)\times10^{-4}$ cm^{-1}, where these values represent the hyperfine interaction alone, dipole fields having been eliminated by the use of Keffer's[9] calculations of the dipole sum. Implications of these results as well as a more detailed account of the experiments will be presented shortly.

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Propagation of Strong Shock Waves in Pulsed Longitudinal Magnetic Fields*

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DEUTERIUM plasma with ion energies >100 ev/ion in the ordered motion at densities $>5\times10^{16}$ ions/cm^3 have been produced behind strong shock waves generated by high current discharges in a transverse magnetic field.[1–3] After the initial acceleration by the electromagnetic driving forces, the shock velocity and thermal energy decay rapidly a few centimeters from the discharge due to heat conduction to the tube walls. The term *shock wave* is used here advisedly to describe the high-velocity luminous fronts observed in these experiments.

A rising longitudinal magnetic field along the ex pansion chamber has been used to insulate the plasma from the walls of the shock tube and to further accelerate the shock wave by compressing the plasma behind the shock front. The shock wave is produced initially by a discharge between two electrodes (50–100 kv, 0.66 μfd, 500 kc/sec) at one end of a T-shaped, 3-cm diameter quartz tube. The return lead to one of the electrodes is placed at the base of the "T" and parallel to the discharge current.[1,3] The current through this lead generates a magnetic field which drives the plasma into the expansion chamber. The longitudinal field was generated by a four-turn coil with each turn connected in parallel to a condenser bank (10–40 kv, 5 μfd, 120 kc/sec). The coil array was 7 cm long with a volume of 50 cm^3.