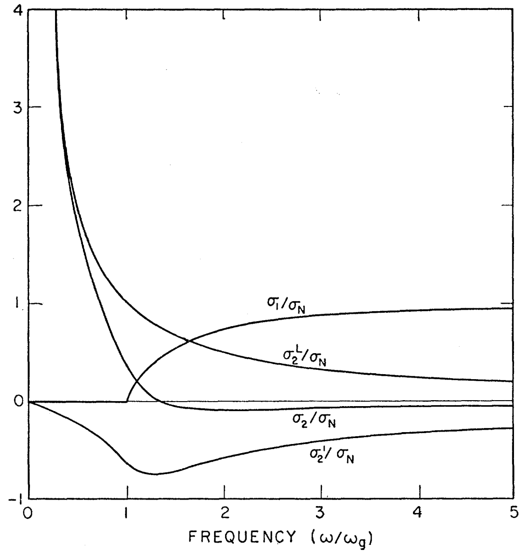

FIG. 1. Frequency dependence of conductivity for an energy-gap model at $T=0$ under the assumption $\sigma_1/\sigma_N=1-\omega_g^2/\omega^2$ and $\sigma_2^L/\sigma_N=\omega_g/\omega$.

For $\omega\ll\omega_g$, this has a constant value of the order of magnitude 10^5 ($\sim 4\pi\sigma_N/\omega_g$), and resembles the ϵ_0 predicted in the theory of Ginzburg and Landau.[6] We note that the appearance of this term is a direct consequence of the cutoff of normal conductivity for $\omega<\omega_g$. Though this σ_2' term is important near $\omega=\omega_g$, it is completely swamped by σ_2^L for $\omega\ll\omega_g$. Thus σ_2^L alone can be determined directly from the microwave points.

To the limited accuracy of these data, both microwave points yield $\nu\sigma_2/\sigma_N=11\pm2$ cm^{-1}. With σ_N estimated to be roughly the value for bulk lead at room temperature (the residual resistance of the film is half its room temperature resistance), this corresponds to a value of the London λ increased from that of pure bulk lead by a factor of 7. This increase in λ appears to be related closely to the increase of λ with reduction of electron mean free path by impurities observed by Pippard[7] and Chambers.[8] For $\omega>\omega_g$ this reduced σ_2^L is nearly cancelled by the σ_2' term, leaving $\sigma_2\ll\sigma_1$. Since σ_2 enters (2) only quadratically, T_S/T_N for $\omega>\omega_g$ is largely determined by σ_1 alone. This allows the form of decrease of $\sigma_1(\omega)$ in the superconducting state to be obtained directly from the excess of T_S over T_N for $\omega>\omega_g$.

The situation is summarized in the figure for the specific assumptions $\sigma_1/\sigma_N=1-\omega_g^2/\omega^2$ and $\sigma_2^L/\sigma_N=\omega_g/\omega$. The K-K relations then give

$$\sigma_2'/\sigma_N=-(1/\pi)\{(1-\omega_g^2/\omega^2)\ln|\omega_g+\omega|/|\omega_g-\omega|+2\omega_g/\omega\}.$$

The sharp peak in transmission (see Fig. 1 of preceding Letter) near $\omega=\omega_g\approx 3kT_c/\hbar$ occurs because both σ_1 and σ_2 are very small there. For $T>0$, it is expected that $\sigma_1>0$, even for $\omega<\omega_g$ and that the rise in σ_1 starts at a lower frequency and is more gradual. This would result in a lower peak in the calculated transmission curve, as observed. Despite the reasonable agreement with experiment which can be achieved in this way, it should be emphasized that the specific forms proposed here are not meant to be exact or unique. They simply formalize an approach which seems promising for the interpretation of these and future experiments.

* Supported in part by the U. S. Office of Naval Research; the Signal Corps; and the Office of Scientific Research, U. S. Air Force.

[1] R. E. Glover, III, and M. Tinkham, preceding Letter [Phys. Rev. **104**, 844 (1956)].

[2] J. A. Stratton, *Electromagnetic Theory* (McGraw-Hill Book Company, Inc., New York, 1941), p. 516.

[3] R. de L. Kronig, J. Opt. Soc. Am. **12**, 547 (1926); H. A. Kramers, Atti congr. intern. fis. Como **2**, 545 (1927).

[4] For $0<T<T_c$, presumably the gap will be partially smeared out, and it may be only a region of sharply diminished density of states. These modifications would round off some features of our theoretical curves but leave the general principles intact.

[5] Corak, Goodman, Satterthwaite, and Wexler, Phys. Rev. **102**, 656 (1956); W. S. Corak and C. B. Satterthwaite, Phys. Rev. **102**, 662 (1956). The relation $\hbar\omega_g=3kT_c$ follows from the exponential in C_{es} if one assumes that the Fermi level is centered in the energy gap.

[6] See, for example, V. L. Ginzburg, J. Exptl. Theoret. Phys. (U.S.S.R.) **29**, 748 (1955) [Soviet Phys. JETP **2**, 589 (1956)].

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Paramagnetic Resonance of Hydrogen Atoms Trapped at Liquid Helium Temperature*

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HYDROGEN and deuterium atoms produced by electrical discharges have been successfully deposited and stored in their respective molecular matrices at liquid helium temperature. The identity of each atom has been established by the characteristic hyperfine splitting of its microwave electron-spin resonance spectrum.

The atoms were produced by an electric discharge in pure hydrogen or deuterium at a pressure of about 0.1 mm Hg. The discharge was of the electrodeless type operating at a frequency of 4 Mc/sec and a power of 100 w. The discharge products were pumped at a speed of about 1500 cm/sec past a short side-tube connected to a low-temperature cell. The side-tube was terminated by a glass slit $\frac{1}{2}$ mm wide by 10 mm long which served as the source slit for a simple molecular beam system. The molecular beam was condensed on a sapphire rod at a distance of 3.1 cm from the glass slit. The sapphire rod which was soldered to the bottom of a liquid helium reservoir was 2 mm in diameter and 22 mm long. With this system a 5-minute deposition generally provided an adequate sample. During sample deposition a good vacuum ($\sim 10^{-5}$ mm Hg) was maintained in the cell by the pumping action of the liquid-helium-cooled surfaces. A liquid-nitrogen-cooled radiation shield surrounded the sample rod and helium reservoir except for the slots used for introducing the molecular beam and for pumping.

For resonance measurements, the sample-coated sapphire rod was inserted into a rectangular microwave cavity through an aperture 4 mm in diameter. The cavity was operated in the *TE* 012 mode and kept at liquid nitrogen temperature by thermal contact with the radiation shield. The penetration of the sample rod into the cavity was adjustable up to a maximum of 16 mm. The broad face of the cavity was perpendicular to the magnetic field supplied by a 12-in. Varian magnet. The microwave frequency of the klystron was stabilized at the sample cavity resonance frequency of about 9066 Mc/sec. The spin resonance was observed by slowly sweeping the magnetic field through resonance and recording the absorption signal derived from the field modulation at 400 cps. The magnetic field was measured by a proton resonance magnetometer. The microwave frequency was measured by using a standard compared with radio station WWV.

Observations of the electron spin resonances in hydrogen and deuterium samples have shown that the trapped atoms are quite stable at liquid helium temperature. The resonance lines appeared immediately after deposition and remained detectable as long as liquid helium temperature was maintained.

The spectrum for hydrogen consisted of two lines of almost equal intensity, one 234.1 oersteds above and the other 274.6 oersteds below the field for free-electron resonance. The half-width for each component was about 0.7 oersted. The observed spectrum for deuterium was a triplet with the center line three to four times stronger than either of the other components. The center line was 2.1 oersteds lower than the free-electron resonance field and was separated from the low- and high-field lines by 76.7 and 78.7 oersteds, respectively. The half-width of the deuterium lines was roughly 1.3 oersteds.

The spectral patterns and line intervals for the observed hydrogen doublet and deuterium triplet are consistent with the known hyperfine structures of free hydrogen and deuterium atoms. By applying the Breit-Rabi formulas,[1,2] we have obtained the hyperfine coupling constants and g_J values for trapped atoms shown in Table I. Comparing these values with the values for free atoms, also shown in Table I, it is seen that the atoms trapped by low-temperature deposition are very nearly, but not exactly, free. We are not ready at this time to explain quantitatively the small deviations from the free states, the difference between the hydrogen and deuterium line widths and, especially, the anomalous intensity of the deuterium center line.

It was also observed that each hyperfine line of the hydrogen atom was accompanied by two satellite lines symmetrically spaced about it. The separation of these satellites from their main line corresponds to the energy required to flip a neighboring proton.[3] Similar satellites have also been observed for each of the deuterium lines except that they were not well resolved from the relatively broad deuterium line.

TABLE I. Hyperfine splitting constants (ν_c) and g_J values for H and D atoms.

	H	D
ν_c (trapped) Mc/sec	1417.13±0.45	326.60±0.23
ν_c (free) Mc/sec[a]	1420.4057	327.3843
Deviation of ν_c from free value	0.23%	0.24%
g_J (trapped)	2.00243±0.00008	2.00244±0.00008
g_J (free)[b]	2.00230	

[a] P. Kusch, Phys. Rev. **100**, 1188 (1955).
[b] R. Beringer and M. A. Heald, Phys. Rev. **95**, 1474 (1954).

In the course of our experiments with hydrogen, a number of strong, sharp lines of unknown origin have been observed in the vicinity of the free electron resonance field. These appeared as triplet and quartet spectral groups, each having uniformly spaced lines. The line spacing varied from 4 to 23 oersteds among the groups. It is possible that these lines are connected with excited molecules stabilized in the low-temperature matrix.

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Antiferromagnetic Resonance in MnF_2[†]

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ANTIFERROMAGNETIC resonance has been observed in a single crystal of MnF_2.[1] Observations on this absorption line have been made in the temperature range from 36° to 65°K and at frequencies from 213 300 Mc/sec to 96 000 Mc/sec.[2] MnF_2 has tetragonal symmetry and a Néel temperature of approximately 68°K. The interpretations of antiferromagnetic resonance experiments on other crystals[3–6] have been complicated by a lower order of crystal symmetry, low Néel temperatures, or the necessity of working very close to the Néel temperature. In contrast, MnF_2 furnishes the most direct and simple test of the basic theory.

It has been shown by Keffer and Kittel[7] and others that the resonance frequency with the external magnetic field applied parallel to the symmetry axis is given by:

$$\omega/\gamma=(2H_EH_A)^{\frac{1}{2}}\pm H_0(1-\alpha/2), \tag{1}$$

where H_E is the exchange field, H_A is the anisotropy field, H_0 is the applied field, γ is $ge/2mc$, and α is the ratio of the parallel and perpendicular susceptibilities.