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Letters to the Editor

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Observation of Cyclotron Resonance in Germanium Crystals*

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WE have observed cyclotron or diamagnetic resonance in n- and p-type germanium crystals at 4°K at a frequency of 9050 Mc/sec. In cyclotron resonance absorption the conduction electrons or holes are curved in spiral orbits by the application of a static magnetic field; resonant absorption of energy from an rf electric field perpendicular to the static magnetic field occurs when the frequency of the electric field is equal to the frequency of rotation of the particle. This is the principle of the cyclotron an the simple magnetron. The angular rotation frequency in a crystal is

$$\omega_L = (eH)/(m^*c), \tag{1}$$

where m^* is the appropriate effective mass; thus the experiment determines the effective mass directly. Cyclotron resonance should not be confused with electron spin resonance. Cyclotron resonance arises from an electric dipole transition, whereas spin resonance arises from a magnetic dipole transition: the transition probabilities for the former are larger by a factor of the order of 10^{10} under the conditions of our experiment.

The theory of cyclotron resonance absorption goes back to Drude, Voigt, and Lorentz. The effect is important to the propagation of radio waves through the upper atmosphere.[1] The translation of the theory to solids has been discussed recently by Dingle[2] and by Shockley;[3] the latter who has pointed out that conditions in germanium are favorable for the observation of the effect. For a plane polarized E field the conductivity at frequency ω is related to the static conductivity σ_0 by the equation

$$\frac{\sigma}{\sigma_0} = \frac{1+i\omega\tau}{1+(\omega_L{}^2-\omega^2)\tau^2+2i\omega\tau}; \tag{2}$$

here τ is the collision or relaxation frequency of the electrons. It is desirable to have $\omega\tau > 1$ to define the resonance; for this it is advantageous to work with pure crystals at low temperatures and high frequencies.

Cyclotron resonance was observed in a 38 ohm-cm n-type germanium crystal at a field of 370±5 oersteds, corresponding to an effective mass at 4°K of

$$m^*/m = 0.11,$$

presumably for electrons. The static magnetic field was parallel to a 100 axis. The relaxation time is approximately 0.7×10^{-10} sec as estimated from the width of the resonance ($\sim$100 oersteds half-width at half-power). We note that Suhl and Pearson,[4] in an unsuccessful attempt to detect cyclotron resonance in n-Ge, were able to set a limit $m^*/m < 0.3$; this is compatible with our measurements.

The relative intensity of the resonance depends on the rf power level. With our present equipment no signal from the specimen is detected at low rf power. As the power is increased the resonance line *suddenly* appears. Further increases in power make the specimen visible over a wider range of static magnetic field intensity. At the highest powers the resonance line is broadened. Similar effects were observed in p-type germanium. The resonance positions are essentially independent of power at the levels employed. The cavity was always filled with liquid helium. The dependence of the signal on power level is consistent with a large increase in carrier concentration caused by avalanche ionization of shallow traps (or perhaps donor impurity atoms) occurring as the electrons near resonance gain sufficient energy from the rf field to cause ionization. Threshold rf fields in the 1 to 10 v/cm range start the carrier multiplication.[5] The presence of ionization effects near resonance eliminates the possibility that paramagnetic impurities cause the resonance. The behavior of the resonance signals during thermal ionization on warming up above 4°K was easily distinguishable from the behavior during rf ionization.

Cyclotron resonance was also observed in a p-type germanium crystal having about 10^{14} acceptors/cm^3. Two resonances were observed, one at 125±5 oersteds with a half-width of about 50 oersteds and another at 970±50 oersteds with a half-width of about 100 oersteds. Ionization was observed near each resonance. The order of magnitude of the intensities of the two lines are comparable. In all runs the field was explored up to 9000 oersteds. The hole resonances correspond to, at 4°K,

$$\text{(a)}\quad m^*/m = 0.04; \quad \tau \approx 0.5\times 10^{-10}\ \text{sec},$$
$$\text{(b)}\quad m^*/m = 0.30; \quad \tau \approx 2\times 10^{-10}\ \text{sec}.$$

The field was applied parallel to 100, 110, and 111 axes in successive experiments. No shift in resonance positions with orientation was observed. The sample on the 100 run was different in size and shape from that used on the other runs, so that "cavity-type" false resonances may presumably be excluded.

We wish to express our gratitude to Dr. A. V. Siefert of Sylvania Electric Products, Inc., and to Mr. R. E. Davis of the Westinghouse Research Laboratories for supplying high-quality germanium crystals for the present program. We are indebted to Professor W. F. Giauque and Dr. D. N. Lyon for the provision of liquid helium, and also to the Shell Development Company for liquid helium. The x-ray orientations were kindly performed by Dr. J. Washburn.

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[1] For a review see H. R. Mimno, Revs. Modern Phys. **9**, 1 (1937).

[2] R. B. Dingle, Proc. Roy. Soc. (London) **A212**, 38 (1952).

[3] W. Shockley, Phys. Rev. **90**, 491 (1953).

[4] H. Suhl and G. L. Pearson, Bull. Am. Phys. Soc. **28**, No. 4, 24 (1953).

[5] It appears that this picture will explain the resistance discontinuities in p-Ge in static electric fields at 4°K and below reported by A. N. Gerritsen, Physica **15**, 427 (1949); it is possible that ionization might also explain the increase in carrier concentration at low temperatures reported by C. S. Hung and J. R. Gliessman, Phys. Rev. **79**, 726 (1950).

The Structure of Liquid Helium

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A STUDY has recently been completed in our laboratories of the angular intensity distribution of x radiation scattered by liquid helium. From this, following essentially the method of analysis described by Gingrich,[1] an atomic distribution function for the liquid has been evaluated. The experimental method has already been indicated elsewhere,[2] and in this note we wish briefly to present the qualitative results obtained.

While minor variations in intensity distribution may result as the temperature of the liquid helium is changed, these are at present considered to be within our observational accuracy. It is, therefore, certain that no large change occurs in the atomic distribution over the whole liquid range from 4°K to 1.27°K, nor can the λ-point transition be regarded as the result of any drastic re-ordering process.

Taking the intensity distribution at 2.06°K, just below the λ point, as typical of the present results, we obtain the atomic distribution shown in Fig. 1. This gives, as usual, the number of

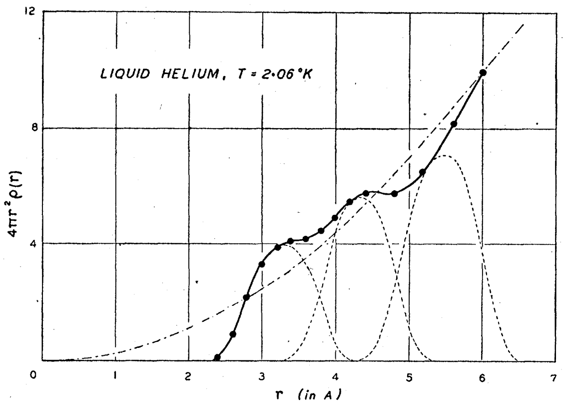

FIG. 1. The distribution function for liquid helium below the λ point.

atoms contained in any shell of radius r and thickness dr; the smooth dotted curve indicates the *mean* atomic density at the same temperature. Using Coulson and Rushbrooke's[3] criterion that $r\rho(r)$ has symmetric similarity about each value of r for which the distribution curve shows a maximum, the latter can then be reduced to its component shells. This is also shown in Fig. 1, from which the following distribution of helium atoms around any one atom may be deduced:

Distance, A	Number of atoms in shell
3.15	4
4.24	6
5.40	8

There may be some uncertainty about the accuracy of the atomic density deduced from our data for the third shell. However, from other considerations there appears to be little doubt that the distribution given is the correct one for liquid helium.

While bulk helium is certainly not possessed of any extensive long-range order, we believe that results of appreciable significance may follow from a consideration of the lattice structure which can be built up to conform to the above distribution. It is readily seen that a simple tetragonal lattice with an axial ratio c/a of $\sqrt{2}$ will approximately satisfy the atomic distribution found for helium, and such a structure with $a = 3.15$A could form the unit cell. Early speculations relating to the atomic distribution in liquid helium, based as they were on the idea of order-disorder transitions, suggested that the actual structure might be developed from a face-centered cubic lattice.[4,5] It is instructive in the present case to consider how the tetragonal cell may be derived by a similar procedure. It will be clear that the distribution found can be made up by simply removing in a particular way eight of the twelve nearest neighbors in a face-centered array, all other atom points remaining occupied. Figure 2 shows a structure resulting from this process, and a striking feature of this array will be immediately evident. One set of (100) planes is appreciably more densely populated than any other plane. If the helium had long-range order, this plane would in fact be an exceedingly effective "slip plane."

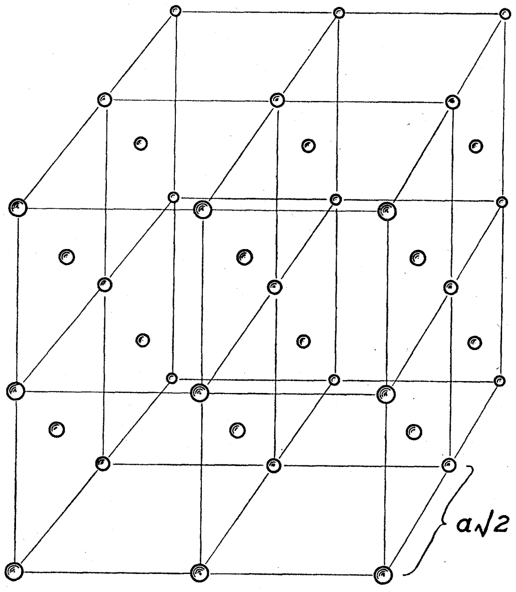

FIG. 2. Lattice configuration for liquid helium, showing preferential (100) planes.

One is tempted to consider, therefore, whether the helium II film (or the "superfluid" component of the liquid) does actually have such an ordered structure as shown in Fig. 2, and whether such order exists over a sufficient extent to permit of easy slip on the preferential (100) plane. The fact that the helium II film is effectively at a temperature of 0°K and has zero entropy[6] lends support to the necessity of its having *some* kind of order, and such physical order is in many ways a more satisfactory concept than an ordering in "momentum space." So long as no appreciable momentum interchange occurs between the preferential (100) planes, the formation of a helium II film on any surface in contact with the liquid, and its nonviscous flow on that surface, would naturally follow. On this view, viscosity would suddenly appear in any extended "superfluid" portion of the liquid, as soon as bulk helium II adjacent to that portion had reached a sufficient temperature that its ("normal") atoms possessed enough energy to destroy the "superfluid" structure. It is of interest to note that a simple calculation of the binding energy[7] between opposite pairs of atoms on the preferential (100) planes of the proposed lattice structure yields a value of about 2×10^{-16} erg. If this is equated to $kT/2$, a value of nearly 3°K is obtained for T. The onset of viscosity in the superfluid regions when the bulk liquid reached this temperature would, of course, be associated with the λ-point transition.

According to this picture, *both helium I and bulk helium II* would simply have the liquid-type distribution actually found; we should not expect present x-ray methods to show any structural change at the λ point.

Finally, we may remark that a calculation of the total energy at 0°K of such a structure as shown in Fig. 2, using the Slater-Kirkwood[7] potential function and London's curve for zero-point energy,[8] gives a binding energy of 15 calories per mole and a molar volume of 27 cc. These figures agree remarkably well with the experimental values deduced for helium II, and give further confidence in the correctness of the proposed structure. Full details of this work will be published elsewhere.

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Čerenkov Effect at Microwave Frequencies*

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ČERENKOV radiation at microwave frequencies has been experimentally detected. Approximately 10^{-7} watt of Čerenkov radiation at a wavelength of 1.25 cm was obtained.

In the arrangement used (see Fig. 1), the radiation is excited by a flat electron beam which passes as closely as possible over