β-radiation showed that all of the intense lines belong to the interference system of the $K\alpha$-radiation. Thus, the data on the structure of hydrogen obtained at the Leiden laboratory, and incorporated into all of the reference literature, are evidently incorrect. With the aid of the Hull-Davey curves, we found that the hydrogen patterns could be equally well interpreted as arising from a tetragonal lattice. That the lattices of hydrogen and deuterium correspond to crystals of non-cubic syngony receives confirmation from our observation that they both possess the property of double refraction. This does not support the older data, according to which solid hydrogen is optically isotropic.[3]

[1]Keesom, DeSmedt, and Mooy, Leid. Comm. 209d (1930).

[2]H. D. Megaw, Phil. Mag. 28, 129 (1939).

[3]W. Wahl, Proc. Roy. Soc. (London) A88, 61 (1913).

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An Experimental Manifestation of Instability Of the Normal Phase in Superconductors

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IN the experiments of Faber,[1] considerable supercooling of the normal phase of Al has been achieved near the critical temperature T_c. The magnetic field H_s at which the transition into the superconducting state takes place is approximately the same for various samples and has a mean value $H_s \sim 0.05\, H_{cm}$, where H_{cm} is the equilibrium critical field for the bulk metal. Values of $H_s \sim (0.035 - 0.04) H_{cm}$ were also observed (cf. Fig. 3 of Ref. 1). This gives rise to the impression that the limiting supercooling is a characteristic of the ideal metal, which cannot be supercooled to values of the field below some value H_{c1}, and that for Al $H_{c1} \sim (0.035 - 0.04)\, H_{cm}$.

We would like to call attention to the fact that this result follows directly from the theory of superconductivity developed in Ref. 2. Actually, it is shown in Ref. 2 that under certain conditions the normal phase of a superconductor becomes unstable with regard to the formation of lamina (nuclei) of the superconducting phase. In particular, these lamina of the superconducting phase are formed when the normal phase is in a magnetic field fulfilling the condition*

$$H = \varkappa H_{cm} / \sqrt{2}\,(n + 1/2), \qquad n = 0, 1, 2, 3, \ldots, \quad (1)$$

$$\varkappa = (\sqrt{2}e/\hbar c)\, H_{cm} \delta_0^2 = 2{,}16 \cdot 10^7 H_{cm} \delta_0^2,$$

where δ_0 is the penetration depth for the superconductor in a weak magnetic field. From Eq. (1) it follows that the magnetic field within the normal phase can be reduced only as far as the value

$$H_{c1} = \sqrt{2}\varkappa H_{cm}, \qquad (2)$$

which is obtained from (1) for $n = 0$. In fields $H > H_{c1}$ —the formation of nuclei of the superconducting phase is associated with the appearance of a surface energy; the normal phase is therefore metastable over the range $H_{c1} < H < H_{cm}$ If, however, $H = H_{c1}$, the normal phase is unstable, and the superconducting transition must take place.** For Al near T_c, $\varkappa = 0.025$[(cf. Ref. 3, in which are given the values*** $\varkappa_0 = 2\varkappa$, $(T_c) = 0.050$)]. Hence, in accordance with (2), $H_{c1} = 0.0354\, H_{cm}$, which is in excellent agreement with the experimental value cited above. We note that for Al the theory is also in complete accordance[3] with experiment[1] with regard to the magnitude of the surface energy, as determined by this same parameter $\varkappa$. For Sn the limiting value H_{c1} is not reached. This circumstance may be connected with the fact that the case of an anisotropic metal is in general more complex. It is more probable, however, that in this case the reason is the same as that applying to Al for $T < 0.9\, T_c$, where superconductivity arises for field $H_s > H_{c1}$. In the region $T > 0.9 T_c$, however, as is shown in Ref. 1, the formation of nuclei is impeded by the fact that the characteristic length Δ exceeds the distance between the lattice "defects", which serve as nucleation centers. For Sn near T_c the length Δ is on the order of four times smaller than for Al, as a consequence of which the formation of nuclei is easier.

For metals having small values of $\varkappa$ the instability of the normal phase can be manifested only through supercooling. On the other hand, as is noted in Refs. 2 and 7 and is clear from (2), for $\varkappa > \varkappa_c = 1/\sqrt{2}$ instability of the normal phase occurs even for $H = H_{c1} \geq H_{cm}$; superconductors for which

$\varkappa > 1/\sqrt{2}$ should therefore behave anomalously. It appears to us that this is just the effect observed in the case of the alloys of Sn with In investigated in Refs. 6, 8, and 9. For concentrations of In below about 2.5% these alloys behave almost as ideal suprrconductors; beyond this point their properties change sharply.[6,9] At the same time, the penetration depth for an alloy containing 2.5% In is roughly twice that for pure Sn (cf. Ref. 6). From this it follows that the parameter $\varkappa = 2.16 \times 10^7 H_{cm} \delta_0^2$ increases by about four times and near T_c is approximately 0.35. This is about one-half the critical value $\varkappa_c = 0.0707$. The discrepancy, however, does not appear too serious when we consider the known inaccuracy of the available data, the complexities associated with the anisotropy of tin****, and, finally, the presence of lattice defects even in identical alloys.[6,9] In view of this latter circumstance $\varkappa$ may exceed $\varkappa_c$ in the vicinity of individual defects even in specimens for which the mean value of $\varkappa > \varkappa_c$; furthermore, the condition for instability of the normal phase may be altered near the defects. From this point of view it is significant that for $\varkappa = 0.35$ the length $\Delta \approx 2\delta_0$ while for pure tin $\Delta \approx 15\delta_0$. It is therefore quite natural to suggest that the value of Δ is reduced to zero without particular difficulty near the defects. Thus, the results given in Refs. 6, 8 and 9 are in qualitative agreement with the theory of Ref. 2, although there are as yet insufficient data for a quantitative comparison (for this latter purpose it would be desirable to investigate alloys based on aluminum or some other cubic metal). The author, therefore, cannot agree with the opinion of Pippard,[6], who feels that the theory of Ref. 2 meets with difficulties in the case of superconductors. As regards the decrease in the concentration of the "superconducting electrons" $n_s = mc^2 / 4\pi e^2 \delta_0^2$ with increasing impurity concentration N_i, the explanation of this fact lies generally outside the scope of the phenomenological theory. If one relies upon the current qualitative ideas concerning the nature of superconductivity, the decrease of n_s with increasing N_i seems quite natural (the value of n_s is determined by the degree of "stiffness" of the wave function for the electronic ground state;[11] with increasing N_i the electronic structure "loosens" and n_s falls). It seems to us that Pippard's ideas[6,8] concerning the change of the "region of coherence" go no further than other such qualitative concepts; with regard to the nonlocal character of the relation between current and field they meet with objections.[12]

*In Ref. 2, on p. 1072, this formula is given in different units (in Ref. 2, the field $H_0 = H/\sqrt{2}H_{cm}$); furthermore, in Ref. 2 Eq. (1) is considered only in the approximation to the case in which $H \gg H_{cm}$ (i.e., $H_0 \gg 1/\sqrt{2}$). This case will also be treated below.

**We note that, as has been shown in Ref. 2, the superconducting phase is metastable and, in consequence, can be superheated within the region of fields $H_{cm} < H_{c2}$. For $H > H_{c2}$, the superconductivity must be destroyed. As $\varkappa \to 0$ the fields $H_{c2} \to \infty$, and decreases with increasing $\varkappa$. Values of H_{c2} for a given $\varkappa$ may be obtained only through numerical calculation. With regard to the fields H_{c1} and H_{c2} in films (cf. Ref. 4).

***We note that the dependence of the free energy upon the concentration $n_s = |\Psi|^2$ of the superconducting atoms assumed in Ref. 3 (cf. also Ref. 5) has been confirmed for all T by the experiments of Whitehead, *et al.*, as D. Shoenberg has kindly informed us (cf. also Ref. 6).

****For a generalization of the theory of Ref. 2 to the case of anisotropic metals cf. Ref. 10, from which expressions analogous to (1) and (2) can readily be obtained for the anisotropic case.

[1] T. E. Faber, Proc. Roy. Soc. (London) **A231**, 553 (1955).

[2] V. L. Ginzburg, J. Exptl. Theoret. Phys. (U. S. S. R.) 20, 1064 (1950).

[3] V. L. Ginzburg, J. Exptl. Theoret. Phys. (U.S.S.R.) 3, 621 (1956). Soviet Phys. JETP 3, 787 (1956).

[4] V. L. Ginzburg, Dokl. Akad. Nauk SSSR **83**, 385 (1952).

[5] V. L. Ginzburg, Dokl. Akad. Nauk SSSR **110**, 358 (1956).

[6] A. B. Pippard, Phil. Trans. Roy. Soc. (London) **248**, 97 (1955).

[7] S. A. Abrikosov, Dokl. Akad. Nauk SSSR **86**, 489 (1952).

[8] A. B. Pippard, Proc. Roy. Soc. (London) **A216**, 547 (1953).

[9] R. B. Doidge, Phil. Trans. Roy. Soc. (London) **248**, 553 (1956).

[10] V. L. Ginzburg, J. Exptl. Theoret. Phys. (U.S.S.R.) 23, 236 (1952).

[11] V. L. Ginzburg, Usp. Fiz. nauk **48**, 25 (1952).

[12] V. L. Ginzburg, J. Exptl. Theoret. Phys. (U.S.S.R.) 29, 748 (1955); Soviet Phys. JETP 2, 589 (1956).

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