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From the Current Literature

BEHAVIOR OF SUPERCONDUCTORS IN A DECREASING MAGNETIC FIELD

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MOST pure superconducting metals belong to the so-called superconductors of the first group. If the normal and superconducting phases are simultaneously present in such a metal placed in an external magnetic field (*mixed state*), then, *according to the Ginzburg–Landau theory*[1], the thickness of the transition layer between the normal and the superconducting phase is $\xi(T) \geq \sqrt{2}\,\delta_0(T)$, where δ_0 is the depth of penetration of a weak magnetic field (10^{-5}—10^{-6} cm). Thus, in superconductors of the first group, the main parameter of the Ginzburg–Landau theory is $\kappa \equiv \delta_0(T)/\xi(T) \leq 1/\sqrt{2}$. It is easy to show that this corresponds to a positive surface energy for the interface between the normal and superconducting phases.

The dependence of the magnetization M (magnetic moment per unit volume) on the external magnetic field H of a long cylindrical superconductor of the first group placed in a longitudinal magnetic field is shown in Fig. 1. The transition of the sample in the magnetic field from the superconducting into the normal state and back is a first-order phase transition. Consequently, when the magnetic field is decreased from values $H > H_c$, the transition from the normal to the *superconducting state may be delayed to fields smaller* than H_c; this will occur if the formation of superconducting-phase nuclei is hindered. This is the supercooling phenomenon. Here H_c is the critical thermodynamic field, i.e., the field at which the normal and superconducting phases are in equilibrium. However, as shown in [1], there exists a field $H_{c2} = \sqrt{2}\,\kappa H_c$ such that the existence of the normal phase becomes absolutely unstable. At temperatures close to T_c the formation of the nuclei is hindered, since $\xi(T)$ is quite large at such temperatures. There is hope therefore that a field H_{c2} will be reached in experiments on supercooling and this will permit the parameter κ to be determined. Lynton[2] believes that the values of κ calculated from supercooling data are in all probability the most reliable ones.

However, a recently published paper by Saint-James and deGennes apparently calls for a review of many values of κ obtained from supercooling experiments.

These authors called attention to the fact that the boundary of an ideally homogeneous fault-free superconductor is in itself a defect of sorts, and by using the Ginzburg–Landau theory they have shown that in supercooling the condition for absolute instability of the normal phase is first satisfied in a surface layer of thickness $\sim\xi(T)$. This occurs in a field H_{c3}

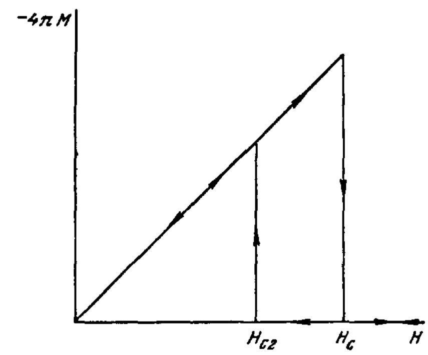

FIG. 1. Magnetization curve of a superconductor of the first group. In a decreasing field, the normal phase can be metastable and can be supercooled to a field H_{c2}, when it becomes absolutely unstable.

$= 1.691\,H_{c2}$, and consequently, in the field interval $H_{c2} \leq H \leq H_{c3}$, the surface layer will be in a superconducting state whereas the interior part will be still filled with a normal phase in a metastable supercooled state, which becomes absolutely unstable when the field drops to H_{c2}.

A different behavior is exhibited by the so-called superconductors of the second group, which includes many alloys and intermetallic compounds and the pure metal niobium. The theory of the behavior of the superconductors of the second group in an external magnetic field was developed by Abrikosov[4]. In such superconductors $\kappa \geq 1/\sqrt{2}$, and it can be readily seen that this leads to a negative energy for the interface between the normal and superconducting phases. This is the key situation for the understanding of the entire process of magnetization of superconductors of the second group.

Abrikosov has shown that in an increasing magnetic field the superconductor of the second group should first behave like a superconductor of the first group, i.e., the complete Meissner effect should be observed: the magnetic field is completely expelled from the volume of the superconductor (except for a thin surface layer—the penetration depth). However, when the field reaches a value $H_{c1} < H_c$ (H_{c1} is the lower critical field), the individual quantum filaments of the magnetic flux begin to penetrate into the superconductor. Each filament carries a magnetic-field quantum $\Phi_0 = 2 \times 10^{-7}$ G-cm^2. This produces a mixed state. With increasing external field H, the distance between filaments decreases, and the average field B in-

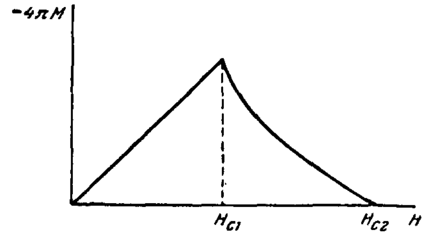

FIG. 2. Magnetization curve of a superconductor of the second group. Transition at H_{c2} is a second-order phase transition.

side the superconductor approaches H (the field on the axis of each filament is equal to H, and the metal is in the normal state on the filament axis). Finally, when the external field reaches a value $H_{c2} = \sqrt{2}\,\kappa H_c$ (upper critical field), the average internal field becomes comparable with H and the superconductor of the second group goes over into the normal state. A second-order phase transition should then be observed. This means full reversibility of the process, and accordingly the absence of any superheating or supercooling. The magnetization curve of superconductors of the second group is shown in Fig. 2. The appearance of the mixed state has a simple physical explanation. Indeed, by virtue of the fact that the energy of the interface between the normal and superconducting states is negative in a superconductor of the second group, it is energetically easier, in a sample placed in an external magnetic field, for the entire volume of the metal to break up into normal and superconducting regions, such that the boundaries between them [with thickness $\sim \xi(T)$] occupy a maximum volume. This leads to the appearance of a mixed state, since the metal is in the normal state along the axes of the filaments and in the superconducting state in the intervals between them. The distribution of the internal field H_i in the mixed state is shown in Fig. 3.

The results of Saint-James and de Gennes call for a review of the behavior of superconductors of the second group in a decreasing field. The upper critical field for such superconductors is now not H_{c2}, but $H_{c1} = 1.691\,H_{c2}$, at which the superconducting state appears in a thin surface layer of the sample [$\sim \xi(T)$]. This surface superconductivity will exist in the field interval $H_{c2} \le H \le H_{c3}$, and when the external field H drops to the value H_{c2} the entire volume of the superconductor goes over into the mixed state.

Several very recent experimental papers report the observation of a third critical field H_{c3} in superconductors of the second group. Thus, Burger et al investigated films of Sn–In alloy 6000 Å thick. The thickness of the surface superconducting layer is estimated at 1000 Å. Conditions favorable for the appearance of

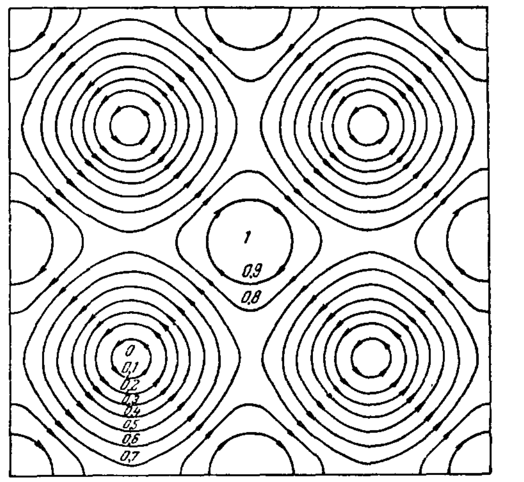

FIG. 3. Distribution of magnetic field in a superconductor of the second group when the external field H is close to H_{c2} ($H \lesssim H_{c2}$). The lines of the magnetizing superconducting currents (denoted by arrows) coincide with the lines of equal magnetic field. The numbers correspond to the relative density n_s of the superconducting electrons. At the points $n_s = 0$ the field is maximal and is equal to the external field. The period of the resultant quadratic lattice is of the order of $\xi(T)$.

surface superconductivity have thus been created in such a film. Actually, this superconductivity was observed by the authors, and the upper critical field was found to be equal to $1.6\,H_{c2}$.

Cardona and Rosenblum used a microwave technique to observe a field $H_{c3} = (1.4-1.9)\,H_{c2}$ in a Pb–Tl alloy (50% each), depending on the conditions on the surface, and found the ratio H_{c3}/H_{c2} to be independent of the temperature.

Finally, four critical fields of the alloy In–6%Pb (H_c, H_{c1}, H_{c2}, and H_R —the field at which resistance appears) were investigated by Gygax et al.[7] H_R was found to coincide with $H_{c3} = 1.691\,H_{c2}$ within 10%.

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Translated by J. G. Adashko