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A. I. Larkin, Fluctuations in Superconductors.

Near the temperature of transition into the superconducting state, just as near other second-order transition points, the role of fluctuations increases. However, the region of temperatures where the fluctuations exert a noticeable influence on the properties of superconductors is very small. According to Ginzburg's estimate[1], for pure bulky superconductors it equals 10^{-15} degrees. The fluctuations play a noticeable role in thin films with small electron mean free paths, and they were observed experimentally in precisely such films of bismuth[2]. It turned out that on approaching the transition temperature the film resistance R decreases smoothly and at temperatures not too close to the transition temperature T_c it is given by

$$1/R = R_\infty^{-1}\left[1+\tau_0 T_c (T-T_c)^{-1}\right], \tag{1}$$

where the parameters R_∞ and τ_0 do not depend on the temperature.

Simultaneously, the fluctuations of the resistance of the superconductors was investigated theoretically[3]. At temperatures higher than T_c, the superconducting pairs do not form a Bose condensate, but can be produced by fluctuation in noticeable amounts. Their density n_p obeys a kinetic equation that can be derived from the Ginzburg-Landau temporal equation

$$\frac{\pi\hbar}{16}\left(\frac{\partial}{\partial t}-2eE\,\frac{\partial}{\partial p}\right)n_p+\left(T-T_c+\frac{p^2}{2M}\right)n_p=T, \tag{2}$$

where E is the electric field intensity, p the pair momentum, and M the parameter of the Ginzburg-Landau theory.

The contribution of the fluctuation pairs to the current density is called paraconductivity, and for a thin film of thickness d it is equal to

$$j=\frac{2e}{Md}\int\frac{d^2p}{(2\pi)^2}\,n_p. \tag{3}$$

Substituting the solution of Eq. (2) in formula (3), we obtain in a weak low-frequency field the second term of expression (1). The ratio τ_0/R_∞ for the resistance of a film square is equal to the universal value

$$\tau_0/R_\infty=e^2/16\hbar=3\cdot 10^{10}/16\cdot 137\ \text{cm/sec}=1.52\cdot 10^{-5}\ \text{cm}^{-1}. \tag{4}$$

The universality of this ratio was later verified for films of different thicknesses.

Many investigations were made of the dependence of paraconductivity on the electric field and its frequency. As seen from (2), the pair density, and consequently their contribution to the conductivity, decrease with increasing field and with increase of its frequency. Equation (2) takes into account the deviation of the pair density from their equilibrium distribution under the assumption that the unpaired electrons come into the equilibrium state more rapidly than the pairs. This is correct if there are magnetic impurities in the film and the film is placed in a magnetic field, or if the energy relaxation of the electrons, which is connected with the electron-photon and electron-electron interactions, is sufficiently large. Otherwise it is necessary to take into account the fact that the fluctuation pairs influence also the conductivity of the unpaired electrons. The current density then acquires the so-called "anomalous" term, which leads to an effective increase of the parameter τ_0[4]. In some experiments with lead films[5] the measured value τ_0 turned out to be half as large as the theoretical one. There is still no satisfactory explanation of this fact.

In addition to the contribution of the fluctuations to the conductivity of thin films, there was observed[6] an influence of fluctuations on the tunnel current. A noticeable contribution is made by fluctuations to the magnetic susceptibility of superconductors at a temperature higher than the transition point[7]. In a wide temperature range, this contribution exceeds the weak paramagnetic susceptibility of normal metals.

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V. V. Shmidt. Critical Currents in Superconductors

1. If the current in a superconductor exceeds a certain (critical) value, then the superconducting state is destroyed. It is necessary to emphasize immediately that in the case of films and superconductors of the second kind, the destruction of superconductivity is not due to the magnetic field of the critical current, but to other causes. Only in the case of bulky superconductors of the first kind does their transition to the intermediate state occur when the magnetic field produced by the current on their surface reaches a critical value (the Silsbee rule).

When the current in the superconductor reaches a critical value, the superconducting state loses stability and a resistive state sets in.

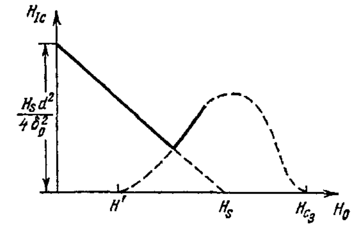
2. The critical current in a film whose thickness is $d \ll \xi(T)$ ($\xi(T)$ is the dimension of the Cooper pair or the coherence length) is determined in accordance with the Ginzburg-Landau theory[1], and the critical current density is

$$j_c \approx (c/4\pi) H_{cm}/\delta_0,$$

where H_{cm} is the critical thermodynamic field and δ_0 is the depth of penetration of the weak magnetic field. A physical explanation of the instability of the superconducting state in the case of such a current reduces to the following. An increase of the current in the superconductor means an increase of the velocity of the superfluid flow of the Bose-Einstein condensate. However, when this velocity increases, the unpairing of the electrons becomes stronger, i.e., the concentration of the Cooper pairs or the concentration of the carriers of the superconducting current decreases. There exists therefore a certain maximum current which can still flow in a stable manner in the superconductor. This indeed is the critical current.

3. Rigid superconductors are heterogeneous superconductors of the second kind. There exist several models of a rigid superconductor.

The "sponge" model: The rigid superconductor is a matrix made of soft superconducting materials, permeated by a network of thin filaments, which retain



superconductivity even when the matrix goes over into the normal state. This includes the case when the superconducting filaments run through a normal matrix. The model is applicable to certain special cases: eutectic alloys, an alloy of the type Zr + 4%Nb[2], when thin filaments of the superconducting β-Nb phase exist in the non-superconducting matrix, and synthetic superconductors obtained by pressing a superconductor through porous glass.

The critical current of the "sponge," its distribution over the cross section of the superconductor, and its dependence on the external magnetic field were calculated[3,4]. It turns out that there exists a characteristic filament density $n_0 = (3\sqrt{3}/\pi)\delta_0^2/Lr_0^3$, where L is the thickness of the "spongy" plate, r_0 is the radius of the cross section of one filament. An increase of the density of the filaments above n_0 does not lead to an appreciable increase of the critical current through the "sponge."

4. The "pinning" model[5], in which the matrix is a superconductor of the second kind. In the matrix there exist non-superconducting segregations in the form of macroscopic particles of another phase, pores, chemical compounds, etc. Superconducting vortices, which are produced in the superconductor when the latter is in the mixed state, become fastened to these segregations, i.e., "pinning" of the vortices occurs. The critical current is the one at which instability of the vortex system occurs, i.e., at which the Lorentz force produced by the current and acting on the vortices exceeds the "pinning" force. The "pinning" model in the form proposed in[5] does not describe the entire aggregate of the experimental data on critical currents in rigid superconductors, particularly the peak effect in the dependence of the critical current on the external field. This model requires refinement.

5. The dependence of the critical current on an external magnetic field in ideally homogeneous films made of superconductors of the second kind is considered in the case when the magnetic field is directed parallel to the surface of the film and perpendicular to the transport current[7,8]. The thickness of the film d satisfies the inequality $\delta_0 \gg d \gg \xi(T)$. In this case the critical current is determined by the start of the development of the vortex instability in the film, and its dependence on the magnetic field H_0 is shown in the figure. The field H' is the minimal supercooling field of the mixed state:

$$H' = (\pi^2\delta_0^2/\sqrt{2}\varkappa d^2) H_{cm}, \qquad \varkappa = \delta_0/\xi(T);$$

the field H_s is the maximum superheat field of the Meissner state, $H_s \approx \sqrt{2}H_{cm}\delta_0/d$; the field H_{Ic} is the magnetic field produced by the critical current on the surface of the film. The results denote the existence of "pinning" in an ideally homogeneous film as a re-