New types of instabilities in nonequilibrium excitation of a superconductor

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It is shown that when the nonequilibrium quasiparticles reach a critical density, a superconductor becomes unstable against a transition to an inhomogeneous state with a periodically modulated gap Δ. At the same time, an instability of a different type arises and corresponds to a transition to a homogeneous state with superconducting velocity V_s.

Interest in experimental[1–2] and theoretical[3–5] study of superconductors with nonequilibrium quasiparticle excitation has increased recently. We are interested in the stability of a nonequilibrium superconductor to fluctuations of the quasiparticle distribution function f_p. As seen from what follows, depending on the parameters, two types of instability are possible, connected respectively with the fluctuations of the symmetrical and asymmetrical parts f_p^0 and f_p' of the function f_p. In the analysis we use for f_p a kinetic equation[6,7][1)] that takes into account the motion of the condensate:

$$\frac{\partial f_p}{\partial t} + \frac{\partial f_p}{\partial \mathbf{r}}\frac{\partial \tilde{\epsilon}}{\partial \mathbf{p}} - \frac{\partial f}{\partial \mathbf{p}}\frac{\partial \tilde{\epsilon}}{\partial \mathbf{r}} + I\{f_p\} = 0, \tag{1}$$

$$\tilde{\epsilon}_p = \epsilon_p + \mathbf{p}\mathbf{v}_s = \sqrt{\Delta^2 + \xi_p^2} + \mathbf{p}\mathbf{v}_s, \quad \bar{\xi}_p = (p^2 + p_s^2 - p_0^2)/2m, \tag{2}$$

$p_0 = mv_0$ is the Fermi momentum. The validity of (1) and (2) is limited by the inequalities $\hbar\omega \ll \Delta$ and $\hbar q \ll /v_0$ (ω and q are the frequency and wave vector of the perturbation). Equation (1) is supplemented by Eq. (3) for the determination of Δ and by the neutrality condition (4):

$$1 = \lambda \sum_p \frac{1 - 2f_p}{\epsilon_p}, \tag{3}$$

$$\operatorname{div}\mathbf{j} = 0, \quad \mathbf{j} = eN_0\mathbf{v}_s + 2e\sum_p \frac{\mathbf{p}}{m} f_p, \quad N_0 = p_0^3/3\pi^2\hbar^3. \tag{4}$$

We represent the function f_p in the form $f_p = f_p^0 + f_p'$, with $f_p' \ll f_p^0 \ll 1$. For simplicity, we assume the symmetrical part of f_p^0 to be at quasiequilibrium,[2)] $f_p^0 = \exp[-(\epsilon_p - \mu)/T]$, where μ is determined by the quasiparticle concentration n. The continuity equation for n follows from (1). Taking into account the generation g and the recombination r, we have

$$-\frac{\delta n}{\delta t} + \operatorname{div}\mathbf{i} = g - r, \quad n = 2\sum_p f_p, \quad \mathbf{i} = n\mathbf{v}_s + 2\sum_p \frac{\partial \epsilon}{\partial \mathbf{p}} f_p'. \tag{5}$$

We neglect thermal generation.

We confine ourselves to consideration of one-dimensional fluctuations of the type $\delta n \sim \exp(\gamma t + ikx)$. Linearizing (1–5), we obtain for $\gamma\tau_p \ll 1$ the dispersion equation

$$[1 + \gamma\tau_p + k^2L_D^2(1 - \zeta)](1 + \gamma\tau_p - \zeta) = \beta\gamma\tau_p k^2L_D^2 \quad \zeta = n/2\rho_0 T;$$
$$\beta \approx (\Delta/\epsilon_0)(n/N_0) \ll 1, \quad L_D = \sqrt{D\tau_r}, \tag{6}$$
$$D = D_0\sqrt{2T/\pi\Delta}, \quad \tau_p \approx \tau_0\sqrt{\Delta/T},$$

$\tau_r \approx (2\alpha m)^{-1}$, $\rho_0 = mp_0/2\pi^2\hbar^3$, $\epsilon_0 = p_0^2/2m$, D_0 and τ_0 are the diffusion coefficient and the elastic-relaxation time in the metal, and α is the recombination coefficient.

In view of the smallness of the parameter β, Eq. (6) breaks up in fact into two independent dispersion equations, which correspond at $\xi > 1$ to two types of instability. The corresponding $\gamma(k)$ curves are shown in Fig. 1 by solid lines. The dashed lines give the more precise form of $\gamma(k)$ with allowance for the suppression of the small-scale fluctuations in the region $k^2\lambda^2 \gtrsim 1$ ($\lambda = \hbar V_0/\Delta$ is the correlation length).

Curve (1) describes the instability of the superconductor to a transition to the inhomogeneous state. Let us explain the physical picture of the instability. A local increase δn of the quasiparticle density leads, in accordance with (3) to a local decrease $\delta\Delta$ of the gap (i.e., to the formation of a potential well for the quasiparticles); this, in turn, involves further growth of δn as a result of the arrival of the quasiparticles from the neighboring regions with dimensions $\sim L_D$. At a given average concentration n, this leads to a periodic modulation of n and Δ in space. The resultant state is the analog of the intermediate state of a superconductor. The period d of the structure is bounded by the condition $\lambda < d < L_D$, where the characteristic values are $L_D \sim 10^{-3}$ to 10^{-4} cm and $\lambda \sim 10^{-4}$ to 10^{-6} cm at $T \ll T_c$; the period of the structure increases like $(1 - T/T_c)^{-1/2}$ as $T \to T_c$. The critical quasiparticle concentration obtained from the condition $\xi > 1$ is $n_c \approx 10^{17}$ to 10^{18} cm^{-3} at $T \sim 1$ °K.

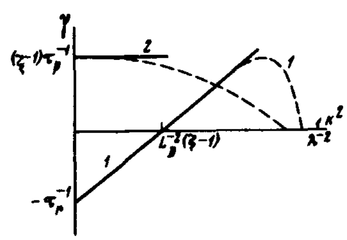

FIG. 1.

This "intermediate" state can be manifested in experiment, for example, by the appearance of a finite resistance prior to the complete transition to the normal state. Results of this kind were reported in a recent paper,[2] where an "intermediate" state induced in Sn films by intense pulsed illumination was observed.

We proceed to consider the second case (curve 2). It becomes decisive under the condition $\lambda > L_D$, when the instability of the second type is suppressed. The increment of the instability of the second type is maximal at $k=0$. An analysis shows that in this case the fluctuations of $\mathbf{v}_s$ and f_p' increase uniformly. The nature of the growth of $\mathbf{v}_s$ consists in the following. The fluctuation of f_p' (and accordingly of the excitation current) leads to the appearance of a compensating superconducting current $eN_0\delta\mathbf{v}_s$ [see (4)], inasmuch as in this case the total current $\mathbf{j}$ is equal to zero. The resultant fluctuation $\delta\mathbf{v}_s$ gives rise, according to (2), to a change in the excitation spectrum $\tilde{\epsilon}_p$, which leads to a further growth of f_p' and of the excitation current. As a result, a superconducting velocity $\mathbf{v}_s$ appears in the sample at $\zeta > 1$, and phase difference $\chi_1 - \chi_2$ is produced between the ends of the superconductors. This phase difference can be measured with a superconducting interferometer or by determining the change of the magnetic flux through the superconducting circuit.

We note that in the instability region ($\zeta > 1$) the quantity N_s, which determines the London length, becomes negative, a fact that might suggest an oscillating penetration of the magnetic field into the sample. Actually, the instabilities cause the superconductor to go over into a new state with $\mathbf{v}_s \neq 0$, $N_s > 0$, and with the usual Meissner effect.

It seems to us that both the nonequilibrium intermediate state and the onset of $\mathbf{v}_s$ make it particularly interesting to investigate photoelectric phenomena in superconductors at high excitation levels.

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[1)]We are grateful to A.G. Aronov and V.L. Gurevich for a preprint of their paper.[7]

[2)]The conclusion concerning the instability remains in force also if f_p^0 is taken in the form of the function obtained in[4] from the Éliashberg equation.

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