PARAMAGNETIC EFFECTS IN SUPERCONDUCTORS

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The magnetic properties of non-equilibrium superconductors are investigated. It is shown that under certain conditions the superconductor can go over from the state of an ideal diamagnet into a state with "idel" paramagnetism. In that case the magnetic fields penetrates into the superconductor and oscillates as a function of the coordinate.

The most important properties of superconductors is their ideal diamagnetism - the Meissner effect. The purpose of the present article is to show that under non-equilibrium conditions a superconductor can go over into an "ideal paramagnetism" state. In this state the magnetic field inside the superconductor differs from zero, although the total magnetic flux through the singly-connected superconductor is equal to zero. To illustrate this statement we consider the magnetic properties of the model of a non-equilibrium superconductor, proposed by Owen and Scalapino [1] to explain Testardi's experiments [2], which has been experimentally verified in [3]. When the superconductor is exposed to light, the produced quasiparticle excitations rapidly enter in equilibrium with the phonons, but because of the large recombination time their number differs from the equilibrium value. The excitation energy distribution function is then of the form

$$n_p = \frac{1}{e^{\frac{\epsilon_p - \nu}{T}} + 1}, \tag{1}$$

where $\epsilon_p = \sqrt{\xi_p^2 + |\Delta|^2}$, $\xi_p = p^2/2m - \mu$, μ is the chemical potential of the electrons in the normal metal, $|\Delta|$ is the half-width of the energy gap, and ν is the Fermi excitation quasilevel. The stability of the model to fluctuations of the order parameter and the collective oscillations were considered in [4].

If the external field is characterized by a vector potential $\vec{A}(\vec{r})$ that varies slowly over a distance on the order of the coherence length, then the current density is [5]

$$j = 2e\sum_p v_p n_p + e p_s \frac{N}{m}, \tag{2}$$

where $\vec{p}_s = \Delta\chi - (e/c)\vec{A}$; 2χ is the phase of the order parameter $\Delta = \Delta_0 \exp(2i\chi)$, N is the total electron concentration, $\vec{v}_p = \partial\chi_p/\partial\vec{p}$ is the electron velocity, and n_p is the excitation distribution function in the presence of the field $\vec{A}(\vec{r})$, which is determined from the solution of the kinetic equation. In our case

$$n_p = \frac{1}{e^{\frac{\epsilon_p - p_s v_p - \nu}{T}} + 1}. \tag{3}$$

We choose a gauge with $\Delta\chi = 0$, and then $\vec{p}_s = -(e/c)\vec{A}$. We obtain first the linear response. Expanding n_p in terms of n_s, we obtain

$$j = -\frac{Ne^2}{mc} A\left[1 + 2\int_0^\infty d\xi \frac{\partial n_p^{(0)}}{\partial \epsilon_p}\right] = -\frac{1}{\Lambda^2} A \tag{4}$$

Λ is the depth of penetration of the magnetic field. At equilibrium, expression (4) is the usual London equation, since the expression in the square brackets is none other than the ratio of the density of the superconducting electrons to the total density. At equilibrium the expression in the brackets is always positive. The situation is different if there is no equilibrium. In this case the expression in the square brackets may reverse sign, corresponding to an imaginary depth of penetration of the magnetic field.

Indeed, in the considered model, the depth of penetration becomes infinite under the condition

$$\left.\frac{\partial n}{\partial \nu}\right|_{\Delta = \text{const}} = \frac{\partial N}{\partial \mu}, \tag{5}$$

where n is the total concentration of the nonequilibrium excitations. Thus, the depth of penetration of the magnetic fields increases with increasing number of nonequilibrium excitations, and becomes infinite at the point defined by condition (5), after which the expression (4) for the current can reverse sign; this leads to an oscillatory dependence of the magnetic field on the coordinate inside the superconductor, with a period $|\Lambda|/2\pi$. The flux over the cross section is then equal to zero. In the case of Blotzmann excitation statistics, when $\Delta - \nu \gg T$, the system is paramagnetic if

$$\frac{3}{2}\frac{T}{\mu} < \frac{n}{N}.$$

We consider a superconducting plate of thickness d placed in a magnetic field parallel to the surface. The distribution of the magnetic field in the plate is then

$$H = H_0 \frac{\cos \frac{x}{|\Lambda|}}{\cos \frac{d}{2|\Lambda|}}, \tag{6}$$

where H_0 is the field at the interface between the superconductor and the vacuum. It is seen from (6) that if the thickness satisfies the condition

$$\frac{d}{|\Lambda|} = \pi(2\ell + 1), \qquad \ell = 0, 1, 2 \ldots$$

then the field distribution (6) is impossible. In this case the linear approximation is insufficient. From (2) we can obtain the nonlinear terms of London's equation by using (3) and the dependence of Δ on $\vec{A}$.

The distribution of the magnetic field can be expressed in terms of Jacobi elliptic functions; this will not be done here. We note only that when the condition $d/|\Lambda| = \pi(2\ell + 1)$ begins to be satisfied the period begins to depend on both H_0 and d. On the other hand, if the magnetic field direction is normal to the plate surface, then a mixed state should arise, and the magnetic field will penetrate in the superconducting phase with oscillations such that the magnetic flux through the plate is equal to zero (accurate to within edge effects. We note in conclusion that the flux through a superconducting ring is quantized, just as at equilibrium. By way of proof we note that if the field oscillates along the diameter of the ring, then there is always inside the ring a closed circuit through which the current $\vec{j}$ is equal to zero, and the flux quantization then follows directly from the condition that $\Delta(r) = \Delta_0 \exp(2i\chi)$ be unique.

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