ACOUSTOELECTRIC AND THERMOELECTRIC EFFECTS IN SUPERCONDUCTORS

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It is shown that a phase difference of the ordering parameter is produced on the boundaries of a superconductor through which sound propagates or in which a temperature gradient exists. This difference is proportional to the difference between the sound intensities or the temperature difference, and can be measured in a superconducting interferometer.

The purpose of the present article is to discuss two effects, the thermoelectric and the acoustoelectric ones, the mechanism of which in superconductors is quite unique. In the acoustoelectric effect the normal excitations of the superconductors are dragged by a traveling sound wave [cf. [1, 2]). This produces a volume current of normal excitations, the density of which is designated j^{ac}. Since no volume current can exist in a bulky superconductor, a superconducting current j_s should arise and compensate for the current of the normal excitations. The superconducting current is proportional to the gradient of the phase of the ordering parameter ϕ. This means that a phase difference $\delta\phi$ of the ordering parameter should appear on the ends of a superconductor through which sound propagates. This difference can be measured by using the sample as one arm of a Josephson interferometer. By the same token, one measures also the volume current of the normal excitations, from the value of which one can assess both the sound intensity [3] and the spectrum and the kinetic characteristics of the normal electrons of the superconductor.

The acoustoelectric current in a normal conductor can be determined from simple considerations due to Weinreich [3]. The acoustic energy absorbed by the electrons per unit volume and per unit time is $\Gamma_n S$, where Γ_n is the sound absorption coefficient and S is the sound energy flux density. This means that the momentum (more accurately, quasimomentum) transferred to the electrons is $\Gamma_n S/w$, where w is the speed of sound, and the order of magnitude of the produced acoustoelectric current is $j^{ac} = \sigma\Gamma_n S/eN_0 w$, where σ is the residual conductivity of the normal metal (it is assumed that impurity scattering predominates), e is the electron charge, and N_0 is the electron density. Not all the electrons in the superconductor are dragged by the sound wave, only a fraction $(N_0 - N_s)/N_0$, where $N_s(T, \Delta)$ is the number of superconducting electrons, determined for example in [4, 5]. This yields the following order-of-magnitude estimate for the acoustoelectric current of normal excitations in a superconductor:

$$j^{ac} = \frac{\sigma\Gamma_n S}{eN_0 w}\,\frac{N_0 - N_s}{N_0}\,. \qquad (1)$$

Rigorous calculations based on the kinetic equation for the excitations of a superconductor show that this formula is actually exact if the dispersion of the conduction electrons is isotropic. It is valid for all values of the parameter $q\ell$ (ℓ is the electron mean free path and q is the wave vector of the sound) and at any sound intensities. The expressions for Γ_n are naturally different in different cases. They are given in [6, 7].

The superconducting current is

$$j_s = eN_s\hbar\nabla\phi/2m, \qquad (2)$$

where m is the effective mass of the electron. Equating the total density of the volume current to zero and taking into account the relation

$$dS/dx = -\Gamma_s S \qquad (3)$$

we can find the phase difference of the ordering parameter at the ends of the conductor, $\delta\phi$, if we know the expression for the sound absorption coefficient in the superconductor, Γ_s. For sound of sufficiently low frequency [6, 7] we have

$$\Gamma_s = \Gamma_n \frac{2}{\exp\left(\frac{\Delta}{T}\right) + 1}\ , \tag{4}$$

where Δ is the width of the superconducting gap. Taking this into account, we get from the quantitative theory of [7]

$$|\delta\phi| = \frac{2\sigma m F\left(\frac{\Delta}{T}\right)}{e^2 \hbar w N_0 N_s}[S(0) - S(L)]\ , \tag{5}$$

where L is the length of the crystal through which the sound propagates, and

$$F(x) = \frac{1}{4}(e^x + 1)\int_0^\infty \mathrm{ch}^{-2}\left(\frac{1}{2}\sqrt{x^2 + y^2}\right)dy\ . \tag{6}$$

We obtain in similar fashion the phase difference due to a temperature gradient in a superconductor. The normal excitation current is $j^T = -\eta\nabla T$, where

$$\eta = \frac{2\pi^2}{9}\frac{eT}{m}\frac{d}{d\epsilon}[\tau_n(\epsilon)\,\nu(\epsilon)\epsilon]\Big|_{\epsilon=\mu} G\left(\frac{\Delta}{T}\right); \quad G(x) = \frac{6}{\pi^2}\int_x^\infty \frac{y^2\,dy}{\mathrm{ch}^2\frac{y}{2}}\ . \tag{7}$$

Here $\tau_n(\varepsilon)$ and $\nu(\varepsilon)$ are respectively the relaxation time and the density of states for the electrons in the normal conductor. The derivative is taken with respect to an energy ε equal to the chemical potential μ. At $\Delta = 0$ we have $G(x) = 1$ and we obtain the well-known (see, e.g., [8]) expression for the thermoelectric power of the normal metal. If we assume that the change in either the temperature T or the gap Δ over the length of the crystal is small, then

$$|\delta\phi| = \frac{2m\eta}{eN_s}[T(L) - T(0)]. \tag{8}$$

Thus, the expected value of both the acoustoelectric and the thermoelectric effect is larger the longer the electron relaxation time τ_n, which determines the residual resistance. If we assume $\tau_n \sim 10^{-9}$ sec (which is apparently at the borderline of the present experimental capabilities), then, far from the transition temperature T_c, $\delta\phi$ is of the order of 1° if S is of the order of 1 W/cm^2 or if the temperature difference δT is of the order of 0.01°. Two circumstances can increase the observed phase difference. First, when the transition point is approached, N_s decreases in accord with $N_s/N_0 = 2(T_c - T)/T_c$ and the effect increases. The second circumstance pertains only to the thermoelectric effect and is connected with the fact that expression (7) for the coefficient η does not take into account the electron dragging by the phonons. If the isotopic and impurity scattering of the phonons is not very large, the dragging can increase the constant η appreciably.

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