Influence of excitation dragging by phonons on the thermoelectric effect in pure superconductors

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We consider the influence of excitation dragging by phonons on the thermoelectric effect in pure superconductors, when the excitation mean free path is bounded by scattering by phonons. It is shown that the dragging can greatly increase the "thermoelectric angle," by a value up to π. Whereas in superconductors in which the excitations are scattered mainly by impurities the effect decreases with decreasing temperature, in pure superconductors the dragging can lead to an increase of the effect with decreasing temperature if the phonon mean free path continues to increase in this case.

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It has been known for a long time that dragging of metal electrons by phonons is capable of greatly increasing the thermoelectric power.[1,2] This effect is particularly appreciable for pure metals in which the electron dragging by the "phonon wind" can increase the thermoelectric power by two orders of magnitude and more.

In superconductors, this dragging can likewise produce an appreciable effect; for the thermal conductivity in pure superconductors, this effect was considered by us in[3].

A peculiar change that the thermoelectric effect experiences in superconductors was recently examined[4] as well as observed experimentally.[5]

We show in this article that the "phonon wind" is capable in this case, too, of increasing the effect.

The expression for the excitation current density in a superconductor in the presence of a gradient of the temperature (T) is given by [4]

$$\mathbf{j}^{exc} = -\eta\vec{\nabla}\mathbf{T} = 2e\int\frac{d^3\mathbf{p}}{(2\pi\hbar)^3}\mathbf{v}f^{(1)}(p)\,; \qquad \mathbf{v} = \mathbf{p}/m \tag{1}$$

here $f^{(1)}(\mathbf{p})$ is the deviation of the excitation distribution function from equilibrium and was obtained by us in[3] for the case of scattering of the excitations by phonons with allowance for the dragging. That part of the deviation which makes the main contribution to the density of the excitation current is of the form (the notation is the same as in[3]):

$$f^{(1)}(\mathbf{p}) = \frac{\partial f_0}{\partial x}\phi_1 = \frac{\partial f_0}{\partial x}\frac{(2\pi\hbar)^3}{C}\frac{\epsilon_F s^5}{T^5}\frac{1}{F_1(b)}\left(F_2(b) + \frac{T^2}{mp_0 s^3}F_3(b)\right);$$

$$b = \Delta/T,$$

where the first term corresponds to scattering of excitations by equilibrium phonons, and the second describes the dragging of the excitations by the phonon flux.

Substituting this in (1), we obtain

$$\mathbf{j}^{exc} = \frac{32}{3C}e\left(\frac{\theta_D}{T}\right)^4\frac{s}{m}\frac{F_8(b)}{F_1(b)}\left(F_2(b) + \frac{T^2}{mp_0 s^3}F_3(b)\right)\vec{\nabla}\times\mathbf{T}, \tag{2}$$

where e is the electron charge

$$F_8(b) = \int_b^\infty\frac{x}{\sqrt{x^2 - b^2}}\frac{\partial f_0}{\partial x}dx\,.$$

This means that

$$\eta = \eta_e + \eta_{e\,ph} = \frac{32e}{3C}\left(\frac{\theta_D}{T}\right)^4\frac{s}{m}\frac{F_8(b)}{F_1(b)}\left(F_2(b) + \frac{T^2}{mp_0 s^3}F_3(b)\right). \tag{3}$$

Bearing in mind the situation considered in[5], we determine the "thermoelectric angle"[4] θ produced in one of two superconductors making up a closed circuit at junction temperatures T_1 and T_2. In this case, according to[4,5], we have

$$\theta = \frac{2m}{\hbar}\frac{\eta(T)}{N_s(T)}(T_2 - T_1); \tag{4}$$

when integrating relations (4.2) and (3.4) of[4] along the circuit, we have assumed that $T_2 - T_1 \ll T_1$ and taken $\eta(T)/N_s(T)$ outside the integral sign.

As seen from (3) and from the estimates given in[3], at $b \ll 1$ (near the cricitcal temperature T_c) we have

$$\frac{\eta_{e\,ph}}{\eta_e} \sim \frac{T}{ms^2}\frac{T}{\theta_D}\frac{F_3(b)}{F_2(b)} \tag{5}$$

This estimate yields $\sim 10^2$ for lead and 10 for tin; at $e^b \gg 1$ (i.e., far from T_c) we have

$$\frac{\eta_{e\,ph}}{\eta_e} \sim 10^2\frac{T_c}{ms^2}\frac{T_c}{\theta_D} = ab^{-7/2}e^b \tag{6}$$

the constant factor in (6) is of the order of 300 for Pb and 50 for Sn.

The "thermoelectric angle" (4) increases for Pb at $e^b \gg 1$ because of the dragging of the excitations by the phonons, from several tenths of a degree to a value on

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the order of π.

The magnetic flux is produced in the devices under consideration by the phase difference between the order parameters in the two superconductors making up the closed circuit, and the contribution of each of them can be different. If one of the superconductors is pure and large enough, while the other is contaminated with impurities and the dragging effect is negligibly small in it, then the described method makes it possible to determine the time and the length of relaxation of the excitations on the phonons. Under ordinary conditions and in the case of normal metals, this determination can be much more complicated.

We note that all three cases: "dirty" superconductors,[3,4] the pure superconductors considered here, and pure superconductors with excitation dragging by phonons lead, as seen from a comparison of (39), (4), and (5) with (2.13) of[3], to a qualitatively different dependence of the magnetic flux Φ on the temperature. Other cases studied in[4] call for a special investigation and will be considered in another paper.

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