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Manifestation of the phonon drag of vortices on measuring HTSC fluctuation thermopower

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Comparative investigations and analysis of the temperature-dependent thermopower and resistivity of HTSC monocrystals are carried out in the temperature interval where superconducting fluctuations are dominant. It is shown that, at the temperatures below mean-field T_c, nonisothermality of thermopower measuring conditions could be responsible for phonon drag of dissociated vortex-antivortex pairs capable of being thermally excited in quasi-two-dimensional systems to which HTSC materials belong.

The comparative investigations of thermopower $Q(T)$ and resistance $R(T)$ behavior of HTSC crystals, which have been carried out by us near the superconducting transition temperature [$\varepsilon = (T - T_c)/T_c \ll 1$], revealed the temperatures at which the above characteristics vanish, not to coincide [1]. In that paper it has been shown that, in principle, such a discrepancy should not seem to be astonishing even in the framework of linearized theories of Cooper pair fluctuations due to dissimilar divergency of the correlation functions that describe energy and charge transport [2–5]. Moreover, we noted that the observed distinction between temperature runs of thermopower and resistance of HTSC crystals was of more fundamental nature within the strong fluctuation region. Below we produce some evidence that the «zero»-level shift of the above properties relative to each other (of up to several Kelvins) cannot be accounted for by a simple concept of a fluctuation contribution from the mere Cooper pairs but demands invoking the idea of dissociated vortices drag when a temperature gradient exists.

Experimental procedure and results

The shown experimental data correspond to the *ab* plane of Ho–Ba–Cu–O (123) and Bi–Sr–Ca–Cu–O (2212) crystals with dimensions about $a \times b \times c = (1 \times 1 \times 0.1)$ mm. Measurements were performed by a dc four-probe procedure using superconducting modulator [6,7], the voltage sensitivity being $\approx 10^{-10}$ V. The contacts were formed via firing a silver paste in oxygen atmosphere. Figure 1 shows the portions of temperature-dependent isothermal resis-

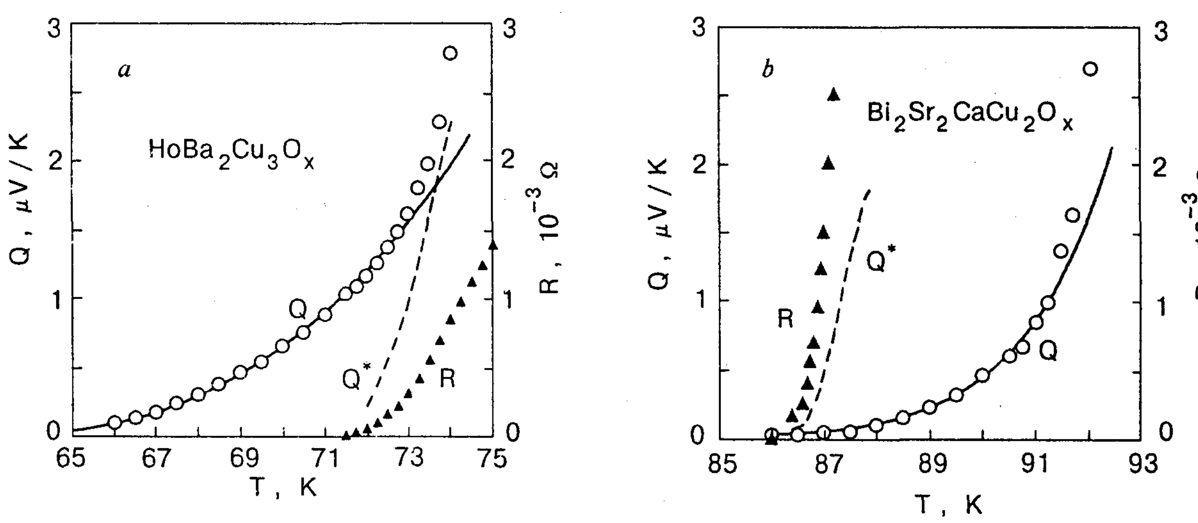

Fig. 1. Differential thermopower and resistance vs. temperature in the vicinity of mean-field T_c for crystal $HoBa_2Cu_3O_x$ (*a*) and $Bi_2Sr_2CaCu_2O_x$ (*b*): ○, ▲, present experiment; dashed lines $Q^*(T)$ are calculated from the concept of common correlation parameter for $R(T)$ and $Q(T)$ behavior; solid lines show the $Q(T)$ fitted according to the Kosterlitz-Thouless model.

tance (R, triangles) and thermopower (Q, circles) of the crystals investigated near the superconducting transition temperature T_c. Here, we display the data for crystals with the same — «hole-like» — thermopower sign [for details see Ref. 7]. The peculiarities discussed are distinctive for crystals with «electron-like» thermopower as well, and furthermore, for crystals of any quality.

As reference measurements of current-voltage characteristics (IVC) of all the crystals investigated showed, those became non-linear when measuring current exceeded about 50 μA. For this reason, in the quantitative comparison of the experimental $Q(T)$ and $R(T)$ data we rely on the $R(T)$ dependence for Ho–Ba–Cu–O crystal, which was obtained at sufficiently low measuring current (20 μA). The data for Bi–Sr–Ca–Cu–O crystal are discussed only in qualitative sense.

Discussion

From the experiment (in a linear IVC regime) it follows that at mean-field T_c the $R(T)$ and $Q(T)$ dependences do not go to zero, but enter smoothly into the temperature range below T_c, which is known to be the lower boundary of linearized theories feasibility. Here, we identify T_c from the temperature-dependent either $R(T)$ or $Q(T)$ as the temperature of divergency of the mean-field correlation parameter ξ_{GL}, i.e., the point where the extension of the $R(T)$ or $Q(T)$ linear sections intersect the axis T.

It appears that thermopower voltages U_Q are of considerable value within that temperature interval where dc voltages U_R, measured independently at the current values keeping the IVC regime linear, $I < I_{max}$, reduce below the measurability level in our experiment. The fact suggests strongly that the fluctuations, regardless their nature, contribute disproportionately to thermopower and conductivity (on the voltage scale).

As can be shown [1], the ratio U_Q / U_R is to be directly proportional to the factor $\Delta T_{min} / I_{max}$, that characterizes the non-equivalence of the non-equilibrium conditions in both cases of measuring. Here, ΔT_{min} is a minor feasible temperature gradient when measuring differential thermopower. The estimate $U_Q / U_R \geq 10$ [1] denotes that the extent of nonequilibrium of the carrier distribution with a temperature gradient, even of small value, but measured to sufficient accuracy, under our measurement conditions inevitably exceeds that with an electric field. We are not acquainted with any papers in which attention has been drawn to this circumstance.

Thus, some distinction of actual $Q(T)$ behavior relative to that of $R(T)$ could be observed even in the case when $Q(T)$ and $R(T)$ were determined by a common temperature dependence of the correlation length $\xi(T)$ [cf. the curves $Q^*(T)$ and $R(T)$]. However, the significant discrepancy between thermopower and resistance behavior suggests that the temperature gradient ΔT plays a particular role as a source of non-equilibrium phonons while measuring thermopower of HTSC materials within fluctuation region. If there exist below T_c (hereafter we shall mean only the linear IVC regime) topological carriers of unbounded magnetic vortices type, which can arise in $2D$ systems in the absence of external fields too due to smallness of their free energy and which dissipate energy, then they inevitably have to dissipate energy of phonons as well and, therefore, be dragged by those. This is not the case under isothermal conditions on measuring conductivity.

It is easy to estimate the contribution of this effect to thermopower with the help of conventional kinetic considerations [8]. Taking into account the fluctuation corrections, the expression for fluctuation thermopower near T_c is following:

$$Q = (e^*/T)K'_{ET} / \sigma' \qquad (1)$$

with fluctuation contribution into conductivity σ' and into heat flux K'_{ET},

$$\sigma' = (e^{*2}/m^*) \sum_k \langle |\psi_k|^2 \rangle \tau_k /2 \;, \qquad (2)$$

$$K'_{ET} = (\hbar^2 T/3m^2) \sum_k k^2 \tau_k \frac{\partial \langle |\psi_k|^2 \rangle}{\partial T} \;. \qquad (3)$$

Here, $\langle |\psi_k|^2 \rangle = k_B T (2m^*/\hbar^2)\, \xi^2/(1 + k^2\xi^2)$ is a thermodynamic average of the order parameter of the kth one-particle eigenfunction proportional to the density of paired electrons; m^* is twice of the free electron-mass m; τ_k is a relaxation time of the k mode related to the relaxation time τ_{GL} by the expression $\tau_k = \tau_{GL} / (1 + k^2\xi^2)$; $\xi = \xi_{GL}(T) \equiv \xi(0)\, |\varepsilon|^{-1/2}$; $\tau_{GL} = \hbar[18 k_B (T - T_c)]^{-1}$; k_B is Boltzmann's constant.

As known [9,10], when free vortices with concentration n_f are moving in a quasi-two-dimensional conducting layer where pinning forces are weak, the initiation of a voltage difference ΔV is possible along the layer which is bound up with phase slipping mechanism, resulting in the effective resistive contribution:

$$\Delta V \propto |d\Delta\theta/dT| = 2\pi L n_f \, |v_D^{+(-)}| \;,$$

L is the specimen length; $v_D^{+(-)}$ is the drift velocity of the vortices across the layer; $\Delta\theta$ is phase difference on specimen ends. Such an electric field can be considered as a result of unbalance, at the sample ends, of some amount of particles of the effective concentration n^* and the conventional charge q, though local concentrations of vortices of an opposite sign will remain equal.

The effective number of particles which defines the charge unbalance between the sample ends, by analogy with (2), can be represented as

$$n^* = \frac{\sum\limits_{l}\sum\limits_{k} \langle |\psi_{k,l}|^2 \rangle \tau_{k,l}}{\langle \tau_{\mathrm{tr}} \rangle} , \qquad (4)$$

where l is the polarization of a fluctuating vortex pair, which would not dissipate until it relaxes within time $\tau_{k,l}$; $\langle \tau_{\mathrm{tr}} \rangle$ is an average time of transport scattering of free charges.

In the $2D$ case, as when calculating the sum in Eq. (2), we find

$$n^* \propto n_{KT} \frac{\xi^2_{+(-)}}{\xi^2(0)} , \qquad (5)$$

where n_{KT} is a number of vortex pairs at Kosterlitz-Thouless transition temperature T_{KT} , proportional to the number of electrons n; $\xi_{+(-)}$ is a correlation length re-defined for vortices which, according to [10,11], can be written as

$$\xi_{+(-)} \approx \alpha \xi(0) \exp\left[(\beta \varepsilon_{KT} / \varepsilon^*)^{1/2}\right] . \qquad (6)$$

Here, $\varepsilon_{KT} = (T_c - T_{KT})/T_{KT}$; $\varepsilon^* = (T - T_{KT})/T_{KT}$; α and β are nondimensional constants.

Now, once U is taken for the energy density of thermal phonon flux, assuming $(dU/dx) \propto c_L(dT/dx)$, where c_L is the lattice specific heat, the corresponding fluctuation contribution to thermopower will therefore behave as follows with changing temperature (dT/dx = const):

$$Q(T) \propto c_L / n^* \propto c_L(T) \xi^{-2}_{+(-)}(T) . \qquad (7)$$

For a two-dimensional phonon flux $c_L \propto T^2$ [12], and one can therefore expect the thermopower behavior in «dirty» limit ($\langle \tau_{\mathrm{tr}} \rangle \approx$ const) to obey the law

$$Q(T) = A\,T^2 \exp\left(-B / \sqrt{T - T_{KT}}\right) , \qquad (8)$$

A and B being constant.

The same result may also be derived directly from Eq. (1), noticing that $K'_{ET} \propto Tc_L$ [13] and the fluctuation conductivity σ'_s due to vortex depairing, according to [10], should depend on the concentration n_f of depaired vortices with mobility μ as follows:

$$\sigma'_s \propto (n_f \mu)^{-1} \propto \xi^2_{+(-)} .$$

Finally, the variational principle approach [14] also clearly interprets the obtained result.

The full curves in both Figures are parameter fits of Eq. (8) to the experimental data on thermopower below T_c , the fitted parameters — Kosterlitz-Thouless phase transition temperatures T_{KT} — are following: 59.6 K for Ho–Ba–Cu–O and 64.7 K for Bi–Sr–Ca–Cu–O. It can be seen that, as the temperature increases, beginning with some temperatures, the agreement between theoretical curves and experimental data breaks down, which can be attributed to decreasing in the contribution of dissociated vortex pairs in comparison with further increase in the contribution of Gauss fluctuations due to Cooper pairs. For the meanings T_{KT} obtained we found that $\varepsilon^{\mathrm{Bi}}_{KT} = 0.4 > \varepsilon^{\mathrm{Ho}}_{KT} = 0{,}22$ as expected. Again, the ratio $\varepsilon^{\mathrm{Bi}}_{KT}/\varepsilon^{\mathrm{Ho}}_{KT}$ is to correspond to the reciprocal ratio of the conductivities at the upper temperature boundary of the linear fluctuation theory applicability [10] (in the case of monophase samples — that of the normal conductivities). Our data also satisfy this requirement with the proper precision.

Therefore, the concept of a drag by phonons of free vortices plasma not only results in a proper description of the experimental data on thermopower of HTSC materials below T_c , but also accounts for the discrepancy between the temperature ranges where thermopower and conductance runs still persist.

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