Thermal drag of vortices in $YBa_2Cu_3O_x$ superconducting films

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Thermal drag of the intrinsic vortices of the transport current has been observed in $YBa_2Cu_3O_x$ superconducting films. This drag is explained in terms of the entropy transported by the vortices. The appearance of a voltage without reaching a threshold value is found to occur as a result of an anomalously small pinning near the critical temperature of the superconductor.

1. We know (see, e.g., Ref. 1) that superconductors have a whole range of thermomagnetic phenomena which are associated with the motion of vortices caused by a temperature gradient ∇T. The motion of flux quanta is associated with the entropy s_φ which they carry. The force acting on the flux quanta in this case is

$$F_T = - s_\varphi \nabla T. \tag{1}$$

The quantity s_φ can be estimated from the extent to which the first critical field H_{c1} changes with temperature:

$$s_\varphi / \Phi_0 = - \frac{1}{4\pi} \frac{\partial H_{c1}}{\partial T}, \tag{2}$$

where Φ_0 is the quantum of magnetic flux.

In high-T_c superconductors the quantity[2] $\partial H_{c1}/\partial T \approx 6$–7 Oe/K is lower by nearly an order of magnitude than in thin-film, soft-superconductor systems. However, because of their high critical temperature (T_c), these superconductors can have much higher temperature gradients. This circumstance can account for a reasonably high level of thermomagnetic phenomena in thin films made from recently discovered superconductors.

2. In the present letter we report the results of an experimental study of superconducting films made from a metal-oxide yttrium compound $YBa_2Cu_3O_x$ by laser deposition on substrates of an oriented $SrTiO_3$ single crystal. The thickness of the samples is in the range 0.5–1 μm, the length is 1–2 cm, and the width is 0.3 cm.

The films have an abrupt, resistive transition (Fig. 1) with a width of about 0.3 K. The temperature at which the resistance vanishes is in the range 86.5–87.2 K. The current density is $\approx 10^5$ A/cm^2 at liquid-nitrogen temperatures.

To produce a temperature gradient, we made use of the sample's capability to heat itself near one of the current leads which had a small amount of pure indium

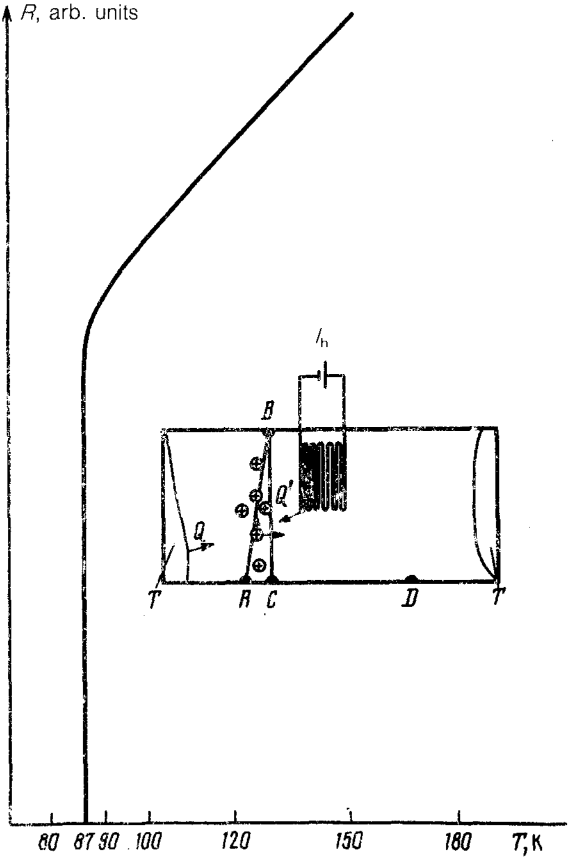

FIG. 1. Temperature dependence of the resistance of one of the typical films of a metal-oxide ceramic $YBa_2Cu_3O_x$. The inset shows the geometry of the test samples

rubbed into them. As an auxiliary heat source (see the inset in Fig. 1) we used a flat resistive heater.

To identify the effects associated with the temperature-gradient-induced motion of the vortices, we recorded the potential by means of an asymmetric Hall circuit at points *A* and *B*, as illustrated in the inset in Fig. 1. The asymmetric nature of the heat release caused the film to be saturated with vortices of the same sign.[3]

3. By arranging the heat source and the potential leads in a manner shown in the inset in Fig. 1 we could record both the "longitudinal" voltage U_j, which corresponds to the Lorentz force (this voltage is equivalent to the voltage measured at the *A* and *C* leads, where *C* is the projection of the position of contact *B* onto the back side of the film), and the "transverse" voltage U_T, which is produced in the presence of a temperature gradient in the sample which is directed along its length. The latter voltage is generated as a result of the crossing of the line *BC* by the vortices. It is important to note that U_j and U_T are applied in a differential manner in the geometry used here. Changing the asymmetry of points *A* and *B*, the direction of the temperature gradient, or the point of entry of the vortices leads to the addition of U_T and U_j.

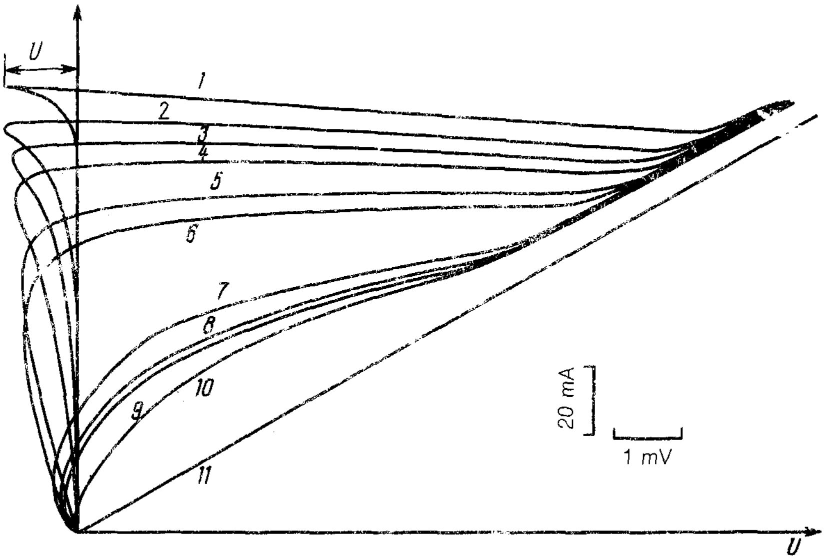

FIG. 2. Current-voltage characteristics of a metal-oxide film at various temperatures of the heat sink: 1—86.14; 2—86.26; 3—86.38; 4—86.5; 5—86.68; 6—86.74; 7—87.1; 8—87.13; 9—87.14; 10—87.16; 11—88 K.

The value of $U_j - T_T$ was measued continuously as the transport current transmitted through the sample was varied. A series of current-voltage characteristics obtained for one of the samples in this manner is shown in Fig. 2. The positive voltages correspond to $+U$ in the normal state and the negative values of U correspond to the case in which U_T is higher than U_j.

The asymmetry of the contacts for this sample, which was measured at a higher than the critical temperature by comparing the voltage drop between points A, B, and A, D, where D is the position of a distant auxiliary lead on the same side of the sample as point A, amounts to 0.3 mm. The difference in the values of U_T and U_j in this case is, as can be seen in Fig. 2, fairly substantial: ~1 mV. For comparison, the value of U_T in the Nernst effect in ordinary superconductors[4] is only 10^{-6} or 10^{-7} V when $\Delta T \approx 1$ K. We wish to emphasize that large values of U_t were obtained primarily when films of large width were used.

We see in Fig. 2 that U_T is higher than U_j only when the current density (j) is lower than a certain value. This situation occurs because $U_j \sim j$, and because the temperature drop has a finite value $T_c - T_0$, where T_0 is the temperature of the heat sink; U_j reaches the saturation point as the current density j is increased.

To verify the nature of this effect, we applied a temperature gradient in the opposite direction. Figure 3 shows the temperature dependence of the maximum negative voltage for three values of the current I_h flowing through the heater. We see that as I_h increases, the amplitude of the anomaly decreases, shifting toward lower values of T_0, and then vanishes at $I_h \approx 200$ mA.

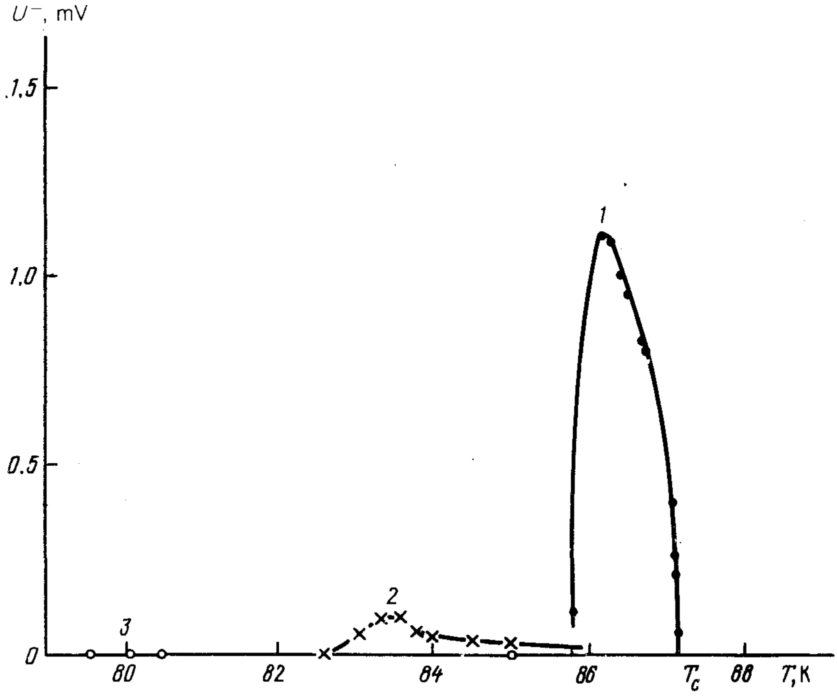

FIG. 3. Temperature dependence of the maximum voltage of the thermal anomaly when a current of three different strengths flows through the auxiliary heater. 1—0; 2—100; 3—200 mA.

4. Let us analyze the results obtained by us. Despite the fact that the effect is appreciable, the larger value of U_T than U_j by no means suggests that the thermal force is greater than the Lorentz force, since $U_{T,j}$ are proportional to the number of "lines" in the vortex-generated effect, i.e., if the distance between the vortices along the length of the film and across it is the same as the length L of the segments CB and AC. Accordingly, we have $F_j \sim U_j/L_{AC}$ and $F_T \sim U_T/L_{CB}$.

The point at which the I-V curves cross the current axis corresponds to $U_j = U_T$, i.e., $F_T = F_j L_{AC}/L_{CB}$. In the experiment we have $L_{AC}/L_{CB} = 0.1$. This means that $F_T \approx 0.1 F_j$ if there is no voltage across the potential leads.

A visual observation of the film immersed in liquid nitrogen shows that a total destruction of the superconducting state near the current contact, which is accompanied by violent boiling of the cryogenic liquid, occurs at currents of about 100 mA. The value of ∇T in this case is ≈ 40 K/cm.

Noting that $F_j = j\Phi_0/c$ and combining this expression with the equations in Refs. 1 and 2, we find

$$0{,}1\,\frac{j}{c\nabla T} = s_\varphi/\Phi_0\ . \qquad (3)$$

Substituting the specific values for the time at which bubble boiling begins to develop, we find $s_\varphi/\Phi_0 = 0.8$ Oe/K. On the other hand, for $\partial H_{c1}/\partial T \approx 6.5$ Oe/K we find from Eq. (2) $s_\varphi/\Phi_0 = 0.52$ Oe/K. The value of s_φ/Φ_0 determined experimentally thus agrees in order of magnitude with the value determined by other independent measurements. This agreement confirms the assumption that the vortex-transported entropy of high-T_c superconductors is an order of magnitude lower than that of the classical systems.

Finally, let us consider one more important feature of the thermal drag of a vortex flow. It follows from Fig. 2 that the negative voltage appears at $j = 0$, without a threshold. This means that vortices can be set in motion even by extremely small forces, suggesting that there is an anomalous creep of the magnetic flux near T_c. Thermal suppression of the potential barrier at the boundary of the film tends to be conducive for the manifestation of this effect.

We note in conclusion that because the effect described by us here is of appreciable magnitude, and because it occurs only at high temperatures when $T < T_c$ (Fig. 3), it can be used to measure exactly the critical temperature of films.

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