Quasiparticles and Thermal Conductivity

K. Krishana *et al.* (*1*) report that the thermal conductivity, κ, of $Bi_2Sr_2CaCu_2O_8$ at low temperature (*T*) becomes independent of the applied magnetic field above a temperature-dependent threshold field H_k (*T*). This result indicates the existence of a phase transition that separates a low-field state (in which thermal conductivity decreases with increasing magnetic field) from a high-field state (in which thermal conductivity is insensitive to the magnetic field). Krishana *et al.* state that this phase transition is not related to the vortex lattice because of the temperature-dependence of $H_k(T)$ (roughly proportional to T^2), as well as its magnitude. Instead, they suggest a field-induced electronic phase transition leading to a sudden vanishing of the quasiparticle contribution to the heat transport. One possible scenario would be the introduction of an additional id_{xy} component to the parent $d_{x^2-y^2}$ superconducting order parameter above the threshold field.

In the mixed state of high-T_c cuprates, the magnitude of κ can depend on the magneto-thermal history of the sample, which leads to different field profiles (*2*). Is the field-independent thermal conductivity of the high-field state insensitive to the way the magnetic field is applied? The report (*1*) does not address this question.

In order to gain insight on the nature of this phase transition, we studied the thermal conductivity of a $Bi_2Sr_2CaCu_2O_8$ single crystal as a function of a magnetic field ramped up and down and then reversed. This procedure is similar to the one used in the magnetization studies. At T = 8.4 K (Fig. 1, top panel), beginning with a Zero-Field Cooled (ZFC) sample, the thermal conductivity decreased with increasing magnetic field and at about 1.5 *T* [≈ H_k(*T* = 8.4 K) in (*1*)], a kink occurred in the graph of κ(*H*), followed by a quasi-constant thermal conductivity of up to 5 *T*. Then the magnetic field was decreased and, unexpectedly, a sharp drop of κ was observed over a small range in magnetic field (0.2 *T*), followed by a second plateau with a lower magnitude. At 2 *T*, κ began to increase again, but it did not attain its initial ZFC magnitude, which indicated that trapped vortices were affecting thermal conductivity. The same sequence of events occurred when the measurements were pursued to negative values of magnetic field (Fig. 1; bottom panel represents subsequent measurements field fields ramped up and down to 10 *T* and −1.3 *T*). The same features were present and the magnitude of the drop in κ at 10 *T* was comparable to those which were observed at 5 *T*. The drop occurred concomitantly with the sign change in the irreversible magnetization. In a simple Bean model, this is related to a modification of field profile in the sample for ascending and descending fields.

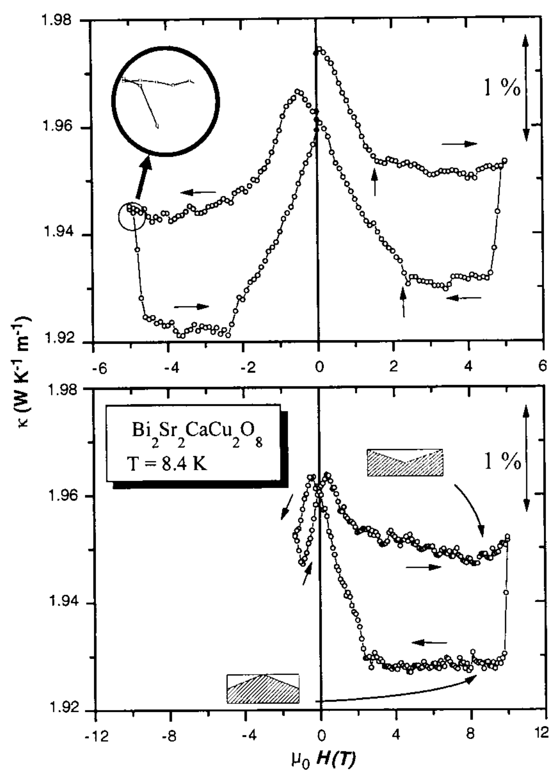

Fig. 1. Field-dependence of thermal conductivity at T = 8.4K. Field was ramped up and down in the directions indicated by arrows. Schematic field profile in the sample for the two ramping directions (demagnetization effects are neglected) is shown.

To explain the plateau of thermal conductivity in the high-field regime, Krishana *et al.* invoke two independent constraints. The first one implies no heat transport by quasi-particles in fields above H_k, and the second regards the absence of vortex scattering of phonons. According to their idea, the background thermal conductivity is exclusively as a result of phonons that do not "see" the vortices. Our findings show that this background depends on the field profile in the sample, which is incompatible with that idea. In conclusion, we think that alternative scenarios for this anomaly must be considered, including those involving the vortex lattice.

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3. We are grateful to L. Fruchter for illuminating discussions.

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Response: Our report (*1*) presented two main features observed in high-purity crystals of $Bi_2Sr_2CaCu_2O_8$. (i) At temperatures *T* below 20 K, a kink in the trace of the in-plane thermal conductivity κ appeared at the field H_k. The singular nature of the kink strongly suggests a field-induced phase transition. Because κ probes the quasi-particle (*qp*) population *n*, we argued that the transition involves a sharp decrease in *n*, possibly to zero. (ii) Above H_k, κ was field-independent, which implies that increasing the vortex density (by an order of magnitude at low *T*) does not change the heat conductivity of either the quasi-particles or phonons.

Aubin *et al.* have repeated the measurements and obtained closely similar traces of κ as it varies with *H* at 8.4 K. While their results largely confirm (i) and (ii), they emphasize the point that, at the plateau, κ is higher in the sweep-up trace as compared with the sweep-down, and suggest that alternate scenarios involving the vortex lattice should be considered.

In any transition in the mixed state, the vortices are important because they constitute the flux piercing the condensate. The issue raised by Aubin *et al.* appears to be whether features (i) and (ii) are primarily associated with a phase change in the vortex lattice or the flux configuration, as opposed to the quasi-particles and condensate (they display without comment the Bean profiles).

It is important to look at the hysteresis in perspective. We studied (Fig. 1) the field profiles measured in increasing field and in decreasing fields. The transition at H_k occurred both above the irreversibility line H_{irr} and below it (H_{irr} intersected, H_k near 18 K). Thus, the transition at H_k was observed with the vortex system in the liquid state (above 18 K), as well as in the solid state (below 18 K). In the former case (traces at 20 K), there was no resolvable hysteresis, while at 8 K, a hysteresis did appear, but was much smaller in our samples than that observed by Aubin *et al.* The difference $\Delta\kappa = \kappa_{up} - \kappa_{dn}$, relative to the zero-field value $\kappa(0)$ at each T, attained a peak value of about 4×10^{-3} near 10 K, but decreased to less than 10^{-3} at 20 K (see inset). It seems implausible that the onset at H_k or the plateau feature could depend in an essential way on the phase of the vortex system or the magnetization history of the sample. If that were so, the transition would not exist above H_{irr}. In our samples, we interpreted the slight hysteresis as a higher-order effect associated with the non-equilibrium flux distribution present at low T (see below). By contrast, (i) and (ii) are features associated with a field-induced transition that affects the quasi-particles and condensate and not with a transition in the vortex system. The solid-to-liquid transition or crossover lines (H_{irr} and H_m) are well studied (*2*). Neither resembles H_k.

The large hysteresis observed by Aubin *et al* [1% of $\kappa(0)$] suggests that a higher amount of disorder or oxygen content exists in their sample. (In crystals that have been annealed in 2 bars of oxygen at 550°C, we did observe hystereses comparable in size to that of Aubin *et al.*). We propose the following explanation. If the transition at H_k involving the condensate is sensitive to the existence of long-range order in the vortex solid (*3*), then the decrease in n to zero will not proceed to completion everywhere in the crystal in the presence of disorder. A small population of *qp*, associated with textures and defects in the vortex solid, may survive and contribute to κ at the plateau. The flatness of κ at the plateau implies that the scattering rates of phonons and *qp*'s remain unchanged as the vortex density increases by a factor of 5 to 10. Thus, the sudden change $\Delta\kappa$ that appears when the sweep direction is reversed must come from an abrupt change induced in the surviving *qp* population. Because the vortex distribution is more uniform during sweep-down scans, we expect the residual population to be smaller during sweep down, in agreement with the observed sign of $\Delta\kappa$.

The hysteresis is interesting, and may provide a probe of the residual *qp* population as disorder is increased in a controlled way. However, it appears to be an artifact of disorder and the nonequilibrium distribution of vortices at low T that is absent at higher T. For these reasons, we have focused our studies on understanding the transition of H_k.

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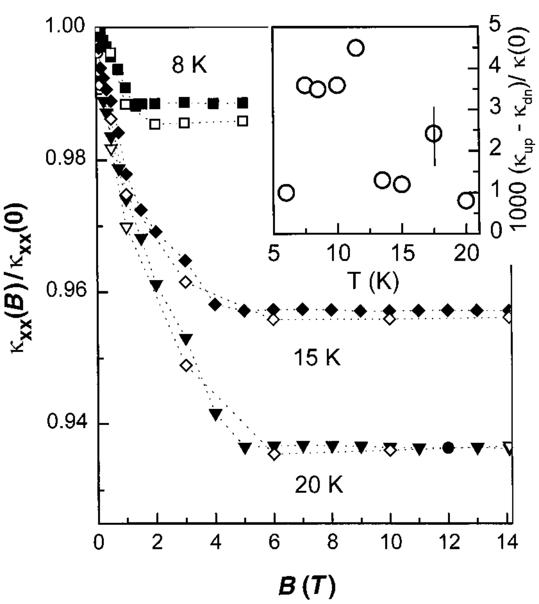

Fig. 1. Comparison of κ measured in increasing (solid symbols) and decreasing (open symbols) fields at 8, 15, and 20 K in Sample 1. Inset shows the temperature dependence of $\Delta\kappa$ expressed as a fraction of the zero-field $\kappa(0)$ at each T (vertical bar indicates the uncertainty).

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