Evidence for Field-Induced Excitations in Low-Temperature Thermal Conductivity of $Bi_2Sr_2CaCu_2O_8$

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The in-plane thermal conductivity κ of $Bi_2Sr_2CaCu_2O_8$ was studied as a function of magnetic field along the c axis. Above 5 K, as recently reported, $\kappa(H)$ decreases, then shows a kink followed by a plateau. By contrast, below 1 K, the thermal conductivity was found to *increase* with increasing field. This behavior is indicative of a finite density of states and is not compatible with the vanishing quasiparticle transport due to a field-induced phase transition as recently proposed to describe the plateau regime. Our low-temperature results are in agreement with recent works predicting a field-induced enhancement of thermal conductivity by Doppler shift of the quasiparticle spectrum. [S0031-9007(98)08250-7]

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Until very recently, thermal conductivity in the vortex state of high-T_c cuprates was analyzed using a picture which was originally developed in the context of conventional superconductors. According to this scheme, vortices constitute new scattering centers for heat carriers and their introduction leads to a decrease in heat conductivity. Even in the absence of a satisfactory account of vortex-quasiparticle interaction in unconventional superconductors, this picture provided a qualitative explanation of the field-induced decrease in $\kappa(H)$ observed in the investigated region of field-temperature plane. However, recent results reported by the Princeton group on the thermal conductivity in the mixed state of $Bi_2Sr_2CaCu_2O_8$ (Bi2212) [1] and $La_{2-x}Sr_xCuO_4$ [2] have demonstrated the need for a more vigorous exploration of transport in the vortex state of the cuprates. Notably, their study of $\kappa(H)$ in Bi2212 [1] indicated that for temperatures below 20 K, above a threshold field $H_k(T)$, κ becomes insensitive to the magnitude of magnetic field applied along the c axis. The authors proposed that H_k—which varies roughly as T^2—is the signature of a phase transition, and the high-field plateau regime represents a new quasi particle-free superconducting state. In their suggested scheme, the low-energy excitations of the parent $d_{x^2-y^2}$ order parameter is suppressed at $H_k(T)$ due to the opening of a large $d_{x^2-y^2} + id_{xy}$ gap [3].

In this Letter we present a study of the field dependence of thermal conductivity at various temperatures down to 0.1 K. Our results reveal an increasing $\kappa(H)$ at subkelvin temperatures. We will argue that this is a strong indication for the presence of field-induced delocalized excitations which cannot be understood within the scenario invoked [1,3] to explain the plateau observed at higher temperatures. Moreover, our results highlight the relevance of field-induced Doppler shifts of the energy spectrum which—as recently pointed out [4]—have been hitherto neglected in analyses of thermal transport in the cuprates.

A standard two-thermometer—one-heater method was used to measure thermal conductivity. Two RuO_2 chips were calibrated in magnetic field and used as thermometers. Figure 1 presents the in-plane thermal conductivity of two optimally doped Bi2212 crystals at temperatures just above 5 K (T_c is 89 K for sample 1 and 88 K for sample 2) as a function of a magnetic field applied along the c axis. Our results in this temperature range confirm the behavior originally reported by Krishana *et al.* [1]: after an initial drop, $\kappa(H)$ presents a kink and then becomes quasiconstant. These authors attributed the plateau of $\kappa(H)$ to a sudden disappearance of quasiparticle (QP) transport due to the opening of a gap induced by the magnetic field. However, as we already argued in a comment presenting the data on sample 1 [5], the existence of a strong hysteretic behavior seriously weakens this

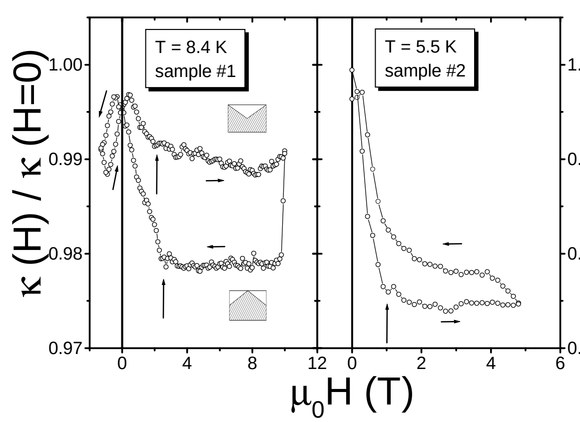

FIG. 1. Field dependence of the thermal conductivity $\kappa(H)/\kappa(H=0)$ for two different samples. Note the initial decrease, the kink, the "plateau," and the large hysteresis.

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interpretation. Indeed, if the high-field state was a superconducting state free of quasiparticles, one cannot see why it should show such an extreme sensitivity to the details of the sample's thermomagnetic history. In their reply [6], Krishana *et al.* confirmed the existence of a hysteretic behavior with a sample-dependent intensity. They suggested that the disorder in the crystallographic structure could induce textures and defects in the vortex lattice forbidding the phase transition occurring at $H_k(T)$ to go to completion everywhere in the crystal. In this way, $d_{x^2-y^2}$ domains with low-energy excitations would survive in the gapped $d_{x^2-y^2} + id_{xy}$ superconducting state. They further argued that in the sweep-down trace of $\kappa(H)$, the flux distribution would be more uniform, with a lower density of $d_{x^2-y^2}$ domains, and consequently, a lower density of electronic heat carriers. However, this proposed explanation of the hysteresis is not completely satisfactory. It supposes that sweeping the magnetic field up to $10H_k(T)$ leaves the density of the hypothetical domains unchanged—which is necessary to keep so flat a plateau. Moreover, it fails to explain the sign of the hysteresis in sample 2.

To follow the temperature dependence of $H_k(T)$, we studied the thermal conductivity of sample 2 at lower temperatures ($T < 1$ K). For these measurements, instead of sweeping the magnetic field at a constant temperature, we used an alternative procedure: a constant magnetic field was applied above T_c and then thermal conductivity was measured as a function of temperature. This was to avoid the well-known problems related to inhomogeneous penetration of vortices in a zero-field-cooled sample. Indeed, by studying the magnetization of the sample at $T = 5$ K, we found the field of complete penetration to be 3500 Oe. For this reason, it is impossible to resolve any kink in $\kappa(H)$ for fields smaller than 3500 Oe by zero-field-cooled measurements. Since this is the case for the expected magnitude of H_k below 4 K (see Fig. 4 below), we performed our low-temperature measurements after cooling the sample in finite magnetic field in order to attain a homogeneous field in the sample.

Figure 2 shows the temperature dependence of thermal conductivity $\kappa(T)/T$ for various magnitudes of magnetic field. Like previous measurements of heat conduction in BSCCO [7], our study did not resolve a cubic term in $\kappa(T)$ characteristic of ballistic phonon conductivity down to the lowest temperature investigated ($T \simeq 0.1$ K). Thus, the separation of the electronic and lattice components of the zero-field thermal conductivity is not straightforward. Here we will concentrate on the effect of the magnetic field which can be analyzed independently.

As seen in the figure, in this temperature range, κ is mostly enhanced when the sample is cooled down below T_c in a finite magnetic field. Figure 3 shows the field profile of thermal conductivity extracted from $\kappa(T)$ data at various fields together with $\kappa(H)$ at 5.5 K already shown in Fig. 1 and obtained by sweeping upwards the magnetic field. The figure shows that at low temperatures, instead of presenting a plateau, $\kappa(H)$ increases with the magnetic field. Furthermore, this field-induced enhancement of thermal conductivity becomes more pronounced with decreasing temperatures. This behavior has strong implications for the debate on the origin of the plateau feature observed at higher temperatures.

We begin by noting that the lattice conductivity can only be reduced by magnetic field due to additional scattering by vortices or by quasiparticles. The only way to explain a field-induced *increase* in thermal conductivity is to invoke an enhancement of the available excitations of the superfluid condensate. There are two possible origins for unpaired electrons in the mixed state. First, there are localized excitations of the normal core. The second source is provided by the Doppler shift of QP energy spectrum due to the superfluid flow around the vortices.

Vortex cores can be excluded as a plausible source of heat transport in our context of investigation. Let us recall that in a s-wave superconductor, the energy of the first bound state inside the vortex cores is $\Delta_0^2/2E_F$ [8], which for cuprates would yield a fraction of meV. In a $d_{x^2-y^2}$ type superconductor, according to analytical [9] and numerical [10] works, one does not expect bound states inside the vortex cores at all. Nevertheless, tunneling spectroscopy measurements have shown the existence of bound states inside the vortex cores of YBCO [11], but the energy of the first one is 5.5 meV (60 K). In Bi2212, the very recent detection of vortices by tunneling spectroscopy [12] revealed a pseudogap behavior in the vortex core and no evidence for bound states. Considering all these points, it is fairly sure that at temperatures as low as 0.18 K, the electronic states inside the vortex cores—if they exist—would not be occupied. Furthermore, they would be localized and could not contribute to heat conduction.

Extended excitations associated with supercurrents around vortices constitute the only other source of field-induced excess conductivity known to us. As first pointed out by Volovik [13], for an anisotropic superconducting

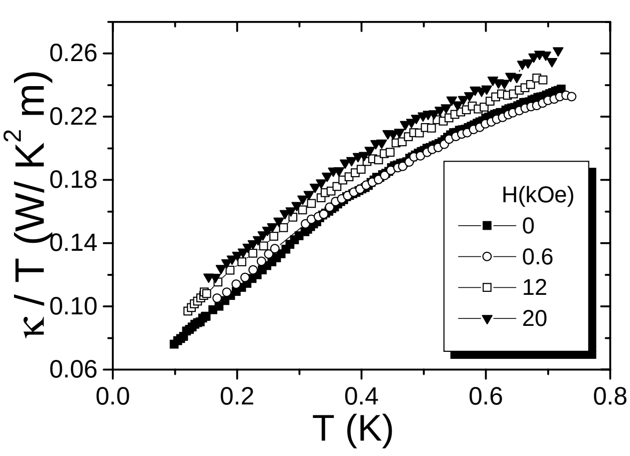

FIG. 2. Temperature dependence of the thermal conductivity $\kappa(T)/T$ with a magnetic field applied above T_c. Note the crossing of the 0.6 and 0.0 kOe curves.

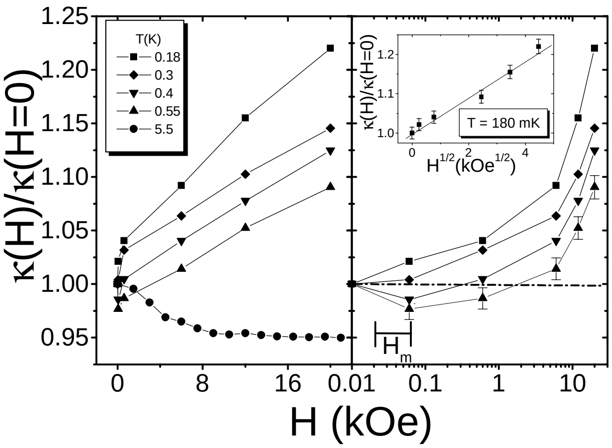

FIG. 3. Field profile $\kappa(H)/\kappa(H=0)$ for various temperatures, left panel: linear-linear; right panel: linear-log. At low temperatures, thermal conductivity increases with the magnitude of the magnetic field. H_m represents the expected position of minimum for 0.55 K (see text). The inset in the right panel shows $\kappa(H)/\kappa(0)$ versus $\sqrt{H}$ at 0.18 K.

gap, their contribution will dominate the variation of the density of states, even at small magnetic fields. They are induced by the Doppler shift of energy spectrum ($\varepsilon \rightarrow \varepsilon - \mathbf{p_F}.\mathbf{v}_s$) due to a finite local value of superfluid velocity $\mathbf{v}_s$. This effect is negligible in the presence of a gap much larger than the expected shift ($\Delta_0 \gg \mathbf{p}.\mathbf{v}_s$) which is the case of conventional superconductors at low field. For a $d_{x^2-y^2}$ gap, on the other hand, the linear energy dependence of the density of states (DOS) $[N(\varepsilon)/N_0 \propto \varepsilon/\Delta_0]$ leads to a $\sqrt{H}$ dependence of DOS. This basic relationship can be derived easily: the increase of the density of states calculated on a vortex lattice cell will be $N(H) \propto \frac{1}{R^2} \int_0^R \mathbf{p}_F \cdot \mathbf{v}_s(r) r\, dr$, where $R \propto 1/\sqrt{H}$ is the intervortex distance. Since $\mathbf{v_s}(r) \propto 1/r$, this leads to $N(H) \propto 1/R \propto \sqrt{H}$. Experimental evidence for the existence of this type of field-induced delocalized excitations in high-T_c cuprates was first provided by specific heat measurements on YBCO [14]. The field-induced shift of the energy spectrum produces effects similar to an increase in temperature. This equivalency is at the origin of the scaling behavior predicted for the field-temperature dependence of specific heat in unconventional superconductors [15]. The experimental observation of these scaling relations in specific heat of YBCO [16] and thermal conductivity of UPt_3 [17], indicates that a convincing picture of the effects of the magnetic field on the density of states in unconventional superconductors is now emerging. Recently, Kübert and Hirschfeld [4] pointed out that one implication of this picture for the transport properties of the mixed state of the cuprates would be an increase in thermal conductivity with magnetic field at low temperatures in contrast to the decrease seen at intermediate temperatures. The observation of a field-induced increase in κ by lowering temperature happens to be compatible with this prediction. Therefore, it can be naturally explained if one assumes the presence of nodes (or very deep minima) in the superconducting gap of Bi2212 at this range of temperature and field.

The presence of a large background due to the lattice contribution to heat conduction constitutes an obstacle to a quantitative check of this picture. The inset of Fig. 3 shows the variation of $\kappa(H)/\kappa(0)$ versus $\sqrt{H}$ at $T = 180$ mK. As expected, the increase in $\kappa(H)$ is proportional to $\sqrt{H}$. However, at these low temperatures, a reliable comparison with the theory would necessarily include the effects of impurity band states [18]. Indeed, the magnitude and the exact field dependence of the thermal conductivity depends strongly on the energy dependence of the density of states $N(\varepsilon)$, which is in turn a function of the concentration of impurities and the phase shift introduced by their scattering potential [19].

One remarkable feature of recent theoretical works on heat transport by field-induced quasiparticles close to the nodes is the prediction of a nonmonotonic field dependence of κ at finite temperature [4,20]. This is a consequence of the energy dependence of the relaxation time of the QP scattered by impurities. In the presence of magnetic field, the Doppler shift of excitations due to the finite local superfluid velocity leads to a decrease in the relaxation time at low fields which can exceed the parallel rise in $N(\varepsilon)$ and disrupt the monotonic increase of thermal conductivity. Hence, this theory is able to provide a unique explanation both for a monotonically increasing $\kappa(H)$ at low temperatures and a nonmonotonic field dependence at higher temperatures without invoking vortex scattering of quasiparticles. In this picture, the position of the minimum in $\kappa(H)$ is predicted to be $H/H_{c_2} \simeq (k_B T/a\Delta_0)^2$ where H_{c_2} is the upper critical field, Δ_0 is the gap maximum over the Fermi surface, and a is a vortex-lattice-dependent constant of order unity. A close examination of Fig. 2 shows that $\kappa(T)$ curves at $H = 600$ Oe and $H = 0$ intersect at $T = 0.4$ K, which is indicative of a temperature-dependent minimum in $\kappa(H)$. This becomes evident in the right panel of Fig. 3, where a logarithmic plot highlights the low-field region. Assuming $H_{c2} = 200$ T, $a = 0.5$, and $\Delta_0 = 2.14 k_B T_c$, a rough agreement is found between the theoretically expected position of the minimum and the experimental data for $T = 0.55$ K. It is important to emphasize that the ordinary electron-vortex scattering which dominates the transport properties of the mixed state in conventional superconductors—and may be present to some extent in the cuprates—is neglected in this model.

What are the implications of our results for the present debate on the nature of the anomaly discovered by Krishana *et al.*? The grey zone in Fig. 4 represents our zone of exploration in the (H, T) plane where the thermal conductivity was found to increase with the magnetic field due to a finite density of states. This region is above the $H_k(T)$ line theoretically predicted by Laughlin [3] and experimentally established from 5 to 20 K. It may be that the transition cannot be seen

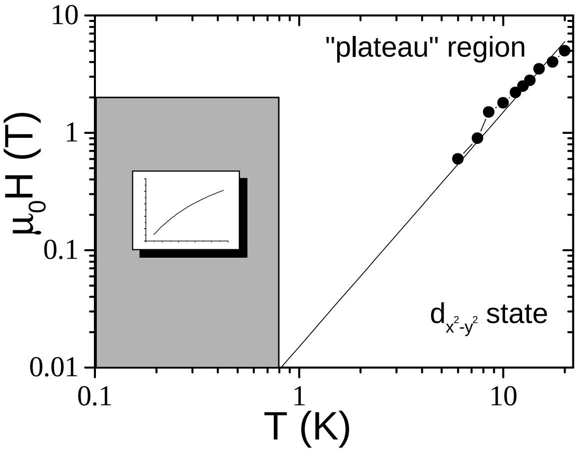

FIG. 4. κ was found to increase with magnetic field in the grey zone of the (H, T) plane. Full circles represent experimental $H_k(T)$ extracted from Ref. [1]. The solid line is the theoretical prediction by Laughlin. The grey region shows the zone of exploration in the (H, T) plane.

in the thermal conductivity profile simply due to the lack of resolution. Nevertheless, the rise of the thermal conductivity with so low a magnetic field implies that the "high-field" state must have a nonzero residual density of states, and consequently deep minima (or nodes) in the superconducting gap. Thus, if a phase transition occurs in the electronic system, its nature or consequences for the electronic heat carriers are different from what is simply expected for a state with a large uniform gap suppressing the excitations of the superconducting state in the whole sample. Already, presenting his model on field-induced transition to a $d_{x^2-y^2} + id_{xy}$ [3] state, Laughlin pointed out that the expected gap is too small to account for a complete vanishing of QP transport. Moreover, he stressed the inherent difficulty in explaining a large field-induced gap exceeding $k_B T^*$, the temperature at which the transition occurs.

The strong hysteretic behavior cannot be easily explained by the presence of trapped vortices. It is puzzling that reversing the orientation of the field sweep produces a change in thermal conductivity which is otherwise insensitive to the magnitude of the magnetic field. A broken time-reversal symmetry associated with the splitting of the $d_{x^2-y^2}$ state may provide a more promising route to explain the origin of the hysteresis. Indeed, the field profile in the sample is associated with a superfluid current of the order of J_c, the critical current. When reversing the magnetic field ramping direction, the most dramatic change in the sample is the direction of the field profile and the direction of circulation of the screening currents. The sensitivity of thermal conductivity to the direction of circulation of these screening currents may indicate that these situations are not symmetric, which would be the case in the presence of a current associated with broken time-reversal symmetry in the superconducting state. Some other experimental results have been recently interpreted as signatures of a splitting of the $d_{x^2-y^2}$ state. For example, Franz and Tesanovic [10] have proposed that the existence of a $d_{x^2-y^2} + id_{xy}$ state could be at the origin of the bound states observed in the vortex cores of YBCO by tunneling spectroscopy [11]. Furthermore, the observation of a spontaneous split of the zero-bias conductivity peak at 7 K in YBCO [21], was attributed to a phase transition at the sample surface from a pure d wave to a time-reversal violating state.

In conclusion, our results show that the new high-field superconducting state in Bi2212 identified by the emergence of a plateau in the field dependence of the thermal conductivity cannot be simply attributed to a vanishing of low-energy excitations in the superconducting state. At low temperature, κ increases with a weak magnetic field, implying a nonzero density of states.

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