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Thermal Conductivity of $Bi_2Sr_2CaCu_2O_8$ in the Mixed State

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We have investigated ab-plane thermal conductivity in single crystals of $Bi_2Sr_2CaCu_2O_8$ in the mixed state. We find that the ab-plane thermal conductivity, κab, below Tc depends on the magnitude and orientation of the magnetic field. A simple empirical expression was found for κab(H⊥c), which suggests that electron component of κab is responsible for the normal state behavior of the ab-plane thermal conductivity. However, the κab anomaly in the superconducting state is attributed to an increase in its phonon component and a rapid decrease of quasiparticle scattering below Tc.

The anomalously large increase of the ab-plane thermal conductivity, κ_{ab}, as the temperature is lowered below T_c of the HTSC's has been extensively studied in the past few years [1-3]. Two models have been proposed to explain this anomaly. First, a decrease in the phonon scattering due quasiparticle-condensation into Cooper pairs gives rise to an increase of the lattice thermal conductivity [2]. Second, a rapid decreased in the scattering of quasiparticles gives rise to an increase in the electronic thermal conductivity [3, 4] producing a peak in the total thermal conductivity below T_c.

We here report on measurements of $\kappa_{ab}(T,H)$, of single crystals of $Bi_2Sr_2CaCu_2O_8$ (BSCCO) in magnetic fields up to 7.5T oriented parallel and perpendicular to the ab-plane. As in previous studies[5, 6] we find that when the magnetic field is oriented perpendicular to ab-plane κ_{ab}(T,**H**||c) of BSCCO exhibits a decrease in the anomaly at temperatures below T_c(H=0). On the other hand,when the magnetic field is oriented parallel to the ab-plane κ_{ab}(T,**H**⊥c) exhibits only a small supression of the anomaly below T_c.

High purity single crystals of BSCCO were prepared by standard methods as described elsewhere[7] The crystals were slabs of typical dimensions 2mm × 1mm × 0.01mm.

Figure 1 shows a typical zero magnetic field ab-plane thermal conductivity and electric resistivity of the samples used in this study. The thermal conductivity decreases as temperature is decreased from room temperature down to ~95K, where it shows a local minimum. On further cooling, κ_{ab} reaches a local maximum at T≈65K; below this temperature κ_{ab} decreases rapidly.

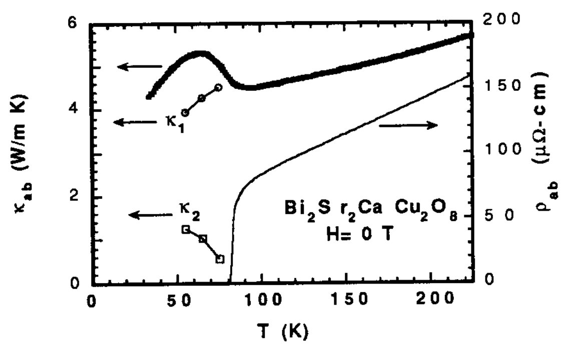

Figure 1. κ_{ab}(T,H=0) and ρ_{ab}(T,H=0) of single crystal BSCCO. κ_1 and κ_2 are the parameters from the fits of the data of Fig. 2 to Eq. (1). The solid lines are guides to the eye

Paecor *et al.* [2] and Yu *et al.* [3] separated the phonon (κ_p) and electron (κ_e) contributions to their $YBa_2Cu_3O_7$ κ_{ab} data using the above different models. However, those analyses failed to explain our data. This is attributed to the increase of κ_{ab} in the normal state with increasing T in BSCCO, unlike the behavior of κ_{ab} in $YBa_2Cu_3O_7$.

An alternative approach to discern the κ_p from the total thermal conductivity is to introduce, in a controlled manner, a phonon scatterer which does not affect the electron part of κ_{ab}, or vice versa. The mean free path of the long wavelength phonons, which are mostly responsible for κ_p, is $l_{mfp,p} \approx 5\mu m$ (Ref. [8]). We can estimate the mean free path of the electron by using $\tau_{e\text{-}ph}=0.62\times10^{-12}(m^*/m)T^{-1}$ (sec·K) from Ref. [9], and by assuming a half-filled conduction band we get $v_F \approx 4\times10^{-25}/m^*$ (Kg m/sec), which yields $l_{mfp,e} \approx 2.7\times10^{-7}/T$ (m ^oK), i.e., $l_{mfp,e} \approx 27$Å at 100K. Since the distance between vortices in the mixed state for a c-axis oriented magnetic field of 1Tesla is ~450Å, much larger than the in-plane $l_{mfp,e}$, we believe the vortices are strong phonon scatterers which leave the electrons essentially unperturbed.

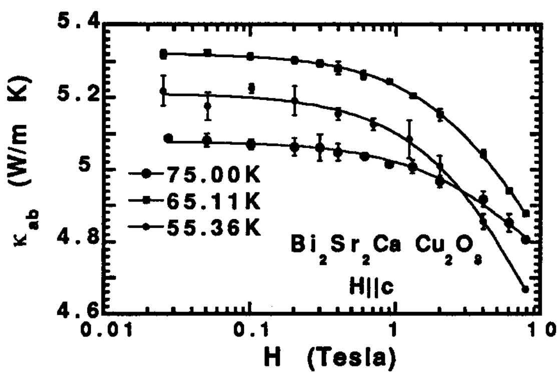

Figure 2. Thermal conductivity dependence on a magnetic field oriented parallel to the c-axis at three fixed temperatures. The solid lines are fits to Eq. (1) with the coefficients plotted in Fig. 1.

Figure 2 shows $\kappa_{ab}(T,H\perp c)$ for selected fixed temperatures. The solid lines are fits to:

$$\kappa_{ab}(H) = \kappa_1 + 1/[(1/\kappa_2) + A\,H] \qquad (1)$$

where κ_1, κ_2 and A are the free parameters to the fits, and we have assumed that κ_{ab} is the sum of only two components. One of them, $1/[(1/\kappa_2) + AH]$, with a thermal resistance that increases in proportion to the density of vortices. Equation (1) describes the data extremely well. The values extracted for the parameters κ_1 and κ_2 at different temperatures are plotted in Fig.1.

We identify κ_1 and κ_2 with the electron and phonon components of κ_{ab} reapectively. The values of $\kappa_e=\kappa_1$ obtained for different temperatures indicate that it develops a maximum in the superconducting state close to T_c (=85K), since $\kappa_e(75K)=\kappa_{ab}(95K, H=0)$ and κ_e is an increaisng function of temperature for 55K<T<75K. This also suggests that the electrons dominate the heat conduction in the normal state close to T_c, where the validity of the Wiedemann-Franz law is questionable (Θ_D=270K). The presence of a local maximum in κ_e below T_c is qualitatively consistent with the experimental observation that the quasiparticle scattering is rapidly suppressed below T_c [10, 11] giving rise to an increase in κ_e.

However, the increase in $\kappa_p(H=0)=\kappa_2$ as the temperature is lowered also indicates that it reaches a maximum below the transition temperature, at some temperature T<55K, contributing to the peak in κ_{ab}. The sharp decrease in $\kappa_p(H=0,\ T<T_c)$ as temperature increases suggests a negligible contribution of the phonons to the thermal conductivity of BSCCO-2212 in the normal state.

In conclusion, we suggest that both the electron and the phonon abilities to carry entropy are responsible for the anomaly in the ab-plane thermal conductivity of BSCCO-2212 below T_c, with the phonons as the dominant contributors.

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