Thermal Conductivity of Bi$_2$Sr$_2$CaCu$_2$O$_8$ in the Mixed State

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We have investigated ab-plane thermal conductivity in single crystals of Bi$_2$Sr$_2$CaCu$_2$O$_8$ in the mixed state. We find that the ab-plane thermal conductivity, $\kappa_{ab}$, below $T_C$ depends on the magnitude and orientation of the magnetic field. A simple empirical expression was found for $\kappa_{ab}(H \parallel c)$, which suggests that electron component of $\kappa_{ab}$ is responsible for the normal state behavior of the ab-plane thermal conductivity. However, the $\kappa_{ab}$ anomaly in the superconducting state is attributed to an increase in its phonon component and a rapid decrease of quasiparticle scattering below $T_C$.

The anomalously large increase of the ab-plane thermal conductivity, $\kappa_{ab}$, 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$_2$Sr$_2$CaCu$_2$O$_8$ (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 $\kappa_{ab}(T,H\parallel c)$ 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 $\kappa_{ab}(T,H\perp c)$ 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 $\times$ 1mm $\times$ 0.011mm.

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 $\sim$95K, where it shows a local minimum. On further cooling, $\kappa_{ab}$ reaches a local maximum at $T=65$K; below this temperature $\kappa_{ab}$ decreases rapidly.

Figure 1. $\kappa_{ab}(T,H=0)$ and $\rho_{ab}(T,H=0)$ of single crystal BSCCO. $\kappa_1$ and $\kappa_2$ 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 ($\kappa_p$) and electron ($\kappa_e$) contributions to their YBa$_2$Cu$_3$O$_7$ $\kappa_{ab}$ data using the above different models. However, those analyses failed to explain our data. This is attributed to the increase of $\kappa_{ab}$ in the normal state with increasing $T$ in BSCCO, unlike the behavior of $\kappa_{ab}$ in YBa$_2$Cu$_3$O$_7$.

An alternative approach to discern the $\kappa_p$ from the total thermal conductivity is to introduce, in a controlled manner, a phonon scatterer which does not affect the electron part of $\kappa_{ab}$, or vice versa. The mean free path of the long wavelength phonons,
which are mostly responsible for $\kappa_p$, is $l_m p = 5 \mu m$ (Ref. [8]). We can estimate the mean free path of the electron by using $\tau_e - ph = 0.62 \times 10^{-12} (m^*/m) T^{-1} \text{ (sec-K)}$ from Ref. [9], and by assuming a half-filled conduction band we get $\nu_F = 4 \times 10^{-25} / m^*$ (Kg m/sec), which yields $l_m p = 2.7 \times 10^{-7} / T \text{ (m 0K)}$, i.e., $l_m p = 27 \AA$ at 100K. Since the distance between vortices in the mixed state for a c-axis oriented magnetic field of 1Tesla is $\sim 450 \AA$, much larger than the in-plane $l_m p$, we believe the vortices are strong phonon scatterers which leave the electrons essentially unperturbed.

![Graph](image)

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 $\kappa_{ab}(T, H, \text{Lc})$ for selected fixed temperatures. The solid lines are fits to:

$$\kappa_{ab}(H) = \kappa_1 + 1/((1/\kappa_2) + A H)$$  \hspace{1cm} (1)

where $\kappa_1$, $\kappa_2$ and $A$ are the free parameters to the fits, and we have assumed that $\kappa_{ab}$ is the sum of only two components. One of them, $1/((1/\kappa_2) + A H)$, 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 $\kappa_1$ and $\kappa_2$ at different temperatures are plotted in Fig.1. We identify $\kappa_1$ and $\kappa_2$ with the electron and phonon components of $\kappa_{ab}$ respectively. The values of $\kappa_{ab}$ 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 $\kappa_{e}$ is an increasing 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 ($\Theta_D=270K$). The presence of a local maximum in $\kappa_{e}$ 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 $\kappa_{e}$.

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 $\kappa_{ab}$. 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-22212 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-22212 below $T_c$, with the phonons as the dominant contributors.

Supported by DOE grant DE-AC03-76SF00098 and NSF grant DMR90-17254.

References: