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Doping dependence of superconducting gap in $YBa_2Cu_3O_y$ from universal heat transport

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Abstract

Thermal transport in the $T \to 0$ limit was measured as a function of doping in high-quality single crystals of the cuprate superconductor $YBa_2Cu_3O_y$. The residual linear term κ_0/T is found to decrease as one moves from the overdoped regime towards the Mott insulator region of the phase diagram. The doping dependence of the low-energy quasiparticle gap extracted from κ_0/T is seen to scale closely with that of the pseudogap, arguing against a non-superconducting origin for the pseudogap. The presence of a linear term for all dopings is evidence against the existence of a quantum phase transition to an order parameter with a complex (ix) component.

Keywords: YBCO transport; Low-temperature thermal conductivity; Doping dependence

In d-wave superconductors the presence of nodes in the gap structure leads to the existence of quasiparticle excitations down to zero energy. The ability of these excitations to transport heat has been shown to be universal (independent of impurity scattering) [1], and the residual linear term κ_0/T in the thermal conductivity $\kappa(T)$ is a direct probe of the low-energy quasiparticle spectrum [2]. At optimal doping in Bi-2212 the agreement between the value of the slope of the gap at the node obtained from κ_0/T and that measured by ARPES is remarkable [3].

In this paper we investigate the doping dependence of κ_0/T in the cuprate superconductor $YBa_2Cu_3O_y$ (YBCO) and find that it decreases monotonically as one moves from overdoped to underdoped samples. The samples used in this study are all high-quality de-twinned single crystals, described elsewhere [4]. Their T_c's are 62, 44, 93 and 89 K for oxygen dopings $y = 6.54$, 6.6, 6.95 and 6.99, respectively. Thermal conductivity measurements were made in a dilution refrigerator down to 40 mK, with current along the *a*-axis.

In Fig. 1, the thermal conductivity of the samples is plotted as κ/T vs. T^2. To seperate out the electronic from the phonon contributions, we model κ to be of the form $\kappa = \kappa_{el} + \kappa_{ph} = AT + BT^{\alpha}$. The T-linear electronic term is a well known result of d-wave superconductors [2], while the T^{α} term is an empirical fit to the phonon conductivity at low temperatures. We find κ_0/T to be 0.16, 0.12, 0.091 and 0.085 mW/K^2 cm for the $y = 6.99$, 6.95, 6.6 and 6.54 samples, respectively, with details of the fits provided elsewhere. [4]

It is clear from Fig. 1 that the value of the linear term decreases monotonically as one moves from the slightly overdoped $y = 6.99$ sample to the strongly underdoped $y = 6.54$ sample, becoming zero in the parent compound $y = 0$. The presence of such a linear term for all dopings

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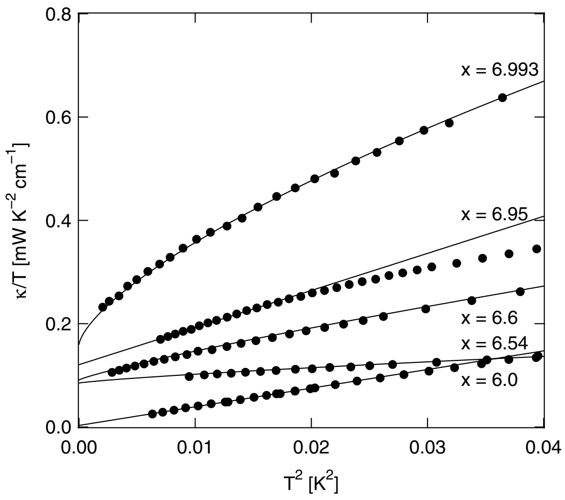

Fig. 1. Thermal conductivity of $YBa_2Cu_3O_y$.

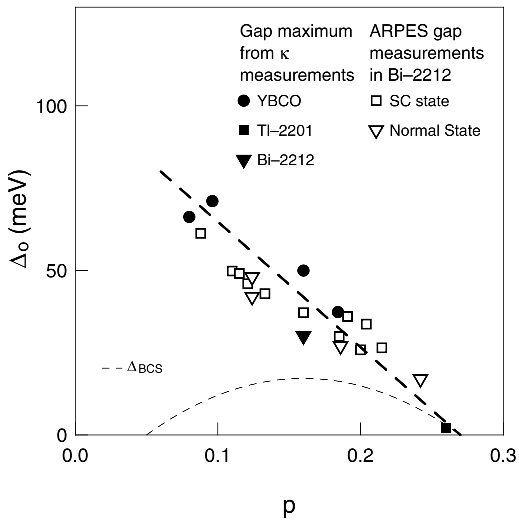

Fig. 2. Δ_0 obtained from our measurements of κ_0/T (see text) on YBCO, as well as previous measurements on Bi-2212 [3] and Tl-2201 [11] (filled symbols). For comparison, a BCS gap of the form $\Delta_{BCS} = 2.14k_BT_c$ is also plotted. The value of the energy gap maximum in Bi-2212, as determined by ARPES, is shown as measured in the superconducting state [7] and the normal state [8–10] (open symbols). The thick dashed line is a guide to the eye.

excludes the possibility of a quantum phase transition from a pure d-wave form to a d+ix state suggested by some authors, since the effect of such a transition would be to gap out the quasiparticle spectrum and hence eliminate any residual linear term.

From our measurements of κ_0/T we can extract a measure of the quasiparticle gap in the following manner. The quasiparticle thermal conductivity of a d-wave superconductor at $T \to 0$ is given by [2]:

$$\frac{\kappa_0}{T} = \frac{k_B^2}{3\hbar}\frac{n}{d}\left(\frac{v_F}{v_2} + \frac{v_2}{v_F}\right), \tag{1}$$

where n is the number of CuO_2 planes per unit cell and d is the c-axis lattice constant. Here v_F and v_2 are the quasiparticle velocities normal and tangential to the Fermi surface at the node, respectively. From ARPES measurements in cuprates, we note that the value of v_F is doping independent over a broad range of dopings [5,6] and thus a study of the doping dependence of κ_0/T is a study of the doping dependence of v_2, where v_2 is simply $\frac{1}{\hbar k_F}\frac{d\Delta}{d\phi}|_{node}$, the slope of the superconducting gap at the nodes. In order to compare with measures of the gap maximum Δ_0, we assume the pure d-wave form $\Delta = \Delta_0 \cos 2\phi$ throughout the doping phase diagram, so that $\Delta_0 = \hbar k_F v_2/2$. In Fig. 2 we plot the value of Δ_0 vs. hole concentration p, estimated from T_c [4]. The value of the energy gap maximum in Bi-2212, determined by ARPES measurements in the superconducting state [7] and the normal state [8–10], is shown alongside our own data. For comparison, a plot of the weak-coupling BCS expectation, $\Delta_{BCS} = 2.14k_BT_c$, is also displayed.

Despite a remarkable quantitative agreement with BCS theory in strongly overdoped cuprates [11], the value of the gap measured in the bulk at $T = 0$ does not follow the trend expected from BCS theory in the underdoped regime, where Δ_0 should scale with T_c. Rather, the gap seen by low-energy quasiparticles follows closely the energy scale set by the pseudogap. This similarity in scaling points to a common origin, which allow us to say the following things on the nature of the pseudogap. First, due to the very existence of a residual linear term, the (total) gap seen in thermal conductivity at $T \to 0$ is one that must have nodes. Secondly, it has a linear dispersion as in a d-wave gap (i.e. it has a Dirac-like spectrum). Thirdly, it is a quasiparticle gap and not just a spin gap. In summary these observations argue strongly for a superconducting origin to the pseudogap, and our measurements also rule out the possibility of a bulk order parameter of the type d+ix, appearing at a putative quantum phase transition.

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