Doping dependence of superconducting gap in YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{y} from universal heat transport

Mike Sutherland\textsuperscript{a}, D.G. Hawthorn\textsuperscript{a}, R.W. Hill\textsuperscript{a}, F. Ronning\textsuperscript{a}, H. Zhang\textsuperscript{a}, E. Boaknin\textsuperscript{a}, M.A. Tanatar\textsuperscript{a,1}, J. Paglione\textsuperscript{a}, R. Liang\textsuperscript{b}, D.A. Bonn\textsuperscript{b}, W.N. Hardy\textsuperscript{b}, Louis Taillefer\textsuperscript{a,∗,2}

\textsuperscript{a}Department of Physics, University of Toronto, Toronto, Ontario, Canada M5S 1A7
\textsuperscript{b}Department of Physics, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1

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\textsubscript{2}Cu\textsubscript{3}O\textsubscript{y}. The residual linear term $\kappa_0/T$ 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 $\kappa_0/T$ 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.

Key words: 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 (i.e. independent of impurity scattering) \cite{1}, and the residual linear term $\kappa_0/T$ in the thermal conductivity $\kappa(T)$ is a direct probe of the low-energy quasiparticle spectrum \cite{2}. At optimal doping in Bi-2212 the agreement between the value of the slope of the gap at the node obtained from $\kappa_0/T$ and that measured by ARPES is remarkable \cite{3}.

In this paper we investigate the doping dependence of $\kappa_0/T$ in the cuprate superconductor YBa\textsubscript{2}Cu\textsubscript{3}O\textsubscript{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 detwinned single crystals, described elsewhere \cite{4}. Their $T_c$’s are 62, 44, 93.5 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 each sample is plotted as $\kappa/T$ vs. $T^2$. To separate out the electronic from the phononic contributions, we model $\kappa$ 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 \cite{2}, while the $T^\alpha$ term is an empirical fit to the phonon conductivity at low temperatures \cite{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 (It becomes zero in the non-superconducting parent compound $y = 0$.) The presence of such a linear term for all dopings 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 $\kappa_0/T$ 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]:

$$\kappa_0/T = \frac{k_B^2 n}{3h d} \left( \frac{v_F}{v_2} + \frac{v_2}{v_F} \right),$$  \hspace{1cm} (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 the 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 $\kappa_0/T$ is a study of the doping dependence of $v_2$, where $v_2$ is simply $\frac{\Delta_{\text{pure} d\text{-wave}}}{\pi}$. The slope of the superconducting gap at the nodes. In order to compare with measures of the gap maximum $\Delta_0$, we assume the pure $d$-wave form $\Delta = \Delta_{\text{BCS}} \cos 2\phi$ throughout the doping phase diagram, so that $\Delta_0 = \hbar k_F v_2/2$. In Fig. 2 we plot the value of $\Delta_0$ 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 [8,9,10], is shown alongside our own data. For comparison, a plot of the weak-coupling BCS expectation, $\Delta_{\text{BCS}} = 2.14k_BT_c$, 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 $\Delta_0$ 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. 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 $d+i\sigma$, appearing at a putative quantum phase transition.

This work was supported by the Canadian Institute for Advanced Research and NSERC of Canada.

References

[1] L. Taillefer, et al., Phys. Rev. Lett. 79 (1997) 483.
[2] A. C. Durst, P. A. Lee, Phys. Rev. B 62 (2000) 1270.
[3] M. Chiao, et al., Phys. Rev. B 62 (2000) 3554.
[4] M. Sutherland, et al., cond-mat/0301105 (2003).
[5] J. Mesot, et al., Phys. Rev. Lett. 83 (1999) 840.
[6] Z.-X. Shen, Private communication.
[7] J. C. Campuzano, et al., Phys. Rev. Lett. 83 (1999) 3709.
[8] M. R. Norman, et al., Nature 392 (1998) 157.
[9] P. J. White, et al., Phys. Rev. B 54 (1996) R15669.
[10] A. G. Loeser, et al., Phys. Rev. B 56 (1996) 14185.
[11] C. Proust, et al., Phys. Rev. Lett. 89 (2002) 147003.