Low-temperature specific heat in high-$T_c$ cuprate Bi$_2$Sr$_{2-x}$La$_x$CuO$_{6+\delta}$ ($x \sim 0.4$): Probing the $d$-wave superconducting gap

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Abstract. We present our recent low-temperature specific heat experiment on a nearly optimally doped Bi$_2$Sr$_{2-x}$La$_x$CuO$_{6+\delta}$ (La-Bi$_2$2201) ($x \sim 0.4$) single crystal. By studying the electronic specific heat owing to nodal quasiparticle excitations, the amplitude of the $d$-wave superconducting gap at the antinodes is determined to be $\Delta_0 \sim 12$ meV. It also enables us to estimate the coefficient of the normal-state electronic specific heat (Sommerfeld constant) of the sample to be $\gamma_n \sim 9$ mJmol$^{-1}$K$^{-2}$. The quantitative probe of the superconducting gap mimics our previous findings in La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) where the superconducting gap has been determined via specific heat as well but in a wide range of doping. By looking back the data in LSCO, it is shown that there seems to be a critical change in the doping dependence of the superconducting gap at about $p \sim 0.19$. We discuss this anomalous behavior and suggest this be further checked in future specific heat measurement on La-Bi$_2$2201 or other cuprates at various doping levels.

1. Introduction

Although now there is a general consensus on that the superconducting gap in hole-doped cuprates has predominantly $d$-wave symmetry, whether it follows the standard $d_{x^2-y^2}$ gap function ($\Delta = \Delta_0 \cos(2\phi)$) along the whole Fermi surface, particularly in the optimal- and underdoped regime, has become a recent debate [1]. While some experiments such as angle-resolved photoemission spectroscopy (ARPES) and scanning tunneling spectroscopy (STS) revealed a deviation of the superconducting gap from the standard $d_{x^2-y^2}$ form, reporting either a flattening of the gap near the nodes [2, 3] or a marked larger gap near the antinodes than that would be expected by extrapolating the gap from the nodes [4], other ARPES experiments traced only a single $d$-wave gap with the simple $\cos(2\phi)$ form from nodes to antinodes, showing no evidence for additional gap structures or energy scales [5, 6]. As the precise gap information is crucially important to understand the mechanism of high-$T_c$ superconductivity in cuprates,
current controversies on it need to be settled and its determination from complementary experimental techniques should be valuable.

In resolving the above issue, a sensitive probe of the superconducting gap in the vicinity of the nodes is indispensable. In experiments, however, this is not an easy task owing to the small magnitude of the gap in that region and other possible obscuring effects such as thermal smearing [1]. Among many experimental tools employed in the research of high-\(T_c\) superconductivity, low-temperature specific heat (LTSH) can be performed to low temperatures and reflects the low-lying quasiparticle excitations of the sample. As these excitations are governed by the energy spectrum near the nodes for a \(d\)-wave superconductor [7], by investigating them one can in principle infer the fine details of the nodal gap from LTSH. Another advantage of LTSH is that it is a bulk measurement and not sensitive to the surface imperfection of the sample. By comparing the result from LTSH with what we observed in spectroscopy or tunneling, one may be allowed to draw important conclusions on the definite structure of the superconducting gap in high-\(T_c\) cuprates. Here we present our recent LTSH measurement and the reliable determination of the superconducting gap in a monolayer high-\(T_c\) cuprate superconductor Bi\(_2\)Sr\(_2\)-\(x\)La\(_x\)CuO\(_{6+\delta}\) (La-Bi2201).

2. Experiment
Single crystal of La-Bi2201 with nominal \(x = 0.4\) was grown by the traveling solvent floating-zone method [8]. The crystal shows a \(T_c\) of 28 K in the magnetic susceptibility measurement. The LTSH measurement was conducted by a thermal relaxation method, as described in detail previously [9]. Magnetic fields up to 12 T were applied along the \(c\) axis of the sample.

3. Results and discussion
Left panel of figure 1 shows the LTSH data in different magnetic fields. To extract the electronic specific heat, we fit the data in \(H = 0\) to \(C(T, 0) = \alpha T^2 + \beta T^3 + \gamma T^5\) and the data in \(H \neq 0\) to \(C(T, H) = \gamma(H)T + \beta T^3 + \eta T^5\), where \(\beta\) and \(\eta\) are parameters to describe the phonon term, \(\gamma(H)\) is the coefficient of the linear-\(T\) term in fields, and \(\alpha\) is the coefficient of the \(T^2\) term in zero-field which is expected for a \(d\)-wave superconductor. By performing a global fit [10], we obtain \(\alpha = (0.10 \pm 0.04)\) mJ mol\(^{-1}\) K\(^{-3}\) and \(\gamma(H)\) in various fields which, as shown in right panel of figure 1, obeys an \(A\sqrt{H}\) dependence with \(A = (0.90 \pm 0.06)\) mJ mol\(^{-1}\) K\(^{-2}\) T\(^{-0.5}\). Both features of the specific heat, i.e., the presence of a \(T^2\) term in zero-field and an \(\sqrt{HT}\) term in fields, are conformity with the \(d\)-wave pairing theory [7], giving the bulk evidence for a predominant \(d\)-wave superconducting gap in optimal-doped La-Bi2201.

For a \(d\)-wave superconductor, the \(\alpha T^2\) specific heat in zero-field comes from the linear energy dependence of the quasiparticle density of states (DOS) near the nodes, while the \(\gamma(H)T = A\sqrt{HT}\) term in magnetic fields results from Doppler shift of the quasiparticle spectrum owing to the supercurrent flowing around vortices. Therefore the magnitudes of both \(\alpha\) and \(A\) are closely related to the nodal gap slope, \(v_\Delta\), which defines the way the gap opens near the nodes. Specifically, \(\alpha = \frac{18\zeta(3)}{\pi} \frac{k^2_F}{\hbar^2} \frac{nV_{mol}}{v_F v_\Delta} \frac{1}{v_F v_\Delta}\) and \(A = \frac{4\zeta(3)}{3\hbar} \sqrt{\frac{\pi}{20}} \frac{nV_{mol}}{d} \frac{\alpha}{v_\Delta}\), where \(\zeta(3) \approx 1.2, n\) is the number of CuO\(_2\) planes per unit cell, \(d\) is the unit cell size along \(c\) axis, \(V_{mol}\) is mole volume of the unit cell, \(v_F\) is the Fermi velocity at the nodes, and \(\alpha = 0.465\) for a triangular vortex lattice [7]. Hence, with \(\alpha\) or \(A\), one can determine the \(v_\Delta\) in a straightforward manner and then infer the amplitude of the superconducting gap at the antinodes via \(2\Delta_0 = h k_F v_\Delta\) (\(k_F\) the Fermi wave vector along the nodal direction) under the standard \(d\)-wave form. With the known parameters specific to La-Bi2201 and the \(\alpha\) or \(A\) from LTSH, we obtain \(\Delta_0 \approx (13 \pm 5)\) meV or \(\Delta_0 \approx (10.4 \pm 0.7)\) meV, respectively. In figure 2 we plot the obtained \(\Delta_0\) from LTSH together with that from ARPES or STS for optimal-doped La-Bi2201 [6, 11, 12]. Good agreement is seen among them, which indicates that, on the one hand, one can reliably determine the
superconducting gap from LTSH, and on the other hand, the superconducting gap essentially follows the simple $d$-wave form.

In $d$-wave framework, $\gamma(H)$ can also be expressed by $\gamma(H) = \sqrt{8/\pi} a_\gamma \gamma_n \sqrt{H/Hc2}$, where $\gamma_n$ is the coefficient of the normal-state electronic specific heat (Sommerfeld constant) and $Hc2$ is the upper critical field [7]. This relation is derived based on the fact that as $H$ increases, the mixed-state electronic DOS, characterized by $\gamma(H)$, increases and ultimately saturates to

**Figure 1.** Left: $C/T$ vs $T^2$ plot of the specific heat in fields up to 12 T for nearly optimally doped La-Bi2201 (symbols). The lines are the fit to data to separate the electronic specific heat from the phonon specific heat. Note that, for clarity, the interval between data sets at different $H$ has been enlarged and the in-field data and fit are shown as $C/T = 20\gamma(H) + \beta T^2 + \eta T^4$. Right: Field dependence of the coefficient of the electronic linear-$T$ specific heat, $\gamma(H)$ (circles). The line is the fit to $\gamma(H) = 0.90\sqrt{H}$ for $d$-wave pairing.

**Figure 2.** $\Delta_0$ vs doping $p$ plot of the superconducting gap for nearly optimally doped La-Bi2201 ($x \sim 0.4$) (diamond) [10] and LSCO across a wide doping range (squares) [13, 14], as determined from the field dependence of the specific heat. The $\Delta_0$ obtained from some ARPES and STS studies are also shown for comparison (circles for La-Bi2201 [6, 11, 12] and stars for LSCO [5, 15] respectively). The dashed line is the $d$-wave BCS gap form $\Delta_{BCS} = 2.14k_BTc$ with $T_c/Tc^{max} = 1 - 82.6(p - 0.16)^2$ and $Tc^{max} = 38$ K. The vertical dotted line marks the doping level $p = 0.19$. The dash dot line is a guide to the eye.
the normal-state electronic DOS, characterized by $\gamma_n$, when $H = H_c2$. With $\gamma(H) = A\sqrt{H}$, it yields $\gamma_n^2 = \pi A^2 H_c2 / 8a^2$. For optimal-doped La-Bi2201, high-field Nernst effect reported $H_c2 \simeq (50 \pm 4) \text{T}$ [16]. As to $\gamma_n$, however, to our knowledge there has seemed no direct experimental determination reported in the literature for La-Bi2201. Present LTSH study offers an opportunity to estimate it. With the $A$ from LTSH and $H_c2$ from Nernst effect, the $\gamma_n$ is inferred to be $\gamma_n \simeq (8.6 \pm 0.7) \text{ mJ mol}^{-1} \text{K}^{-2}$ via the above equation, which certainly deserves to be checked by direct measurement in the future.

The LTSH in optimal-doped La-Bi2201 is an extension of our previous study in La$_{2-x}$Sr$_x$CuO$_4$ (LSCO) where the superconducting gap has been successfully determined by LTSH across the whole superconducting phase diagram [13, 14]. Figure 2 shows the excellent agreement of the $\Delta_0$ determined by LTSH, ARPES [5], and STS [15] in LSCO, which further illustrates the virtue of LTSH as a probe of the superconducting gap and indicates that going away from the $\Delta_0$ retain the simple $d$-wave form. It is interesting to note that with varying the hole doping $p$, the superconducting gap seems to exhibit an anomalous kink at $p \sim 0.19$, below which the departure of the $\Delta_0$ from the weak-coupling $d$-wave BCS behavior becomes progressively larger as the $p$ decreases. Previously we have shown that below $p \sim 0.19$, the superconducting gap in LSCO determined from LTSH tracks the normal-state pseudogap [13]. The observed anomalous kink in the $\Delta_0$ at $p \sim 0.19$ seems to be in accordance with a vanishing of the pseudogap or its emergence into the superconducting gap beyond a critical doping point. It should be reminded that other physical properties, such as the superconducting condensation energy and normal-state resistivity, have also been found to show anomalous changes at $p \sim 0.19$ for LSCO [17, 18]. Further work is needed to elucidate the underlying origin of these intriguing phenomena.

4. Summary

In summary, we have determined the slope of the superconducting gap near to the nodes in nearly optimally doped La-Bi2201 from LTSH [10]. By assuming a simple $d$-wave form, the amplitude of the superconducting gap at the antinodes is inferred to be $\Delta_0 \sim 12$ meV, which shows good consistency with spectroscopy or tunneling measurements. This suggests that, to a very large extent, the superconducting gap follows the standard $d_{x^2-y^2}$ function from nodes to antinodes. As a byproduct, the Sommerfeld constant of the sample, is also estimated to be $\gamma_n \sim 9 \text{ mJmol}^{-1} \text{K}^{-2}$. We finally review our previous LTSH result in LSCO and shows that there seems to be a critical change in the doping dependence of the superconducting gap at $p \sim 0.19$.

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