Temperature dependence of the superconducting gap anisotropy

in Bi$_2$Sr$_2$Ca$_1$Cu$_2$O$_{8+x}$

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Abstract

We present the first detailed data of the momentum-resolved, temperature dependence of the superconducting gap of Bi$_2$Sr$_2$Ca$_1$Cu$_2$O$_{8+x}$, complemented by similar data on the intensity of the photoemission superconducting condensate spectral area. The gap anisotropy between the $\Gamma - \bar{M}$ and $\Gamma - X$ directions increases markedly with increasing temperature, contrary to what happens for conventional anisotropic-gap superconductors such as lead. Specifically, the size of the superconducting gap along the $\Gamma - X$ direction decreases to values indistinguishable from zero at temperatures for which the gap retains virtually full value along the $\Gamma - \bar{M}$ direction.

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The order parameter of high-temperature superconductors is of extreme current interest, and has been investigated by several techniques, including penetration depth, \[1\] tunneling, \[2\] Raman scattering, \[3\] Josephson current in an applied magnetic field, \[4\] and angle-resolved photoemission. \[5,6\] Angle-resolved photoemission has the advantage of directly investigating the momentum-dependence of the gap. Already, results establishing a marked anisotropy in the gap at low temperatures have ruled out an isotropic s-wave symmetry order parameter. \[8–11\]

Our main result is that, contrary to anisotropic-gap conventional superconductors such as lead, \[12–14\] the gap anisotropy of \(Bi_2Sr_2Ca_1Cu_2O_{8+x}\) increases with increasing temperature as one approaches the superconducting transition temperature, \(T_c\). This result was discovered by estimating the gap from angle-resolved photoemission data, using the BCS-like lineshape \[15,16\] and computer code of Olson, Lynch and Liu. \[7\] Our results place stringent constraints on any theory of high-temperature superconductivity.

Fig. 1 illustrates the experimental and sample standards we have achieved as prerequisites for our study. Fig. 1(a) illustrates an angle-resolved photoemission spectrum of a gold film deposited \textit{in situ}; the temperature of the film is 36K. The 10-90\% energy width of the Fermi-Dirac distribution function Fermi edge is 15±2 meV. Fig. 1(b) illustrates magnetic susceptibility measurements taken for a \(Bi_2Sr_2Ca_1Cu_2O_{8+x}\) single crystal sample. The 10-90\% transition temperature width is 1.3K. To our knowledge, this is the narrowest transition width published for \(Bi_2Sr_2Ca_1Cu_2O_{8+x}\) single crystal samples, and is comparable to the best results on \(YBa_2Cu_3O_{7-x}\) single crystals. Our photoemission measurements were performed in an ultrahigh vacuum chamber with a base pressure of \(6 \times 10^{-11}\) torr. The light source is the four meter normal incidence monochromator at the Wisconsin Synchrotron Radiation Center. The electron energy analyser is a 50 mm VSW hemispherical analyser, mounted on a two axis goniometer, with an acceptance full angle of 2 degree. The total energy resolution employed was 25 meV. Samples were transferred from a load lock chamber and were cleaved \textit{in situ} at 35K. The sample holder includes the capability to rotate the sample about the surface normal, at low temperature, for precision alignment with respect to the
photon electric field. The sample crystal structure, and orientation, were determined by in situ low energy electron diffraction (LEED). The sample temperature stability was ±1K.

We have studied the angular extent of the photoemission superconducting condensate and its symmetry. Here we concentrate on the temperature dependence of the gap. For this purpose, we chose two locations in the Brillouin zone where the gap and the photoemission superconducting condensate spectral area $n_s$ are large. These points are (a) along the $\Gamma - \bar{M}$ direction (Cu-O-Cu bond axis in real space) near $\bar{M}$, $k_x = 0.82 \, \text{Å}^{-1}$, and (b) along the $\Gamma - X$ direction (Bi-O-Bi direction, without superlattice structure, in real space) at $k_x = k_y = 0.33 \, \text{Å}^{-1}$. For example, pure $d_{x^2-y^2}$ symmetry has a maximum gap along the $\Gamma - M$ direction and zero gap along the $\Gamma - X$ direction. Fig. 2 illustrates (a) angle-resolved photoemission data (raw data, without smoothing) taken at a location along the $\Gamma - \bar{M}$ direction, near the $\bar{M}$ point, in the surface Brillouin zone for temperatures from 36K to 95K, and (b) a direct comparison of the spectra at 35K, 75K and 85K with the normal-state spectrum at 95K. The count rate in photoemission superconducting condensate spectral area at 36K was about 1 kHz. The main temperature-dependent features of these spectra include: A shift of the leading edge that reveals the opening of the superconducting gap; a photoemission superconducting condensate spectral area with an energy full width at half maximum of 25 meV is observed immediately below the leading edge; a dip at binding energy of about 80 meV for temperatures up to 0.84$T_c$. Note that along the $\Gamma - \bar{M}$ direction, the photoemission superconducting condensate spectral area has been reproducibly observed at temperatures within 2K of the transition temperature ($T_c$) of 83K, and disappears above $T_c$. Similarly, the shift of the leading edge is quite large, even close to $T_c$. Using the Olson-Lynch-Liu code, we find that the gap opens quite rapidly below $T_c$, reaching its full value at 0.85$T_c$.

The results of Fig. 2 are in striking contrast to the corresponding results of Fig. 3, obtained at the location along the $\Gamma - X$ symmetry direction. The results of Fig. 3 include (a) spectra taken at temperatures from 40K to 95K and (b) a direct comparison of the spectra at 40K, 75K and 85K with a normal-state spectrum at 95K. Several differences compared
with Fig. 2 are noteworthy. The photoemission superconducting condensate spectral area is weaker and the shift of the leading edge of the spectrum at 40K is significantly less than along the $\Gamma - \bar{M}$ direction. As Fig. 3(b) illustrates, at temperatures well below $T_c$ there is a non-zero superconducting gap. This is a significant point: it rules out the simplest type of $d$-symmetry order parameter, specifically pure $d_{x^2-y^2}$, well below $T_c$. \[17,18\] On the other hand, the gap becomes indistinguishable from zero along the $\Gamma - X$ direction at a temperature (70K) for which the gap is at 90-100% of full value along the $\Gamma - \bar{M}$ direction (see Fig. 4, below).

The detailed plot in the superconducting gap with temperature and symmetry direction is illustrated in Fig. 4(a) for both the $\Gamma - \bar{M}$ and $\Gamma - X$ directions. We emphasize that the data of Fig. 4(a) and (b) were obtained on the same sample, and checked as noted below on additional samples. Fig. 4(a) illustrates our main result: the gap anisotropy between the $\Gamma - M$ and $\Gamma - X$ directions increases with increasing temperature. For the $\Gamma - M$ direction, the gap is still visible for temperatures as high as $(0.94 - 0.98)T_c$, and retains its full value up to $(0.82 \pm 0.03)T_c$. By contrast, in the $\Gamma - X$ direction the gap begins to decrease at $(0.57 \pm 0.03)T_c$ and is indistinguishable from zero at $0.81T_c$. Consequently, the gap anisotropy, already present at low temperatures, increases as the temperature approaches $T_c$. Taking the most conservative error bars, the gap anisotropy for the two directions increases from 1.8 at $0.40T_c$ to 14 at $0.85T_c$, an increase of at least a factor of 8.

We made several checks to insure that the differences illustrated in Fig. 4(a) are due to the different symmetry directions. We observed a temperature dependence of the momentum-resolved photoemission superconducting condensate spectral area, $n_s$. $n_s$ is proportional to the number of electrons that are removed by the superconducting transition from an energy domain roughly equal to the gap, and because of forming Cooper pairs are found at energies immediately below the gap. Fig. 4(b) illustrates the change in $n_s$ with temperature, normalized to the spectral area at $0.40T_c$. We obtained $n_s$ by subtracting the normal state(quasiparticle) spectral area from the superconducting state spectral area between 10 – 55 meV binding energy. We found that the change in $n_s$ with temperature was
a robust quantity, not sensitive to exactly what binding energy range was used to define
the photoemission superconducting condensate spectral area. Although there is no detailed
theoretical calculation of $n_s(T)$, several noteworthy points emerge from the data. At $0.40T_c$, $n_s$ is non-zero in both the $\Gamma - M$ and $\Gamma - X$ directions, as expected for a non-zero gap in both directions. [9,11] As the temperature increases from the lowest temperature, $n_s$ goes down more rapidly in the $\Gamma - X$ direction than in the $\Gamma - \bar{M}$ direction; note particularly the data between $0.50T_c - 0.80T_c$. When the gap in the $\Gamma - X$ direction becomes very small (Fig. 4(a)), $n_s$ in the $\Gamma - X$ direction drops to virtually zero. Further, $n_s$ in the $\Gamma - X$ direction is indistinguishable from zero for temperatures at which in the $\Gamma - \bar{M}$ direction $n_s$ is still appreciable. The behavior of $n_s$ mirrors the temperature dependence of the gap anisotropy.

As an additional check, we fabricated samples with different oxygen and cation stoichiometries. We found that different samples exhibited the same size gap at low temperatures, one in the $\Gamma - \bar{M}$ and another in the $\Gamma - X$ direction. We found a growing gap anisotropy with increasing temperature— the same behavior as in Fig. 4(a).

We also checked the effect of the normal state (quasiparticle) binding energy. We compared samples where the quasiparticle binding energy along the $\Gamma - \bar{M}$ direction of one sample and along the $\Gamma - X$ direction of a different sample were the same. We found that the difference illustrated in Fig. 4 persisted. We conclude that the difference illustrated in Fig. 4 is related to the two symmetry directions, rather than the absolute size of the superconducting gap or the quasiparticle binding energy from which the photoemission superconducting condensate arises.

Because quantitative calculations comparing to our experimental data of Figs. 2-4 are not currently available, we neither endorse nor rule out specific models. [17] [31] Instead, we note how various models are constrained by our results. Any model must explain how the gap anisotropy arises. [21][22] More stringent is that any model must explain how the anisotropy changes from 1.8:1 at $0.40T_c$ to at least 14:1 at $0.85T_c$, a change of a factor of 8-9. The increasing gap anisotropy as the temperature approaches $T_c$ is a peculiar feature
of high-temperature superconductors. A conventional BCS superconductor such as lead can
have a gap anisotropy at low temperatures; [12–14] however, this anisotropy disappears as
$T_c$ is approached from below. [12]

Our data can be interpreted in terms of a two-component order parameter, [33] of which
there are several models. [26–28,33] One possibility is a model that exhibits only a $d_{x^2−y^2}$
symmetry component near $T_c$ and both components at lower temperatures. It is noteworthy
that the best fit to our data at 70K and above along the $\Gamma − X$ direction yields a zero gap.
[17–19]

However, such two-component models [26–28,33] do not yet provide a quantitative anal-
ysis of the temperature dependence of the two components. Earlier theoretical work on the
superconducting order parameter symmetry [31] indicate that two transition temperatures
should be observed for a two-component order parameter. We note a recent, unpublished
mean field analysis of a two-component order parameter. [32] The investigators in Ref. [32]
assume an order parameter that is a mixture of $s$– and $d$–wave components. Minimiza-
tion of the corresponding Ginzburg-Landau free energy gives a temperature-dependent gap
anisotropy in agreement with the data of Fig. 4(a).

One additional point is clear: our data imply strong-coupling. This is based on the
estimated $2\Delta/kT_c$, which is 4.6 for the $\Gamma − \bar{M}$ direction, and has been reported by other
authors as exceeding the BCS value of 3.5. [34] Further, the temperature dependence of the
gap along the $\Gamma − \bar{M}$ direction (Fig. 4(a)) is not consistent with a weak-coupling analysis.
[35]

In summary, we have presented the first detailed, momentum-resolved, study of the
temperature dependence of the superconducting gap and photoemission superconducting
condensate spectral area. We find that the gap anisotropy increases markedly, by at least
a factor of 8-9, as $T_c$ is approached. Within our experimental error, the size of the super-
conducting gap decreases to zero along the $\Gamma − X$ direction at a temperature where the gap
retains virtually full value along the $\Gamma − \bar{M}$ direction. Furthermore, neither the estimate of
$2\Delta/kT_c$ at low temperatures, nor the temperature dependence of the gap along the $\Gamma − M$
direction, is consistent with weak-coupling. The temperature dependence of the gap anisotropy is mirrored by the temperature dependence of $n_\text{a}$. The increase in gap anisotropy with increasing temperature is related to the two symmetry directions, and appears not to be due to the absolute size of the gap or the quasiparticle binding energy. The increasing gap anisotropy with temperature places severe constraints on all models of high-temperature superconductivity.

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FIGURES

FIG. 1. (a) Gold Fermi edge photoemission spectrum and (b) magnetic susceptibility data for our $Bi_2Sr_2Ca_1Cu_1O_{8+x}$ single crystal.

FIG. 2. (a) Angle-resolved photoemission spectra versus temperature for the $(k_x,k_y) = (0.82,0.0)$ Å$^{-1}$ location along the $\Gamma - \bar{M}$ direction. The photon energy was 21 eV. The data were taken from 36K ($0.40T_c$) to 95K ($1.15T_c$); (b) direct comparison for the spectra at 36K and 95K, at 75K and 95K, and at 85K and 95K. The superconducting gap ($\Delta$) obtained for each spectrum is noted.

FIG. 3. (a) Angle-resolved photoemission spectra versus temperature for the $(k_x,k_y) = (0.33,0.33)$ Å$^{-1}$ location along the $\Gamma - X$ direction. A photon energy of 21 eV was used. The data were taken from 40K ($0.46T_c$) to 95K ($1.15T_c$); (b) direction comparison of the spectra at 40K and 95K, at 75K and 95K, and at 85K and 95K. The superconducting gap ($\Delta$) obtained for each spectrum is noted. Note that at 75K, the gap is zero, while in Fig. 2(b) it is non-zero.

FIG. 4. (a) The size of the superconducting gap for the location in the $\Gamma - \bar{M}$ direction (diamonds) and in the $\Gamma - X$ direction (squares) as a function of temperature. Note that the gap remains at full value up to $0.85T_c$ along the $\Gamma - \bar{M}$ direction, but is reduced starting at $0.57T_c$, and zero at $0.82T_c$, along the $\Gamma - X$ direction; (b) the intensity $n_s$ (see text), normalized to the value at 40K, versus temperature for the location in the $\Gamma - \bar{M}$ direction (diamonds) and in the $\Gamma - X$ direction (squares). Note that $n_s$ decreases faster in the $\Gamma - X$ direction, and drops markedly above $0.80T_c$, compared to the $\Gamma - \bar{M}$ direction.