Analyzing Intrinsic Superconducting Gap by Means of Measurement of Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ superconductors***

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For the mechanism of high-$T_c$ superconductivity in inhomogeneous Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ superconductors, we demonstrate the intrinsic superconducting gap, $\Delta_i$, and pairing symmetry by using a developed $\Delta = \Delta_i/\rho$, where $\Delta$ is the observed energy gap and $0 < \rho \leq 1$ band filling. When $\rho=1$, $\Delta = \Delta_i \leq 10$ meV, measured at a node, is intrinsic. When $0 < \rho < 1$, $\Delta$ implies an averaging of $\Delta_i$ over the measurement region, which is an effect of the measurement. From spectra of the density of states (DOS), $b = 2\Delta_i/k_BT_c$ is less than 4 when $\rho=1$ and the DOS indicates $s$-wave symmetry. The superconducting gap anisotropy is attributed to the inhomogeneity of the metal phase and the insulating $d$-wave phase in the measurement region.

To clarify the mechanism of high-$T_c$ superconductivity, it is essential to know the intrinsic superconducting energy gap and the intrinsic density of states (DOS). High-$T_c$ superconductors are intrinsically spatially inhomogeneous; this is attributed to metal-insulator instability in which a half-filled metal lies in an unstable position at the local charge-density-wave potential. The instability implies that the probability of one electron occupying a cubic unit is less than one. This indicates that a metallic system is separated into metal and insulator phases composed of cubic units with and without an electron, respectively, because the electron is not divided. Pan et al. and Wang et al. have suggested as an alternative explanation that nonlinear screening of the ionic potential leads to strong inhomogeneous redistribution of the local hole density. The inhomogeneity was proven experimentally by scanning tunneling microscopy (STM). Both the local DOS and the energy gap are correlated spatially and vary on the surprisingly short length scale of about 14 Å. The transitions from superconducting state to a low-temperature pseudogap state are spatially continuous and occur on a very local scale of 1-3 nm. The smallest characteristic size of superconducting islands is about 3 nm in diameter.

In the inhomogeneous superconductors, which are a mixture of an insulating phase and a metal phase (superconducting phase at low temperatures), the metallic (or insulating) characteristics are measured by the average of the two phases, (Fig. 1). The measured data are always composed of the effects of two phases, consequently, the intrinsic characteristics in the respective phases cannot be measured exactly. Therefore, since the discovery of high-$T_c$ superconductors, problems such as the pseudogap, the intrinsic superconducting energy gap, the intrinsic DOS, and pairing symmetry remain unsolved, although numerous experimental data and theories have been obtained and developed.

In this paper, we analyze the intrinsic superconducting gap and pairing symmetry by evaluating the local carrier density (or band filling), with spectra measured by STM and angle-resolved photoemission spectroscopy (ARPES) for Bi$_2$Sr$_2$CaCu$_2$O$_{8+x}$ (Bi-2212) superconductors. STM and ARPES are very powerful tools for determining the most homogeneous spatial regions in a crystal and for observing the intrinsic effect, respectively.

The well-known BCS DOS of Eq. (2), which is obtained applied to a homogeneous superconductor and defined at 0 K, cannot be applied to experimental data measured in an inhomogeneous superconductor (Fig. 1), which does not define k-space; therefore the DOS must be converted into that of a homogeneous superconductor. Here, the metal phase on homogeneous superconductors implies that there is no charge difference between nearest neighbor sites, for example, when there is one electron per atom in the electronic structure. When the carriers in the metal phase in the inhomogeneous superconductor are averaged over all atomic (or lattices) sites in the measurement region, it is possible to change the inho-
mogeneous superconductor into a homogeneous one with a carrier of an effective charge,\textsuperscript{7,8} The effective charge of the carrier is given as a fractional charge, $e' = \rho e$, where $0 < \rho = n/l \leq 1$ is band filling, $n$ is the number of carriers in the metal phase (region B in Fig. 1) and $l$ is the number of lattices.\textsuperscript{7,8} The number of bound charges, $n_b = l - n$, is bound in the insulating phase with a pseudogap (region A in Fig. 1); the total charges are conserved even in the inhomogeneous superconductor. The effective charge is justified only by means of measurement, that is, when not measured, the effective charge becomes the elementary true charge in the metal phase.

In the tunneling conductance ($\frac{dI}{dV}$), the observed energy gap, $\Delta$, is given by

$$\Delta = eV_{\text{bias}} = \Delta_i/\rho,$$  \hspace{1cm} (1)

by substituting $e$ with $e'$. $\Delta$ increases as $\rho$ decreases and is an average value of the intrinsic energy gap, $\Delta_i$, over a measured region. $\Delta_i$ is attributed to pairing of two electrons of true charge when $\rho = 1$, is constant irrespective of the extent of $\rho$, and is determined by the minimum bias voltage. Moreover, we apply Eq. (1) to the tunneling spectra and the photoemission spectra.

The BCS DOS, tunneling conductance in the inhomogeneous superconductor, is given by

$$N_s(E)/N_n = \text{Re} \left( \frac{E}{\sqrt{E^2 - (\Delta_i/\rho)^2}} \right),$$  \hspace{1cm} (2)

where $\Delta_i$ is $\Delta_{s}$ in a $s$-wave superconductor, $\Delta_{s}\cos(2\phi)$ in a $d$-wave superconductor, and $E$ is an applied bias voltage. Considering the broadening effect, $E$ is substituted with $E = E - i\Gamma$ where $\Gamma$ is the broadening parameter.\textsuperscript{9} Equation (3) is valid in $|E| \geq \Delta$ in the s-symmetry case and is averaged by phase angle $\phi$ in the $d$-symmetry case. Equation (3) has a coherence peak at the energy gap which increases with decreasing $\rho$, (Fig. 2); thus, the unsolved problem\textsuperscript{10}-\textsuperscript{12} in the tunneling conductance, is explained. It was experimentally demonstrated that analogous to Bi-2212, the energy gap in Bi-2201 monotonically increases with a decreasing hole concentration.\textsuperscript{13} Equation (3) and the coherence peak energy when $\rho = 1$ are regarded as the intrinsic DOS and $\Delta_{s}$, respectively. Equation (3) and the peak energy when $0 < \rho < 1$ imply an averaging of the intrinsic DOS and $\Delta_{s}$ over the measurement region, which is the effect of the measurement.

Pan et al.\textsuperscript{2} measured the well-shaped tunneling conductance curve 5 with a clear coherence peak at $\Delta \approx 25$ meV, using STM, as shown in Fig. 3 (c) of their paper. On the basis of their analysis, curve 5, which is observed at a larger $\rho$ value than other curve numbers, resembled the spectra behavior of an oxygen over-doped Bi-2212 crystal. This implies that the intrinsic DOS curve is similar to the curve measured in over-doped crystals. Similar analyses were presented by several other groups as well.\textsuperscript{4}-\textsuperscript{6} Hasegawa et al.\textsuperscript{14} and Kitazawa et al.\textsuperscript{15} observed tunneling conductances for single crystals of Bi-2212 with atomic resolution which can be regarded as $\rho \approx 1$, using STM. The conductances revealed clear coherence peaks at about $\Delta \approx 22$ meV\textsuperscript{14} and at about $\Delta \approx 17$ meV as shown in Fig. 6 of Kitazawa et al.’s paper\textsuperscript{15}, with flat bottom regions around $V_{\text{bias}} = 0$. The broadening parameter $\Gamma$ is less than 1%. They suggested that the observation is favored by the $s$-wave pairing mechanism. Moreover, analysis results for YBCO were the same as those for Bi-2212.\textsuperscript{14} Using intrinsic tunneling spectroscopy for high-quality Bi-2212 crystals and films, the energy gaps were measured as $2\Delta \approx 25$ meV by Lee and Iguchi\textsuperscript{16} and as an inter-branch value, $2\Delta \approx 25$ meV, from I-V curves by Doh et al.\textsuperscript{17}.

On the other hand, the photoemission spectra imply the same DOS as the tunneling conductance. The measured spectra have a much larger insulating effect than spectra measured by STM because the size of the X-ray beam cannot be reduced to less than 30 Å. However, angle-resolved PES gives information on DOS at a node and a non-node.

Although the gap anisotropy has been suggested as evidence of $d$-wave symmetry,\textsuperscript{18} on the contrary it indicates, according to Eq. (1), that $\rho_{Y-n}$ for the small gap at a node $Y - n$ is larger than $\rho_{Y}$ for the large gap at $M$ of $(\pi,0)$. The large $\rho_{Y-n}(= \rho_{Y} + \frac{2\Gamma}{\rho_{Y}} \approx 1)$ is because bound charges, $n_b$, become carriers when the lump

![Diagram](https://example.com/diagram.png)
structure in the spectra disappears at the node $\Gamma - Y$; transition from insulator (region A in Fig. 1) with the pseudogap to metal occurs. Figure 1 of Shen et al.’s paper showed the absence of the hump at the node, which indicates that the pseudogap has $d$-wave symmetry. The gap anisotropy is the effect of measurement and the gap anisotropy of $\Delta_i$ cannot be measured for inhomogeneous superconductors. A clear coherence peak at the node with $\rho \approx 1$ was observed with a small gap, $\Delta \leq 10$ meV, and the small gap is much closer to $\Delta_i$ than the large gap at $M$: $\Delta_i \leq 10$ meV. Note that the energy gap observed by STM is larger than the small gap observed at the node by PES, because the averaged STM gap over the Fermi surface is an average of the small gap at a node and the large gap at a non-node. The observed dip-hump structure in the tunneling spectra comes from the non-node $\bar{M}$. Furthermore, when the hump structure disappears at nodes and non-nodes, the gaps become isotropic due to the same $\rho$. The isotropic gaps in the structures without humps were experimentally observed, although the observation depended on the properties of the cleaned sample surface; the metal phase with $\rho = 1$ at the sample surface is unstable because of the metal-insulator instability. Electronic Raman scattering also showed the isotropic gaps measured in an overdoped Bi-2212 crystal. The isotropic gap is evidence of $s$-wave symmetry.

The strong spin-fermion model for a homogeneous $d$-wave superconductor of $\rho = 1$ proposed both the dip-hump structure and the broad coherence peak. However, according to the model, although the coherence peak and the dip-hump structure should disappear at the same time at the node $\Gamma - Y$, only the dip-hump structure disappeared, while the coherence peak remained. This indicates that the model does not explain the experimental data.

The paramagnetic Meissner effect of the Josephson-$\pi$ junction suggested as evidence of $d$-wave symmetry, was revealed to be the effect of a trapped flux. Wollman and co-workers observed the integer flux ($1\Phi_0$) and a Fraunhofer modulation pattern as evidence of $s$-wave symmetry and the half flux ($\frac{1}{2}\Phi_0$) and a dip modulation pattern at zero field as evidence of the Josephson-$\pi$ junction of $d$-wave symmetry, simultaneously, using a corner SQUID for YBCO single crystals. Current in the corner SQUID passes through a (110) plane showing $d$-wave characteristics while cornering. Evidence of $d$-wave symmetry came from the $d$-wave insulating phase (region A in Fig. 1) when compared with the result of the angle-resolved PES as mentioned previously, although Wollman and co-workers indicated that experiments were performed with crystals with a single phase of $\rho = 1$.

The zero-bias conductance peak (ZBCP) as evidence of $d$-wave symmetry, theoretically suggested by Kashiwaya et al. and Tanaka and Kashiwaya, was observed in a thin film and an under-doped crystal by tunneling experiments. They assumed that the crystals used had a single phase with $\rho = 1$. However, this author insists that the ZBCP came from the $d$-wave insulating phase for the inhomogeneous superconductors, because Kohen et al. could not observe the ZBCP on overdoped films by planar tunneling or point contact measurements; overdoped crystals have only slight or no $d$-wave insulating phase. In addition, Ekin and co-workers indicated that the ZBCP observed with break-junction tunneling is attributed to the interface of the break junction.

In conclusion, only in the metal phase (superconducting phase at low temperatures) of region B in Fig. 1 (a), $b = 2\Delta_i/kBT_{c,\text{max}}$ is applied, where $T_{c,\text{max}}$ is the intrinsic critical temperature of the maximum measured value. Here, note that $T_c$ in region B has the maximum value irrespective of the extent of the metal phase with $\rho = 1$ because of the largest DOS. When $T_{c,\text{max}}$ is observed at an optimal doping and $\Delta_i \approx 10$ meV observed at the node are used, the coupling constant, $b$, is less than 4.0. The intrinsic DOS showed $s$-wave symmetry. Thus, high-$T_c$ superconductivity can be explained within the context of the BCS theory.

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