Pairing symmetry analyzed by a peak shape of density of states in an Bi2Sr2CaCu2O8+x superconductor

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Abstract - For an inhomogeneous superconductor, we reveal a relation of an observed superconducting gap, Δ_{obs},and the intrinsic true gap, Δ_i, $\Delta_{obs}=\frac{\Delta_i}{\rho}$ where band filling, $0<\rho\leq 1$. Δ_{obs} is the effcet of measurement when $0<\rho<1$. The true gap is observed only when ρ=1. Pairing symmetry analyzed by a coherence-peak shape of density of states, observed in $Bi_2Sr_2CaCu_2O_{8+x}$ superconductors, is
s-wave.

It has been known that high-Tc superconductors are intrinsically inhomogeneous. The fact that the omogeneous superconducting region is within 14Å [1] or 30 Å[2 - 4] was revealed by scanning tunnelling microscopy (STM). Lang *et al*.
[4] showed that underdoped crystals are much more inhomogeneous than verdoped crystals and have more than two phases. Krasnov *et al*. [5] and Miyakawa *et al*. [6] revealed the coexistence of the superconducting gap and the pseudo-gap forhigh-Tc superconductors. In addition, since the discovery of cuprate high-Tc superconductors, controversy on the pairing symmetry of superconducting gaps has continued for the mechanism of high-Tc superconductivity.

In this paper, we analyze pairing symmetry of a superconducting gap with a shape of a coherence peak of density of states (DOS measured in an inhomogeneous $Bi_2Sr_2CaCu_2O_{8+x}$(Bi-2212) superconductor, using means of measurement.

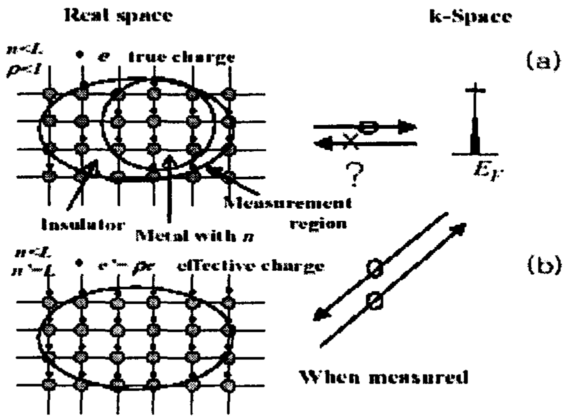

Fig. 1. (a) An inhomogeneous system in the measurement region in real space. Transformation of real-space vs k-space.
n is the number of carriers and L is the number of lattices, and $\rho = n/L$. Transformation from real-space to k-space is possible, reverse transformation is not. (b) When the system is measured, the averaged system is equivalence between two spaces. Spectral wight in k-space is maximum at $\rho = 1$ and decreases with a decreasing ρ(or the extent of metal region).

The well-known BCS DOS of Eq. (2), which is applied to a homogeneous superconductor and defined at 0 K, cannot be applied to experimental data measured in an inhomogeneous superconductor, which does not define kspace, so that the DOS must be converted into a DOS of a homogeneous superconductor (Fig. 1 (b)).

Here, metal phase on homogeneous superconductors imply that there is no charge difference between nearest

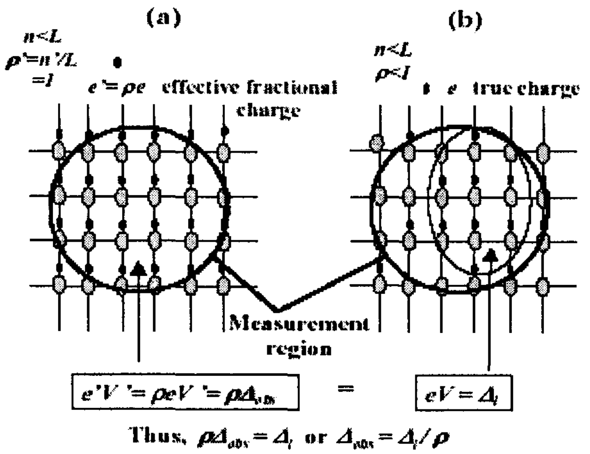

Fig. 2. In real-space, Fig. (a) is an averaged thing when an inhomogeneous region in Fig. (b) is measured. When only an homogeneous region is measured in Fig. (b), the true energy gap is $eV = \Delta_i$. When the inhomogeneous region in Fig. (b) is measured, the observed gap is $\Delta_{obs} = \Delta_i/\rho$.

neighbor sites, for example when there is one electron per atom in the electronic structure (Metal region in Fig. 1 (a)). When the carriers in the metal phase of the inhomogeneous superconductor are averaged over all atomic (or lattices) sites in the measurement region, it is possible to change the inhomogeneous superconductor into a homogeneous one with a carrier of an effective charge.
Then, 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 and l is the number of lattices [7 8]. The number of bound charges, $n_b = l - n$, is bound in the insulating phase with a pseudogap; 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 tunnelling conductance $(\frac{dI}{dV})$, the observed energy gap, Δ_{obs}, is given by

$$\Delta_{obs} = eV_{bias} = \Delta_i/\rho \qquad (1)$$

from substituting e with e'. Δ_{obs} increases as ρ decreases and is an averaged value of the intrinsic true energy gap, Δ_i over a measurement region (Fig. 2). Δ_i is attributed to pairing of two electrons of true charge when ρ=1, is constant irrespective of the extent of ρ , and is determined by the minimum bias voltage.

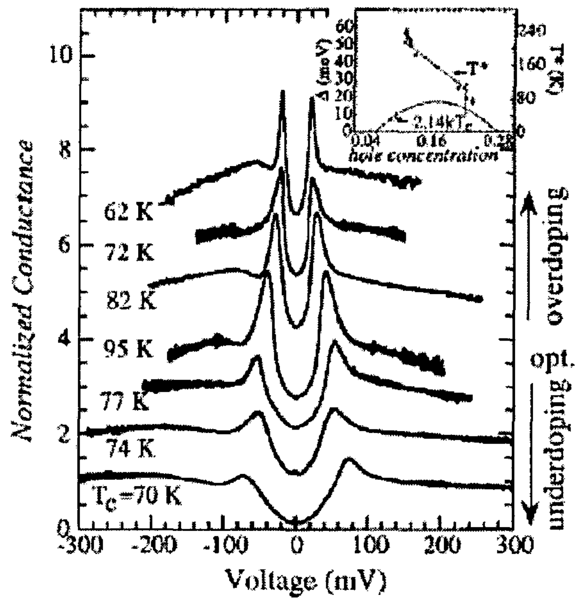

Fig. 3. Miyakawa et al., Phys. Rev. Lett. 83 (1999) 1018. The energy gap decreases with going from underdoping to overdoping; this indicates the decrease of the energy gap with increasing doping, as suggested in Eq. (1).

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

$$N_s(E)/N_n = Re(\frac{E}{\sqrt{E^2 - \Delta^2}}), \qquad (2)$$

$$= Re(\frac{E}{\sqrt{E^2 - \Delta_i/\rho)^2}}), \qquad (3)$$

where Δ_i is Δ_s in an s-wave superconductor, Δ_s cos(2ϕ) in a d-wave superconductor, and
E is an applied bias energy (or voltage). Considering the broadening effect, E is substituted with $E = E - iT$ where T is the broadening parameter. Eq. (3) is valid in $|E| \geq \Delta$ in the s-symmetry case and is averaged by phase angle ϕ in the d-symmetry case. Eq. (3) has a coherence peak at the energy gap

which increases with decreasing ρ, (Fig. 4); this, the unsolved problem [9, 10, 11] in the tunnelling 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 [12]. The decrease of the energy gap for Bi-2212 is shown in Fig.3. Eq. (3) and the coherence peak energy when ρ=1 are regarded as the intrinsic DOS and Δ_i, respectively. The broadening parameter is always zero at 0 K when ρ=1. Eq. (3) and the peak energy when $0 < \rho < 1$ imply an average of the intrinsic DOS and Δ_i over the measurement region, which is the effect of measurement.
This is because a tunnelling spectrum observed by STM is the averaged spectrum over the Fermi surface.

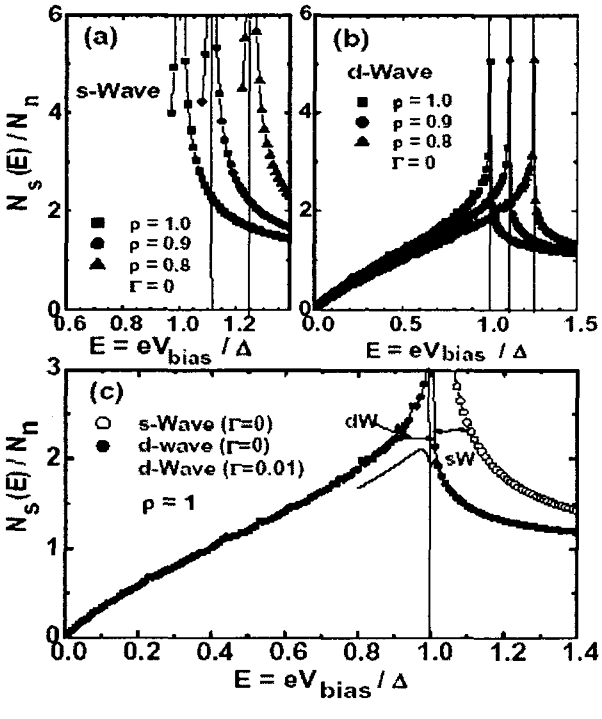

Fig. 4. (a) Band filling, ρ, dependence of the s-wave DOS of Eq. (3). $\frac{N_S(E)}{N_n}$=0 is assumed in $\left|\frac{(E=eV_{bias})}{\Delta}\right| < 1$. Peak curves when $\left|\frac{eV_{bias}}{\Delta}\right| < 1$ are just given for a comparison to curves when $\left|\frac{(E=eV_{bias})}{\Delta}\right| > 1$. (b) Band filling dependence of the d-wave DOS of Eq. (3). The DOS's were precisely calculated from $\frac{N_S(E)}{N_n}=\frac{1}{2\pi}\int\frac{N_S(E,\phi)}{N_n}d\phi$ with $\Delta=\Delta_s\cos(2\phi)$ and $T=0$ by numerical analysis not using complete elliptic integrals.
Divergences in calculations were ignored because the divergences have no derivative width ($d\phi=0$). (c) Comparison of s and d-wave DOS's with T=0 and T=0.01. sW denotes the s-wave width and dW represents the d-wave width.

When $\left|\frac{eV_{bias}}{\Delta}\right| < 1$ conductance curve, the DOS for the s-wave pairing symmetry has flat bottom regions, while the DOS for the d-wave symmetry has a V shape near zero-bias voltage and a peak width near the peak, (Fig. 4 (b)). This is not used for judging pairing symmetry in this research. When $\left|\frac{eV_{bias}}{\Delta}\right| >$ 1, the DOS for the s-wave symmetry has a much wider peak-width than the DOS for d-wave symmetry, (Fig.4 (c)). Furthermore, even theoretical calculations for the superconductor-insulator-superconductor junctions in a d-wave superconductor showed a peak width of the coherence peak when $\left|\frac{eV_{bias}}{\Delta}\right| < 1$ rather than when $\left|\frac{eV_{bias}}{\Delta}\right| > 1$ [13,14]. The peak width plays a decisive role in judging pairing symmetry. When $\left|\frac{eV_{bias}}{\Delta}\right| = 1$ (or gap edge peak), the magnitude of the d-wave DOS, $N_s(0)/N_n \approx 5$, which is given by numerical calculations and is less than the values near the divergence in the s-wave DOS, (Fig. 4 (b) and see the caption), because the DOS is averaged over phase angles of $d_{x^2-y^2}$ symmetry. This indicates that quasi particles are distributed inside the peak energy, but exist at the peak in the case of the s-wave. The true measured N_s(E)/N_n cannot reach the calculated value 5 and may be less than a value 2 because there is no outside peak width above the value 2. N_s(E)/N_n is an experimental coherence-peak height to a background value. Moreover, note that Nn in the normal state decreases as ρ decreases[8].

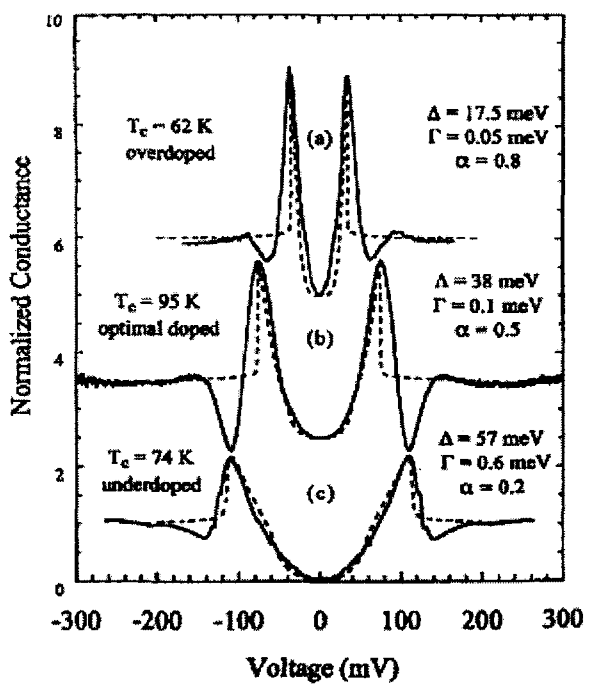

FIG. 5. Zasadzinski et al: Phys. Rev. Lett. 87 (2001) 67005. Fig. (a) deviates from the d-wave DOS and the peak width is wide, which seems to follow the s-wave DOS as mentioned. Figs. (b) agrees with the d-wave DOS at zero bias, but the peak width does not fit the d-wave DOS. Fig. (c) agrees with the d-wave DOS. When there are two phases, DOS's of two phases are overlapped near zero bias, but the peak widths are separated. We can say that pairing symmetry of optimal-doped and over-doped crystals is s-wave. This analysis differs from Zasadzinski et al..

Bi-2212 superconductors have been judged as d-wave superconductors by analysis of conductance curves near zero-bias voltage [15,16]. However, this analysis contains a fatal error in which a pseudogap in the data, in which the effct of the two phases was merged, was not removed. For a tunnelling conductance measured for Bi-2212 thin films, a low temperature pseudogap (LTPG) has no coherence peak and gap widths of 30-35 meV corresponding to nearly the superconducting energy gap of optimal doped crystals [17]. Similar analysis's were given by several groups [11,18,19]. This indicates that two DOS curves overlap when $| \frac{eV_{bias}}{\Delta} | < 1$, and that the coherence peak is only the superconducting energy-gap peak without LTPG. Thus, we can judge pairing symmetry through observations of the magnitude and shape of the coherence peak for a conductance without the diphump structure from experimental data measured at a local superconducting region of $\rho \approx 1$ and $T=0$, although the dip-hump structure is a universal feature of high-Tc superconductors [2,6]. It has been suggested that the dip-hump structure is a high-energy pseudogap with a V-shape near zero-bias voltage [20,21]. In conclusion, results of Eq. (3) and Fig. (3) suggest that a large gap peak and small gap are more intrinsic.
The over-doped gap peak rather than the under-doped peak follows the results. Fig. 5 shows that pairing symmetry of the over-doped peak is s-wave.

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