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Implications of tunneling studies on high-T_c cuprates: superconducting gap and pseudogap

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Abstract

Tunneling spectra have been measured on high-T_c cuprates including single crystals $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (Bi2201) and $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) using superconductor–insulator–normal metal point contact or superconductor–insulator–superconductor break junction methods. The doping dependence of the energy gap parameter is similar in both Bi2212 and Bi2201, increasing monotonically to very large values in the underdoped regime even as T_c decreases. This doping dependence of superconducting gap is similar to that of pseudogap temperature, T^*, indicating this is consistent with the scenario whereby the low-energy pseudogap is due to some type of precursor of superconductivity. The high-energy feature observed as the hump structure may be another kind of pseudogap whose energy scale is much larger than superconducting gap, and it may be magnetic in origin.

Keywords: Tunneling; Doping dependence; HTSC; Superconducting gap; Pseudogap

The pseudogap is highlighted as one of the unusual characteristic common features in high-T_c cuprates, and lots of theoretical models for pseudogap phenomena have been proposed [1–6], but there is no consensus at the present time in the origin of the pseudogap. One of the main arguments is whether the pseudogap phenomenon is closely related to superconductivity or not.

The doping dependence of the pseudogap-like feature by various experimental techniques [7] has been vigorously investigated. The trend of the pseudogap-like features as a function of doping is consistent among various experiments, but the temperature scale depends on the particular experimental technique. That is, the pseudogap temperature estimated by in-plane resistivity [8], $1/T_1T$ [9], Knight shift [9] and ARPES [10,11] etc., (which is T^*, the so-called low-energy pseudogap temperature) is different from that done by magnetic susceptibility [8], c-axis resistivity [12], Knight shift [9] and specific heat [13,14] etc., (which is T^m, the so-called high-energy pseudogap temperature). The characteristic temperature for the latter is much higher than that for the former. Both the low- and high-energy pseudogaps have been observed in angle-resolved and angle-integrated photoemission studies of Bi2212 [15]. ARPES has

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established that the low-energy pseudogap has nearly the same energy scale as the superconducting gap and disappears at T^* [10,11]. The possibility of a second, higher-energy pseudogap might explain the observation of a gap-like feature, considerably larger than the superconducting gap, persisting up to above 200 K [16]. The confusing aspect of two different temperature scales might be resolved by the existence of two different pseudogaps, one linked to the superconducting energy gap measured below T_c, and another gap of much higher energy that might be of magnetic origin.

In this article, we discuss these two kinds of pseudogaps from tunneling results as a function of doping on $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) and $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (Bi2201). If there are two distinct energy gaps for the quasiparticle excitations, they should show up as two distinct features in the tunneling spectra.

Bi2201 and Bi2212 single crystals were grown by a floating zone method, where the doping level was changed through the La content in the former and oxygen content in the latter. For the Bi2212 we started with optimally doped crystals with a T_c onset of 95 K, which were then annealed in various oxygen pressures to achieve over- and underdoping. For the La-doped Bi2201 it is necessary to verify by other methods that the underdoped state is achieved (see Ref. [17]). The superconducting transition temperature T_c was determined as the temperature where the resistivity becomes zero or as the onset temperature using AC susceptibility.

Superconductor–insulator–superconductor (SIS) break junctions and superconductor–insulator–normal metal (SIN) junctions were prepared by point contact technique with a Au tip [18,19]. Tunneling conductance were measured by a standard AC lock-in technique.

We have already reported detailed measurements of the tunneling conductance on Bi2212 single crystals with various oxygen concentrations [18–22] as well as some preliminary results for La-doped Bi2201 [17]. For Bi2212, we have compared SIN point contact [18,21,22], SIS break junction [18–21] and STM/STS [20] techniques. All of spectra showed the sharp conductance peaks at the gap voltage, the low zero-bias conductance, and the dip and hump structures at high bias (see in the inset of Fig. 1) [18]. The inset of Fig. 1 is a tunneling result on Bi2212 with $T_c = 95$ K by SIN point contact method. Here we consider the possibility that the hump feature is due to a high-energy pseudogap, and as shown in Fig. 1, we plot the superconducting gap Δ vs. hole concentration p together with the energy of the humps. In this figure, the solid squares, the solid circles, and the solid diamonds are superconducting gaps observed by SIS break junctions [18,19], SIN point contact [18] and STM/STS [20], respectively. In addition, the open circles are the hump energy from Fermi energy, $\Omega^{hump} = eV^{hump}$ by SIN junctions and the open squares are $\Omega^{hump} = eV^{hump} - \Delta$ by SIS junctions. The dotted line indicates $2.14k_BT_c$, which is the predicted superconducting energy gap by mean-field theory for d-wave [23]. This figure shows that superconducting gap monotonically increases with decreasing hole concentration despite the reduction of T_c in the underdoped regime, although it approaches the mean-field value for d-wave in the heavily overdoped region. From the plot of hump energy in this

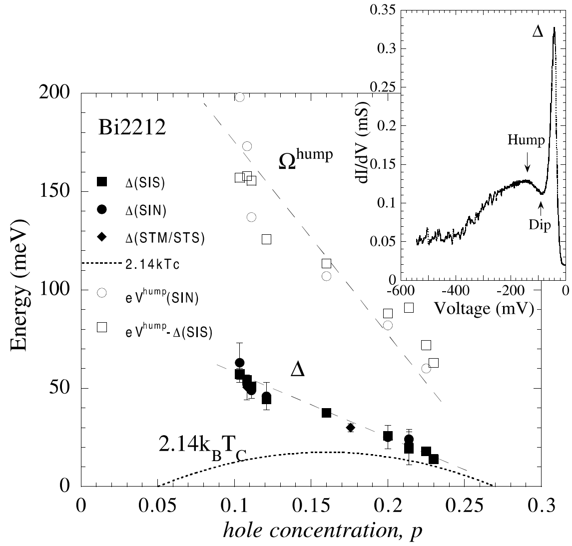

Fig. 1. Doping dependence of the superconducting gap, Δ and the hump structure which were observed on tunneling conductance of Bi2212 by SIN point contact, SIS break junction and STM/STS technique. Dotted line shows the mean-field gap $\Delta^{MF} = 2.14k_BT_c$. Inset shows an example of the tunneling conductance on occupied state to exhibit a peak, a dip and a hump structure.

figure, we found the relation as $\Omega^{hump} \sim 3\Delta$. Thus this result shows that if the hump corresponds to another kind second gap, the energy scale is roughly three times larger than the superconducting gap, Δ.

It is very important to investigate whether the doping dependence of superconducting gap and the correlation between hump structure and superconducting gap are generic in high-T_c cuprates or not. For this reason we have measured tunneling conductance on $Bi_2Sr_{2-x}La_xCuO_{6+\delta}$ (Bi2201). Shown in Fig. 2 is Δ vs. La content obtained from tunneling studies on Bi2201 by SIN point contact technique, where La content is nominal and Δ is defined as peak position eV_p for simplicity. In Fig. 2, the mean-field gap magnitude $\Delta^{MF} = 2.14k_BT_c$ is also plotted by the open squares, where T_c is determined from zero resistance temperature. It is clear that the unusual doping dependence of Δ is generic to Bi cuprates and could be universal features for all high-T_c cuprates. In addition, the scatter of data may originate from using of nominal La content as well as the definition of Δ as eV_p. However the generic trend of doping dependence of Δ is clearly same as that for Bi2212.

Concerning the correlation between Δ and Ω^{hump} on Bi2201, previous tunneling results showed a V-shaped background conductance, which obscured the hump structures [17]. However as shown in Fig. 3, a new tunneling result with $x = 0.3$ clearly shows an almost flat background as well as the dip and hump structures at $\sim 2\Delta$ and $\sim 3\Delta$. The data in Fig. 3(a) are dI/dV vs. V at 4.2 K for $Bi_2Sr_{1.7}La_{0.3}CuO_{6+\delta}$ single crystals with $T_c \sim 25.3$ K. The shape of tunneling conductance is similar with that of Bi2212 except for the large density of states at Fermi level. The strong conductance peak at $eV_p \sim \Delta$ indicates a superconducting gap, where V_p value was ~6.2 mV and Δ becomes ~5.8 meV from d-wave DOS fitting [24]. In Fig. 3(b), the dip and hump structure observed on Bi2201 ($x = 0.3$) is enlarged, and arrows stand at 2Δ and 3Δ position. From this figure, we found that the dip and hump structures can be observed

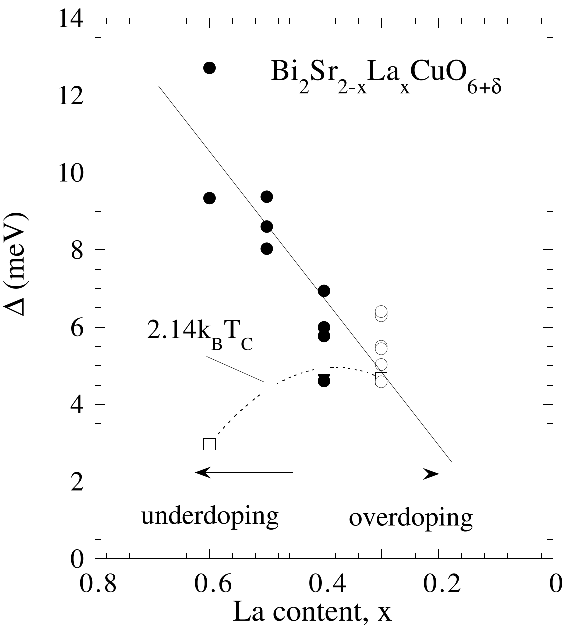

Fig. 2. The superconducting gap, Δ vs. La content on Bi2201. Solid circles are Δ from as-grown crystals and open circles are Δ from crystals, which were heat treated at 773 K. Open squares are the mean-field energy gaps, $\Delta^{MF} = 2.14k_BT_c$, where T_c is determined as temperature at which resistivity became zero.

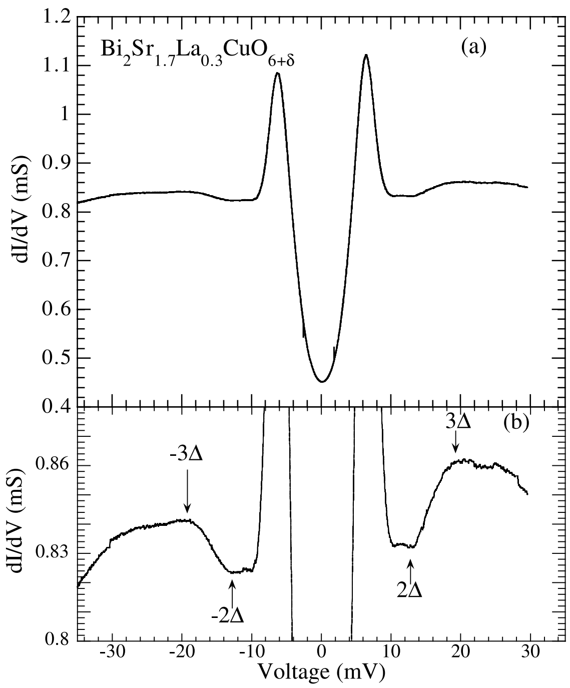

Fig. 3. (a) Tunneling conductance on $Bi_2Sr_{1.7}La_{0.3}CuO_{6+\delta}$ with $T_c \sim 25.3$ K. (b) Dip and hump structures, where allows stand at 2Δ and 3Δ position.

at $\sim 2\Delta$ and $\sim 3\Delta$ for near optimally doped Bi2201, just as is found in Bi2212. Thus it is possible that the correlation between Δ and Ω^{hump} is generic for high-T_c cuprates.

We now discuss the implication of our tunneling results with regard to the pseudogap. As stated earlier, the confusing aspect is that it seems to exist two different temperatures and energy scales. ARPES and tunneling studies showed that the low-energy pseudogap, which has the energy almost as same as superconducting gap and smoothly merges into superconducting gap at T_c [10,11,25], disappears at T^* [10,11]. On the other hand, recent intrinsic Josephson junction [16] and specific heat [13,14] etc., showed a pseudogap-like feature at a much higher-energy scale with the order of superexchange energy J and it persists up to much higher temperature. Thus we investigated the correlation between superconducting gap and low- and high-energy pseudogap temperature (see Fig. 4). In Fig. 4, the superconducting gap is estimated from a fit to our Δ vs. p plot shown in Fig. 1 and T^* temperatures are from resistivity [8], $1/T_1T$ [9], Knight shift [9] and ARPES [10,11] measurements for different p values. The T^{m} temperatures are from Knight shift [9] and magnetic susceptibility [8] measurements. In this figure, we found that both T^* and T^{m} have strong correlation with superconducting gap. The tunneling gap scales as $2\Delta \sim 6k_BT^*$ which is consistent with the scenario that the (low energy) pseudogap is due to some type of precursor of superconductivity. On the other hand, it is found that T^{m} is about 2.4 times larger than T^* in Fig. 4. In Figs. 1 and 3, we showed that the hump energy is about three times larger than superconducting gap, however it is possible that the dip feature is masking the true location of hump, that is, any dip feature due a strong coupling effect will artificially put the hump at a higher voltage. Despite this uncertainty, the correlation indicates that T^{m} is closely related to hump structure on tunneling conductance and therefore the hump may be a second gap feature. The recent observation of a large pseudogap in angle-integrated photoemission of Bi2212 [15] shows that it is approximately twice the superconducting gap value, although it is difficult to quantify due to the weakness of the feature.

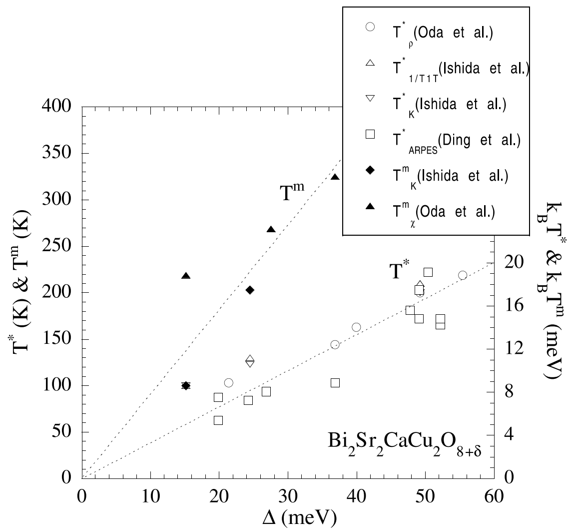

Fig. 4. T^* [8–11] and T^{m} [8,9] estimated from various experimental techniques is plotted as a function of superconducting gap which were determined by tunneling study.

Since the high-energy pseudogap is weak with a high state density at the Fermi level, then the introduction of a superconducting gap should not have much effect on the location of the hump feature. Therefore the hump energy measured from Fermi level in SIN tunneling should have a physical meaning. From comparison with recent Raman studies for two-magnon structures as a function of doping [26,27], we found that $\Omega^{\mathrm{hump}} \sim 3\Delta \sim 2J$ [21,26], that is, the hump has strong correlation with magnetic interactions. Furthermore, this correlation also showed that Δ follows the trend of the antiferromagnetic exchange energy, J, which indicates that the underling interaction for superconducting pairing as well as high-energy pseudogap is due to magnetic interaction.

We found that we can measure spectra out to the bias, 800 mV without any strong barrier effect [20,24], an example of which is shown in the inset of Fig. 1. All such measurements indicate a decreasing background conductance beyond the hump voltage. A recent STM study showed a similar shape, which indicated a broad conductance maximum near zero bias [28]. These results suggest that the barrier for the Sr–O layer should be high, about 800 mV, even though the Bi–O layer is only 100 mV or so. Considering the tunneling matrix element, it is clear that for *c*-axis tunneling there is no cancellation of the band structure since ordinarily this would come from the group velocity which is normal to the barrier, a prohibited direction. Thus the broad maximum is likely due to the van Hove singularity [29,30]. Recent t–t'–J calculations indicate that the VHS is pinned to the Fermi level, which would explain why the background peak does not change much with doping. Our tunneling data suggest that the broad peak in the background conductance comes from the band structure DOS, and the high-energy pseudogap appears as a shallow depression on this background. Furthermore the superconducting gap open inside the high-energy pseudogap. Since the high-energy pseudogap has states at the Fermi level, then it is not affected much for the opening of superconducting gap.

In summary, we found that the anomalous doping dependence of the superconducting gap and hump energy is generic in the Bi cuprates and could be universal in high-T_c cuprates, where $\Omega^{hump} \sim 3\Delta \sim 2\,J$. In addition, two kinds of pseudogap temperatures, T^* and T^m obtained from various experimental techniques have strong correlation with superconducting gap measured by tunneling although T^m is about 2.4 times larger than T^*. We have suggested a scenario whereby the low-energy pseudogap is associated with precursor superconductivity and the high-energy pseudogap is of magnetic origin, with both gaps scaling with the effective exchange interaction, J.

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