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Superconducting gap and pseudogap from tunneling conductance on $Bi_2Sr_2CaCu_2O_{8+\delta}$ with various oxygen concentration

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The evolution of tunneling spectra on $Bi_2Sr_2CaCu_2O_{8+\delta}$ measured by SIN point contacts, SIS break junctions and STM/STS has been studied as a function of doping and temperature. The detailed examinations of the spectra show that the energy gap measured at low temperature appear to be due to superconducting pairing. The doping dependence of the superconducting gap at low temperature suggests a strong connection to the pseudogap temperature, T*, and this indicates that the pseudogap region is at least partly a consequence of some form of precursor superconductivity. In addition, dip/hump structures observed at high bias scale approximately with not only Δ but also superexchange interaction J over the entire doping range examined, indicating these features are linked to the underlying interaction responsible for superconductivity. We suggest that the hump structure may originate from short-range magnetic correlations.

High-T_c cuprates have exhibited many unusual properties that indicate these are unconventional superconductors. In particular, pseudogap phenomena in both the spin and charge excitations have been observed by a number of different experimental techniques [1]. A recent NMR study suggested that the observed pseudogap in the quasiparticle DOS at $T_c<T<T^*$ [2] has the same origin as the spin-gap behavior [3] which was observed in magnetic excitation spectra. This is generally referred to as the low-energy or strong pseudogap. Recently, tunneling studies on $Bi_2Sr_2CaCu_2O_{8+\delta}$(Bi2212) in the superconducting state have revealed a well-defined energy gap that remarkably exhibits a strong, monotonic dependence on doping, increasing substantially in the underdoped region even as T_c decreases [4,5]. In addition, the observed gap at low temperature follows the trend of the low energy pseudogap temperature, T^* with doping [5,6]. Thus if the gap has a purely superconducting origin, it strongly suggests that the pseudogap state at $T_c<T<T^*$ is due to some type of precursor superconductivity. This is also suggested by experiments that show the low temperature gap smoothly evolving into a pseudogap with the same dx^2-y^2 symmetry [2]. Because quasiparticle-tunneling spectroscopy has the capability to probe any gap in the quasiparticle excitation spectrum at E_F [7] it is important to examine the entire tunneling spectrum to clarify the physical origin of measured gaps.

In addition, the magnetic susceptibility [6] and Knight shift [3] studies observed another characteristic temperature, T^m that is above T^*. While it is generally agreed that T^m corresponds to the development of short-range antiferromagnetic (AF) order, it is not clear whether another distinct energy scale or high-energy pseudogap emerges below T^m. In general, it is of great interest to explore how the development of AF correlations can be seen in the quasiparticle DOS as the doping decreases.

In this paper, we address the pseudogap issue, and examine the evolution of tunneling spectra on Bi2212 as a function of doping and temperature in detail. We will present arguments that the energy gaps measured at low temperature are of purely superconducting

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origin. In addition, we find the scaling of dip/hump structures with superconducting gap Δ, suggesting these features are linked to the underlying interactions responsible for superconductivity. Finally we suggest that the hump may be a structure for a high-energy pseudogap which originates from short-range magnetic correlation.

We grew single crystals using self-flux or floating-zone method where the optimal T_c was 95K. The doping level or the oxygen content was controlled by annealing optimally-doped crystals in flowing gases adjusted for different partial pressures of oxygen, where the doping range is from overdoped with T_c=56K to underdoped with T_c=70K. Hole concentration, p was estimated from the empirical relation between T_c and p, $T_c/T_c^{max}=1-82.6(p-0.16)^2$, with T_c^{max}=95K. Both SIN (S=superconductor, I=insulator, N=Normal metal) point contacts and SIS break junctions were prepared by using Au tip as described elsewhere [4,5]. Tunneling conductance was measured by standard ac lock-in technique, where for SIN spectra, the bias voltage is that of the sample with respect to the tip so that negative bias corresponds to the occupied electron states below E_F.

We now focus on the oxygen doping dependence of tunneling spectra on Bi2212 measure at 4.2K. Shown in figs. 1(a) and (b) are the representative tunneling conductances over the wide doping range for SIN and SIS junctions, respectively. Crystals are labeled with T_c and the notation where u- is underdoped, opt- is optimally-doped, o- is overdoped. All the spectra show consistently the same generic features: a low zero bias conductance, well-defined gap feature which are indicated by the sharp conductance peaks at energy, $|eV|\sim\pm\Delta$ (2Δ) for SIN (SIS) junctions, and dip/hump structure at high energy. Values of Δ were estimated by fitting the spectra to a d-wave DOS as described elsewhere [8]. For SIN junctions, the fitted DOS are shown by a dotted line with fit parameters Δ, Γ, on each spectrum, where Γ is quasiparticle scattering rate. In fig.1, the arrow indicates the dip energy, Ω^{dip}, and the thick vertical dotted bar indicates the hump energy Ω^{hump}, at which spectrum changes slope as highlighted by the intersecting straight lines. A similar analysis has shown that the dip feature corresponds to a loss of spectral weight in Raman spectra [9]. For SIN junctions, the characteristic dip/hump structures were most clearly seen at negative bias.

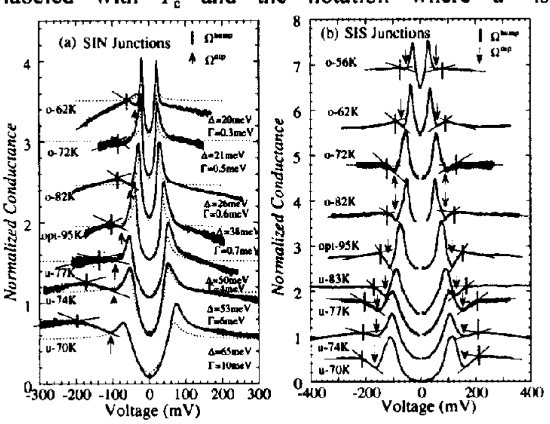

Figure 1. Representative tunneling conductance measured at 4.2K on Bi2212 with various oxygen contents by (a) SIN point contacts and (b) SIS break junctions. The dotted lines represent the fitted results by d-wave DOS with corresponding parameters. Arrows and vertical dotted bars stand for Ω^{dip} and Ω^{hump}, respectively.

From the evolution of these tunneling spectra as a function of doping, we found that as the doping decreases from overdoped region, the energy gap increases monotonically even in the underdoped region where T_c decreases [4,5]. Moreover we find these dip/hump structures have a strong correlation with the energy gaps measured at 4.2K over the entire doping range, as shown in fig.2 in which Ω^{dip}, Ω^{hump}, and Γ, have been plotted as a function of the energy gap, Δ. Thus, the position of dip (hump) for SIN and SIS junctions was at $\sim 2\Delta$ (3Δ) and $\sim 3\Delta$ (4Δ), respectively, over the entire doping range examined. There is a slight deviation of the data from the simple straight line in fig. 2 such that the dip is below the line for underdoped and is above the line for overdoped. The origin of this is not clear at present.

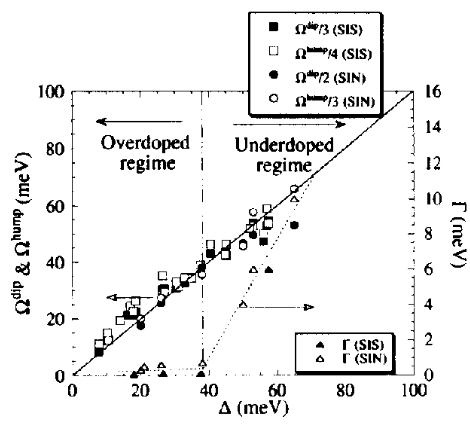

Figure 2. Ω^{dip}, Ω^{hump}, Γ as a function of Δ.

The scattering rate, Γ, which closely relates to the broadening of the conductance peaks, rapidly increases in the underdoped regime. The increase of Γ may originate from a competition between superconductivity and AF order as the insulator is approached. Furthermore, the increasing hump energy with underdoping suggests that this feature might smoothly evolve into the insulating gap associated with long-range AF order in the parent insulator. Recent ARPES studies also observed similar trends of the hump structures on Bi2212 [10]. They found that the hump persists above T_c in the pseudogap states, and the hump seen in $A(\boldsymbol{k},\omega)$ below T_c is consistent with theoretical notions of a high-energy pseudogap originating from magnetic interactions. Tunneling conductance is proportional to $\Sigma A(\boldsymbol{k},\omega)|T_{\boldsymbol{k}}|^2$ where the summation is over quasiparticle momentum $\boldsymbol{k}$ [4], and therefore the hump structures from tunneling may be closely related to those found in ARPES. This suggests the hump is due to a high-energy pseudogap.

Since the dip/hump features scale approximately with Δ, it is crucial to address whether the energy gap observed by tunneling originates entirely from superconducting pairing or has a contribution from some other electronic effect (e.g. charge density wave). This issue becomes more confused by reports that suggest a superconducting order parameter that scales with T_c [7] and the observed energy gap by STM/STS was independent of temperature [11]. We have already addressed this issue in ref [5], where we showed that the large energy gaps in underdoped regime are predominantly of superconducting origin. Here we show some unpublished I-V curves on break junctions as a function of doping in fig.3, where I_cR_n value is 8.1, 6.7, 4.1 and 2.27 mV for u-70K, u-74K, opt-95K and o-62K, respectively. We have selected I-V curves that exhibited a clear linear shape outside the gap region and a linear fit was used to estimate R_n. These curves suggest that the quasiparticle excitation gap is linked to the Josephson strength, I_cR_n, a purely superconducting energy scale.

In addition, we also assert the superconducting origin of the quasiparticle excitation gap from the temperature dependence of the gap by SIS break junctions. Shown in fig.4 is $\Delta(T)/\Delta(4.2\text{K})$ vs. T/T_c for o-56K, opt-95K, u-83K and u-77K along with normalized Josephson strength for o-56K and u-77K. The latter plot allows a direct measure of T_c for the junction. In this figure, a characteristic feature is that the gap magnitude significantly decreases as T increases near T_c over the entire doping range. Furthermore Josephson $I_cR_n(T)$ disappeared near the bulk T_c; indicating long-range coherence disappeared. If the large gap from underdoped crystals had been due to contribution from some other electronic effect, it would be very difficult to understand the rapid decrease of the magnitude of the energy gap near T_c. In addition, we also find the different characteristic feature between underdoped and heavily overdoped crystals. For a heavily overdoped with T_c=56K, the energy gap approaches zero at T_c by following BCS curve. On the other hand, for underdoped with T_c =77K and 83K, the magnitude of the gap rapidly decreases as T increases near T_c but a weak depletion in the conductance near zero bias remains even at T> T_c [4,5].

To summarize our tunneling studies, we plot our Δ,

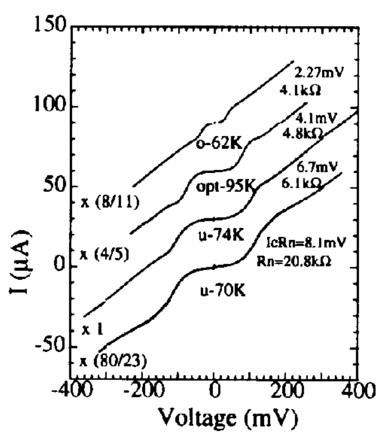

Figure 3. Representative I-V curves measured at 4.2K by SIS break junctions for o-62K, opt-95K u-74K and u-70K.

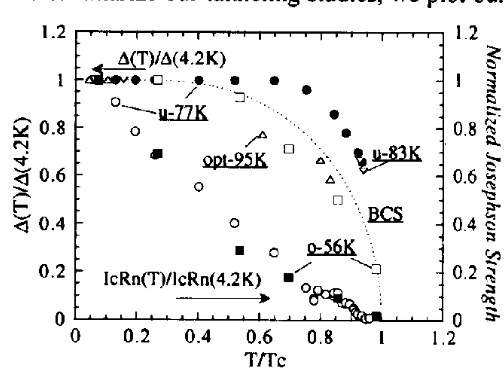

Figure 4. $\Delta(T)/\Delta(4.2\text{K})$ vs. T/T_c with normalized Josephson strength, $I_cR_n(T)/I_cR_n(4.2\text{K})$. The dotted curve represents the BCS temperature dependence.

Ω^{hump} as a function of doping together with T^* and T^m observed by various experimental probes in fig. 5 [2,3,6]. Shown in fig. 5 are the superconducting gap Δ obtained from three different techniques that are SIN point contacts (filled circles), SIS break junctions (filled squares) and STM/STS (filled diamonds) [12]. We find that tunneling results from three different kinds of techniques consistently show that Δ approaches the mean-field prediction for a *d*-wave superconductor on the overdoped side but monotonically increases as doping decreases even in the underdoped regime. Moreover, we found that pseudogap temperature, T^* scales with Δ, where $2\Delta/kT^*$~6.6 over the entire doping range examined. In addition, T^m also increases with underdoping and it scales with Δ as well as Ω^{hump}. $2\Delta/kT^m$ is less than the weak-coupling limit for *d*-wave, but $2\Omega^{hump}/kT^m$ is almost as large as $2\Delta/kT^*$.

From our present study, while the energy gap measured at low temperature appears to be due to superconducting pairing, and it exhibits a strong reduction for T~T_c, it is not clear from the present data how this gap merges into the pseudogap found above T_c. The doping dependence of the superconducting gap at low temperature suggests a

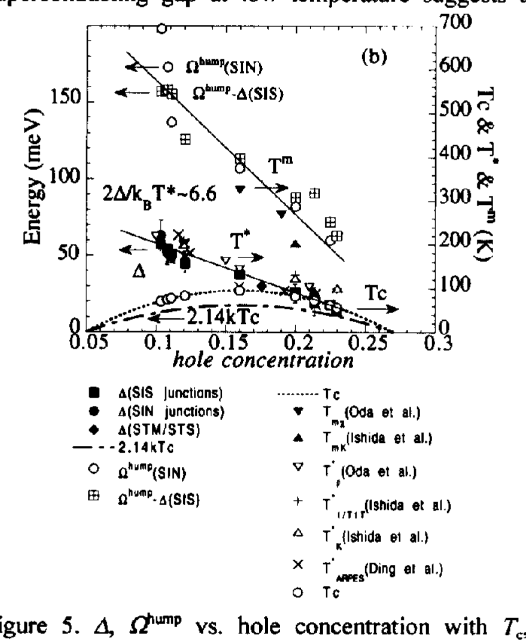

Figure 5. Δ, Ω^{hump} vs. hole concentration with T_c, T^*[2,3,6] and T^m[3,6]. A solid line for T^* and T^m represents $2\Delta/kT^*$~6.6 and $2\Omega^{hump}/kT^m$~6.6, respectively. The dashed line is $\Delta_{MF}=2.14kT_c$ from the BCS mean-field *d*-wave prediction.

strong connection to the pseudogap temperature, T^*, and this indicates that the pseudogap region is at least partly a consequence of some form of precursor superconductivity. If there is an additional, non-pairing contribution to the pseudogap, there is no direct evidence of such a distinct gap in the low-temperature spectra.

Moreover, from this study and Raman scattering [9], it is found that Ω^{hump}~3Δ~$2J$ for the entire doping range. Taken together, these results may suggest the following story. T^m is temperature at which short range AF fluctuation occurs, and it naturally links with long range AF ordering state for non-doped cuprates. The AF fluctuation produces the high-energy "pseudo-" gap that appears as hump structures on tunneling conductance. As temperature decreases some form of precursor pairing state develops below T^* leading to the low energy pseudogap. Finally long range phase coherence sets in at T_c and a clean superconducting gap emerges. Here we stress the importance of magnetic interactions, since T^m, T^*, Ω^{hump} and Δ all seem to scale with J [9]. This suggests a competition between the superconducting pairing gap, perhaps driven by AF fluctuations, and the high-energy pseudogap associated with AF order. Ultimately as doping decreases, AF order wins out and an insulating gap emerges.

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