Non-conservation of Density of States in Bi$_2$Sr$_2$CaCu$_2$O$_y$: Coexistence of Pseudogap and Superconducting gap

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Abstract: The tunneling spectra obtained within the ab-plane of Bi$_2$Sr$_2$CaCu$_2$O$_y$ (Bi2212) for temperatures below and above the critical temperature ($T_c$) are analyzed. We find that the tunneling conductance spectra for the underdoped compound in the superconducting state do not follow the conservation of states rule. There is a consistent loss of states for the underdoped Bi2212 implying an underlying depression in the density of states (DOS) and hence the pseudogap near the Fermi energy ($E_F$). Such an underlying depression can also explain the peak-dip-hump structure observed in the spectra. Furthermore, the conservation of states is recovered and the dip-hump structure disappears after normalizing the low temperature spectra with that of the normal state. We argue that this is a direct evidence for the coexistence of a pseudogap with the superconducting gap.

The existence of a pseudogap in high-$T_c$ cuprate superconductors is a very well established fact [1]. However, there is no agreement among theorists regarding its origin. One popular belief is the pre-formation of pairs well above $T_c$ without any coherence [2]. Such pre-formation should carry some signatures of the existence of pairs above $T_c$ such as a diamagnetic response or Andreev reflection. No such supporting evidence in this direction has come so far, partly because of the experimental difficulties. Independent of such a lack of direct evidence for pre-formed pairs, there is ample evidence in support of a loss of states near $E_F$ [1]. This loss of states can also arise because of other possibilities, for instance, a lattice distortion or a magnetic instability as suggested by various authors [2].

The superconducting energy gap ($2\Delta$) of these high-$T_c$ superconductors is a monotonic function of doping, with the gap decreasing as the carrier concentration increases (while $T_c$ is peaked at a doping called optimum doping) [1]. The pseudogap is known to exist in the underdoped and slightly overdoped regime. If the pseudogap is different from the superconducting gap, the former will continue to exist as a depression in the DOS together with the latter as the temperature is reduced below $T_c$. Recent intrinsic tunneling measurements on mesa structures have shown the existence of a pseudogap together with the superconducting gap below $T_c$ [1]. In these experiments, the superconducting gap is found to vanish above $T_c$ or in high magnetic fields with the pseudogap remaining [1]. Further, a peak-dip-hump structure in the DOS below $T_c$ seems to arise as a result of the two coexisting gaps.

Such a peak-dip-hump structure has also been observed earlier in the c-axis as well as ab-plane tunneling spectra at low temperatures [1,2]. Furthermore, the normalized quasiparticle peak height at low temperatures is found to be higher for higher doping [1,3], without much change in the zero bias conductance. This fact implies that, even in the superconducting state, more states are lost near ($E_F$) with underdoping. Some other measurements, like specific heat [12] and NMR [13], have also concluded this kind of loss of states and hence the coexistence of the two gaps. A direct consequence of this coexistence is the violation of conservation of states rule. As a result of this, there will be a loss of states as we go from overdoped to underdoped regime. We believe that the reduction in the normalized peak height with underdoping is a consequence of this depression in the DOS and the peak-dip-hump structure is a result of the superposition of the two gaps, one being slightly larger than the other.

The total number of states must be conserved within a band. So a depression at $E_F$ means that some of the states are pushed out from near $E_F$ to higher or lower energies (above or below $E_F$). For example, when superconductivity sets in at $T_c$, the states within the gap region, $\pm \Delta$, are pushed out to higher energies; a majority of these states are concentrated at $\pm \Delta$ as singularities. The average DOS in between $\pm \Delta (\epsilon > \Delta)$ stays the same as the background DOS (i.e. DOS at $|\epsilon| > \Delta$). Hence, in the tunneling experiments, if the average tunneling conductance is less than the background conductance, there is an underlying depression in the DOS. Our interpretation of the pseudogap as a depression in the DOS at $E_F$ differs from the ARPES results, where the pseudogap is interpreted as a true energy gap from the leading edge analysis of the photoemission spectra [14]. This kind of state-conservation analysis is difficult to carry out for the photoemission measurements, partly, because of a poor understanding of the photoemission line-shape, and also because the data are limited to below $E_F$.

For a conventional BCS superconductor the DOS below $T_c$ is given by, $N_{sup}(E) = N(E)|E|/\sqrt{(E^2 - \Delta^2)}$. If we ignore the thermal smearing related effects, the tunneling DOS below and above $T_c$ for a SIN (Superconductor-Insulator-Normal metal) junction are proportional to $N_{sup}(E)$ and $N(E)$, respectively. Here, $N(E)$, the normal state DOS, is assumed to be constant near $E_F$. We believe that for underdoped high-$T_c$
superconductors $N(E)$ has a depression near $E_F$ which may also depend on the angle $\theta$ in ab-plane. In this case, the DOS below $T_c$ is given by, $N_{sup}(E, \theta) = N(E, \theta)/\sqrt{\langle E^2 - \Delta(\theta) \rangle^2}$. Hence $N(E, \theta)$ can be normalized away from the tunneling spectra at low temperatures by the tunneling spectra above $T_c$ for ab-plane tunneling at a particular angle $\theta$. For the c-axis tunneling, where the tunneling conductances below and above $T_c$ are $\int N_{sup}(E, \theta) d\theta$ and $\int N(E, \theta) d\theta$, respectively, the normal state DOS cannot be normalized away from the low temperature spectra. However, the effect of pseudogap could still be observable in terms of non-conservation of states if there is a depression or hump in $N(E)$.

For an SIS (Superconductor-Insulator-Superconductor) tunneling junction the tunneling current is given by (neglecting the thermal smearing effects), $I(V) \propto \int_0^{|eV|} N_{sup}(E, \theta) N_{sup}(E - eV, \theta) dE$ (for $T < T_c$) and $I(V) \propto \int_0^{|eV|} N(E, \theta) N(E - eV, \theta) dE$ (for $T > T_c$). For $|eV| > \Delta$, $N_{sup}(E, \theta) \approx N(E, \theta)$ and hence it turns out that for $|eV| > 2\Delta$, $I(V)$ and $dI/dV$ are determined by $N(E, \theta)$ at low temperatures. Thus, the normalization procedure for tunneling conductance is still valid for higher bias voltages ($|eV| > 2\Delta$) for ab-plane SIS tunneling junctions. Furthermore, we know that for a BCS type SIS tunneling junction the average conductance matches with the background conductance and so any deviation from this implies some structure in the normal state DOS.

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**FIG. 1.** ab-plane tunneling SIS junction geometry. For the SIN junction, one of the superconductors is replaced by a sharp metal foil.

In this paper we analyze the ab-plane spectra of underdoped and slightly overdoped Bi2212 as obtained with SIS and SIN type junctions realized in a low temperature STM. This STM has been used previously for studying the gap anisotropy [15] and more recently to observe the pseudogap [3] in ab-plane of Bi2212. The crystal growth and underdoping have been described elsewhere [9]. The junction configuration is as shown in Fig.1. For SIS tunneling, a single crystal of Bi2212 is cut in the air and the two pieces are attached to two different metal electrodes. The two electrodes are brought closer, with the two crystals at 90° (see fig.1), until a tunneling current is detected. For SIN tunneling, a sharpened Pt-Ir foil replaces one of the superconductors. This method has an advantage in terms of tunneling in a particular direction of the ab-plane as opposed to c-axis or the break junction configuration. As argued earlier, in the c-axis tunneling the conductance gives an average DOS for all the angles in ab-plane. In a break junction, the conductance is also an average over certain angles in an uncontrolled way. In our junction configuration, electrons tunnel in a narrow angular cone at a particular angle in the ab-plane.

The temperature dependent tunneling spectra for underdoped and slightly overdoped Bi2212 SIN and SIS junctions have been reported elsewhere [9,10]. In Fig.2a we plot a low temperature (15K) and a higher temperature (85.1K) SIS tunneling spectra for a underdoped Bi2212 ($T_c = 65K$) superconductor. The energy gap estimated from the peak-to-peak separation is about 34mV with the dip feature occurring at about $\pm 100mV$. We do not know the exact tunneling direction in the ab-plane and it will not affect the argument presented here. However, from such a low zero bias conductance, it is clear that the tunneling angle should be very close to the maximum gap direction. A broad gap-like feature (inside $\pm 160mV$) is also clearly visible at low temperatures, to-
gether with the superconducting gap. The gap value and the symmetry of the spectra changes slightly from one junction to another; however, these three features, peak-dip-hump, are clearly visible in all the SIS spectra for either polarity of the bias voltage. We believe that the inverted parabolic background (also seen in interlayer Josephson measurements [15]) is a result of the convolution of a linear background DOS in both the superconductors. It can be shown analytically that a linear background DOS in the two electrodes of a tunneling junction gives rise to an inverted parabolic background in the tunneling conductance. Such a linear background has been observed in SIN junctions previously [6–8].

One very important point to notice about the spectra is that the conservation of states rule is violated. To analyze this better, an average DOS is calculated for both the spectra in between the humps (±175 mV). By average DOS, we mean the integrated conductance in between the specified bias voltages divided by the bias voltage difference. This average conductance is shown as a continuous (broken) horizontal line in the same figure for 15K (85.1K). It can be seen from the figure that these lines are well below the background. This implies that there is a loss of states at low temperature as well as for T > Tc. This can be interpreted in terms of an underlying structure in the DOS other than the quasiparticle type gap. The non-conservation feature is consistently reproducible for different junctions with junction resistance varying between 10kΩ to 10MΩ. This rules out the possibility of capacitive effects giving rise to a depression near zero bias.

From Fig.2a the average DOS above Tc seems to be lower than that below Tc, which is quite contrary to the belief that the pseudogap gets weaker with increasing temperature. We do not quite understand this fact and it does not change the argument in terms of the non-conservation of states for the same spectrum; however, we want to point out that the two spectra have been normalized so as to match the conductances at 100mV. This affects the relative position of the average DOS of the two different spectra. This normalization procedure to superimpose the two spectra for comparison purposes has been used for all the spectra described in this paper.

Further, we divide the 15K curve by 85.1 K curve to normalize away the background DOS. This is plotted in Fig. 2b. After this normalization, the dip-hump structure disappears and the average DOS matches with the background. As pointed out earlier, this kind of normalization procedure is valid only for the biases outside the gap structure and in terms of demonstrating the loss of states. This normalization procedure was used in the pioneering work of McMillan [16] on strong coupling superconductors for removing the normal state background from the SIS and SIN junctions. This procedure was found to be necessary in terms of removing the normal state background effects to deduce the strong coupling features from the tunneling conductance. DeWilde et. al. [17] modeled the background with a sloped straight line; however, no such normalization was carried out with the experimentally measured tunneling conductance above Tc to remove the normal state background DOS.

Several other groups have clearly seen such non-conservation features with underdoping in the tunneling DOS in c-axis tunneling junction configuration [18] while DOS for the overdoped Bi2212, where there is no pseudogap, follows the conservation of states rule [19], consistent with our interpretation. Matsuda et. al. [8] considered the pseudogap as a band structure effect, however, no quantitative analysis was done to determine the loss in states. Although they normalized the low temperature spectra with the 100K spectra, the spectra looked very unrealistic after normalization. Since the c-axis spectrum is an angular averaged ab-plane spectrum as we have discussed previously in this paper, such normalization procedure is not valid for the c-axis tunneling spectra given the highly anisotropic nature of the two gaps.

![Fig. 3. a. SIN tunneling conductance spectra for underdoped Bi2212 (Tc = 68K) at 10.8K and 97.3K (normalized at 100mV without offset). The continuous (dotted) line is the average conductance between ±100mV for 10.8K (97.3K) spectrum. b. The 10.8K spectrum divided by 97.3K spectrum. The horizontal line is the average conductance between ±100 mV.](image)
sample is at the zero potential. The dashed (continuous) horizontal line shown in the figure is the average DOS for 10.8K (97.3K), which is well below the background conductance for both the temperatures implying the loss of states. One very interesting feature about these and the SIS spectra (Fig.2a) is that the backgrounds below \( T_c \) and above \( T_c \) match remarkably well and the dip feature seen on the right for \( T < T_c \) seems to be a result of the product of the background depression in DOS and a BCS like gap DOS. This is a very strong evidence in support of the fact that the same pseudogap exists for both temperatures, above and below \( T_c \).

In Fig.3b, we divide the low temperature curve by the high temperature one. The average tunneling conductance of the normalized spectrum matches well with the background implying that the conservation of states is recovered. Moreover, the normalized tunneling spectrum is symmetric and most of the dip feature on the right is absent. A little depression, which is still present as the dip feature, can be attributed to a slight weakening of the pseudogap with increasing temperature.

![FIG. 4. a. SIN tunneling conductance spectra for slightly overdoped Bi2212 (\( T_c = 85 \)K) at 15.2K and 89.7K (normalized at 100mV without offset). The horizontal line is the average conductance which, in this case, is equal for both the spectra. b. The 15.2K spectrum divided by 89.7K spectrum with the horizontal line as average conductance between \( \pm 100 \)mV.](image)

To compare with the overdoped case, we plot the tunneling spectra for a SIN junction at 15.2K and 89.7K for slightly overdoped Bi2212 (\( T_c = 85 \)K). From the 15.2K spectrum the average conductance was calculated and we find that the loss of states is negligible. This means that the pseudogap in this compound is much weaker than the underdoped one. The low temperature spectrum has an asymmetry, smaller than the underdoped SIN spectrum, and a dip feature for the positive bias. This asymmetry is also present in 89.7K spectrum. On normalization of the 15.2 K spectrum with the 89.7K spectrum the asymmetry disappears, however, the dip feature still persists.

Recent c-axis tunneling measurements from two different groups \[2\] found that the surface of Bi2212 is quite inhomogeneous with some areas having much larger gap compared to the superconducting gap. It could be argued that the non-conservation features we observed could be a result of the contribution from such large gap regions which may not conserve states, given that the junction area in our tunneling configuration is larger than a STM tip. In this case, it should be possible to subtract out the contribution from such regions by subtracting the normal state spectra from the low temperature spectra. We carried out this subtraction and found that the state conservation was almost recovered. This can also be seen from Fig. 2a,3a, and 4a, since the average conductances for the two spectra are almost equal. It should be noted that this procedure is sensitive to the relative normalization factor between the two spectra as mentioned earlier. However, the subtraction procedure does not remove the dip features from the SIS and SIN spectra and also it does not symmetrize the SIN spectra completely. Although we cannot rule out this inhomogeneity scenario completely, it does not affect our argument in terms of non-conservation of states for the underdoped Bi2212 and hence the coexistence of the two gaps.

To summarize, from our ab-plane tunneling studies on Bi2212, we find that the states conservation rule is violated for the underdoped material. By normalizing the low temperature spectra with the \( T > T_c \) spectra, the conservation of states rule is recovered. Moreover, the dip-hump feature which is observed below \( T_c \) disappears on normalization. From this, we conclude that the pseudogap does not evolve into the superconducting gap at \( T_c \); rather, the two gaps coexist below \( T_c \). Furthermore, the dip-hump feature can be interpreted in terms of the coexistence of the two gaps, one being slightly larger than the other. This coexistence of two gaps can rule out the scenario that the superconducting gap and pseudogap arise from the same origin, i.e. pair formation with and without coherence, respectively.

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[18] For eg., see fig.1 of ref.7, fig.3 of ref.8; the tunneling spectra at low temperatures show the loss of states for the underdoped superconductors. This systematic loss of states can be seen from the decrease in the coherence peak height and enhanced dip structure with underdoping. This loss of states gets weaker with overdoping.

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