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**SCALING PROPERTIES OF THE TUNNELING
DENSITY OF STATES IN CUPRATE SUPERCONDUCTORS***

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Abstract

The tunneling density of states (dos) in the energy gap region is reported for a variety of cuprate superconductors with T_c values ranging from 5.5 K to 100 K. It is shown that for tunneling data with relatively low zero bias conductance ($< 30\%$ of normal state) the dos exhibits features that are similar for all cuprates and the energy dependence of the dos studied scales with the gap parameter, Δ . In particular, the "dip" in the dos for $E > \Delta$ that has also been seen in photoemission data on Bi-Sr-Ca-Cu-O, is shown to be a common feature of cuprate tunneling data. The fact that the location and width of the "dip" scale with the energy gap puts serious constraints on its interpretation as an exchange boson.

There has been a considerable effort worldwide to use tunneling spectroscopy as a probe of oxide superconductors, but often with ambiguous or contradictory results.¹ In an attempt to identify those tunneling characteristics which are tied to the unique properties of cuprate superconductors, we have undertaken a systematic study of many different cuprates using an identical tunneling procedure. Tunneling data are presented here which show common, reproducible features, which are distinctive and non-BCS, but which scale with the energy gap parameter, Δ . The wide variation in transition temperature, T_c , (5.5 to 100 K) of the cuprates studied here weakens arguments that these non-BCS features result from the very short coherence length found in the highest T_c cuprates, and their commonality suggests they may be intrinsic properties which can give insight into the underlying pairing mechanism. A dip in the tunneling density of states for $E > \Delta$ is found to be a common feature of the cuprate data and, in the case of 2212 Bi-Sr-Ca-Cu-O, reproduces the dip feature seen in photoemission experiments².

While tunneling spectroscopy is generally regarded as the most powerful probe of the superconducting state, the early tunneling efforts on cuprate superconductors were plagued with a number of problems making interpretation of the data difficult. The data were characterized by strong broadening of the gap features and additional structures due to charging effects, noise and non-tunneling processes. In the past few years there has been a significant improvement in the quality and reproducibility of point-contact and break-junction tunneling data due to better quality materials and improved techniques. Junctions with low zero-bias conductance and sharp conductance peaks display reasonably

reproducible characteristics leading¹, for example, to more consistent estimates of Δ .

In ideal Superconductor/Insulator/Normal metal (SIN) tunnel junctions, the dynamic conductance, $\sigma(V) \equiv dI/dV$, in the superconducting state is directly proportional to the object of principal interest, the quasiparticle density-of-states (dos) of energy $E=eV$. The best tunneling in cuprates to date displays BCS-like dos, but with some distinctive differences, including a degree of broadening which is larger than that due to thermal smearing alone¹. While such characteristics are easily cast into the category of "poor quality" junctions (e.g., surface damage, leakage currents, proximity effects, etc.) the growing body of evidence implies that some of these anomalous features may be intrinsic to the cuprates. Features which are consistently observed, using a variety of tunneling methods, are worth noting as they may give insight into the underlying pairing mechanism.

We use representative point-contact tunneling data in the gap region for a variety of cuprates including $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ (BSCCO-2212) with $T_c=86-96$ K, $\text{Nd}_{2-x}\text{Ce}_x\text{CuO}_{4-y}$ (NCCO) with $T_c=23$ K, $\text{Tl}_2\text{Ba}_2\text{CaCu}_2\text{O}_8$ (TBCCO) with $T_c \sim 100$ K as well as new results for the $\text{Bi}_2\text{Sr}_2\text{CuO}_6$ (BSCCO-2201) phase with $T_c = 5.5$ K. Some of these results have already been published³⁻⁵, but new SIS (superconductor-insulator-superconductor) point-contact tunneling data on single crystals are presented for BSCCO-2201 and BSCCO-2212 for comparison of tunneling data in cuprates over a wide range of T_c values. The SIS junctions apparently arise from the microcleaving that easily occurs in BSCCO crystals when our Au tip scrapes the sample surface³ and are readily recognized by the highly

symmetrical $\sigma(V)$ and by the conductance peak voltages, V_p , which are approximately twice the value observed in SIN junctions.

We first concentrate on BSCCO-2212, as there are also many published tunneling results from other groups¹. Curves a-d of Fig. 1 show a comparison of our point-contact SIS junctions with two published SIS results, namely, the break-junction work of Forro, et al⁶ and the single-crystal edge junctions⁷ on Pb-doped crystals. The data have been normalized by $\sigma(V=187 \text{ mV})$ and the y-axes shifted by one for clarity. There is a strong similarity in the shape of the curves, indicating that the observed features are reproducible from sample to sample and by different tunneling methods. These features include a weakly decreasing σ at high-voltages, a low value of $\sigma(0)$ of $\sim 1\%$ of the high-bias value which increases monotonically with voltage up to $V \sim 2\Delta/e$ and sharp dips near 90 mV. These dips represent a deviation of about 30-40% compared to a BCS-like dos which would monotonically decrease above V_p to its high-bias value of unity. Almost identical features have been observed very recently in an SIS study⁸ of BSCCO-2212. Although $\sigma(0)/\sigma_n$ is $\sim 1\%$, that is close to the experimental noise limit and thus only implies an upper limit of 10% for the superconducting dos of BSCCO at E_F . The ratio of the peak conductances to the high-bias values is always around 2.2-2.8. Furthermore, we find that simple thermal broadening of the low-temperature data, even at $T=100 \text{ K}$, cannot reproduce the high-temperature data⁶ indicating that its origin is the superconducting dos.

The data of Fig. 1 do not represent the true superconducting dos because the normal-state $\sigma_n(V)$ has not been taken into account. It is difficult to measure σ_n since temperature increases of $\sim 100 \text{ K}$ are needed to enter the normal state which poses problems for mechanical contacts

and, furthermore, it is not clear that σ_n at high temperatures is exactly the same as σ_n at 4.2 K. However, the work of Forro, et al⁶ shows that σ_n for $T > T_c$ is a smoothly varying function that decreases slightly with increasing bias voltage and shows no evidence of the structures seen in the superconducting state. We have observed a similar decreasing $\sigma(V)$ in BSCCO-2212 at high voltages, but at sufficiently large voltages, σ eventually increases, a necessary condition for tunneling.

Similar features are found in SIN junctions and to demonstrate the consistency, the SIS curve (e) of Fig. 1 was generated from our SIN point-contact data shown as a solid line in Fig. 2. The SIS curve was generated by a simple convolution integral of $\rho(E)$ and $\rho(E-eV)$, including thermal smearing, where $\rho(E)$ is the tunneling dos obtained by normalizing the SIN data by a constant. The dip feature, which is a subtle effect ($\sim 5\text{-}10\%$) in the SIN junction of Fig. 2, is much more pronounced when convoluted to simulate an SIS junction, and the dip appears near 90 mV as is found in the measured SIS junctions. Note that the peak in σ for SIS tunneling is at $V \sim 2\Delta/e$, whereas for SIN it is at $V \sim \Delta/e$: this also gives rise to a shift of the dip feature in SIS by $\sim \Delta/e$. We have consistently observed this dip-like feature in SIN junctions on BSCCO, noting³ that it is often more pronounced for one polarity compared to a "shoulder" for the other polarity. Such asymmetry is intrinsic to SIN junctions, but not to SIS junctions, where strong, symmetric dips are found.

In Fig. 2, we compare the tunneling dos (from SIN junctions on BSCCO-2212) with the dos from photoemission² on BSCCO single crystals (dashed line). Each curve measures the superconducting dos, but multiplied by a different background. The larger instrumental broadening (~ 25 meV) in the photoemission experiment may be partly responsible for the differences in the two curves, but a dip in the dos is observed in both

at energies of 55-70 meV. Thus, the dip observed in photoemission experiments on 2212 BSCCO appears to be the same dip that is commonly found in both SIN and SIS tunneling. This dip is more visually pronounced in SIS junctions which enhance the subtle structures in the dos, but we have shown good consistency between the SIS and SIN data.

It is tempting to associate this dip with electron lifetime effects due to an exchange boson⁹, analogous to the phonon structure observed in strong-coupled low T_c superconductors. In order to test this, we have studied a wide variety of cuprates with T_c and Δ varying by a factor of ≥ 15 . Figure 3 shows representative SIS tunneling conductances for BSCCO-2201, NCCO, TBCCO and BSCCO-2212 (curve a from Fig. 1). The SIS curves of NCCO and TBCCO have been generated by convoluting the normalized SIN data^{5,6} as described above. We have normalized the voltages by $V_p/2 \sim \Delta/e$, where V_p is the voltage of the conductance peak, so that the rescaled voltage axis of Fig. 3 is approximately in units of Δ/e .

The data for BSCCO-2212 and NCCO have the sharpest structure which is consistent with the smallest $\sigma(0) \sim 10\text{-}15\%$ in SIN junctions. The data for BSCCO-2201 and TBCCO are somewhat broader, consistent with the larger values of $\sigma(0) \sim 25\text{-}30\%$ in the SIN data. However, the general shapes are similar including the monotonically increasing conductance near zero bias and the dip structure, which is apparent in all the data and occurs at a voltage that is proportional to V_p and thus to Δ . It should also be noted that the width of the dip scales with Δ as well. The minimum of the dip is at $\sim 3\Delta/e$, and we emphasize that this represents vastly different absolute energy scales for the various HTS materials, ranging from $\Delta \sim 0.9$ meV in BSCCO-2201 to ~ 30 meV in Pb-doped BSCCO-2212.

This observation of the scaling property of the dip with Δ seems to contradict its identification as an exchange boson⁹, Θ_b , since, e.g., with phonons, T_c and Δ are predominantly determined by the coupling *strength*, λ , rather than the characteristic phonon energy, Θ_D . However, in the very strong coupling limit, BCS-like theories indicate T_c is proportional to Θ_b , and if λ were approximately constant among the cuprates, such a scaling property might be possible. But our tunneling results for NCCO⁵ put it in the moderately coupled regime with $2\Delta/kT_c \sim 3.5-4.1$. Also, the scaling of the width of the dip feature is difficult to understand within the context of conventional boson exchange theories.

We note that in NCCO the dip occurs at an energy ~ 4 meV above the conductance peak, which is well below its characteristic phonon energies, i.e., the peaks in the phonon dos¹⁰, $F(\omega)$, which range from 10 to 70 meV. In fact, the observance of characteristic phonon energies in the tunneling dos of NCCO has been reported⁵ and the resulting $\alpha^2F(\omega)$ agrees well with $F(\omega)$ from neutron scattering¹⁰ and can explain the measured T_c . If the dip is due to an exchange boson, then at least for NCCO it seems to be acting in addition to phonon-mediated coupling from modes at higher energy. However, the dip location in BSCCO-2212, roughly 25-40 meV above the conductance peak, is well within the range of phonon energies, and thus it may obscure the observation of phonon coupling.

In Fig. 1 the possibility exists that the dip is followed by a peak in the dos at higher voltages (near 120 mV) as been suggested in STM studies¹¹ of BSCCO-2212. However, it difficult to assess whether this peak is real or is a manifestation of the dip merging into a decreasing background conductance which is inferred from the high bias data in Fig. 1 and has been measured in some cases.^{3,8} Such a peak in the dos at 3Δ has

been predicted within a marginal Fermi liquid model¹² and in this picture the dip represents a local minimum in the dos between the peaks at Δ and 3Δ . We emphasize that proper identification of a peak at 3Δ awaits careful measurement of the normal state conductance. Considering all of the available data, including photoemission results², it appears that the dip itself is the prominent feature and the one which we found scales with the gap parameter, Δ .

Another possible explanation for a dip in the tunneling dos is the proximity effect due to a surface layer which is damaged or for other reasons has weaker superconductivity. Photoemission, being a surface probe like tunneling, might be sensitive to such a proximity layer as well. Indeed, the dip structure is reminiscent of that found in proximity-effect tunneling in conventional superconductors¹³ which is well-described by the Arnold model¹⁴. In the Arnold model of proximity-effect tunneling, the conductance peak is due to a bound quasiparticle state and the dip is due to the gap between this bound state energy and the superconductor's energy gap, Δ_s . The bound state energy in that model depends on the thickness of the proximity layer and the coherence length of the underlying superconductor. We have measured tunneling data on BSCCO-2212 crystals with Au overlayers (200-600 Å) and have found agreement¹⁵ between the conductance peak voltage and the bound state energy calculated in the Arnold model for the various Au thicknesses.

However, there are aspects of the data in Fig. 3 which are difficult to explain with the proximity-effect. First, such a surface proximity layer might be expected to be sensitive to preparation conditions and tunneling technique: thus a sample dependence would be expected for the location of the conductance peak, which does not seem to be observed.

Second, a surface proximity effect might be expected to depend strongly on the in-plane coherence length, ξ_{ab} , of the cuprates, which is estimated to vary by a factor of ~ 16 for our samples. In the Arnold model¹⁴, superconductors with the smallest ξ_{ab} would be most affected by a proximity layer of given thickness. Yet the shapes of the tunneling data in Fig. 3 are similar and, in fact, some of the sharpest structures, including the lowest $\sigma(0)$, are observed for BSCCO-2212 which has one of the smallest ξ_{ab} amongst the cuprates.

If $\sigma(V)$ measures an intrinsic bulk property of the cuprates (rather than a surface effect), then the shape of the dos would be related to the nature of the pairing state or to the layered character of the cuprate structure. Evidence for the latter is found in the tunneling dos of layered organic superconductors¹⁶, which exhibit shapes quite similar to those reported here.

In summary, we have reported representative tunneling data in the gap region for a variety of cuprate superconductors with T_c values ranging from 5.5 K to 100 K and which all exhibit, for the SIN configuration, a value of the zero-bias conductance which is $< 30\%$ of the normal state. The dos exhibit similar features for all the cuprates studied and the energy dependence of the dos scales with the gap parameter, Δ . In particular, the "dip" in the dos that is also seen in photoemission data on $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_8$ is shown to be a common feature of the cuprates. The location and width of the dip scale with the gap parameter, Δ , and this fact puts severe constraints on its interpretation as an exchange boson. The dip in the quasiparticle dos is a reproducible, non-BCS feature, and may play an important role in elucidating the nature of the pairing state in cuprate superconductors.

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Figure Captions

Fig. 1. Comparison of SIS tunnel junctions of BSCCO from this study and from published work: (a) single-crystal edge junction, Pb-doped sample (Ref. 9); (b) break junction (Ref. 8); (c) point-contact junction, Pb-doped sample; (d) point-contact junction; (e) SIS conductance generated from the SIN junction shown in Fig. 2a. Both point-contact junctions are from this work. Pb-doped samples in Fig. 1 display a conductance peak at slightly higher voltages presumably due to the higher T_c (typically 96 K compared to 86 K for undoped BSCCO).

Fig. 2. Comparison of photoemission data on BSCCO with tunneling data in the SIN geometry. The conspicuous dip seen near 70 meV in the photoemission is observed also in the tunneling data.

Fig. 3. Representative SIS tunnel junctions for various cuprate superconductors (T_c from 5.5 K to 100 K) plotted on a voltage axis renormalized in units which are $\sim \Delta$, the gap parameter: (a) TBCCO; (b) BSCCO-2201; (c) NCCO; and (d) BSCCO-2212 from curve (a) of Fig. 1.

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