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Aspects of the tunneling dip feature in $Bi_2Sr_2CaCu_2O_{8+\delta}$ and its relation to the resonance spin excitation

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Abstract

Break-junction tunneling data are reported in $Bi_2Sr_2CaCu_2O_{8+\delta}$ over a wide range of hole concentration from underdoped to overdoped. The strong conductance peaks in the superconducting state reveal a single gap consistent with d-wave symmetry. In addition, sharp dips are observed at a voltage, Ω/e, measured with respect to the gap edge. These features are shown to be reproduced in other junction types from the literature including atomically resolved STM and *c*-axis mesas, establishing their intrinsic character. Trends are observed with doping and temperature which link the dip to the resonance spin excitation and indicate that the quasiparticles are strongly coupled to this mode. © 2002 Elsevier Science Ltd. All rights reserved.

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Fine structure in the tunneling spectra of conventional superconductors such as Pb or Nb reveals completely the nature of the electron–phonon interaction responsible for pairing and superconductivity [1]. For high T_c cuprates, however, tunneling and other spectroscopies have not led to any consensus on the pairing mechanism. On the contrary, spectral features are currently being interpreted within radically different theoretical frameworks. One such feature is a suppression of spectral weight, more commonly termed the 'dip', which is observed in ARPES, tunneling and a.c. conductivity measurements and which has received considerable theoretical attention [2]. Interpretations of the dip in tunneling have ranged from it being described as an ordinary background effect to suggestions that it is a strong-coupling effect tied to the mechanism of superconductivity [3]. One way of removing such ambiguities is to examine how the dip evolves with thermodynamic variables such as temperature or hole concentration. Such trends might also serve to identify the origin of this and other spectral features.

In this article, we examine a large set of superconductor–insulator–superconductor (SIS) tunneling data on $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) over a very wide doping range from underdoped ($T_c = 74$ K) to optimal doped ($T_c = 95$ K) to overdoped ($T_c = 48$ K). From zero bias up to the gap voltage, $2\Delta/e$, the measured conductances are close to that expected from the density of states (DOS) found in weak-coupling, mean-field models of a d-wave order parameter. In conjunction with the presence of Josephson currents, this suggests the gap is always of superconducting character. However, the conductances also reveal sharp dips at a voltage, Ω/e, beyond the gap edge. These dip features are similar to structures ascribed to phonons in conventional superconductors in that there appears to be a corresponding pile-up of states at the gap edge. This suggests that electrons are coupled to some type of collective excitation of energy $\sim\Omega$. Recently, it has been shown that Ω extracted from the dip minima scales as $4.9kT_c$ over the entire doping range [4] which is close to that of the resonance spin excitation energy, Ω_{res}, found in neutron scattering [5–7]. These data are discussed in further detail here. In particular, we present a comparison of an SIS break junction spectrum with other tunneling results on Bi2212 from the literature which demonstrates a remarkable consistency of the observed phenomena. Also, new results on the temperature dependence of an

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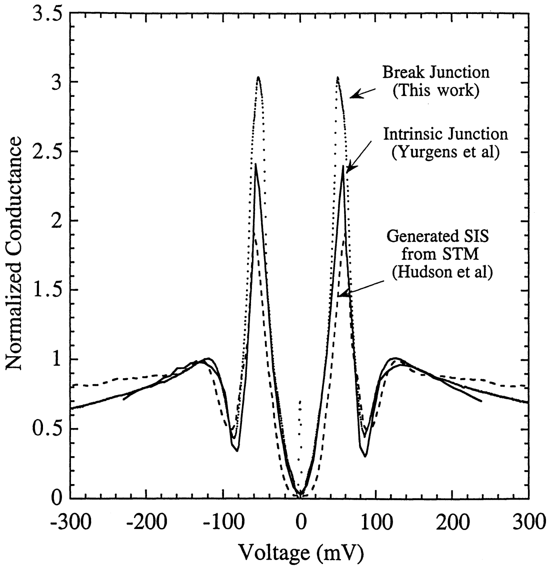

Fig. 1. Comparison of SIS tunneling spectrum from this work (dots) with others in the literature. Solid line is from Ref. [11] from intrinsic *c*-axis mesa junction and dashed line is a generated SIS curve from a local STS spectrum [12]. All data sets have been normalized by a constant given by the conductance at $V = -130$ mV.

overdoped Bi2212 crystal are used to support the idea that the dip is a strong-coupling effect.

It is important to stress that the spectral dip feature in the tunneling data of Bi2212 is highly reproducible. It was noted as early as 1989 in superconductor–insulator–normal metal (SIN) junctions [8] where the dynamic conductance, $\sigma(V)$, is expected to be proportional to the electronic DOS, $N(E)$. This feature was repeatedly observed in many subsequent tunneling studies of Bi2212, e.g. scanning tunneling spectroscopy (STS) [3,9], break junctions [3,10] and recently in intrinsic *c*-axis junctions [11] of Bi2212 crystals intercalated with $HgBr_2$. These consistent observations (both magnitude and location) of the dip in such a variety of junction types has pointed to its intrinsic nature. However, a confusing aspect of the dip in the SIN geometry has been an often-observed asymmetry in its strength, especially in point-contact tunnel (PCT) junctions. It is generally more pronounced for bias voltages which remove electrons from the Bi2212 electrode and this is inconsistent with strong coupling effects as seen in conventional superconductors. Local probes such as STM, when spatially resolved at the atomic level, have shown that the dip strength was much more symmetric in bias voltage [3,12] and normalization of the data revealed a suppression of the DOS consistent with a strong-coupling effect [3]. This shows that at least part of the asymmetry originates from background effects and surface averaging in large area junctions. PCT measurements of single layer (Tl2201) and four-layer (Cu1234) cuprates [13] have shown nearly identical dip features indicating this is not peculiar to Bi2212 but is intrinsic to quasiparticles in the Cu–O plane.

We demonstrate the reproducibility of the dip feature and overall conductance spectra of Bi2212 in Fig. 1 where an SIS break junction from this study is compared to published results from an intrinsic *c*-axis mesa stack [11] and from atomically resolved STS [12]. In order to compare these, an SIS spectrum was generated from the STS data (which is SIN type) by convoluting the conductance with itself using standard tunneling theory. All junctions exhibit a Δ value near 30 meV, which, according to Miyakawa et al. [14] corresponds to slightly overdoped Bi2212. The overall agreement in spectral shape among the three very different junction types in Fig. 1 is remarkably good. It demonstrates a consistency between SIN and SIS junctions as well as between surface probes and intrinsic junctions. Thus Fig. 1 can be viewed as generic, revealing intrinsic properties of the quasiparticle excitations. Fig. 1 also shows that there is not any large degree of inhomogeneity in either the break junctions or *c*-axis mesa junctions as they agree with a local STS spectrum in a superconducting region. It has generally been noted [15,16] that the dip voltage scaled with the maximum d-wave gap, e.g. $eV_{\mathrm{dip}} \sim 3\Delta$ in SIS junctions as is evident in Fig. 1. However, it has been shown that the dips in these sharp SIS data [4] reveal a trend with doping whereby the minimum is at $2\Delta + \Omega$, and Ω is proportional to T_c.

The break junctions were obtained by a point contact technique (described elsewhere [3,14]) on Bi2212 crystals oxygen doped over a wide range of hole concentrations. We stress that these break junctions are formed under high vacuum, cryogenic conditions and they occur deep in the Bi2212 crystal [17], thereby minimizing surface contamination. In Fig. 2, the dynamic conductance spectra at 4.2 K are shown for four SIS break junctions. These SIS spectra are a snapshot of a much larger data set (18 junctions) and they capture the principal features of interest. The main conductance peaks reveal the energy gap at $|eV_p| = 2\Delta$, which increases in the underdoped region even as T_c decreases [14]. For $|eV|$ beyond 2Δ there is a pronounced dip feature that is strongest at optimal doping. The negative dI/dV in the optimal doped data is not unphysical but merely reflects a strong dip in $N(E)$ (see, for example, Ref. [18]). To analyze such spectra we argue that no matter the origin of the dip, the low-energy excitations in the sub-gap region ought to be only weakly affected by renormalization effects. Thus the spectra are compared with a weak coupling, d-wave fit [17] which includes a quasiparticle scattering rate, Γ, and a tunneling directionality factor, α. This simple BCS, d-wave model provides reasonable agreement in the sub-gap region (up to $eV = 2\Delta$). This is also found for SIN junctions [17] where the d-wave DOS provides a very good fit in the sub-gap region, capturing the cusp feature measured at zero bias.

For $|eV| > 2\Delta$ there is an immediate positive deviation from the fit, followed by the strong negative deviation (dip) and finally a recovery toward a hump feature. Broadening

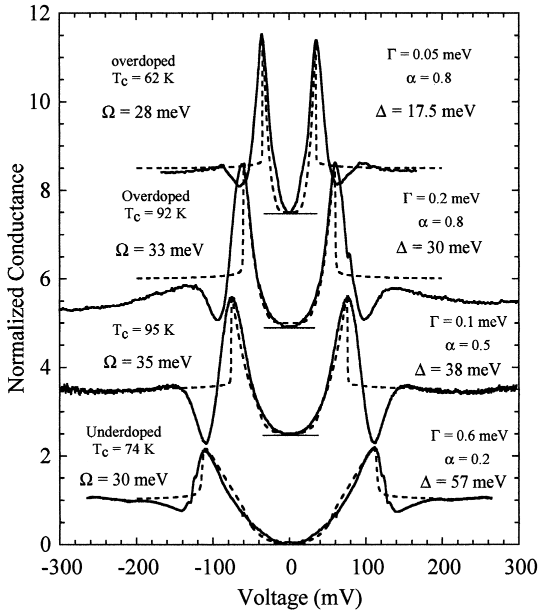

Fig. 2. Representative SIS tunneling conductances for Bi2212 from overdoped to underdoped. Data have been normalized either by a constant or by a smooth background and shifted for clarity. Dashed lines are BCS d-wave fits using $\Delta(\phi) = \Delta\cos(2\phi)$, a scattering rate, Γ, and a weighting function, $f(\phi) = 1 + \alpha\cos(4\phi)$ as described in Ref. [17]. The zero of conductance for each curve is given by the measured and fitted curves at zero bias. The Ω values are determined by the differences between peak and dip energies.

the peaks in the d-wave model by increasing the scattering rate, Γ, leads to severe reduction of the peak heights which is clearly incompatible with the data. The excess width of the experimental conductance peaks therefore seems to be intrinsic, being observed for a wide range of doping and for different junction types as Fig. 1 shows. Our interpretation is that the excess width reflects a pileup of states which compensates for the depletion at the dip and that these deviations from the d-wave fit resemble the states-conserving, strong coupling effects from the electron–phonon interaction in conventional superconductors [1]. This suggests that the dip features are due to some type of bosonic collective excitation (or a relatively narrow spectrum of excitations).

The temperature dependence of the SIS break junction spectra [14] and c-axis junctions [11] are consistent with this strong-coupling interpretation, showing that strong dip features disappear at T_c. However, most of the T-dependent studies have been on optimal or underdoped Bi2212 and the pseudogap depression in the DOS above T_c again introduces some ambiguity into the interpretation. In Fig. 3 is shown some new SIS data on heavily overdoped Bi2212 with $T_c = 56$ K which exhibits a small gap, $\Delta = 14.5$ meV. Although the dip feature is weak it can still be tracked and it seems to completely disappear at T_c. This is apparent because the background is extremely flat showing no evidence of a pseudogap in this heavily overdoped crystal. This T-dependent behavior, where all gap related structure disappears, is exactly what is observed for gap features and phonon structures in conventional superconductors.

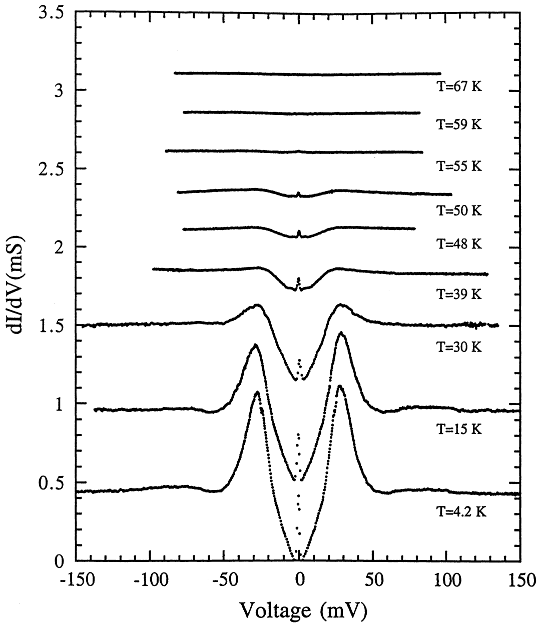

Fig. 3. Temperature dependence of the SIS tunneling conductance for a heavily overdoped Bi2212 crystal with $T_c = 56$ K. The peak at zero bias is due to the Josephson current which disappears, along with all gap structure, above 56 K.

So far it has been suggested that the dip is a strong-coupling effect and that the minimum might provide a quantitative measure of the excitation energy Ω. But some justification for this is required, especially since this method is somewhat different than for phonon structures. We first note that SIN data, which should directly reflect $N(E)$, show reproducibly that the dip minimum is about 35–40 meV beyond the gap edge in optimal doped Bi2212 [3,9,14]. This is close to the resonance mode energy measured in optimal doped Bi2212 [5–7]. Considering conventional phonon structures in s-wave superconductors [1], phonon modes with energy, Ω_{ph} would produce tunneling dip features *near* $eV = 2\Delta_s + \Omega_{ph}$ in SIS junctions where Δ_s is the s-wave superconducting gap, but the dip minima would over-estimate the mode energy. However, the cuprates are d-wave superconductors and the presence of gap nodes can affect the location of strong coupling features. This result comes from the analysis of ARPES data in Bi2212 [18–20] which show a similar dip/hump feature for electrons near the (π,0) point, i.e. maximum gap region. The ARPES data can be analyzed within a model whereby the electrons near (π,0) are interacting with a collective mode. This model has been extended to calculations of the SIS tunneling spectrum [18] by considering a d-wave gap and the result is that the dip minimum is very close to $2\Delta + \Omega$. It has also been

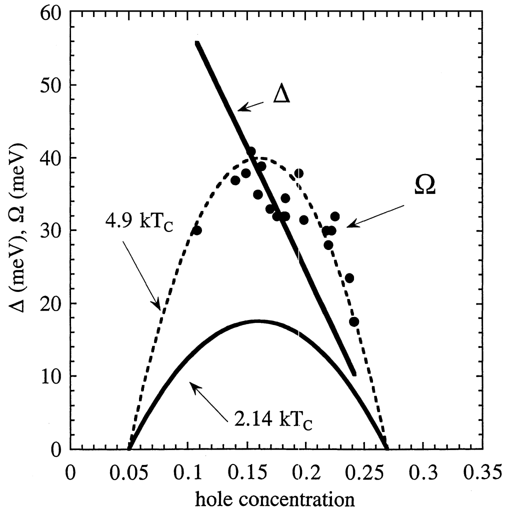

Fig. 4. Measured tunneling mode energy Ω vs. hole doping level obtained from 18 junctions over a wide doping range from underdoped (74 K) to overdoped (48 K). Ω values lie close to the dashed line, $4.9kT_c$. Δ values from the work of Miyakawa et al. [14] are shown as a straight line which is fit to the data.

demonstrated using Eliashberg formalism for d-wave superconductors that the SIS tunneling dip minimum provides a good estimate for the energy of a generic, single-peak boson spectrum [21].

Thus Ω is determined by assuming the dip minimum is at $2\Delta + \Omega$. In Fig. 4 are plotted the measured values of Ω vs. doping obtained on 18 SIS junctions over the full doping range. The doping level is obtained from the measured gap, Δ, which is nearly linear in hole concentration [14] and the fit has been plotted as a straight line in Fig. 4. It is found that the maximum measured value of $\Omega \sim 42$ meV occurs near optimal doping and agrees with the maximum resonance mode energy obtained in neutron scattering [5–7]. Using the empirical quadratic relation between T_c and hole concentration [14], a dashed line corresponding to $4.9kT_c$ is shown in Fig. 4 which was found to be a good fit to the Ω data [3]. This result is in good quantitative agreement with neutron results [5–7] for $\Omega_{res}/kT_c \sim 5.1$–$5.5$. Fig. 4 shows that on the overdoped side $\Omega > \Delta$ but on the underdoped side $\Omega < \Delta$. This relation has been examined further in Ref. [4] where it was shown that Ω has the character of an excitonic level within the superconducting gap, 2Δ. This is in agreement with spin fermion models of high T_c superconductivity and the resonance mode [2,22,23].

To summarize, we have reviewed and examined various aspects of the tunneling dip feature found primarily in Bi2212 but seen also in other cuprates. The strong similarity in spectra from STS, break junctions and intrinsic *c*-axis mesas shows that this is an intrinsic property of the quasiparticle spectrum. Interpretations of the dip which suggest it is a background effect (e.g. linked to the van Hove singularity) are difficult to reconcile with the various properties outlined here, including the T-dependence, which clearly points toward it being a superconducting property. Comparison of the SIS spectra with a BCS d-wave fit, along with the T-dependence, suggests this is a strong coupling effect due to quasiparticles interacting with collective excitations of characteristic energy, Ω. The doping dependence of the tunneling dip minima shows that Ω scales approximately as $4.9kT_c$ which is close to that of the resonance spin excitation. Since the dip resembles a strong coupling effect, the tunneling data are therefore providing evidence that spin excitations are playing a crucial role in the superconductivity.

It should be noted that a similar dip feature has been observed in the superconducting tunneling spectra of a heavy fermion superconductor [24] which has also been linked to a peak that develops in the spin excitation spectrum. Thus a spin fluctuation mechanism may have a more general relevance to superconductors beyond the high T_c cuprates. A natural question might be whether a phonon spectrum is consistent with the above results. For optimal doped Bi2212 the dip minimum leads to $\Omega \sim 40$ meV which is certainly within the range of optical phonons. However, Fig. 4 shows that for heavily overdoped Bi2212, Ω drops below 20 meV and shows no evidence of departing from the scaling with T_c. This is difficult to understand within an electron–phonon picture, where the mediating boson would be expected to have a similar energy over the doping range. On the other hand, the scaling of Ω and T_c is more natural for an all-electronic pairing mechanism where feedback effects play an important role. Furthermore, phonon fine structures are not showing up in a clear and reproducible manner.

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