Correlation of Tunneling Spectra in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ with the Resonance Spin Excitation

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New break–junction tunneling data are reported in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ over a wide range of hole concentration from underdoped ($T_c = 74$ K) to optimal doped ($T_c = 95$ K) to overdoped ($T_c = 48$ K). The conductances exhibit sharp dips at a voltage, $\Omega/e$, measured with respect to the superconducting gap. Clear trends are found such that the dip strength is maximum at optimal doping and that $\Omega$ scales as $4.9kT_c$ over the entire doping range. These features link the dip to the resonance spin excitation and suggest quasiparticle interactions with this mode are important for superconductivity.

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Acceptance of the phonon mechanism for electron pairing in conventional superconductors began with the isotope effect, showing $T_c$ scaling with a characteristic phonon energy, $\Omega_{ph}$, and culminated with detailed, quantitative agreement between features in tunneling spectroscopy and the phonon spectrum measured by neutron scattering. For high $T_c$ cuprates, however, tunneling and other spectroscopies have not led to a consensus on the pairing mechanism and in fact are currently being interpreted within radically different theoretical frameworks. The doping dependence of spectral features can be a key in determining their origin. Thus we present superconductor–insulator–superconductor (SIS) tunneling data on Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ 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 superconducting gap voltage, $2\Delta/e$, the measured conductances are close to that expected from the density of states found in mean–field models of a $d$–wave order parameter. However, the conductances also reveal sharp dips at a voltage, $\Omega/e$, beyond the gap edge. This dip feature is similar to structures ascribed to phonons in conventional superconductors and suggests that electrons are coupled to some type of collective excitation of energy ~ $\Omega$, measurable by the dip minimum. Most importantly, the scaling of $\Omega$ as $4.9kT_c$ over the entire doping range is close to that of the resonance spin excitation energy, $\Omega_{res}$, found in neutron scattering. Thus the tunneling and neutron measurements, coupled together, present a strong case that spin excitations play an important role in the pairing mechanism of high $T_c$ superconductors.

An unusual spectral dip feature in the tunneling data of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212) was pointed out as early as 1989 in superconductor–insulator–normal metal (SIN) junctions where the dynamic conductance, $\sigma(V)$, is expected to be proportional to the electronic density of states, $N(E)$, with $E = eV$. This feature was repeatedly observed in many subsequent tunneling studies, including scanning tunneling spectroscopy (STS), break junctions and recently in a stack of intrinsic $c$–axis junctions within a Bi2212 crystal intercalated with HgBr$_2$. These consistent observations (e.g. location and magnitude of the dip) in such a variety of junction types tends to rule out extrinsic surface related phenomena as being responsible. An earlier tunneling study showed that the dip represented a suppression of the density of states and that the strength of the dip correlated with $T_c$ in overdoped Bi2212. It was argued to be some form of strong coupling effect analogous to the dip features from the electron–phonon interaction in conventional superconductors. Phonon modes with energy $\Omega_{ph}$ produce a dip feature with a minimum near $\Delta_s + \Omega_{ph}$ in SIN junctions and near $2\Delta_s + \Omega_{ph}$ in SIS junctions where $\Delta_s$ is the $s$–wave superconducting gap. Although preliminary tunneling measurements on Bi2212 suggested that the dip voltage scaled with the maximum $d$–wave gap $\Delta$, we will demonstrate here that the sharp dips observed in these new SIS junctions have a minimum at $2\Delta + \Omega$, where $\Omega$ is proportional to $T_c$.

The linking of the tunneling dip feature to the resonance spin excitation has been made possible due to the confluence of a number of experimental and theoretical developments. Neutron scattering has shown that the resonance mode is generic to bi–layer high $T_c$ cuprates reaching a maximum energy of $41 – 43$ meV at optimal doping and tracking $T_c$ with underdoping or slight overdoping. Other spectroscopies including angle resolved photoemission (ARPES) and optical conductivity have exhibited spectral features that can be explained by assuming the conduction electrons are coupled to the spin excitations. Theoretical spin–fermion type models which have been invoked to explain the ARPES data have also been shown to produce dip features in the quasiparticle density of states and SIS tunneling spectra that resemble those reported...
gion even as T varies at interest. The main conductance peaks reveal the energy larger data set and they capture the principal features of overdoped, b) an optimally doped and c) an underdoped shown for three SIS break junctions on Bi2212: a) an crystal [17], thereby minimizing surface contamination. cryogenic conditions and they occur deep in the Bi2212 these break junctions are formed under high vacuum, over a wide range of hole concentration. We stress that described elsewhere [5,10]) on Bi2212 crystals oxygen doped junctions were obtained by a point contact technique (de-

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stronger dip. The spectra are compared with a weak coupling, d-wave fit (see ref. [17] for details) which includes a quasiparticle scattering rate, Γ. Considering the simplicity of the d-wave model, the agreement in the sub-gap region (up to εV = 2Δ) is surprisingly good. Even better agreement is found for SIN junctions where the d-wave fit captures the cusp feature found at zero bias. [17]

For |εV| > 2Δ there is an immediate positive deviation from the fit, followed by the strong negative deviation (dip) and finally a recovery toward a hump feature. There is no way to broaden the peaks in the d-wave model (e.g. by increasing the scattering rate, Γ) without severely reducing the peak heights and that would be clearly incompatible with the data. We emphasize that the identical behavior is found throughout the doping range and that these deviations from the d-wave fit resemble the strong coupling effects from the electron–phonon interaction in conventional superconductors suggesting that the dip features are due to some type of bosonic collective excitation (or a relatively narrow spectrum of excitations).

A larger set of spectra over the entire range of doping is plotted in Fig. 2 on a voltage axis which is scaled by Δ = εVp/2. In addition to the dip strength being maximum at the highest Tc, which suggests a strong coupling effect, another trend is evident. On this plot it can be seen that while the dip minimum is very close to 3Δ at optimal doping (as noted in previous work [10,14]) it is significantly greater than (less than) 3Δ with overdoping (underdoping). This trend is easy to see here because the newer SIS spectra all have a peak height to background

\[
\Delta = 17.5 \text{ meV} \\
\Gamma = 0.05 \text{ meV} \\
\alpha = 0.8
\]

\[
\Delta = 38 \text{ meV} \\
\Gamma = 0.1 \text{ meV} \\
\alpha = 0.5
\]

\[
\Delta = 57 \text{ meV} \\
\Gamma = 0.6 \text{ meV} \\
\alpha = 0.2
\]

\[
T_c = 62 \text{ K} \quad \text{overdoped}
\]

\[
T_c = 95 \text{ K} \quad \text{optimal doped}
\]

\[
T_c = 74 \text{ K} \quad \text{underdoped}
\]

FIG. 1. SIS tunneling conductances for a) overdoped, b) optimally doped and c) underdoped Bi2212. Data have been normalized by a smooth background and shifted for clarity. Dashed lines are BCS d-wave fits using ∆(φ) = ∆ cos 2φ, a scattering rate, Γ, and a weighting function, f(φ) = 1 + α cos4φ as described in ref. [14].

here. Unique to this tunneling work, however, is that we have measured the relations between Ω, Tc and Δ where the latter varies by a factor of six over this doping range. Such a systematic study allows trends to be observed and thereby makes a more convincing case that the tunneling dip is due to the resonance mode and not some other excitations such as phonons. In addition, we demonstrate an interesting relation between the mode energy and the superconducting gap that has provided some important insights into the nature of the resonance mode itself. The focus here is on SIS junctions because the dip is very pronounced in this geometry. The break junctions were obtained by a point contact technique (described elsewhere [5,10]) on Bi2212 crystals oxygen doped over a wide range of hole concentration. 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. 1 the dynamic conductance spectra at 4.2 K are shown for three SIS break junctions on Bi2212: a) an overdoped, b) an optimally doped and c) an underdoped crystal. These SIS spectra are a compendium of a much larger data set and they capture the principal features of interest. The main conductance peaks reveal the energy gap at |εVp| = 2Δ, which increases in the underdoped region even as Tc decreases [14]. For |εV| beyond 2Δ there is a pronounced dip feature that is strongest at optimal doping. The new optimal doped data of Fig. 2 are quite similar to those of ref. [10], but exhibit a somewhat stronger dip. The spectra are compared with a weak coupling, d-wave fit (see ref. [17] for details) which includes a quasiparticle scattering rate, Γ. Considering the simplicity of the d-wave model, the agreement in the sub-gap region (up to εV = 2Δ) is surprisingly good. Even better agreement is found for SIN junctions where the d-wave fit captures the cusp feature found at zero bias. [17]

For |εV| > 2Δ there is an immediate positive deviation from the fit, followed by the strong negative deviation (dip) and finally a recovery toward a hump feature. There is no way to broaden the peaks in the d-wave model (e.g. by increasing the scattering rate, Γ) without severely reducing the peak heights and that would be clearly incompatible with the data. We emphasize that the identical behavior is found throughout the doping range and that these deviations from the d-wave fit resemble the strong coupling effects from the electron–phonon interaction in conventional superconductors suggesting that the dip features are due to some type of bosonic collective excitation (or a relatively narrow spectrum of excitations).

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ratio > 2 and exhibit sharp dip features. Both of these trends clearly link the dip to the superconductivity, but rule out trivial connections such as proximity effects [18]. Also, the shift of Ω inferred from the dip minima in Fig. 2 is consistent with theoretical predictions [14] for the location of a resonance mode energy Ω_{res} within the gap 2Δ in the spin excitation spectrum. Thus Figs. 1 and 2 make a strong case that: (1) the dip feature arises from quasiparticles coupled to some type of collective excitation of energy, Ω, and (2) the doping dependence of Ω bears a qualitative resemblance to the resonance spin excitation in experiment [14] and theory [14].

So far we have implied that the dip minimum might provide a quantitative measure of Ω, but some justification for this is required, especially in the absence of a full microscopic theory. Considering conventional phonon structures in s-wave superconductors [16], the dip minimum in SIS spectra would give a slight overestimate of the excitation 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 [11,12] 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 and the mode energy is given by the dip minimum [11] which is at Δ + Ω. This model for Bi2212 has been extended [13] to calculations of the SIS spectra by considering a d-wave gap, a realistic Fermi surface and the coupling of electrons of all momenta to the resonance spin excitation at the (π,π) point. The result is that the dip minimum in SIS junctions is very close to 2Δ + Ω. It should be noted that a dip feature has been observed in the angle-integrated photoemission spectra of Pb and Nb and linked to peaks in the phonon density of states [14] clearly demonstrating that this type of dip in photoemission can be a characteristic of strong coupling superconductivity.

Considering the above discussion, it seems reasonable to extract Ω by assuming the dip minimum is at 2Δ + Ω. In Fig. 2 are plotted the measured values of Ω and Tc vs. the measured Δ obtained on 17 SIS junctions from crystals with bulk Tc ranging from 74 K (underdoped) to 95 K (optimal doped) to 48 K (overdoped). It is found that the maximum measured value of Ω ~ 42 meV occurs near optimal doping and agrees with the maximum resonance mode energy obtained in neutron scattering [2,3]. The scatter in the data of Fig. 2 arises from an experimental uncertainty in determining the mode energy, Ω, from the dip minimum and also from the narrow spread of gap values from junctions made on different regions of a crystal with a common bulk Tc. Despite the scatter in the data there is an unmistakeable correlation between Ω and Tc. This is seen with simple quadratic fits to Ω and Tc vs. Δ (solid and dashed line respectively in Fig. 2) which are nearly congruent and lead to the scaling Ω/kTc ~ 4.9 which we note is in good quantitative agreement with neutron results [2,3] for Ω_{res}/kTc ~ 5.1 – 5.5. This scaling is reminiscent of the conventional isotope effect in superconductors where Tc scales with Ω_{ph}. We note that the tunneling Ω scales with Tc far into the overdoped region, well beyond what has been measured so far for the neutron resonance.

In the plot of Ω/Δ vs. Δ (inset of Fig. 3) the relation of Ω to Δ is more clearly seen, providing important information on the nature of the excitation probed by tunneling. For the most overdoped region, the mode energy approaches but never exceeds 2Δ, and Ω/Δ monotonically decreases as doping decreases and the superconducting gap grows. Thus the excitation itself is linked to the superconducting gap which varies by a factor of six in this study. This behavior would seem to rule out phonons completely and instead suggests an electronic excitation. It is consistent with general ideas about collective modes of the conduction electrons in superconductors [20] (i.e., that mode energies > 2Δ are heavily damped), as well as with specific models of the resonance spin excitation [14]. In the latter, the overdoped region is considered to have weaker coupling of electrons to spin excitations and therefore the resonance mode is close to the gap edge, 2Δ, in the spin excitation spectrum. As doping decreases and the coupling gets stronger, the superconducting gap gets larger but the mode energy moves deeper into the gap and thus Ω/Δ decreases. In this picture the neutron resonance is a spin exciton [14] and we believe the tunneling data provide the first evidence for such a viewpoint.

To summarize, we have used the doping dependence of the tunneling dip feature, as shown in Fig. 2, to link it to the resonance spin excitation. Since the dip resembles
a strong coupling effect, the tunneling data are also providing evidence that spin excitations are playing a crucial role in superconductivity. It should be noted that a similar dip feature has been observed in the superconducting tunneling spectra of a heavy fermion superconductor \[21\] which has also been linked to a peak that develops in the spin excitation spectrum. Thus a spin fluctuation mechanism may have relevance to superconductors beyond the high \(T_c\) cuprates.

It is important to contrast this interaction with phonon mediated pairing. Phonons are collective excitations of the lattice and therefore exist in the normal state, whereas this collective spin excitation mode seems to develop only below \(T_c\) (except for heavily underdoped materials). Thus this scenario displays a remarkable feedback effect: superconductivity hollows out a gap in the spectrum of damped spin excitations, allowing a propagating collective mode to exist, but then that mode is at least partly responsible for the pairing mechanism. If, in addition, there are phonon contributions to the pairing, the phonon structures are not showing up in a clear and reproducible manner. The selective coupling of electrons near \((\pi, 0)\) to spin excitations near \((\pi, \pi)\) as suggested in ARPES \[11, 12, 14, 15\] leads naturally to \(d\)-wave superconductivity \[22\] and explains the mysterious asymmetry of the dip strength with voltage polarity as observed in SIN tunneling \[4–6\]. In this picture, the quasiparticles at \((\pi, 0)\) are the most strongly renormalized and since this is an occupied state in Bi2212 \[12\], the strongest dip features should be found for bias voltages which remove electrons, as is observed in SIN experiments and model calculations \[15\]. There are still a number of unresolved issues. As with phonon structures in conventional superconductors \[1\], one hopes to show that the tunneling spectra quantitatively reproduce the measured \(\Delta\) and \(T_c\). This will require a microscopic model, and the present results suggest that a Fermi–liquid, Eliashberg type of approach will work. While it is true that the pseudogap leads to a distinctly non–Fermi–liquid normal state, superconductivity seems to restore the quasiparticle concept. Finally, we should note that similar dip features have been observed in the tunneling spectra of Tl2Ba2CuO6 indicating that the neutron resonance ought to be observed in a cuprate with a single Cu–O layer per unit cell \[12\].

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