PHYSICAL REVIEW B **68**, 180504(R) (2003)

Tunneling spectroscopy of $Bi_2Sr_2CaCu_2O_{8+\delta}$: Eliashberg analysis of the spectral dip feature

J. F. Zasadzinski,[1,2] L. Coffey,[1] P. Romano,[3] and Z. Yusof[2]
[1]*Physics Division, Illinois Institute of Technology, Chicago, Illinois 60616, USA*
[2]*High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, USA*
[3]*INFM and Facolta di Scienze, Universita del Sannio, Via Port'Arsa 11, I-82100 Benevento, Italy*

(Received 2 September 2003; published 14 November 2003)

Eliashberg strong-coupling theory, extended to a *d*-wave symmetric gap function, is used to fit quantitatively a published tunneling spectrum of $Bi_2Sr_2CaCu_2O_{8+\delta}$ near optimal doping. The shape, location, and strength of the high-bias spectral dip feature is adequately reproduced using a single-peak $\alpha^2F(\omega)$ centered at 36.5 meV. $\alpha^2F(\omega)$ also self-consistently determines the measured gap value $\Delta = 32$ meV. Possible origins of the bosonic spectrum that give rise to high-T_C superconductivity are discussed.

DOI: 10.1103/PhysRevB.68.180504 PACS number(s): 74.45.+c, 74.50.+r, 74.70.Ad

Tunnel junctions on conventional superconductors such as Pb or Nb exhibit fine structure in the high-bias ($eV > \Delta$) electrical conductance that corresponds to peaks in the phonon density of states $F(\omega)$, thereby giving direct evidence of the electron-phonon mechanism for superconductivity.[1,2] The relationship is made quantitative through Eliashberg strong-coupling theory which allows the fine structure to be "inverted" to obtain the electron-phonon spectral function $\alpha^2F(\omega)$. $\alpha^2F(\omega)$ self-consistently determines basic, low-energy superconducting properties such as the minimum excitation gap for quasiparticles, Δ.[1,2] For high-temperature superconductors (HTS) such as $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212), $Tl_2Ba_2CuO_6$ (Tl2201), and $YBa_2Cu_3O_7$ (YBCO) the only reproducible high-bias tunneling structure is that which is commonly referred to as the dip feature.[3–5] While good arguments have been made to suggest that this feature in Bi2212 is a strong-coupling effect, analogous to the phonon structures of conventional superconductors,[3] a quantitative analysis has been lacking. Consequently, arguments that the dip was a simple background effect, e.g., from the Van Hove singularity (VHS) or pseudogap, were not completely refuted.

Here we demonstrate that the sharp, symmetric dip features found in atomically resolved scanning tunnel microscope (STM) data[6] cannot be treated as a background effect, but more importantly, can be quantitatively understood using Eliashberg theory suitably modified for *d*-wave symmetry. The detailed shape and strength of the dip structure can be fit using a single-peak $\alpha^2F(\omega)$ centered at 36.5 meV, which self-consistently leads to the measured, d-wave, superconducting gap value $\Delta = 32$ meV. This self-consistency cannot be accidental and therefore makes a compelling argument that high-T_C superconductivity can be described within an Eliashberg framework. Possible origins of the bosonic spectrum described by $\alpha^2F(\omega)$ are discussed later, along with comments on dip features found in other cuprate superconductors.

Given the spectacular success of the tunneling method when applied to conventional superconductors, the lack of a similar, quantitative analysis of tunneling spectra in HTS cuprates has been a disappointment. The origins of this failure in cuprates can be traced to several effects, including novel *d*-wave phenomena such as Andreev or virtual bound states which arise from interface or defect scattering[6] and which interfere with the observation of the bulk quasiparticle density of states (DOS). There are also strong doping dependencies of the energy gap[7] which can lead to local variations in spectra. Such effects can lead to a variety of tunneling characteristics and the apparent lack of consistency has caused attention to shift to other spectroscopic methods such as optical conductivity[8] or angle-resolved photoemission (ARPES) (Ref. 9) to search for the pairing mechanism.

However, tunneling remains uniquely capable of directly measuring the quasiparticle DOS with high (<meV) resolution. Also, the tunneling matrix element contains a group velocity term which often provides a fortuitous suppression of band-structure effects.[2,10] Thus recent discoveries in Bi2212 of significant Cu-O bilayer splitting in ARPES,[11] which leads to a double VHS peak in the DOS, are not inconsistent with the apparent weakness of such effects in tunneling data. Furthermore, the improvement in materials, methods, and overall understanding has now led to a high degree of reproducibility among nominally *c*-axis junctions on Bi2212. It has been demonstrated recently[12] that the tunneling conductances obtained on near optimally doped Bi2212 from widely different methods, including atomicallly resolved STM,[6] break junctions,[3,12] and intrinsic *c*-axis junctions,[13] are nearly identical, especially with respect to the location, shape, and magnitude of the spectral dip feature. Thus while our analysis is for a particular, high-quality STM spectrum,[6] it certainly applies to the dip features found on other junctions.[12] Although there have been numerous articles discussing the origin of the tunneling dip feature[9,12,14–16] this work is a quantitative fit of a complete experimental tunneling DOS spectrum using a self-consistent, *d*-wave, Eliashberg formalism.[17]

A published, atomically resolved STM spectrum[6] is reproduced in Fig. 1. The superconducting tunneling conductance (dI/dV versus V) exhibits sharp coherence peaks, a *d*-wave-like subgap region, and clear dip features (for both voltage polarities), all on top of a sloping background. There are two basic approaches to analyzing such data. One approach attempts to fit the background and superconducting effects together.[10] This requires knowledge of the electronic band structure and tunneling matrix element, the latter of which is difficult to ascertain. The approach taken here, as in conven-

 ©2003 The American Physical Society

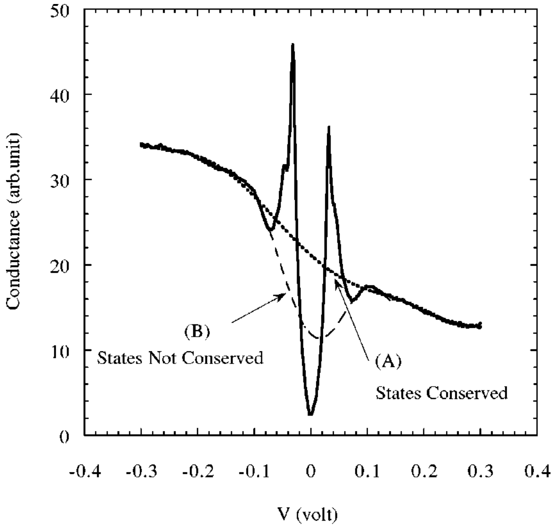

FIG. 1. STM tunneling data (solid line) on Bi2212 from Ref. 6. States-conserving normal-state curve *A* (short-dashed line) and non-states-conserving normal-state curve *B* (long-dashed line).

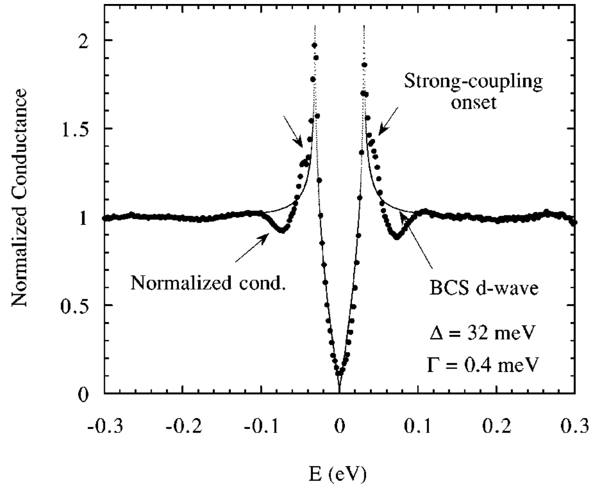

FIG. 2. Normalized tunneling conductance data (dots) from Fig. 1 using curve *A*. Solid line is a BCS *d*-wave DOS for comparison.

tional tunneling spectroscopy,[1,2] is to normalize out all background effects leaving only that part of the DOS which arises solely from superconductivity. Here the background must be inferred. A reasonable guess is possible because in the rare cases where direct measurements have been made far above T_C, the tunneling background shape in Bi2212 was found to be smoothly and weakly varying.[13] Recognizing that for increasingly higher-bias voltages the superconducting and normal-state conductances must merge, the full background shape can be estimated by selecting only the data for $|V| \geqslant V_C$, and smoothly interpolating between these data points. Here V_C is an arbitrary cutoff voltage chosen to ensure that conservation of states holds.

Two background conductances are shown in Fig. 1 and are labeled as *A* and *B*. Curve *A* (short dashed line) is achieved by choosing a cutoff, $V_C = 100$ meV and using a sixth-order polynomial fit of the selected data. Note that conservation of states is apparent with curve *A*, i.e., the spectral weight of the superconducting data above curve *A* is balanced by the weight below. Importantly, the superconducting conductance drops below the normal state at the dip voltages, which is consistent with direct measurements[13] and with other STM data using a similar normalization procedure.[18] Curve *B* in Fig. 1 is an example of a background that results when the dip features are assumed to be part of the normal-state spectrum, e.g., from an extrinsic pseudogap. A cutoff $V_C = 70$ meV is chosen (the dip minimum) along with a similar polynomial fit. Curve *B* indeed exhibits a strong suppression near zero bias, but it is immediately obvious that this type of normal state will not lead to conservation of states. The spectral weight of the experimental data above curve *B* far exceeds the weight below. More sophisticated models that attempt to fit the data of Fig. 1 directly using the band structure[10] and an extrinsic pseudogap lead to similar inconsistencies and indicate that the dip features are not due to any type of normal-state effects.

The normalized conductance achieved by dividing the data of Fig. 1 by curve *A* is shown in Fig. 2 where it is compared with a BCS *d*-wave DOS using a maximum *d*-wave gap value of $\Delta = 32$ meV, a small scattering rate $\Gamma = 0.4$ meV, and a tunneling weighting factor $\alpha = 0.4$ as described in Ref. 20. The BCS DOS provides an excellent fit of the subgap region as well as the conductance peaks and the gap magnitude is consistent with Bi2212 being slightly overdoped.[7] The dip features are nearly symmetric in the normalized conductance as is found in two other STM studies of Bi2212 (Refs. 5,18) for various doping concentrations. This firmly establishes the symmetry of dip features in the quasiparticle DOS in defect-free regions of Bi2212 crystals. The strong asymmetry of dip strength found in large-area, point-contact tunneling spectra[7] is most likely associated with parallel tunneling contributions from Bi2212 regions that contain defects. The STM conductance spectra from disordered regions exhibit a peak only at positive bias voltages and the transition region between clean and disordered clearly show an asymmetric dip.[19]

The integrated area of the data of Fig. 2 out to 300 meV conserves states to within 1% of the BCS DOS. This occurs because the negative deviation of the dip feature from the BCS fit is balanced by the pileup near the gap edge and at the higher-energy hump which is a characteristic signature of strong-coupling effects as found in conventional superconductors.[1,2] A particular feature of these STM data is noted by the top arrows in Fig. 2, which indicate the onset of strong-coupling effects, i.e., the voltage where the data begin a significant positive deviation from the weak-coupling, BCS fit. We believe this feature is a key experimental discovery,[21] for it signals the threshold of quasiparticle lifetime effects and, as found in some of the earliest studies of strong-coupled superconductivity,[22] it indicates that the underlying boson spectrum is a relatively narrow band of excitations.

The result of a *d*-wave Eliashberg analysis of the data[23] is shown in Fig. 3. Conventional application of Eliashberg theory to phonon mediated *s*-wave superconductors[22] results in a pair of coupled equations for the complex valued, energy

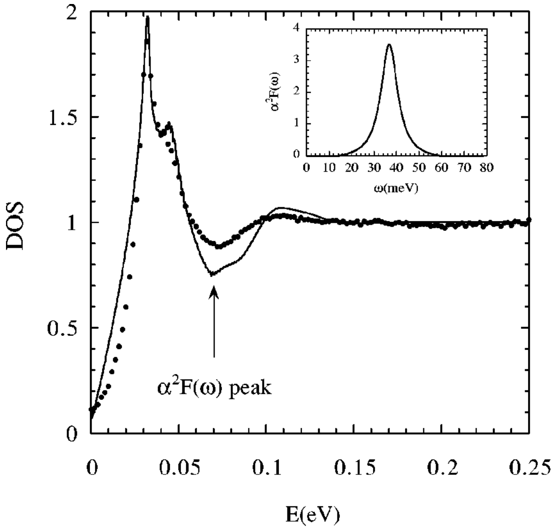

FIG. 3. Positive bias normalized conductance data (dots) from Fig. 2 compared with *d*-wave Eliashberg fit (solid line). Arrow shows the location of the $\alpha^2F(\omega)$ peak as measured with respect to the gap edge (conductance peak). Inset: the $\alpha^2F(\omega)$ spectrum used in the Eliashberg analysis to fit the tunneling data.

dependent gap $\Delta(\omega)$ and renormalization $Z(\omega)$. To extend this approach to *d*-wave symmetry superconductors, the present work assumes an energy dependent $Z(\omega)$ and an energy dependent, *d*-wave symmetry superconducting gap given by $\Delta(\omega)\cos(2\phi)$. The conventional phonon spectral function is replaced with one that is consistent with *d*-wave symmetry, namely,

$$\alpha^2F(\phi-\phi',\omega)=(c_S+c_D\cos[2(\phi-\phi')])\alpha^2F(\omega). \quad (1)$$

A single-peak Lorentzian function is chosen for $\alpha^2F(\omega)$ and is adjusted to fit the data. With no further assumptions, two coupled equations result for $Z(\omega)$ and $\Delta(\omega)$.[23] The presence of the *s*-wave channel c_S results in a nontrivial, energy dependent $Z(\omega)$. The choice of values for c_S and c_D is guided by the analysis of Ref. 24 which indicates that the pairing interaction in Eq. (1) will lead to a pure *d*-wave symmetry state provided c_S is kept small relative to c_D. The main challenge is not just to produce a dip feature, which has been demonstrated in the high-T_C literature in the past, but to fit, quantitatively, all the main features of the measured tunneling conductance: the shape and position of the main density-of-states peak, strong-coupling onset features indicated by the top arrows in Fig. 2, and the precise position of the dip and higher-energy hump on the tunneling density of states.

The overall shape, location, and magnitude of the tunneling spectral dip feature are adequately reproduced using $\alpha^2F(\omega)$ shown in the inset of Fig. 3, along with coupling factors $c_S=0.14$ and $c_D=1.0$. This leads to a conventional coupling constant $\lambda=2.2$. Most importantly, $\alpha^2F(\omega)$ generates the correct magnitude of the *d*-wave gap, $\Delta=32$ meV, given by the position of the conductance peak.[25] The conductance peak height and shape are fit quite well. Furthermore, the onset feature indicated by the arrows in Fig. 2 is present at the same bias voltage in the Eliashberg analysis, providing additional support for the present interpretation of the experimental data. This onset arises from the low-frequency threshold in $\alpha^2F(\omega)$ near 15 meV. The self-consistency between the dip structure and the gap magnitude cannot be accidental. Spectral features arising from spurious or extrinsic effects (e.g., improper normalizations) would have arbitrary shapes and magnitudes incompatible with self-consistent, strong-coupling theory. The ability to fit the entire tunneling spectrum provides compelling evidence that the superconductivity of Bi2212 can be described within an Eliashberg framework.[26] Improvements in the fit can likely be obtained by finetuning the boson spectrum line shape. One possibility is to put a high-energy tail into $\alpha^2F(\omega)$.[8]

The above analysis does not explain the nature of the bosonic excitations described by $\alpha^2F(\omega)$. The centroid of the spectral function is at $\omega_R=36.5$ meV which is close to that of the resonance spin excitation found in neutron-scattering studies[27] of slightly overdoped Bi2212 (38 meV). The characteristic widths are comparable as well. While such agreement is striking, the possibility must be considered that $\alpha^2F(\omega)$ corresponds to other excitations such as optical-mode phonons. An important feature of this *d*-wave Eliashberg analysis may provide some clues. Note that the position of the dip minimum, indicated by the arrow in Fig. 3 occurs at a bias voltage $eV=\Delta+\omega_R$. Recent studies of the shift of the dip minimum with doping show that ω_R follows the doping dependence of the resonance mode, providing additional support that spin excitations are the cause of superconductivity.[3,12]

Turning to related issues, tunneling dip features are also observed in YBCO (Ref. 5) and Tl2201.[4] Estimating ω_R in YBCO from Ref. 5 leads to a value of 25–30 meV, significantly below the resonance mode energy of 41 meV. However, the tunneling gap magnitude in YBCO (20–25 meV) is also much smaller than that found in optimal doped Bi2212.[7] Conductance spectra on Tl2201 are consistent with those found on overdoped Bi2212 including gap values in the range 20–25 meV.[4] Until the origins of the smaller tunneling gaps in YBCO and Tl2201 relative to Bi2212 are resolved and/or a full Eliashberg analysis is attempted, it is premature to draw conclusions from these studies.

In summary, we have shown that symmetric tunneling dip features, reproducibly observed in Bi2212 junctions, are not a consequence of a pseudogap or other normal-state phenomena but can be explained as strong-coupling effects within a *d*-wave Eliashberg model. The bilayer split VHS peaks below the Fermi energy[28] are not observed indicating that the tunneling matrix element may have suppressed these features. The tunneling DOS exhibits a BCS *d*-wave shape in the gap region and a distinct strong-coupling onset. Along with the dip feature, these effects indicate that the boson spectrum is a relatively narrow band of excitations with zero weight at low energies. A single-peak $\alpha^2F(\omega)$ centered at 36.5 meV adequately reproduces all aspects of the dip feature and self-consistently leads to the measured gap value.

The authors would like to thank S.H. Pan for providing the experimental data used in this analysis.

[1] W.L. McMillan and J.M. Rowell, in *Superconductivity*, edited by R.D. Parks (Dekker, New York, 1969), pp. 561–613.

[2] E.L. Wolf, *Principals of Electron Tunneling Spectroscopy* (Oxford University Press, Oxford, 1985).

[3] J.F. Zasadzinski *et al.*, Phys. Rev. Lett. **87**, 067005 (2001).

[4] J.F. Zasadzinski *et al.*, Physica E (Amsterdam) **341C–348C**, 867 (2000).

[5] T. Cren, D. Roditchev, W. Sacks, and J. Klein, Europhys. Lett. **52**, 203 (2000).

[6] E.W. Hudson, S.H. Pan, A.K. Gupta, K.-W. Ng, and J.C. Davis, Science **285**, 88 (1999).

[7] N. Miyakawa *et al.*, Phys. Rev. Lett. **83**, 1018 (1999).

[8] J.P. Carbotte, E. Schachinger and D.N. Basov, Nature (London) **401**, 354 (1999).

[9] M. Eschrig and M.R. Norman, Phys. Rev. Lett. **85**, 3261 (2000); M.R. Norman *et al.*, *ibid.* **79**, 3506 (1997).

[10] Z. Yusof, J.F. Zasadzinski, L. Coffey, and N. Miyakawa, Phys. Rev. B **58**, 514 (1998).

[11] A.A. Kordyuk *et al.*, Phys. Rev. B **66**, 014502 (2002); D.L. Feng *et al.*, *ibid.* **65**, 220501 (2002).

[12] J.F. Zasadzinski *et al.*, J. Phys. Chem. Solids **63**, 2247 (2002).

[13] A. Yurgens *et al.*, Int. J. Mod. Phys. B **29–31**, 3758 (1999).

[14] D. Coffey and L. Coffey, Phys. Rev. Lett. **70**, 1529 (1993); Y.M. Nie and L. Coffey, Phys. Rev. B **59**, 11982 (1999).

[15] A.S. Alexandrov and C. Sricheewin, Europhys. Lett. **58**, 576 (2002).

[16] Ar. Abanov and A.V. Chubukov, Phys. Rev. Lett. **83**, 1652 (1999).

[17] Previous studies of *d*-wave Eliashberg equations have utilized a model $\alpha^2F(\omega)$ obtained from *s*-wave analyses of relatively broad SIS spectra. See G.A. Ummarino and R.S. Gonnelli, Physica C **328**, 189 (1999). The STM data here are much sharper and the DOS is fit directly.

[18] Y. DeWilde *et al.*, Phys. Rev. Lett. **80**, 153 (1998).

[19] T. Cren, D. Roditchev, W. Sacks, J. Klein, J.B. Moussy, C. Devilla-Cavillin, and M. Lagues, Phys. Rev. Lett. **84**, 147 (2000).

[20] L. Ozyuzer, J.F. Zasadzinski, C. Kendziora, and K.E. Gray, Phys. Rev. B **61**, 3629 (2000).

[21] Upon closer examination of other published STM data (Ref. 18) a similar onset feature can be found in several of the Bi2212 tunneling spectra for different doping levels.

[22] J.R. Schrieffer, D.J. Scalapino, and J.W. Wilkins, Phys. Rev. Lett. **10**, 336 (1963).

[23] L. Coffey, cond-mat/0103518 (unpublished).

[24] K.A. Musaelian, J. Betouras, A.V. Chubukov, and R. Joynt, Phys. Rev. B **53**, 3598 (1996).

[25] The poorer agreement
in the subgap region compared with the
BCS fit in Fig. 2 is due to the tunneling weighting factor (Ref. 20), which was not included in this strong-coupling analysis. We note that the subgap shape might be due to small deviations of the momentum dependent gap from the $\cos 2\phi$ form (Ref. 11).

[26] A similar *d*-wave Eliashberg model was used to fit optical conductivity in YBCO [S.V. Shulga, in *Shape High-T_c Superconductors and Related Materials*, edited by S.-L. Drechsler and T. Mishonov, NATO Science Series 3—High Technology Vol. 86 (Kluwer, Dordrecht, 2002); S.V. Shulga cond-mat/0101243 (unpublished)] however the resulting boson spectrum was not unique. Using a phonon spectrum resulted in strong-coupling effects in the gap region (reduced peak height) which are not observed in these Bi2212 tunneling data.

[27] H. He *et al.*, Phys. Rev. Lett. **86**, 1610 (2001).

[28] M. Eschrig and M.R. Norman, Phys. Rev. Lett. **89**, 277005 (2002).