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Temperature and field dependence of the intrinsic tunnelling structure in overdoped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

T. M. Benseman, J. R. Cooper, and G. Balakrishnan

1Physics Department, Cavendish Laboratory, University of Cambridge, J.J. Thomson Avenue, CB3 0HE, United Kingdom
2Department of Physics, University of Warwick, CV4 7AL, United Kingdom

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We report intrinsic tunneling data for mesa structures fabricated on three over- and optimally-doped Bi$_{2+\delta}$Sr$_{1.85}$CaCu$_2$O$_{8+\delta}$ crystals with transition temperatures of 86–78 K and 0.16–0.19 holes per CuO$_2$ unit, for a wide range of temperature ($T$) and applied magnetic field ($H$), primarily focusing on one overdoped crystal (OD80). The differential conductance above the gap edge shows a clear dip structure which is highly suggestive of strong coupling to a narrow boson mode. Data below the gap edge suggest that tunnelling is weaker near the nodes of the $d$-wave gap and give clear evidence for strong $T$-dependent pair breaking. These findings could help theorists make a detailed Eliashberg analysis and thereby contribute towards understanding the pairing mechanism. We show that for our OD80 crystal the gap above $T_c$, although large, is reasonably consistent with the theory of superconducting fluctuations.

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I. INTRODUCTION

Despite intensive and wide-ranging research in the past thirty years, detailed understanding of the fundamental physical properties of high temperature cuprate superconductors, especially the pairing mechanism, remains elusive. Much of the microscopic information about their fascinating electronic properties comes from surface probes such as angle-resolved photoemission (ARPES) [1] and scanning tunneling microscopy (STM) [2–4], while in the past decade measurements of transport, e.g., Ref. [5] and structural properties, e.g., Refs. [6,7] in extremely high magnetic fields have also been fruitful. It is important to verify the results of the surface probes by bulk measurements whenever possible. For many years it has been known that mesa structures fabricated from highly anisotropic high-$T_c$ superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi-2212) may be regarded as stacks of planar “intrinsic tunnel junctions” (ITJs) connected in series, and their $I$-$V$ characteristics correspond to $c$-axis, superconductor-insulator-superconductor ($SIS$) tunneling spectra [8]. Planar geometry was used for the groundbreaking tunneling work on classical superconductors [9] and tunneling in planar ITJs may be easier to understand than in break junctions [10–12] where different junctions may sample different regions in $k$ space. Furthermore one of us has argued [13] that in STM studies the tunneling probability may have significant $k$ dependence. A longer term goal of the present work is to understand the structure we observe above the gap edge and see whether it can be analyzed using Eliashberg theory [14,15] to give direct information about a pairing boson. It will also be important to compare any such results with Eliashberg analysis of the optical reflectivity [15] which can be performed over a much wider energy range. In the present paper we do not attempt this but report high quality ITJ data and highlight some unexpected findings regarding the temperature ($T$), voltage ($V$), and magnetic field ($H$) dependence of the tunneling characteristics observed.

In an earlier report [16] we showed experimental data for ITJs fabricated on two overdoped single crystals of Bi-2212 with $T_c$ values of 80 and 78 K, denoted OD80 and OD78, and an optimally doped crystal, OP86 with $T_c = 86$ K. Tunnelling results for the latter crystal and others with hole concentrations $p < 0.19$ per CuO$_2$ unit are probably complicated by the presence of the pseudogap and also of charge density waves that have been observed for both Bi-2212 [3,4] and YBa$_2$Cu$_3$O$_{6+\delta}$ (YBCO) with $x$ between 0.45 and 0.93 [17].

Here we focus more on OD80, so our data are complementary to a recent ITJ study [18] dealing with moderately and slightly undoped Bi-2212 crystals that do have a pseudogap. Our interpretation is different in that we suggest that in OD80 the clear $T$-dependent structure above $2\Delta_0$, where $\Delta_0(T)$ is the superconducting gap at the antinodes, could arise from coupling with pairing boson(s) and not from the pseudogap. For such overdoped crystals ARPES [1] and STM [3] data gives evidence for a large Fermi surface and no pseudogap at low $T$, which is in agreement with bulk probes such as specific heat [19], static magnetic susceptibility [19,20], and measurements of the London penetration depth [21,22]. In our tunneling data for OD80 there is evidence for a gap persisting above $T_c$, which we argue that it is consistent with the microscopic theory [23] of superconducting fluctuations based on the Ginzburg-Landau free energy expansion, with relatively small values of the Ginzburg temperature, $\tau_G$.

II. METHODS

Single crystals of Bi-2212 were grown using a traveling solvent floating zone furnace and feed rods with nominal stoichiometry of Bi$_{2.15}$Sr$_{1.85}$CaCu$_2$O$_{8+\delta}$. These have a maximum $T_c$ of 86.5 K measured by SQUID magnetometry before
FIG. 1. Typical I-V curves for the three mesas at low bias voltages. Red points show data taken at 10 K while increasing I to an appropriate maximum value and then decreasing it. This generates a series of curves in which, from left to right, the Josephson currents of an increasing number of junctions are suppressed because there is a finite voltage across them. The blue lines show fits of the form \( I = m_1 V + m_2 V^3 + m_3 V^5 \) to the \((N - 1)\)th curve. The coefficients \(m_1, m_2, \) and \(m_3\) are then scaled by \([\frac{(N - 1)}{n}]i\) where \(i = 1, 3, \) and \(5\), respectively, and \(n\) is an integer between 1 and \(N\). Differences between the red data points and the blue lines give an indication of possible nonuniformity in junction areas, or more likely, their resistances.

fabrication of the mesas, and we infer \(p\) from the empirical relation [24] \(T_c = T_c^{\text{max}}(1 - 82.6(p - 0.16)^2)\), finding \(p = 0.194, 0.191, \) and 0.16 for the three crystals studied. For OD80, \(T_c\) measured by SQUID magnetometry agrees to within 1 K with the temperature where \(2\Delta_0(T)\), defined by the maxima in \(dI/dV\) curves and shown in Fig. 6(b), reaches its minimum value of 34 meV. For OD78 and OP86, the minima in \(2\Delta_0(T)\) are 2 K and 6 K lower than \(T_c\) values from SQUID magnetometry. The 6 K discrepancy for OP86 is probably caused by the presence of the pseudogap. This is not a problem because in Fig. 2(a) the values of \(dI/dV\) at high \(V\) show that the doping level of mesa OP86 is significantly less than that of OD80, while that of OD78 is slightly larger, in qualitative agreement with \(p\) values obtained from SQUID magnetometry. Typical I-V characteristics for the three mesas at small bias, taken while sweeping the current up and down in a controlled manner at 10 K, are shown in Fig. 1. The branches correspond to different numbers of Josephson junctions being switched into the resistive state. Switching to another branch occurs when the critical (Josephson) current of a particular junction is exceeded and a voltage develops across it. The computer-controlled current is then swept down to a finite value before being increased again. When \(I\) is large enough, all Josephson currents are suppressed, there are no further jumps in \(V\), and the extreme right hand red curves, extending to the largest values of \(V\), are obtained. The number of junctions \((N)\) in the stack is equal to the total number of branches observed. As shown in Fig. 1, these branches scale on to each other to a large extent, confirming that the junctions in the mesa have uniform area, and therefore all junctions switched to the resistive state will have the same voltage bias.

However variations in resistance at the level of 10–15% do have significant effects on the magnitude of the structure in \(dI/dV\) above the gap edge. This is a prime cause of a certain lack of reproducibility in this structure, e.g., between data for OD80 and OD78 in Ref. [16] and shown later in Fig. 2(a)
The power dissipation per unit area in HTS mesa structures is large, sometimes resulting in extreme distortion of \( I - V \) curves by self-heating effects and consequent obliteration of any weak features in \( dI/dV \). Zhu et al. [27] have studied mesa structures in near-optimally doped Bi-2212 containing \( N = 10-11 \) junctions in series, finding that there is little heating-induced distortion of the \( I - V \) characteristic only when the mesa area \( A \) is \( \cong 1 \ \mu m^2 \) or less. Here all three mesas have \( N = 10 \), the OD78 and OD80 mesas have \( A \) below this limit while OP86, although larger, has twice the resistivity above \( T_c \). A high level of oxygen homogeneity in the mesa is necessary to ensure that any structure in \( dI/dV \) is observed. To avoid possible problems with ion milling [28], we fabricate our mesas solely by chemical wet etching [26]. Finally, irrespective of the size of the mesas, there is a possibility of electron heating. For a given \( V \) this will not depend on \( N \) or \( A \) but only on the electrical resistance of the junction per unit area and the thermal resistance for heat transfer between quasiparticles and phonons. We can rule this out for the OD80 mesa in Fig. 7 because the structure at higher \( V \) continues to evolve between 10 and 1.4 K.

### III. Basic Theoretical Background

The origin of the pairing mechanism in cuprate superconductors continues to attract the attention of many talented condensed matter theorists. We hope that some of the points made here will contribute towards their understanding of this problem. Within the simple “semiconductor” picture for \( SI S \) tunneling [9] and writing the matrix element for tunneling from k-space angle \( \theta_1 \) in electrode 1 to angle \( \theta_2 \) in electrode 2 as \( M_{\theta_1 \theta_2} \), the expression for the tunnel current between two identical electrodes is given by:

\[
I(V) = \int_0^{2\pi} \int_0^{2\pi} \int_{-\infty}^{\infty} |M_{\theta_1 \theta_2}|^2 N(E,\theta_1) N(E-eV,\theta_2) 	imes \{ f(E-eV) - f(E) \} dE d\theta_1 d\theta_2, 
\]

where \( E \) is the energy of a Bogoliubov quasiparticle measured from the Fermi energy, \( N(E,\theta) \) is the angle-dependent quasiparticle density of states (DOS) whose form in the Dynes approximation [29] is given in Eq. (2), and \( f \) is the Fermi function. As explained in Ref. [30] a distinction needs to be made between incoherent tunneling where the in-plane component of \( k \) is not conserved and coherent tunneling where it is approximately conserved, see Ref. [31]. For incoherent tunneling \( |M|^2 \) can be taken outside the integral and \( I \) is given by the product of two angular integrals of the density of states factors. For coherent tunneling \( |M|^2 \) is constant to illustrate the contrast with incoherent tunneling shown in Fig. 2(a). It has been argued [30] that in the coherent case the antinodal states completely dominate the overall \( G(V) \equiv dI/dV \) curves. We think this viewpoint needs further evaluation because it depends on the presence of a substantial antinodal Van Hove singularity deduced [30] from ARPES studies, which as pointed out by Loram [33] may not be not consistent with the weak \( T \) dependence of the paramagnetic susceptibility [19,20]. In later discussion, for simplicity, we consider a cylindrical Fermi surface for which there is no Van Hove singularity. Previous work on ITJs [34–36] also concluded that there was a certain amount of coherent tunneling, but only at the level [34] of 10%.

---

**FIG. 2.** (a) Log-log plots of \( dI/dV \) curves measured for the three mesas at 1.4 K in zero magnetic field when sweeping \( I \) down from its maximum value. The green curve agrees with an earlier calculation [25] and shows that purely incoherent tunneling gives completely different behavior. (b) \( dI/dV \) for mesa OD80 at 1.4 K in 0 and 13 T fields after normalizing to the normal state conductance. The solid black curve corresponds to a normalized coherent part calculated from Eqs. (1) and (2) with \( M^2 \propto (\cos 2\theta)^4 \), and multiplied by 0.8 plus a normalized incoherent part multiplied by 0.2. It gives a good description of the data below \( V = \Delta_0 \) after adding a small residual term, 0.012, to \( G(V)/G_N(V) \). The longer and shorter dashed curves show the calculations for purely coherent tunneling with \( M^2 \) constant and \( M^2 \propto (\cos 2\theta)^4 \), respectively.

as well as for underdoped mesas [26]. Mesa \( dI/dV \) spectra [26] were measured as the bias current was swept down from its maximum value towards zero, thereby maintaining the resistive state. A lock-in technique with a small 77.7 Hz current modulation was employed, although standard \( I - V \) curves were recorded simultaneously.

The power dissipation per unit area in HTS mesa structures is large, sometimes resulting in extreme distortion of \( I - V \) curves by self-heating effects and consequent obliteration of any weak features in \( dI/dV \). Zhu et al. [27] have studied mesa structures in near-optimally doped Bi-2212 containing \( N = 10-11 \) junctions in series, finding that there is little heating-induced distortion of the \( I - V \) characteristic only when the mesa area \( A \) is \( \cong 1 \ \mu m^2 \) or less. Here all three mesas have...
The theoretical curves in Fig. 2 were obtained using the Dynes formula [29] for \( N(E, \theta) \) of a d-wave superconductor, namely:

\[
N(E, \theta) = n(0, \theta) \text{Re} \left[ \frac{|E| - i \Gamma}{\sqrt{|E| - i \Gamma)^2 - (\Delta_0 \cos \theta)^2}} \right].
\]

(2)

Here \( \Gamma \) is the Dynes damping factor and \( n(0, \theta) \) is the normal state DOS per unit energy per spin per radian at the Fermi energy. For an isotropic, cylindrical Fermi surface, \( n(0, \theta) = n(0)/(2\pi) \), where \( n(0) \) is the normal state DOS per unit energy per spin. The Dynes formula was originally used to extract the lifetimes (recombination rates) of excited quasiparticles in classical superconductors [29] from the \( T \)-dependent broadening of tunneling curves. It is somewhat different from the classical superconductors [29] from the time dependence of tunneling curves. It is somewhat different from the classical superconductors [28] and from the pair-breaking formula [29] for the three mesas obtained from the latter \( m_1 \) values, i.e., straight line fits to \( IV \) vs \( V^2 \), is shown later in Fig. 4. It can be seen that all three mesas are consistent with \( G(0)/G(0) = 0.012 \pm 0.001 \) at \( H = 0 \). It is interesting to compare this with the normalized DOS 0.138/1.2 = 0.115 ± 0.005 obtained from the low \( T \) specific heat data for Bi-2212 in Ref. [39], where the specific heat coefficient \( \gamma = 0.138 \) mJ/gK2, and the estimated normal state value \( \gamma_n = 1.2 \) mJ/gK2 at \( T \) given in Ref. [19]. This value is also consistent with microwave conductivity data on two optimally doped Bi-2212 crystals [40], which showed a residual normal fluid fraction of 0.11 and 0.12 for the simpler (Drude) analysis, or alternatively 0.15 and 0.16 for a non-Drude one, as well as with various heat capacity studies of YBCO [41–43]. However in response to a suggestion from one of the referees we have also fitted data for the lowest voltage branches of the \( I-V \) curves shown in Fig. 1 to \( I/V = \alpha + \beta V^2 \) and compared the coefficients \( \alpha \) and \( \beta \) with \( m_1 \) and \( m_2 \) obtained on downward sweeps when all 10 junctions are resistive. Details for the three mesas are given as a table in the Supplemental Material [44], where it can be seen that \( m_1 \) and \( m_2 \) are systematically 20–40% larger than \( \alpha \) and \( \beta \). It is not clear at present whether this represents an interesting physical effect or whether it could arise from an unwanted extra conductance path (with a resistance of \( \leq 0.4 \) MΩ) in parallel with the 10 junctions. In either case it implies that the residual conductances estimated from our tunneling data are 20–40% too high. This does not change our overall conclusions since the discrepancies we discuss later are much larger. Also our \( T \)-dependent data are in good agreement with break junction work, for example Fig. 1 of Ref. [12]. This rules out possible effects from a parallel conductance path with a strong \( T \) dependence that were suggested by one referee.

In the following we consider 0.16 and 0.11 as upper and lower limits to the residual DOS obtained from heat capacity and microwave studies. Previously we ascribed [16] this residual term to pairs being broken around the nodes. But it is ruled out within the Dynes formulation used here because for a cylindrical Fermi surface with a residual DOS, \( \delta n(0)/n(0) \), in the range 0.11 to 0.16, there would have to be broken...
pairs over an angular range $\pm \alpha$ around each node with $\alpha$ ranging from 5 (0.11 $\times$ 45) to 7.2 (0.16 $\times$ 45) degrees. With $M^2 \propto (\cos 2\theta)\sqrt{\sin(2\alpha)}$ there is a large attenuation factor given by $\int_0^{\pi/4} \sin(2\alpha) d\alpha / \int_0^{\pi/4} \sin(2\alpha) d\alpha$, which ranges from 0.52 to $3.3 \times 10^{-4}$ for these values of $\alpha$. The contribution from incoherent tunneling between nodes would be larger, ranging from $(0.11)^2 \times 0.2$ to $(0.16)^2 \times 0.2$, but still a factor of 5 to 2 smaller that our experimental value of $G_{xx}(0)/G_N(0) = 0.012$. The above estimates lead to the conclusion that the residual conductance, specific heat, and unpaired electron states are associated with non-nodal regions. They must have larger values of $\Gamma$, but are not necessarily completely normal, and seeing them in ARPES data might be hampered by the bilayer splitting. One intriguing possibility is that they are associated with the “hot spots” wave vector $Q = (\pi/a, \pi/a, 0)$ spans the Fermi surface. Namely electron states separated by $Q$ are (a) strongly scattered by spin fluctuations and (b) must themselves combine in order to give rise to spin fluctuations at this wave vector, in the same way that electron states separated by a nesting vector combine to give a charge or spin density wave. We note that the residual specific heat of YBCO crystals is very similar to those of coherence so we are justified in neglecting it.

However high-quality mesa data taken over 18 years ago [34] and analyzed theoretically [34–36] was interpreted in terms of pair breaking at the nodes. In this theory, in the completely coherent limit, broken pairs near the nodes give a quasiparticle conductivity at zero bias given by:

$$\sigma_q = 2(e^2/\hbar) t_N^2 N(0) s/(\pi \Delta_0).$$

Here, in the notation of Ref. [34], $t_N$ is the $c$-axis tunneling parameter at the nodes, $N(0)$ is the 2D carrier DOS per spin direction in the normal state, and $s = 15.2 \times 10^{-8}$ cm is the interlayer spacing. In Ref. [34] the additional incoherent contribution to $\sigma_q$ was found to be negligible for much smaller levels (10%) of coherence so we are justified in neglecting it here. In contrast to the Dynes formulation, the scattering rate does not affect $\sigma_q$ because of cancellation between an increase in DOS near the nodes caused by scattering and a decrease in the tunneling probability associated with the broadening of the quasiparticle spectral function $A(k, E)$. This tunneling probability effect is absent in Eq. (1). Experimentally $\sigma_q$ is in the range 1–3 (k$^2$/cm)$^2$, as indeed it is in our mesa, specifically $\sigma_q = 1.6$ (k$^2$/cm)$^2$ for OD80. However in contrast to Ref. [34] we believe that $t_N$ must be angle dependent, because setting $\sigma_q = 1.6$ (k$^2$/cm)$^2$ in Eq. (3) gives a very low value for $\langle t_N^2 \rangle = 8.4 \times 10^{-4}$ meV$^2$, which is much smaller than what is expected from the electronic resistivity and its anisotropy at 300 K, $\rho_{ab} = 0.22$ m$\Omega$ cm and $\rho_c = 1.8$ $\Omega$ cm [20,45]. Work on anisotropic organic conductors [45,46] suggests that in situations where the in-plane conductivity is described by the usual band theory and the out-of-plane conductivity is via tunneling, the formula for resistivity anisotropy ($A$) is the same [47] to within a factor 2, as that given by standard Boltzmann transport theory, namely $A = (v^2_{1})/(v^2_{2})$, where $v_1$ and $v_2$ are the in- and out-of-plane Fermi velocities, respectively. Taking the Fermi surface of Bi-2212 to be a warped cylinder with tight-binding dispersion in the $c$ direction, using $v_1 = 1.6 \times 10^7$ cm/sec and $A = 8200$ gives $\langle t_N^2 \rangle = 0.28$ meV$^2$. There is some uncertainty here because our mesa data gives larger values of $\rho_c = 8.1$ $\Omega$ cm at 300 K, corresponding to $\langle t_N^2 \rangle = 0.064$ meV$^2$.

The large difference between the value of $\sigma_q$ given by Eq. (3) for $\sigma_q = 1.6$ (k$^2$/cm)$^2$ and the value from the resistivity anisotropy at 300 K is consistent with $M$ being highly anisotropic. But as mentioned already, for a cylindrical Fermi surface with a residual DOS between 0.11 and 0.16, the attenuation from the $M^2 \propto (\cos 2\theta)^3$ factor ranges from $5.2 \times 10^{-5}$ to $3.3 \times 10^{-4}$. So even for the larger value $\langle t_N^2 \rangle = 0.28$ meV$^2$, $\sigma_q$ given by Eq. (3) is still a factor of 58 to 9 too low. To summarize, if we apply Eqs. (1) and (2) then we would conclude that the residual conductivity and DOS mainly arises from low-energy states well away from the nodes, a conclusion hinted at in $H$-dependent specific heat work [41]. Further evidence against significant pair breaking near the nodes comes from ARPES data for OD80, for example from Fig. 2(c) of Ref. [1] we estimate that any quasinormal region is less than $\pm 3$ degrees around each node. More calculations may be needed regarding broken pairs near the nodes because in Ref. [34] the data were analyzed in terms of strong (resonant) scattering and a large pair breaking parameter $\gamma \sim 0.1 \Delta_0$. There is evidence from subsequent microwave studies [40] that weaker, small-angle scattering from out-of-plane defects may be dominant in Bi-2212 crystals.

We note that the structure above the gap edge for OD78 and OP86 in Fig. 2(a) is smaller than for OD80. We suggest that this is not an intrinsic effect, namely it arises from small (10%) variations in the resistance of junctions within a stack. As can be seen from Fig. 1, several of the red $I$-$V$ curves for OP86 and OD78 have lower values of $\Delta$ than the blue scaled curves for the same values of $V$, i.e., their resistances are at least 10% higher. Figure 3 shows that if three junctions out of 10 have 10% higher resistance then this nonuniformity has a strong effect on the depth and shape of the dip above the gap. We believe that this is the main reason for a certain lack of reproducibility in this structure from one ITJ to another [16,26].

IV. MAGNETIC FIELD DEPENDENCE

A. At zero bias

The quasiparticle DOS produced by a magnetic field in a $d$-wave superconductor at low $T$, is predicted [48] to be $N(H) \sim n(0)[H/H_c(0)]^{1/2}$, where $H_c(0)$ is the upper critical field as $T \to 0$ and $n(0)$ is the electronic DOS at the Fermi energy in the normal state. This pair breaking effect arises from Doppels shifts in the energies of $+k$ and $-k$ states caused by the superfluid flow around the vortices in the vortex state. For low $H$, pairs are broken near the nodes, where the superconducting gap is small, but the region widens as $H$ is increased. The effect is seen in heat capacity studies of YBa$_2$Cu$_3$O$_7$ crystals, for example Ref. [41]. We estimate $H_{c2} \parallel c$ for OD80 using the clean limit formula $H_{c2} \parallel c = 0.59 \Phi_0/[2 \pi \xi_{ab}(0)^2]$ given in Ref. [23], where $\Phi_0$ is the flux quantum for pairs and $\xi_{ab}(0)$, the in-plane superconducting coherence length as $T \to 0$, equals $h v_F/|\pi \Delta(0)|$. Here $v_F$ is the Fermi velocity and $\Delta(0)$ the superconducting gap parameter as $T \to 0$. We estimate $v_F = 1.58 \pm 0.12 \times 10^7$ cm/sec by applying a simple
The cylindrical Fermi surface model to quantum oscillation data [49] for overdoped Tl2201 crystals for which the doping-independent effective mass is 5.2 ± 0.4$m_r$. Taking the measured value $\Delta(0) = 26.9$ meV at the antinodes for our OD80 Bi-2212 mesa, and applying the above formulas, which may contain extra constants of order unity for $d$-wave rather than $s$-wave pairing, gives $\xi_{dd}(0) = 12.3 \pm 0.9 \times 10^{-8}$ cm and $H_{cd}(0) \approx 128 \pm 20$ T. By analyzing specific heat data for YBa$_2$Cu$_3$O$_7$ crystals the authors of Ref. [41] found $N(H)/n(0) = a \sqrt{8H}/[\pi H_{cd}(0)]$, where experimentally the constant $a = 0.7 \pm 23\%$. According to this formula and the above value of $H_{cd}(0)$ we would expect the field-induced DOS to be 36 ± 9% of the normal state value $n(0)$ at 13 T. Plots of $G_S(0)/G_N(0)$ vs $H$ for the three mesas are shown in Fig. 4. They all have the same general shape and magnitude, both of which agree rather well with previous ITJ experiments [35]. However the increase in $G_S(0)/G_N(0)$ between 0 and 13 T, $\approx 0.01$, is very small compared with the 36 ± 9% increase in DOS predicted by the theory of Volovik [48]. In Refs. [35] and [36] this was ascribed to cancellation between the increased DOS and the increased scattering of quasiparticles on vortices, when vortex pancakes in adjacent layers are uncorrelated.

The above estimates of the constant $a$ and $H_{cd}(0)$ show that for a cylindrical Fermi surface, at 13 T pairs should be broken over an angular range of $0.36 \pm 0.09 \times 45 = 16.2 \pm 4.0$ degrees either side of a $d$-wave node. We have considered three simpler interpretations of the $H$ dependence in Fig. 4, (i) coher-ent tunneling, (ii) incoherent tunneling, both between nodal regions in neighboring layers, and (iii) incoherent tunneling between a nodal region in one layer and non-nodal regions in the neighboring layer. We use the same coherence/incoherence ratio (4:1) as before. Because of the $M^2 \propto (\cos 2\theta)^4$ factor, case (i) gives a very wide range of values for the increase in $G_S(0)/G_N(0)$ from 0 to 13 T, the upper limit (0.007) is somewhat lower than the experimental value, and the $H$ dependence, dominated by the $M^2 \propto (\cos 2\theta)^4$ factor, is completely wrong. Case (ii) gives values which are too high by a factor of 2.7 ± 1.3 and a linear $H$ dependence. Case (iii) gives very good agreement with experiment both in magnitude and $H$ dependence as shown by the dashed lines in Fig. 4, namely the increase in $G_S(0)/G_N(0)$ between 0 and 13 T is $0.010 \pm 0.004$ and is proportional to $H^{1/2}$. The rather large error arises from the uncertainty in the constant $a$ in the formula used for the Volovik DOS, and the uncertainty in the residual DOS at $H = 0$. We note that case (iii) implicitly assumes that the vortex pancakes in neighboring layers are uncorrelated, and this fact would suppress the nodal-nodal contributions in cases (i) and (ii) which might otherwise be significant. So, somewhat surprisingly, the Dynes formulation used here plus the assumption that there is 20% incoherent tunneling to zero-energy states well away from the nodes, seems to give a good description of the $H$ dependence of $G_S(0)/G_N(0)$.

B. At higher bias

Figure 5(a) shows $dI/dV$ per unit area for one junction of OD80, at 1.4 K vs the bias voltage per junction, for many fields $H = 0$ to 13 T applied perpendicular to the CuO$_2$ planes. The curves are symmetric for $\pm V$, so for clarity we only show data for $V > 0$. For such $SIS$ junctions the sharp peaks are located at voltages of $2\Delta_0/e$, where $\Delta_0$ is the maximum value of the $d$-wave gap. At 1.4 K this gives $\Delta_0 = 27.3, 26.9$, and 27.4 meV for the three mesas studied here, OD78, OD80, and OP86, respectively, in good agreement with the lower values shown in Fig. 15 of Ref. [2] for these doping levels. The ratio

![Diagram](image-url)
was that nodal quasiparticles were having a strong effect on spacing. Various energies associated with this value of the strong above. In view of the V olovik effect, the interpretation of is a rough correspondence with the simple description given shown in Figs. 5 and 7 for OD80. It can be seen that there

eV

most apparent at \(Q\), close to \((\pi/a,\pi/a)\), where \(a\) is the in-plane lattice spacing. Various energies associated with this value of \(\Omega\) are shown in Figs. 5 and 7 for OD80. It can be seen that there

\[
2\Delta_0/k_B T_c = 8.08 \pm 0.1, 7.83 \pm 0.1, \text{ and } 7.5 \pm 0.15 \text{ for these three mesas is } \sim 1.75 - 1.9 \text{ times larger than for a weak-coupling d-wave superconductor [25].}
\]

The \(dI/dV\) data for OD80 in Figs. 5(a)–5(c) show two \(H\)-dependent dips above \(eV = 2\Delta_0\). (Data in Figs. 5(b) and 5(c) have been normalized, see Ref. [38]). For a \(d\)-wave energy gap varying as \(\Delta_0 \cos 2\theta\), where \(\theta\) is the angle between \(k\) and the antinodal direction, and for a dispersionless \((k\)-independent) boson-induced structure is expected to be most apparent at \(eV = 2\Delta_0 + \Omega\). At this bias voltage, states at the gap edge at \(\Delta_0\) for \(\theta = 0\) on one side of the junction and any structure at \(\Delta_0 + \Omega\) and \(\theta = 0\) on the other side are aligned to the same energy, and strong tunneling occurs between these. The effect is largest there because the peak in the superconducting \(d\)-wave quasiparticle DOS is largest at \(\theta = 0\). Additional structure is expected near \(eV = 2\Delta_0 + 2\Omega\) where boson-induced anomalies on each side of the junction at \(\theta = 0\) have the same energy. However, for a reasonably isotropic Fermi surface (without a substantial Van Hove singularity as discussed earlier) we would expect this structure to extend to lower energies since at other angles in \(k\) space, \(2\Delta_0 + \Omega\) will be smaller.

The \(S = 1\), magnetic resonance excitation, seen by inelastic neutron scattering [50], is a candidate pairing boson \([30,51]\). It has an energy \(\Omega = 5.4k_BT_c\) \([30,50]\) and a momentum vector \(Q\), close to \((\pi/a,\pi/a)\), \([30,50]\) where \(a\) is the in-plane lattice spacing. Various energies associated with this value of \(\Omega\) are shown in Figs. 5 and 7 for OD80. It can be seen that there

the structure above the gap edge. This is still a possibility but we cannot rule out a much more prosaic interpretation in which the disorder associated with having uncorrelated vortex pancakes in neighboring layers \([35,36]\) smooths out this structure. Quasiparticles tunneling from regions between vortices in one layer (where in the first approximation the gap parameter will be the same as at \(H = 0\) to vortex cores in the next layer will give different contributions to the \(I-V\) curve that depend on the interlayer vortex correlations. If the vortex cores are uncorrelated this statistical effect will tend to smooth out the structure above the gap in a similar way to the effect of resistance variations shown in Fig. 3. In support of this latter scenario we note that the dip in optimally-doped Bi-2212 SIS break junctions \([52]\) was not suppressed by fields of up to 12 T parallel to the \(c\) axis. Also recent STM work \([53]\) on YBCO shows the presence of dips in applied fields of up to 6 T \(\parallel \) \(c\) though in the diagrams shown they are rather small.

V. TEMPERATURE DEPENDENCE

A. Below \(T_c\)

Figure 6(a) shows the overall \(T\) dependence of our raw \(dI/dV\) data for OD80 in zero field at selected temperatures, while data for a total of 31 temperatures below and above \(T_c\) are given as Supplemental Material \([44]\). The data in Figs. 6(a) and 7 show that the dip and the hump at higher \(V\) are strongly \(T\)-dependent and have almost disappeared at 50 K even though \(\Delta_0\) has hardly changed from its low \(T\) value there. The attenuation of the hump is much smaller up to 40 K, but it shifts down...
with increasing $T$ and also disappears rapidly between 50 and 60 K. We feel that this strong $T$ dependence, especially the shifts of the dips and humps with $T$, is unlikely to be caused by a conventional phonon pairing mechanism. As shown in Fig. 7, the lower dip is partially suppressed by a magnetic field, but it is not shifted, unlike the effect of temperature. For all three mesas a relatively sharp fall in $2\Delta_0(T)$ also sets in abruptly below $T_c$, extending up to 60 K. We feel that this strong $T$ dependence of $2\Delta_0(T)$ is only weakly dependent on $\theta$. We are therefore justified in estimating a scattering rate $\Gamma$ from the relation $\Gamma = \frac{\gamma}{\Delta_0(T)^2}$, where $\gamma$ is a $T$-independent damping value, i.e., $\gamma = y + 0.07x^2/(1 + x^2)$ with $y$ ranging from 0.09 to 0.3. Figure 8 highlights the fact that the peak at $2\Delta_0(T)$ becomes narrower at the same temperature, near 50 K, where the dip-hump structure is strongly attenuated. It implies that below 50 K this structure and the broadening have a common origin, namely renormalization from the pairing boson(s).

In Figs. 8(d) and 8(e) the upturn in the Dynes calculation near $V = 0$ is clearly seen. This is well known in classical $ST$ tunneling work [9] and arises from the thermal population of quasiparticle states above and below the gap edge when $\Delta \approx k_BT$. But the experimental data show an important difference in that $G(V)$ remains constant up to larger voltages $\sim 0.02 V$ than the calculated curves before merging smoothly with them. This must mean that $\Gamma$ is relatively large where $\Delta$ is large and where $M$ is only weakly dependent on $\theta$. We are therefore justified in estimating a scattering rate $\Gamma$ from the relation $\Gamma = \frac{\gamma}{\Delta_0(T)^2}$, where $\gamma$ is a $T$-independent damping value, i.e., $\gamma = y + 0.07x^2/(1 + x^2)$ with $y$ ranging from 0.09 to 0.3. Figure 8 highlights the fact that the peak at $2\Delta_0(T)$ becomes narrower at the same temperature, near 50 K, where the dip-hump structure is strongly attenuated. It implies that below 50 K this structure and the broadening have a common origin, namely renormalization from the pairing boson(s).

Using Eq. (2) at various temperatures do not support this procedure, so in Figs. 8(a)–8(e) we show instead comparisons of our data with Eq. (2) at selected values of $T$. The calculated curves all have the same ($E$-dependent) values of $\Gamma = 0.009 + 0.07x^2/(1 + x^2)$, used in Fig. 2(b), but now $x = E/\Delta_0(T)$, with $\Delta_0(T)$ given in Fig. 6(b). In Fig. 8(f) we show the effect of extra $E$-independent damping values, i.e., $\Gamma = y + 0.07x^2/(1 + x^2)$ with $y$ ranging from 0.09 to 0.3. Figure 8 highlights the fact that the peaks at $2\Delta_0(T)$ become narrower at the same temperature, near 50 K, where the dip-hump structure is strongly attenuated. It implies that below 50 K this structure and the broadening have a common origin, namely renormalization from the pairing boson(s).
appropriate plots are shown in Figs. 10(a) and 10(b). Figure 10(a) shows the data for the three mesas together with fits to an empirical formula describing inelastic scattering between quasiparticles which is expected to vary as $T^4$ at low $T$ and then cross over to $T^2$ as $2k_BT$ becomes comparable with the maximum superconducting energy gap $\Delta_0(T)$. This formula gives a good fit to the data but the crossover temperature $\sim 50$ K corresponding to $2k_BT = \Delta_0(T)/3$ could be rather low, and a more precise calculation is needed. Figure 10(b) shows Arrhenius fits to the scattering rate. The values of $E_A$ are $\sim 12$ meV for all three mesas. This is reasonably close to the energy difference between the $S = 1$ resonant mode at $5.4k_BT_c = 37$ meV for OD80 and the value $2\Delta_0 = 54$ meV. So another possible interpretation of the activated behavior is that it represents thermally induced decay of the $S = 1$ resonant mode into the quasiparticle continuum above the gap edge. It could be argued that for a $d$-wave superconductor the gap edge extends down to zero energy at the nodes. But decay processes there would be restricted by $k$ conservation and the fact that the $S = 1$ mode has a reasonably well-defined $Q$.
FIG. 9. Values of $G_S(0)/G_N(0)$ vs temperature for the three mesas. (a) shows the data together with fits to $m_1 + m_2(T/m_3)^4$ with $m_1 = 0.0129, 0.0115,$ and $0.0122$ and $m_3 = 33, 36,$ and $31$ K for mesas OD78, OD80, and OP86, respectively. (b) shows the same data and fits to the Arrhenius law shown with $m_4 = 0.0139, 0.0119,$ and $0.0131$, $m_5 = 2.60, 0.65,$ and $1.67$, and $m_6 = 182, 158,$ and $147$ K for mesas OD78, OD80, and OP86, respectively. All fits have been made from 1.4 to 40 K. For clarity the data for OD78 and OP86 have been displaced along the logarithmic $y$ axis by the multiplying factors shown.

FIG. 10. Values of $\Gamma(T) \equiv \sqrt{G_S(0)/G_N(0)} \times [\Delta_0(T)]$ vs temperature for the three mesas. (a) shows the data together with fits to the formula shown that is expected for electron-electron scattering with $m_1 = 3.07, 2.89,$ and $3.07$ meV, $m_2 = 7.1, 8.5,$ and $6.2$ meV, $m_3 = 50, 55,$ and $42$ K for mesas OD78, OD80, and OP86, respectively. (b) shows the same data and fits to the Arrhenius law shown with $m_4 = 3.13, 2.91,$ and $3.16$ meV, $m_5 = 56, 49,$ and $64$ meV, $m_6 = 136, 139,$ and $128$ K for mesas OD78, OD80, and OP86, respectively. All fits have been made from 1.4 to 50 K. For clarity the data for OD78 and OP86 have been displaced along the logarithmic $y$ axis by the multiplying factors shown.

We see from Fig. 10 that the scattering rate for states near the antinodes is $10–12$ meV as $T_c$ is approached from below, while from Fig. 6(b) $\Delta_0(T \rightarrow T_c) \sim 16–17$ meV. We therefore conclude that the larger values of $dI/dV$ at low $V$, i.e., $(dI/dV)_{\text{res}}$ are caused by $T$-dependent pair-breaking processes in line with early break junction work [12]. The scattering rates are surprisingly large and must be connected in some way with the fact that as shown in Fig. 6(b) $\Delta_0(T \rightarrow T_c)$ is also large, possibly suggesting that $T_c$ is suppressed by inelastic scattering. The same general viewpoint was proposed by us in Ref. [16] as well as in two ARPES papers [56,57] that have inspired a detailed comparison [58] of ARPES data.
with several bulk properties. But, in contrast to these last three papers, we believe that the gap above $T_c$ in OD80 can be understood reasonably well in terms of the accepted theory [23] of superconducting fluctuations, as explained below.

Finally, to conclude this section, in Fig. 11 we show that the amplitude of the dip-hump feature for OD80 obeys an $A - BT^2$ law to high accuracy, becoming almost zero at 50 K. This seems to be completely at odds with expectations for electron-phonon scattering. Data for the other two mesas do not show this behavior but in contrast to Ref. [16] we now ascribe this to the interlayer conductance of OD80 being more uniform than for the other two mesas.

B. Above $T_c$

The $dI/dV$ data for mesa OD80 at all temperatures measured above $T_c$ [44] are shown in Fig. 12(a) and data at higher $T$, normalized as explained in Ref. [38], are shown in Fig. 12(b). The theory of superconducting fluctuations [23] predicts that in the 2D limit the fluctuation contribution to the tunneling conductance of an $NIS$ junction at $V = 0$ is given by:

$$G_{FL}(0,T)/G_N(0,T) = -2\tau_G \ln(1/\epsilon),$$

(4)

where $G_N(0,T)$ is the conductance in the normal state in the absence of fluctuations, $\tau_G$ is the Ginzburg parameter, and $\epsilon = \ln(T/T_{MF})$, where $T_{MF}$ is the mean field superconducting transition temperature (at which the first term in the Ginzburg-Landau free energy expansion changes sign from positive to negative). The voltage dependence of the fluctuation contribution is given in terms of the second derivative of the digamma function $\Psi$ by [23]:

$$G_{FL}(V,T) \propto G_{FL}(0,T)Re \left[ \Psi'' \left( \frac{1}{2} - i \frac{eV}{2\pi k_BT} \right) \right].$$

(5)

Equation (4) shows that, unusually, the fluctuation contribution to the conductance has a very weak $T$ dependence because of the double logarithm while Eq. (5) shows that the voltage dependence extends to unexpectedly high voltages since $G_{FL}(V,T)$ has a positive maximum at $eV = \pi k_BT$. In order to make a detailed comparison with our data these equations would need to be extended to the case of coherent tunneling between two $d$-wave superconductors with a tunneling probability $M^2 \propto (\cos 2\theta)^4$. But to within some numerical factors of order unity, for $SIS$ junctions we would expect there to be an extra factor of 2 in $G_{FL}(0,T)/G_N(0,T)$ [23] and that the peak in $G_{FL}(V,T)/G_N(V,T)$ will occur at $eV = 2\pi k_BT$, a factor of 2 higher than for an $NIS$ junction. Figure 13 shows the voltages of the maxima in $G_{FL}(V,T)/G_N(V,T)$ vs $T$ on a log-log plot. The precise positions of the peaks are somewhat dependent on the normal state conductance and we show two limits for this. It can be seen that there is indeed a linear region between 87 and 110 K, and furthermore the slope (1.76) is reasonably close to 2.
We have examined the applicability of Eq. (4) by subtracting a normal state background contribution of the form \( G_N(0, T) = 1/(a + bT) \) where \( a \) and \( b \) are constants fixed by our two measured points at 250 and 300 K, but a quadratic form \( G_N(0, T) = a + bT^2 \) with \( a \) fixed by the first term (8.85) in the polynomial used for normalizing \( G_\text{S}(V, 1.4K) \), and \( b \) by the 300 K data point gave very similar results. The raw data and the \( G_N(0, T) = 1/(a + bT) \) background are shown in Fig. 14. The normalized values \( |G_{\text{FL}}(0, T)|/G_N(0, T) \) obtained from Fig. 14 are plotted vs \( \ln[1/(\ln(T/T_MF))] \) in Fig. 15 for three values of \( T_{MF} \). Because of the weak dependence of the double logarithm on both \( T \) and \( T_{MF} \) we cannot use the quality of the straight line fits shown to determine \( T_{MF} \). However, using Eq. (4) the slopes of the straight lines shown give values of the 2D Ginzburg parameter \( \tau_G \) that in the 2D case the suppression of \( T_c \) is given by [23]:

\[
\frac{T_{MF} - T_c}{T_{MF}} = 2\tau_G \ln(1/(4\tau_G)),
\]

and \( \tau_G = 0.038 \) corresponds to a suppression of 13 K. Because of possible uncertainty in numerical factors in Eq. (4) it is worth comparing this estimate of \( \tau_G \) with that obtained from the superconducting condensation energy [19] and the 2D coherence volume mentioned earlier. The original definition of \( \tau_G \) was in terms of the reduced temperature above \( T_c \) where the Gaussian fluctuation contribution to the heat capacity becomes as large as the mean-field jump that would occur in the absence of fluctuations [23]. For a classical superconductor with the usual parabolic dependence of the thermodynamic critical field \( H_c(T) = H_c(0)[1 - (T/T_c)^2] \), the mean field specific heat jump at \( T_c \) is \( H_c(0)^2/(\pi T_c) \) and setting this equal to the 2D Gaussian fluctuation term \( k_B/(4\pi \xi_{ab}(0)^2 s T_c) \) at \( T_c \) gives a formula that is probably more general and more suitable for the \( d \)-wave superconductor with a larger value of \( \Delta(0)/(k_B T_c) \) considered here, namely:

\[
\tau_G = \frac{k_B T_c}{32\pi U \xi_{ab}(0)^2 s}.
\]

where the condensation energy density \( U = H_c(0)^2/(8\pi) \). For OD80 we find \( U \xi_{ab}(0)^2 s = 40 \) K, giving a smaller value \( \tau_G = 0.02 \) and from Eq. (6), a suppression in \( T_c \) of 10%. Therefore the line in Fig. 15 with \( T_{MF} = 87 \) K is probably more appropriate than \( T_{MF} = 92 \) K. Recently [18] the contrasting effects of parallel and perpendicular magnetic fields on underdoped ITJs were used to distinguish the pseudogap from the gap arising from superconducting fluctuations. These authors reached a similar conclusion regarding superconducting fluctuations but here we have made a more precise numerical comparison with
VI. CONCLUSIONS

In summary we have reported intrinsic $S$/$S$ planar tunneling data for three crystals of the cuprate superconductor Bi-2212 and discussed their field and temperature dependence. We believe that there is enough information in our data to assess the pairing contribution from the $S = 1$ magnetic mode that has $Q \simeq (\pi/a, \pi/a)$ [30,50]. On the basis of our analysis using the Dynes equation we conclude that the residual specific heat and normal fluid fraction do not arise from nodal regions. We argue that inelastic scattering is large and probably anisotropic since our tunneling data, which are more sensitive to the antinodal regions, give scattering rates near 60 K that are approximately four times larger than those obtained by microwave studies [40]. We have discussed the temperature dependence of this scattering in terms of electron-electron scattering. However a more exciting possibility is that it is caused by the same excitations whose virtual exchange is providing the pairing “glue.” We have shown that the tunneling gap above $T_c$ persisting up to 150 K is reasonably consistent with the theory of superconducting fluctuations [23] for relatively small values of the 2D reduced Ginzburg temperature, $\tau_G = 0.02$. This is consistent with the Gaussian fluctuation analysis used for various cuprates [60] that crosses over smoothly to the critical region at approximately 1.02–1.1$T_c$.

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