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Tunneling in the *ab* plane of the high-T_c superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ in high magnetic fields

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Tunneling break junctions of single crystals of Bi-Sr-Ca-Cu-O show a reproducible superconducting-gap structure that can be fully described with a broadened BCS density of states. The obtained ratio between the energy gap Δ and the critical temperature T_c amounts to $2\Delta/T_c = 6.2$. In a magnetic field up to 20 T, the conductance curve shows additional broadening but the energy gap remains constant. From a comparison of the magnetoresistance and tunneling data for different orientations of the magnetic field, it follows that the break junctions probe the superconducting properties in the *ab* plane. Both the magnetic field and temperature dependence of the tunneling characteristics are in agreement with the known dependences for the classical superconductors.

I. INTRODUCTION

A careful investigation of the density of states of quasiparticle excitations of the high-T_c copper oxide superconductors is very essential for the understanding of the mechanism responsible for the superconductivity in these materials. One of the important issues in this respect is the question of the presence of states within the superconducting gap and the symmetry of the superconducting state in these layered materials with a strong anisotropy in the physical properties.

Tunneling experiments have been very important to verify the BCS theory in the conventional superconductors. The conductance of a tunnel junction is directly proportional to the quasiparticle density of states. The fine structure found in the tunneling conductance at voltages above the forbidden energy gap was a direct proof of the electron-phonon interaction as the coupling mechanism for the superconductivity in the old superconductors.

Since the very first tunneling experiments the experimental situation has not been very clear for the high-T_c superconductors.[1] The tunneling characteristics obtained with high-T_c superconductors show a peak in the tunneling conductance that could be related to the order parameter of the superconductor, but the shape of the curves is far from the ideal BCS density of states. The conductance curves reveal a strong broadening of the superconducting-gap structure, with a nonzero contribution at zero voltage and a (linear) increasing background at voltages above the gap. In view of unconventional superconductivity, both the broadening and the conductance at zero voltage could be related to the occurrence of allowed states below the energy of the superconducting order parameter.

With the availability of better samples (single crys-

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tals with well-defined superconducting properties), both the reproducibility and the quality of the tunneling experiments have improved considerably.[2] For most of the high-T_c systems, the tunneling experiments of different research groups converge to similar results with respect to the value determined for the superconducting order parameter. For some systems the obtained ratio for $2\Delta/k_BT_c$ (order parameter Δ, critical temperature T_c) can reach values up to 7 which would point to a very strong coupling mechanism in the superconducting state as compared to the weak coupling value 3.5. Although during the last years the tunneling data of high-T_c superconductors can be compared better with the BCS theory (i.e., data with smaller broadening and zero-bias conductance), many basic questions related to the symmetry and the pairing mechanism of the superconducting state remain unsolved. With respect to the quality of the tunnel junctions, we remark that the tunneling current probes a region of the order of the coherence length. The small coherence length in the high-T_c superconductors ($\simeq$ 1–30 Å depending on the crystal orientation) makes the tunneling process extremely sensitive on the sample quality of a thin layer close to the tunneling barrier.

For the $Bi_2Sr_2CaCu_2O_{8-\delta}$ high-T_c superconductor tunneling experiments agree on a ratio $2\Delta/k_BT_c$ between 6 and 7 (see Ref. 2 for a recent review). This result for the obtained order parameter is independent of the preparation method of the tunnel junction (macroscopic junction, break junction, point contact, scanning tunneling microscope). However, the tunneling data still show a broadening and a nonzero conductance at zero-bias voltage with strong scattering in the reported values for these phenomena. BCS-like tunneling data on the BiSrCaCuO can be seen as an indication for s-wave-type pairing in this high-T_c superconductor.[3,4] Although less reproducible between different experiments, an anisotropic energy gap has been concluded from tunnel-junction experiments on different crystal surfaces of Bi-Sr-Ca-Cu-O with a smaller energy gap (or no gap at all) along the c axis compared to the ab-plane.[2]

We performed tunneling experiments on $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals using break junctions in high magnetic fields up to 20 T. There are two main reasons to apply a magnetic field in a tunneling experiment. First, the magnetic field is very useful in order to distinguish relevant information in the tunneling characteristic from anomalous signals due to critical current effects in weak links of the junction. Second, information on the magnetic-field dependence of the density of states could shed some light on the symmetry of the superconducting state. Although no detailed theory exists for the magnetic-field dependence of an anisotropic density of states (e.g., nodes or lines with a zero-valued order parameter), one could expect a significant effect on the small energy gaps (or on the states within the gap close to zero energy).

The tunneling experiments on single-crystal $Bi_2Sr_2CaCu_2O_{8+\delta}$ show a reproducible BCS-like density of states with small broadening. As expected in the Abrikosov-Gorkov theory for pair breaking in a magnetic field, the measured tunneling density of states is not strongly influenced in fields much smaller than the critical magnetic field.

II. EXPERIMENT

Grown from a solution in KCl, the single-crystal samples of BiSrCaCuO had typical sample dimensions $2 \times 1 \times 0.2$ mm^3.[5] The chemical composition of the 2:2:1:2 phase (BSCCO) corresponds to the formula $Bi_{2.4}Sr_{1.5}Ca_{0.9}Cu_{2.2}O_{8+\delta}$. X-ray diffraction revealed that the crystals consist of macroblocks (200–500 μm) with a misorientation of 2°–3° in the basal plane. The superconducting transition temperature T_c and transition width ΔT_c (at 10–90 % of the transition) were measured by means of dc resistivity and ac susceptibility, yielding $T_c = 80 \pm 3$ K and $\Delta T_c = 2$ to 6 K. The resistivity ρ of the samples is of the order of 40–50 $\mu\Omega$ cm at $T = 100$ K with a linear temperature dependence at higher temperatures (slope $d\rho/dT = 0.3 - 0.4$ $\mu\Omega$ cm/K). The characterization of the samples shows the high quality and high homogeneity of our samples.[5] Low-resistance electrical contacts (0.1–1 Ω) were made to the samples using fired-on gold films.[6]

The tunneling junctions were made at 4.2 K by the break-junction technique. As indicated in the inset of Fig. 1, the crystals are fixed with In solder in such a way that the ab plane of the crystals is perpendicular to the supporting substrate. With a differential screw mechanism the flexible substrate is bent and the sample is bro-

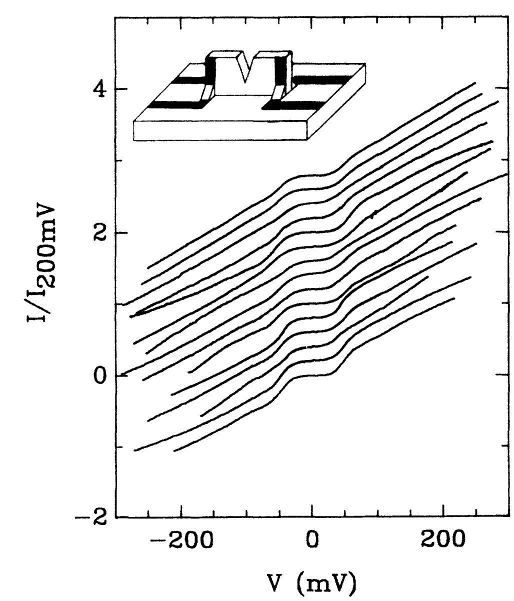

FIG. 1. I-V characteristics of tunnel break junctions on 15 different BSCCO samples at 4.2 K. The current has been normalized with the high-voltage value $I_{200\ \mathrm{mV}}$ at 200 mV. The curves have been shifted with respect to the bottom one. In a schematic way, the inset shows the geometry of the break junction: the crystal is fixed with In solder on a flexible substrate with the current-voltage leads.

ken along an incision made earlier, resulting in a symmetric BSCCO-BSCCO weak link as the tunneling contact (*S-S* junction). With this break-junction setup we suppose that the quasiparticle tunneling occurs along CuO planes because many *ab*-plane edges are created. The junction resistances in our experiments varied from 0.3 to 5 kΩ. The current-voltage (*I-V*) characteristics and derivatives $dV/dI(V)$ and $d^2V/dI^2(V)$ were measured by the four-terminal method using phase-sensitive detection techniques.

In order to study the junctions under the influence of external parameters, the tunneling characteristics have been investigated at temperatures up to the critical temperature and in magnetic fields up to 20 T.

III. TUNNELING RESULTS IN A MAGNETIC FIELD

In Fig. 1 we have plotted the *I-V* characteristics of tunnel break junctions at $T = 4.2$ K for 15 different BSCCO samples. The plotted curves are normalized by the maximum value of current and displaced vertically for clarity. The curves reveal the characteristic features for a superconducting tunnel junction with an almost flat region around zero bias and a sharp increase in the tunneling current around ±50 mV. The currrent at zero bias corresponds to a leakage conductance which varies from contact to contact with, for the best cases, only 5% of the above gap conductance. The voltage position (at ±50 mV) for the onset of tunneling current at the superconducting energy gap reproduces well in tunneling contacts for different samples. In fact, we did not find a contact with the superconducting gap structure at a different voltage. At large bias voltages the *I-V* characteristics are linear with small deviations (both increasing and decreasing conductance) at large bias voltages. Because for different tunnel junctions on the same single crystal these deviations were of different character, we relate this phenomenon rather to a change of the tunneling barrier transparency with applied voltage than to intrinsic properties of the sample.

Figure 2 shows the *I-V* characteristics of different tunnel junctions measured at 4.2 K in a magnetic field of 20 T compared with the zero-field data. The applied magnetic fields up to 20 T do not change the tunnel-junction resistances pointing to the independence of the tunnel barrier on the magnetic field.

The effect of the magnetic field on the superconducting gap structure is illustrated more clearly in Fig. 3, where we show the differential conductance dI/dV versus voltage for 0 and 20 T. For the studied *S-S* junctions, the distance between the two main maxima on the curves corresponds to $4\Delta_{\mathrm{BSCCO}}$. The position of the gap peaks remains almost unchanged in the applied magnetic fields up to 20 T. Only a small broadening of the energy-gap structure is observed, probably due to the pair-breaking influence of the magnetic field. As can be seen in Fig. 3, no distinct difference was observed in the magnetic-field dependence of the tunneling data for the two orientations of the magnetic field with respect to the crystal orientation ($B \parallel c$ and $B \perp c$). In Fig. 4 we have plotted the $dI/dV(V)$ curves for one of our break junctions in magnetic fields of 0, 5, 10, 15, and 20 T. The sharp peak at zero-bias voltage in the zero-field curves can be suppressed by a magnetic field (see Figs. 3 and 4). We ascribe this zero-bias structure in the conductance (related to zero-bias critical currents in the *I-V* curves and always observed for junctions with resistances smaller than 1 kΩ) to the Josephson effect.

The applied magnetic fields (< 20 T) are only a small perturbation with respect to very high critical magnetic fields in BSCCO.[7] In the Abrikosov-Gorkov theory of pair breaking in the conventional superconductors, the density of states is only broadened for a small pair-breaking strength of the magnetic field.[8,9] The observed small broadening of the superconducting gap structure in a magnetic field would agree qualitatively with the Abrikosov-Gorkov theory of pairbreaking.

In order to address the question if the observed gap spectrum is related to tunneling (and superconducting properties) in the *ab* plane, we have measured for the

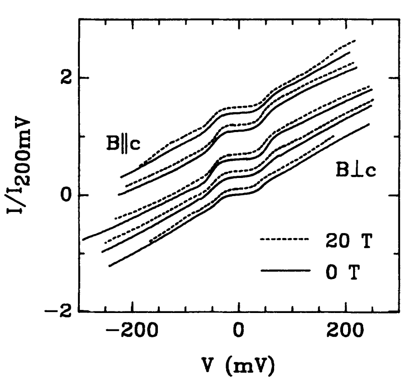

FIG. 2. *I-V* characteristics of different tunnel break junctions at 4.2 K in 0 and 20 T with normalized current. The curves have been sifted with respect to the bottom one. The two sets of curves at the top are for $B \parallel c$, and the other curves for $B \perp c$.

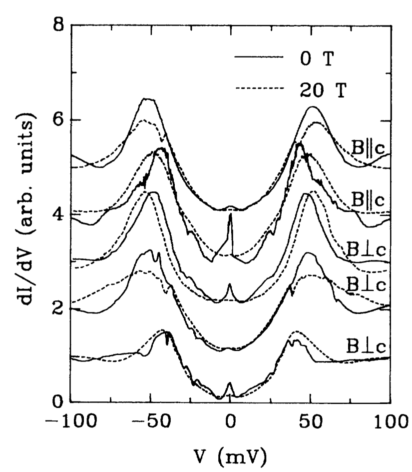

FIG. 3. Differential conductance dI/dV of different tunnel break junctions at 4.2 K in 0 and 20 T. The orientation of the sample (*c* axis parallel or perpendicular to the magnetic field) is indicated.

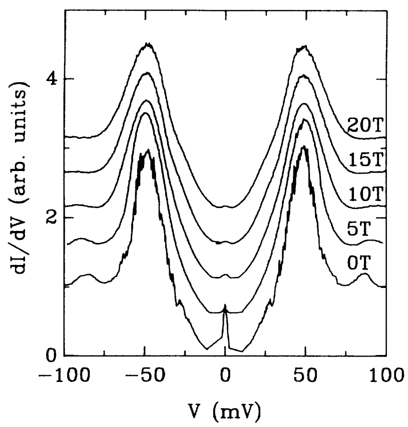

FIG. 4. Differential conductance dI/dV for a tunnel break junction at 4.2 K for magnetic fields up to 20 T ($B \parallel c$ axis), shifted with respect to the 0 T curve.

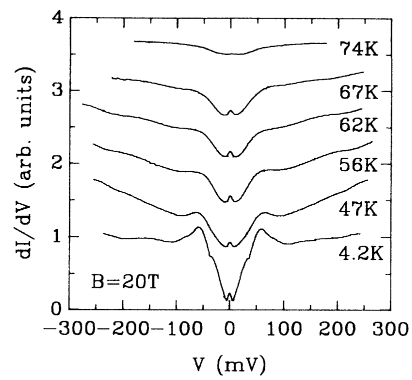

FIG. 6. Temperature dependence of the tunneling conductance dI/dV of a tunnel break junction at $B = 20$ T parallel to the c axis. The curves have been shifted vertically with respect to the 4.2 K curve.

same crystals the temperature dependencies of the ab-plane resistivity (ρ_{ab}) and of the resistivity along the c axis (ρ_c) for magnetic fields up to 20 T oriented parallel to the c axis. For the resistivity measurements we used a four-probe contact configuration in a symmetrical position on one side of the sample (for ρ_{ab}) and on opposite sides of the sample (for ρ_c). The results of these measurements are shown in Fig. 5. The observed anisotropic temperature dependence of the magnetoresistance is completely similar to that observed previously in BSCCO crystals in magnetic fields up to 7 T.[10] In a magnetic field the $\rho_{ab}(T)$ curve reveals a significant increase in the width of the superconducting transition, but the value T_c for the onset of superconductivity remains constant [Fig. 5(a)]. Theoretical models explain the broadening of superconducting transition in the ab plane in terms of disspative flux flow[11] or thermally activated phase-slip events.[12] In these theories the value of the energy gap is kept constant. In Fig. 5(b) the data for ρ_c show evidence for a strong suppression of the superconductivity along the c axis in a magnetic field of 20 T. The observed decrease of the T_c value by a factor 2 should remarkably decrease the energy gap. Because in all tunneling contacts in magnetic fields between 0 and 20 T the same magnitude for Δ_{BSCCO} was observed, we conclude that this is rather the ab-plane superconducting energy gap. We note that in an alternative explanation of the anisotropic magnetoresistance a dissipation mechanism in independently fluctuating, superconducting channels was put forward,[10] postulating an isotropic order parameter. However, the fact that we do not see any anisotropy in the magnetic-field dependence of the tunneling data, where as transport data show such an anisotropy in ρ_c and not in ρ_{ab}, points to a tunneling current in the ab plane.

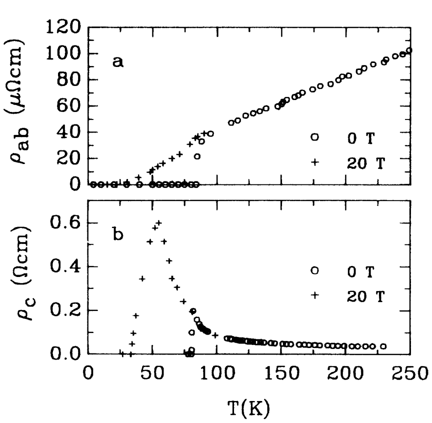

FIG. 5. Temperature dependence of the resistivity ρ_{ab} in the ab plane for a BSCCO crystal with the indicated magnetic-field $B \parallel c$ axis (a). Idem for the resistivity ρ_c parallel to the c axis (b).

In a recent tunneling experiment by Mandrus *et al.*,[13] very similar curves for the differential conductance have been observed. The setup used for breaking the junctions results probably in contacts with the same preferential tunneling current in the ab plane.

Figure 6 shows a series of $dI/dV(V)$ curves of a BSCCO-BSCCO tunnel break junction at various temperatures in a 20-T field oriented along the c axis of the single crystal. It can be seen that the gap structure, as expected, diminishes and broadens with increasing temperature, but the superconductivity remains still visible even at 74 K. These temperature-dependent tunneling data in a strong magnetic field coincide with those of the temperature dependence of the ab-plane magnetoresistance,[11] and confirm again the interpretation in terms of ab-plane tunneling.

IV. TUNNELING DENSITY OF STATES

In order to understand the nature of the superconductivity in BSCCO, we have to look at the tunneling conductance in more detail. The observed nonzero conductance and smearing of the gap structure are the most prominent discrepancies with respect to the ideal BCS model for the quasiparticle density of states. A quantitative comparison with the BCS theory requires the normalization of the conductance $(dI/dV)_s$ of the tunnel junction in the superconducting state by the conductance $(dI/dV)_n$ in the normal state. The conductance $(dI/dV)_n$ was obtained by a measurement of the conductance in the normal state at $T > T_c$. To correct for the thermal change of the tunneling barrier transparency with increasing temperature we added a constant term to $(dI/dV)_n$ in order to get a coincidence with the corresponding $(dI/dV)_s$ curves at 200–250 mV. Because of contact instability upon increasing the temperature to 90 K we could not measure the normal conductance for each tunnel junction at $T > T_c$. In this case, the $(dI/dV)_n$ curves were deduced by broadening the data in the superconducting state in order to smooth the gap-related structures. A justification for this procedure can be found in the fact that these calculated $(dI/dV)_n$ curves were similar to the ones obtained experimentally at $T > T_c$.

The tunneling data have been fitted according the expression

$$(dI/dV)_s/(dI/dV)_n = \frac{d}{deV}\int_0^{eV} N(E)N(E-eV)\,dE, \quad (1)$$

for the normalized conductance of a superconductor-superconductor tunnel junction, where

$$N(E) = \mathrm{Re}\frac{E-i\Gamma}{((E-i\Gamma)^2-\Delta^2)^{1/2}} \quad (2)$$

is the modified BCS density of states.[14] The phenomenologically introduced parameter Γ takes account for the lifetime broadening of the quasiparticle states. For the example in Fig. 7 a reasonable agreement is found between the experimentally obtained normalized conductance and the broadened tunneling conductance according to Eq. (1). For many other conductance curves, both deviations from the BCS behavior (broadening and nonzero conductance at low voltages) could be described by means of the expression for the broadened BCS density of states [Eq. (2)]. To take account for possibe leakage currents through the tunneling barrier, an improvement in the description of the data was sometimes obtained by adding a constant to Eq. (1) for the normalized conductance (in the best cases the constant value was no more than 0.5% of the conductance at large voltages). The values of the obtained energy gap Δ ranged from 19 to 24.5 meV, and of the broadening parameter Γ from 1.5 to 5.5 meV. The average value $2\Delta/k_BT_c = 6.2$ points to a very strong coupling mechanism. These values for the order parameter agree with other experimental data on tunneling,[2] and are consistent with data of angle-resolved photoemission spectroscopy[15] for BSCCO single crystals.

To find out a possible relation between the order parameter Δ and the broadening parameter Γ, we have investigated the temperature dependence of Δ and Γ over the range from 4.2 to 100 K. Figure 8 shows a series of measured conductances $dI/dV(V)$ for a tunnel break junction BSCCO-BSCCO at various temperatures. It can be seen that the gap structure broadens and diminishes at increasing temperature with a decrease in peak position for increasing temperatures. To determine the temperature dependences of Δ and Γ from the measured tunneling characteristics, the experimental conductances $dI/dV(V)$ have been matched to calculated ones using the expression

$$I(V) = K\int_0^{\infty} N(E)N(E-eV) \times [f(E,T) - f(E-eV,T)]\,dE, \quad (3)$$

for the tunneling I-V characteristic at finite temperatures analoguously to Eq. (1). Here, K is a constant which contains the tunneling probabilities and f is the energy-dependent Fermi function at a temperature T. The strong broadening of gap structure made an accurate fit of the data impossible for $T > 70$ K. Figure 9 shows the obtained values for Δ and Γ as found for the data in Fig. 8 and for another tunneling contact. The low-temperature values for these contacts are $\Delta = 24.4$ meV, $\Gamma = 4.9$ meV and $\Delta = 24.5$ meV, $\Gamma = 3.6$ meV. The

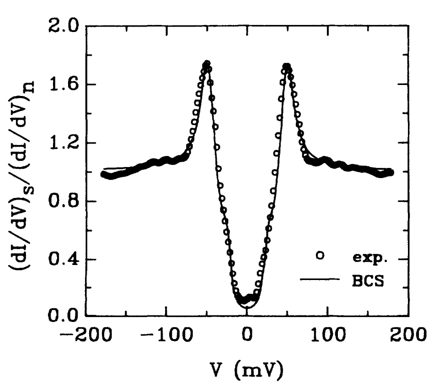

FIG. 7. Normalized conductance $(dI/dV)_s/(dI/dV)_n$ for a tunnel break junction at 4.2 K compared with the broadened BCS density of states (solid line).

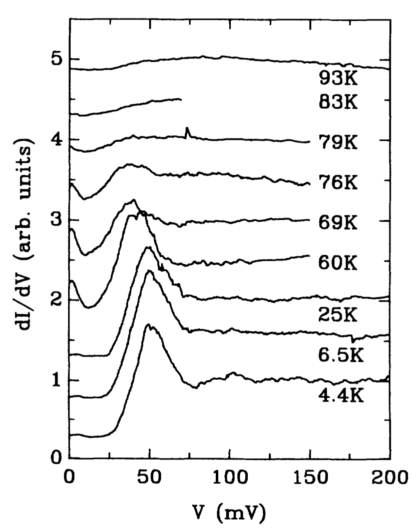

FIG. 8. Tunneling conductance dI/dV for a tunnel break junction at the indicated temperatures up to the critical temperature.

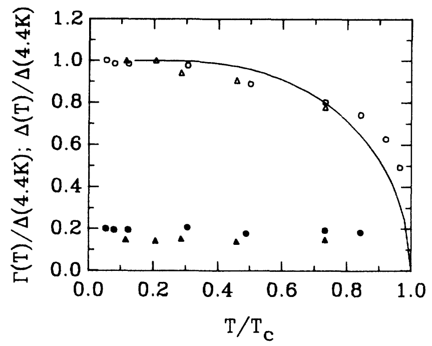

FIG. 9. Temperature dependence of the superconducting energy gap Δ (open symbols) and the broadening parameter Γ (closed symbols) for two different contacts (the circles correspond to the data of Fig. 8). The full curve displays the BCS curve for $\Delta(T)$.

solid line in Fig. 9 shows the dependence $\Delta(T)/\Delta(0)$ on reduced temperature T/T_c according to the weak coupling BCS theory for $T_c = 82$ K. The magnitude of T_c is consistent with ac susceptibility and dc resistance measurements on our single crystals. Considering the uncertainty in our data given by the broadening, the width $\Delta T_c = 2 - 6$ K of the transition and the sample dependence in $T_c = 80 \pm 3$ K, our data show that the temperature dependence of the superconducting energy gap in BSCCO can be reasonably described by the BCS model. Similar temperature-dependent results for the order parameter have been obtained in other tunneling studies of BSCCO.[2,16–18,20]

It is important to note that in our case the value of Γ does not depend on temperature, at least up to $T/T_c = 0.84$ where Γ could be determined (see Fig. 9). This experimental result is in contrast to published results on evaporated Pb junctions on cleaved *ab* planes,[18,19] where a temperature dependence for Γ was found for $T/T_c \geq 0.6$. Also the extracted energy gap showed an enhanced value in this temperature region. However, we note that the reported broadening in these tunneling experiments was much larger ($\Gamma/\Delta \geq 0.4$) at the lowest temperatures.

The tunneling density of states $N(E)$ of the BSCCO crystals shows up in the experimental conductance of the *S-S* contact via a convolution of two energy-shifted density of states. In order to get the density of states, the expression for the tunneling conductance in Eq. (1) has to be deconvoluted. For the deconvolution we used an iterative procedure starting from a broadened density of states according to Eq. (2) and correcting the data in intermediate steps by a comparison with the experimentally measured conductance until convergence is reached between calculation and experiment. In Fig. 10(a) the data points represent the result of this deconvolution for two different tunneling contacts. According to the solid curves in Fig. 10(a), the obtained density of states can be fitted quite well to a broadened BCS density of states. We remark that the two given examples in Fig. 10 correspond to tunnel junctions with the obtained minimal (19 meV) and maximal (24 meV) values of the superconducting energy gap. In Fig. 10(b) we show the experimental conductance curves $(dI/dV)_s/(dI/dV)_n$ compared with

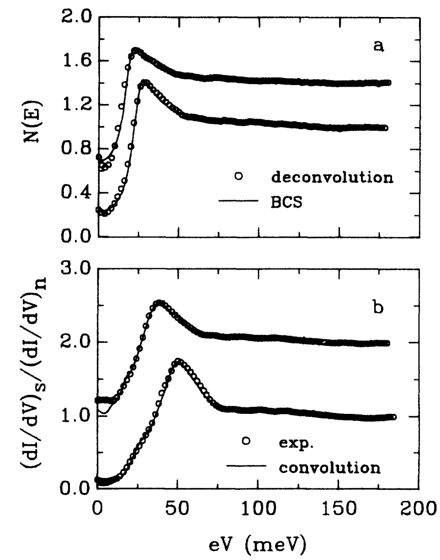

FIG. 10. (a) Tunneling density of states $N(E)$ (data points) obtained from a deconvolution of the normalized tunneling conductances [data points in (b)] for two BSCCO-BSCCO break junctions. For comparison, the solid curves in (a) show the broadened BCS density of states (for the top curve $\Delta = 19$ meV and $\Gamma = 5.5$ meV; for the bottom curve $\Delta = 24$ meV and $\Gamma = 5.5$ meV). The full curves in (b) show the calculated curves for the conductance using in Eq. (1) the density of states in (a).

the calculated curves using the density of states in Fig. 10(a) obtained from the deconvolution of Eq. (1). It can be seen in Fig. 10 that the agreement is quite good in the whole voltage range except for a small area near zero-bias voltage where the Josephson effect perturbs the data analysis. The good coincidence of the data in Fig. 10(b) confirms the validity of the followed iterative procedure to obtain the tunneling density of states $N(E)$ for BSCCO as given in Fig. 10(a). The observed shoulders at $eV = \Delta$ in the theoretical and experimental conductivity curves of Fig. 10(b) result from the nonzero density of states at low voltages, in complete agreement with the description of the tunneling data according to Eq. (1).

Since the broadening parameter Γ in our experiments was different for different contacts with the same energy-gap value, the smearing of the energy-gap structure in the tunneling data is probably due to the poor quality of the tunnel junction on the scale of the coherence length in BSCCO ($\xi_{ab} \simeq 30$ Å and $\xi_c \simeq 1$ Å , respectively in the *ab* plane and parallel to the *c* axis.)[7] A similar conclusion has been drawn by Zhang and Lieber.[3]

In some of the conductance curves (Figs. 4, 7, and 10) additional structure can be seen at voltages above the superconducting energy gap. In the traditional superconductors such nonlinearities in the *I-V* characteristics of the tunnel junctions could be linked with the phonon-mediated coupling mechanism between the quasiparticles. We show an example of how the magnetic field can be useful in performing energy-resolved spectroscopy in the tunneling characteristics at voltages above the superconducting energy gap. In Fig. 11 the second derivative

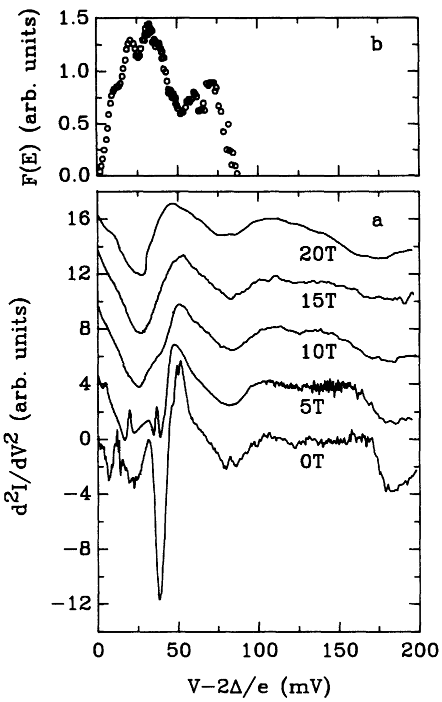

FIG. 11. Second derivative d^2I/dV^2 curves for a BSCCO-BSCCO break junction in different magnetic fields (a). The structure corresponding to the minima in d^2I/dV^2 can be compared with the phonon density of states obtained from inelastic neutron scattering (b) (Ref. 21).

has been plotted for different magnetic fields up to 20 T. The observed structure in d^2I/dV^2 at zero field is broadened in a magnetic field. However, for fields above $\simeq 5$ T the main features in the curves persist. The broadening of the fine structure could be related to the broadening of the superconducting density of states in a magnetic field, or to the suppression of anomalous critical current effects in weak links of the contact. Such a magnetic field dependence of the fine structure in the tunneling characteristics was observed for more contacts.

Tentatively, we have added in Fig. 11 for comparison the phonon density of states measured by inelastic neutron scattering.[21] Strong coupling effects in the tunneling data correspond to minima in the measured d^2I/dV^2 curves. The high-field data in Fig. 11 reveal broad minima at voltages (after subtraction of the superconducting energy gap) corresponding to the energies of the phonon density of states. Although the observed nonlinearities occurred in the voltage range of corresponding phonon frequencies, the voltage position of the nonlinearities was not reproducible between different contacts. In a forthcoming publication a more detailed analysis of these nonlinearities will be given.

V. CONCLUSIONS

For many different tunneling break junctions on different BSCCO samples a reproducible energy gap value Δ has been found. The value for the ratio $2\Delta/k_BT_c$ equals 6.2 ± 0.6, which would correspond to a very strong coupling mechansim for the electron pairing. Introducing a broadening parameter Γ the tunneling conductance curves can be described by the BCS density of states. Such an analysis describes not only the broadening very well but also the conductance at zero voltage.

Both the observed temperature and magnetic-field dependences of the tunneling data agree with the dependences as known for the conventional superconductors. At 20 T the pair-breaking influence of the magnetic field is very small and leads only to a broadening of the conductance curves. The observed tunneling characteristics are independent of the magnetic-field orientation with respect to the junction. Because ρ_c shows a strong anisotropic suppression in a magnetic field but not ρ_{ab}, we conclude that the tunneling contacts probe the superconductivity in the *ab* plane.

Apart from the phenomenologically introduced broadening parameter Γ, the tunneling results would be compatible with *s*-wave pairing of the quasiparticles in the superconducting state. However, just this broadening in the tunneling data could reflect an anisotropy in the superconducting order parameter. Although we have no microscopic information about the actual tunneling contact, the investigated break-junction configuration does not exclude an averaging of the tunneling current over different angles in the *ab* plane. Because the value of Γ differs from contact to contact, its origin is probably not only related to an intrinsic property of the superconducting material, but also to the quality of the tunnel barrier.

At voltages above the superconducting energy gap a broadened structure in the second-derivative spectra remains present in applied magnetic fields up to 20 T. Although these structures occur close to the phonon frequencies, small differences between different contacts prevent us from giving a conclusive interpretation in terms of a phonon-related strong coupling mechanism in the BSCCO system.

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