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Model for tunneling experiments on the 90- and 60-K $YBa_2Cu_3O_{7-\delta}$ phases

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The tunneling conductances of 90- and 60-K YBCO-based junctions in both the superconducting and the normal state have been quantitatively modeled by a superposition of two BCS-like contributions and a linear one. Strong-coupling superconductivity in the CuO_2 planes with $2\Delta_1/k_BT_{c_1}=4.1$ and weak-coupling superconductivity with $2\Delta_2/k_BT_{c_2}=2.1$ along the CuO chains are inferred. A consistent explanation of the experiments is found by assuming an internal proximity effect between strongly and weakly superconducting layers.

Since the discovery of high-T_c superconductivity in layered copper oxides much experimental and theoretical work has been done in an effort to understand the nature of the superconducting and the normal state. Of primary importance is the knowledge of the density of states at the Fermi level, from which information about the energy gap and the coupling mechanism can be obtained. At present, the mechanism responsible for superconductivity is still controversial; however, as better-characterized samples have been realized, a more consistent picture is emerging.

Referring to the $YBa_2Cu_3O_{7-\delta}$ (YBCO) compound, perhaps the most extensively studied among the cuprates, different experiments indicate the important role played by the anisotropy.[1–3] On the other hand, the theoretical work is focusing on the layered structure[4–7] and on the unusual normal-state properties.[7–10] Following these indications, we have introduced a model that, in spite of its simplicity, quantitatively reproduces experimental results obtained by tunneling spectroscopy. We have studied the YBCO 90- and the 60-K phases, since it is our opinion that a correct characterization of both phases, with the role of the oxygen vacancies properly taken into account, is of great importance for the understanding of high-T_c superconductivity.

One of the most intensive tunneling studies has been made on junctions realized on chemically etched YBCO single crystals.[11,12] The quality of the junctions and the reproducibility of the results[13] have been carefully tested. The investigation of oxygen-deficient samples[14] and of the 60-K phase[15] has also been reported.

The main issues arising from these studies can be deduced from the experimental results reported in Fig. 1, where the normalized conductance vs voltage, at $T=8$ K, for a 90-K junction (open circles) and a 60-K junction (stars) is reported.

They can be summarized as follows.

(1) The two gaplike structures at about 5 and 19 mV in the 90-K junction appear smeared out and less pronounced in the 60-K phase; these features show a weak temperature dependence.

(2) The linear conductance at high biases (background conductance) has a steeper slope for the lower-T_c compound.

(3) A nonvanishing zero-bias conductance $G(0)$ is found for both phases.

Corresponding to these experimental facts, we assume the following.

(1′) Two gap structures Δ_1 and Δ_2, with $\Delta_1>\Delta_2$, are associated with the CuO_2 planes and with the one-dimensional CuO chains along the b axis, respectively; both Δ_1 and Δ_2 have a BCS temperature dependence.

(2′) The linear contribution is associated to the tunnel-

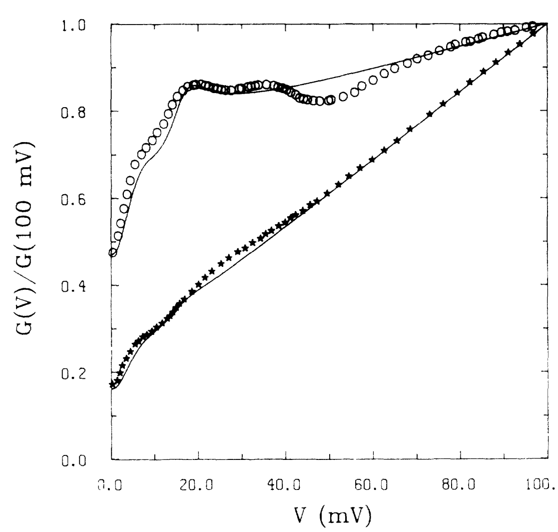

FIG. 1. Normalized conductance vs voltage of junctions made on 90- (open circles) and 60-K (stars) YBCO single crystals at $T=8$ K. The full lines are the theoretical fittings obtained from (1) with $\Delta_1=16$ meV, $\Gamma_1=3$ meV, $\Delta_2=4$ meV, and $\Gamma_2=4$ meV. The other parameters are $\alpha=2.31\times10^{-2}\ \Omega^{-1}V^{-1}$, $\sigma_1=1.17\times10^{-3}\ \Omega^{-1}$, and $\sigma_2=5.16\times10^{-3}\ \Omega^{-1}$ for the 90-K phase and $\alpha=28.4\times10^{-2}\ \Omega^{-1}V^{-1}$, $\sigma_1=0.86\times10^{-3}\ \Omega^{-1}$, and $\sigma_2=7.1\times10^{-3}\ \Omega^{-1}$ for the 60-K phase.

ing along the c axis.

(3′) Two phenomenological parameters, Γ_1 and Γ_2, account for the conductance values at zero bias as well as for the smearing of the experimental structures.

The hypothesis of multiple gap is supported by the results coming from different experimental techniques.[2,11,16] In particular, the association of two distinct gap structures to the layers and the chains is consistent with the fact that in our experiments the peaks at 5 and 19 mV are affected by a magnetic field parallel to the a-b planes.[11,12] From a theoretical point of view, two-component superconductivity models have been proposed by many authors.[4–7] Among them, we find the Takahashi-Tachiki model[4] to conform to our hypothesis. In their approach the YBCO system is treated as a stack of strongly superconducting CuO_2 layers alternated by weakly superconducting CuO chains, and bulk superconductivity is maintained by internal proximity effect.

The anomalous linear behavior of the background conductance is routinely found in the literature in different high-T_c compounds, independently of the junction fabrication method (for a discussion of this point, see, for example, Ref. 15). Because of the difficulties in making a "true" directional tunneling, it is not clear if this contribution can be associated to the conduction along one of the crystal axes.[17] There are several models put forth to explain the linearity of the background conductance. This behavior may indicate that the normal density of states depends linearly on energy around the Fermi level. Among the theoretical models based on density-of-state effects, we mention the resonating valence bond[8] (RVB) and the marginal Fermi liquid.[9] Alternative explanations suggest that the linearity stems from barrier effects[18] or inelastic tunneling.[10] Our point of view is that the linear contribution comes from the conduction along the c axis and, as discussed in Refs. 11 and 12, it seems to result from intrinsic properties of these materials.

The Γ parameter, proposed by Dynes, Narayanamurti, and Garno,[19] is commonly used in the literature to produce a smearing in the peak structures of the conductance curves. Its physical origin in high-T_c compounds has been explained in terms of lifetime effects, stoichiometry variations, noise smearing, etc.

Taking into account the above assumptions, we have expressed the conductance of an YBCO-insulator-normal metal junction as a sum of three contributions coming from the CuO_2 layers, the CuO chains, and the c direction, respectively:

$$G(V,T)=\sigma_1\int_{-\infty}^{\infty}\mathrm{Re}\left[\frac{(E+i\Gamma_1)^2}{(E+i\Gamma_1)^2-\Delta_1(T)^2}\right]^{1/2}\frac{\partial f(E+eV)}{\partial V}dE$$
$$+\sigma_2\int_{-\infty}^{\infty}\mathrm{Re}\left[\frac{(E+i\Gamma_2)^2}{(E+i\Gamma_2)^2-\Delta_2(T)^2}\right]^{1/2}\frac{\partial f(E+eV)}{\partial V}dE+\alpha\int_{-\infty}^{\infty}|E|\frac{\partial f(E+eV)}{\partial V}dE\ . \qquad (1)$$

Here $f(E)$ is the Fermi distribution function and σ_1, σ_2, and α take into account the normal counterelectrode density of states, the tunnel probabilities, and the YBCO normal density of states. All these quantities are assumed constant as in conventional S-I-N tunneling. The weight of the three contributions is also included in these constants. Expression (1) is consistent with the fact that, in addition to the usual contribution along the c axis, in chemically etched YBCO junctions the etch pits formed on the single crystal's surface expose to the tunneling also the a and b directions.[11,12]

In Fig. 1 the conductances calculated from (1) are compared with the tunneling data, at $T=8$ K, obtained on YBCO-Pb junctions. The values of α and $\sigma\equiv\sigma_1+\sigma_2$ are derived from the experiments. They represent the slope and the intercept at $V=0$ of the extrapolated linear high-bias conductance $G^{\mathrm{extr}}(0)$. We have derived the values $\alpha=2.31\times10^{-2}\ \Omega^{-1}\,V^{-1}$ and $\sigma=6.33\times10^{-3}\ \Omega^{-1}$ from the 90-K data and $\alpha=28.4\times10^{-2}\ \Omega^{-1}\,V^{-1}$ and $\sigma=8.0\times10^{-3}\ \Omega^{-1}$ from the 60-K data. As shown later (Fig. 4), experiments indicate that these parameters do not depend on the temperature. The values $\Delta_1=16$ meV, $\Delta_2=4$ meV, $\Gamma_1=3$ meV, and $\Gamma_2=4$ meV have been used for both phases. This choice can be reconciled with the dynamics of the T_c degradation in the YBCO system. In fact, as the oxygen content is reduced, vacancies are formed along the CuO chains and T_c is found to decrease continuously to about 60 K.[20] Our hypothesis is that in the lower T_c phase, superconductivity of the CuO_2 planes and of the remaining oxygen-complete chains is unaffected and the T_c of the bulk compound is reduced by internal proximity effect due to the increased contribution of the nonsuperconducting incomplete chains.

In our model, the ratio $[G(V)-G^{\mathrm{extr}}(0)]/G(V)=(1+\sigma/\alpha V)^{-1}$ can be considered as the contribution of the c-axis conductance with respect to the total measured conductance. From Fig. 1 this ratio at $V=100$ mV is equal to 0.27 in the 90-K junction and to 0.78 in the 60-K one, indicating that the c-axis contribution is almost tripled in the lower T_c sample. At the same time, a ratio $\alpha/\sigma=3.65V^{-1}$ in the 90-K phase and $\alpha/\sigma=35.5V^{-1}$ in the 60-K phase can be deduced. We have found that the fitting of the experimental data is not affected by variations of the α and σ values that keep their ratio constant. We observe that this result has been predicted in the Varma description of a marginal Fermi liquid[9] and has been verified in $Ba_{1-x}K_xBiO_3$-based junctions.[21]

One of the most intriguing results obtained on YBCO junctions[14,15] concerns the temperature dependence of the zero-bias conductance. As shown in Fig. 2, in the 90-K phase (open circles) a gap opening at $T=T_c$, though less pronounced than what is expected from the BCS theory (dotted line), can be observed, while there is no evidence of a similar discontinuity at $T=T_c$ in the 60-K junction (stars). These experiments, which refer to the same junctions as in Fig. 1, seem to indicate that a

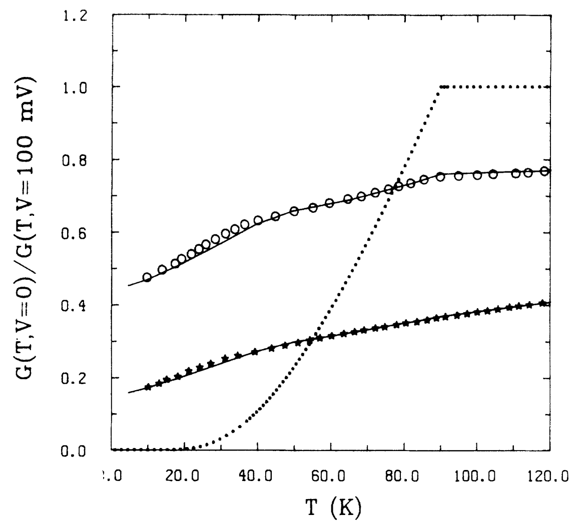

FIG. 2. Normalized zero-bias conductance vs temperature of the same junctions as in Fig. 1. The same symbols and the same fitting parameters as in Fig. 1 have been used. The dotted line is the BCS dependence.

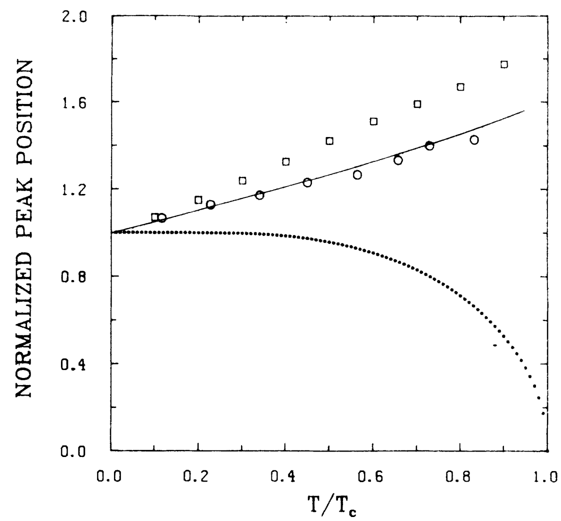

FIG. 3. Voltage position of the conductance peak, normalized to its value at $T=1$ K, vs reduced temperature for the 90-K junction (open circles) and for a conventional *N-I-S* junction (squares). The full line is the theoretical fitting obtained from (1) with the same parameters used in Fig. 1 and the dotted line denotes the BCS dependence of the normalized energy gap.

nonsuperconducting surface layer is sampled in the lower T_c junction even if the $G(V)$ vs V curve shows evidence of two gaplike structures. This apparent contradiction is settled within the framework of our model. Indeed, as a consequence of the increased value of α, which is responsible for the conductance along the c axis, the gap opening in the 60-K phase can be hidden. The full lines in Fig. 2 are the theoretical fittings of the data obtained from (1) at $V=0$, with the same parameters used in Fig. 1. These curves are very sensitive to the value of the temperature at which $\Delta_2(T_{c_2})=0$. $T_{c_2}=45$ K is consistent with the experimental observation that the very broadened low-energy structure disappears at about 30 K.[12,15] T_{c_1} has been fixed at 90 K.

One of the most debated issues about the high-T_c compounds concerns the temperature dependence of the peak structures in the conductance curves, for which contradictory results have been reported.[11,22] It is worth noticing that in some cases the peak positions in voltage have been assumed as energy gaps. The equivalence of the two quantities is correct only in isotropic BCS superconductors at $T \ll T_c$. Because of the thermal smearing, in conventional junctions the peak positions are shifted toward higher biases for increasing temperatures (squares in Fig. 3), so moving in the opposite direction with respect to the energy-gap temperature dependence predicted by the BCS theory (dotted line in Fig. 3).

In the same figure, the voltage positions of the 90-K junction conductance peak corresponding to Δ_1 are represented by open circles, and the full line has been obtained from (1) with the previously reported values of the parameters. Considering that the experimental points near T_c are affected by unavoidably large error bars, the agreement is satisfactory. This nice and simple result indicates that the unusual weak temperature dependence of the main conductance peak is well explained assuming a BCS temperature dependence for Δ_1 and a constant smearing parameter Γ_1. We have not included the analysis of the lower bias structure because of the experimental difficulty in following the temperature dependence of such a smeared feature. According to the values used in Figs. 1 and 2, we obtain $2\Delta_1/k_B T_{c_1}=4.1$ and $2\Delta_2/k_B T_{c_2}=2.1$, indicating strong coupling on the CuO_2 planes and weak coupling on the CuO chains. These considerations do not necessarily imply that electron-phonon interaction is responsible for high-T_c superconductivity but that, given a pairing mechanism, a satisfactory agree-

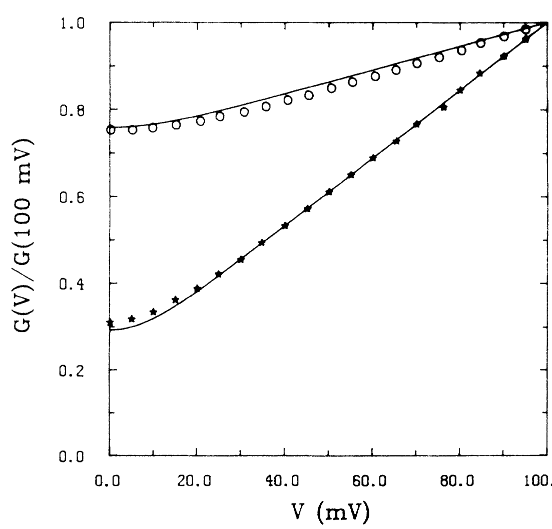

FIG. 4. Normalized conductance vs voltage of the same junctions as in Fig. 1, at $T=100$ K for the 90-K phase (open circles) and $T=64$ K for the 60-K phase (stars). The full lines are the theoretical fittings obtained from (1) at $T > T_c$.

ment with experiments can be found within a BCS-like description.

In Fig. 4 the normal-state characteristics of the same junctions are shown at $T=98$ K (circles, 90-K phase) and $T=64$ K (stars, 60-K phase), together with the theoretical fittings (full lines) obtained from (1) for $T>T_c$. We point out that the values of the parameters α and σ are the same as those used in the superconducting state. The good agreement between theory and experiment indicates that the rounding at low biases is due to the effect of the thermal smearing on the linear conductance for $eV<k_BT$.

To conclude, we want to stress that, in spite of the number of parameters appearing in our model, only a few of them are actually free because of the constraints imposed by the experiments. Furthermore, it is remarkable that the values of the parameters employed to fit the low-temperature curves have led to satisfactory quantitative fittings of the experiments in the whole range of temperatures, in the superconducting as well as in the normal state, for both the 90- and the 60-K phases.

We also notice that the experimental tunneling results we refer to are consistent with NMR studies[3] and specific-heat measurements[23] on the two YBCO phases. At the same time, smeared gaplike structures, linear background conductances, and nonvanishing zero-bias conductances are not peculiar to the YBCO system but have been found in different high-T_c superconductors. Both these facts seem to indicate a wider range of applicability of the proposed model.

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