Zero-bias anomalies in high-T_c-superconductor tunnel junctions

A. M. Cucolo and R. Di Leo
Dipartimento di Fisica, Università di Salerno, 84081 Baronissi, Italy
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The zero-bias conductance peak that is often found in the tunneling characteristics of high-temperature-superconductor (HTS) junctions is analyzed in the framework of the Anderson-Appelbaum model for electron magnetic interaction. We have found that when the anomaly develops at $T > T_c$, its temperature behavior is determined by the superconducting properties of the HTS, while, when it develops at $T < T_c$, the presence of normal or semiconducting surface regions can be supposed. A giant resistance peak seems to indicate interdiffusion of the counterelectrode into the base material.

Anomalous behavior centered at zero voltage has often been observed in the tunneling characteristics of high-temperature-superconductor (HTS) junctions. Both conductance peak and dip have been reported and different hypotheses on their origin have been made.[1-5] Particularly puzzling appears the temperature behavior of such features that can develop both above and below the T_c of the HTS. Recently, these anomalies have received much more attention, and the first detailed reports have appeared in the literature.[6,7] Particularly notable is the contribution of Ref. 7 in which the problem has been analyzed in terms of the phase diffusion that occurs when the thermal energy $k_B T$ is comparable to the Josephson coupling energy of the junction. However, there is at least another class of zero-bias anomalies (ZBA) that often appear in HTS junctions in which the existence of a supercurrent can be ruled out.

In this paper we report a systematic study of anomalies for which a magnetic origin can be hypothesized. Our analysis collects the results we obtained in studying more than 300 tunneling characteristics of different HTS's. All the junctions had natural barriers formed by a short exposition (≈ 30 min) of chemically etched (1% Br by volume in methanol) single crystals to the ambient atmosphere and were completed by evaporating a thin-film counterelectrode. The nature of this barrier is unknown, however, it is likely that the HTS surface layer is contributing to its formation. The nonanomalous behavior of this kind of junction was discussed in Refs. 8–12. The present study has been realized on the 90-K and the oxygen-deficient 60-K $YBa_2Cu_3O_{7-\delta}$ (YBCO) phases, on Fe-doped YBCO systems and on the $Bi_2Sr_2Ca_1Cu_2O_8$ (BSCCO) 2:2:1:2 phase.

An example of the first type of ZBA is shown in Fig. 1(a), in which the differential conductance vs voltage of an Fe-doped YBCO/Pb junction with $T_c(\rho=0)=57$ K, is reported at $T=60$ K. We notice that the anomaly appears as a quite asymmetric conductance peak at zero bias, superimposed to a parabolic background.

Similar kinds of ZBA have been extensively studied in the past and have been found in transition-metal based (Nb,Ta) junctions,[13,14] with thermally grown oxides, in metal-semiconducting junctions[15,16] and in Al/Al and Al/Ag junctions with magnetic impurities in the insulating barrier.[17]

This *normal*-state effect was modeled by the Appelbaum[18] and Anderson[19] theory in which localized magnetic states near a side of the barrier provide a "new tunnel channel," which is described by adding an extra term to the conventional tunneling Hamiltonian. According to this model, the total conductance around zero bias is expressed as a sum of three contributions: the first includes no magnetic interactions, the second takes into account spin exchange between electrons and impurities, and the third describes a Kondo-type scattering:

$$G(V,T)=N[K_1+K_2+K_3\ln(E_0/(e|V|/nk_BT))] , \quad (1)$$

and the excess conductance, defined as the difference between the total conductance and the normal background, is written as

$$\Delta G(V,T)=NK_3\ln\{E_0/[e|V|+nk_BT]\} . \quad (2)$$

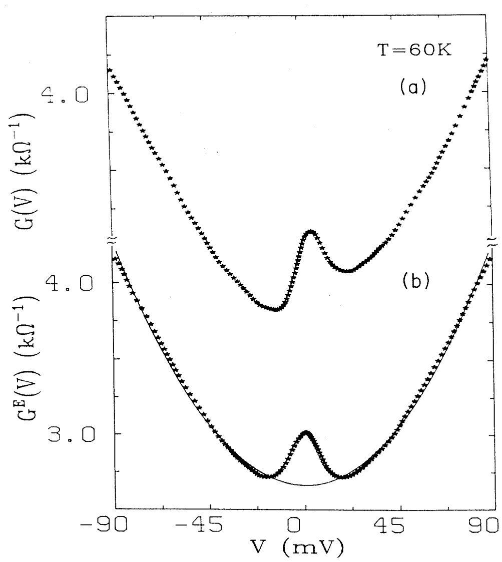

FIG. 1. (a) Conductance vs voltage for an Fe-doped YBCO/Pb junction at $T=60$ K; (b) the even conductance vs voltage has been computed. The solid line shows the extrapolated background parabola.

where $K_{1,2,3}$ are constants that include the normal density of state of the counterelectrode, the matrix elements for tunneling electrons, with the two last terms containing the impurity density and spin, and the strength of the magnetic interaction. In the formula, n is a numerical factor close to unity, E_0 is a cutoff energy, and we have kept the base-electrode normal density of states near the Fermi level, N, as a prefactor.

At low temperatures, in conventional junctions, the effect is studied by applying a low magnetic field to quench the superconductivity of both electrodes. This is not possible for HTS's for which, at $T<T_c$, due to the high H_{c2} values, the energy and temperature dependence of the superconducting density of states has to be taken into account.

To better compare experiments and theory, in the case of an asymmetric background, the even conductance $G^E(V)=\frac{1}{2}[G(+V)+G(-V)]$ is computed,[15] as reported in Fig. 1(b). By this procedure the background is well approximated by a least-squares best-fit parabola $G_0(V)=G_0+3\gamma V^2$ (full line), which is inferred from the high-bias data. From the G_0 and γ values, at $T=4.2$ K, an average barrier height of 0.5 eV, and thickness of 30 Å have been deduced.[20] We consider these values only indicative of a low tunnel barrier, since the presence of Fe ions in the barrier can decrease the effective barrier size for those electrons that tunnel across the junction by means of localized states.

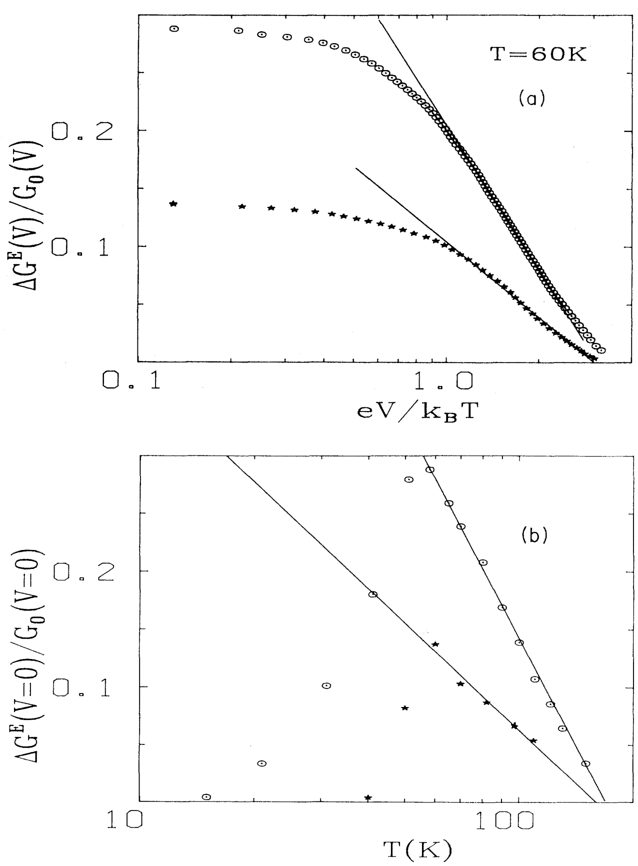

FIG. 2. (a) Energy dependence of the normalized even excess conductance at $T=60$ K for the same junction as Fig. 1, stars, and for another Fe-doped YBCO/Pb junction, open circles; (b) temperature dependence of the same quantity at $V=0$.

Figure 2(a) shows the normalized even excess conductance vs normalized voltage, at $T=60$ K, for the junction of Fig. 1 (stars), and for another Fe-doped YBCO/Pb junction with $T_c=57$ K, which, at the same temperature, develops a 28% amplitude ZBA (open circles). It can be noticed that the logarithmic energy dependence of expression (1) (full lines), is found at $\mathrm{eV}>k_BT$ for both samples, while, at low energy, because of thermal smearing, the conductance drops below the linear logarithmic plot.

Figure 2(b) shows the temperature dependence of the normalized even zero-bias excess conductance for the same junctions. The anomalies develop and disappear at different temperatures, however, the logarithmic dependence of expression (1) (full lines) is quite well observed for $T>T_c$. The data show inversion around 57 K, while for $T<T_c$ the behavior is determined by the decreasing temperature dependence of the superconducting density of states of the HTS. In the figure the extrapolated lines for $T<T_c$, $\Delta G^{\mathrm{Ex}}(0)/G_0(0)$, represent the expected temperature dependence of the anomalies if the HTS were kept in the normal state.

To clarify this point, in Fig. 3(a) a schematic drawing of the conductance characteristic at $T<T_c$ is shown. In the figure, $G_0(V)$ is the background parabola that describes the junction normal state, $G^S(V)$ is the depressed unknown value of the conductance due to the appearance of the superconductivity in the high-T_c material, $G^M(V)$ is the measured conductance, and $G^{\mathrm{Ex}}(V)$ is the extrapolated value of the conductance if the HTS is kept normal.

Let us assume an arbitrary temperature dependence, $1-F(T)$, for the fraction of electrons that condense in the superconducting state. For any $T<T_c$, $N_S+N_N=N$, with the N and S subscripts referring to the normal and

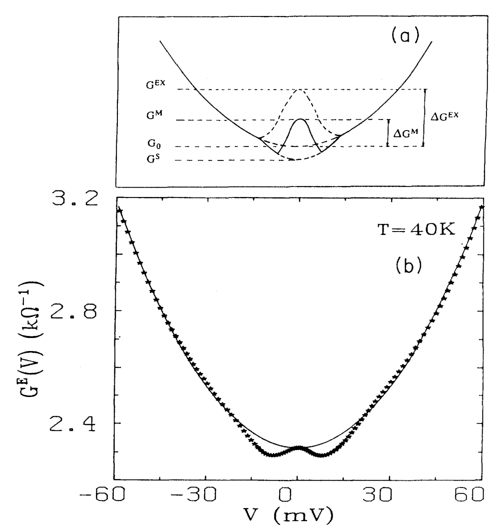

FIG. 3. (a) Schematic drawing of the ZBA at $T<T_c$. The indicated quantities are defined in the text; (b) even conductance vs voltage at $T=40$ K for the same junction as Fig. 1.

superconducting electrons, respectively. As a first approximation, by supposing that the two-electron systems do not interact, as the temperature is lowered, we can assume that both expressions (1) and (2) are reduced by a factor $F(T)$, that is by the amount of which the normal electron density is reduced. By these assumptions, $\Delta G^M(0)=0$ when $G^M(0)=G_0(0)$, as is observed in Fig. 3(b), which refers to the same junction of Fig. 1 at $T=40$ K, and $G^M(0)/G^{Ex}(0)\approx F(T)$. The temperature dependence of this quantity is reported in Fig. 4 for both junctions of Fig. 2. The triangles in the figure represent the quantity $G^S(0)/G_0(0)$ directly measured on the junction in which the anomaly disappears at $T=40$ K. The comparison of this behavior with the gap opening measurements of Refs. 8–11 reveals that this kind of ZBA is very sensitive to the superconducting properties of the HTS.

As a second example of ZBA, in Fig. 5, the temperature dependence of the normalized zero-bias even conductance of a 2:2:1:2 BSCCO/Pb-Bi junction is reported. The T_c of the BSCCO single crystal was of 85 K. As shown in the left inset, also in this case, at $T=10$ K, the anomaly appears as a conductance peak at zero bias, and we have found that it exhibits the logarithmic dependence on energy, right inset, and on temperature as predicted by expression (2).

One can hypothesize a magnetic origin for this anomaly, consistently with the important role that spin fluctuations have in the cuprate superconductors. However, in this kind of junction, the ZBA develops below the T_c of the HTS and reaches its maximum amplitude at low temperatures. This seems to indicate that the density of states prefactor of expression (2) does not vary or varies slowly with temperature, and that normal or semiconducting regions at the junction interface are present.

The behavior of the third kind of ZBA is reported in Fig. 6, which refers to a 2:2:1:2 BSCCO/Pb junction with $T_c=83$ K. As seen in the left inset, in this case at $T=10$ K, a rapid resistance change, $R(0)/R(100\text{ mV})\approx 18$, is observed, while the conductance characteristic shows a linear dependence on voltage, as is observed in the right

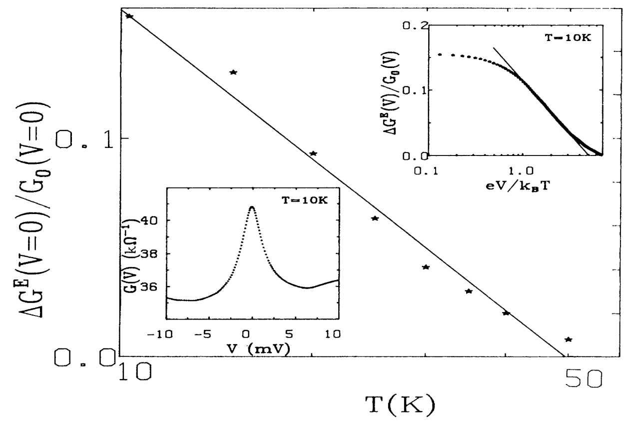

FIG. 5. Temperature dependence of the normalized even excess conductance for a BSCCO/Pb-Bi junction. Left inset: conductance vs voltage at $T=10$ K. Right inset: energy dependence of the normalized even excess conductance at $T=10$ K.

inset. In this type of junction, at $T=4.2$ K, the superconducting structures of both electrodes were highly smeared and in some cases were completely lost, indicating that the whole current flowing through the barrier is anomalous.

This "giant resistance peak" has been studied in the past[14] and there are some experimental evidences about the magnetic origin of this feature.[21] Possible interpretations in terms of a depression of the electron density of states near an impurity layer at the interface,[22] or in terms of the effect of the capacitance of small agglomerates of nonmagnetic particles in the barrier,[23] have been given. None of these hypotheses has been unambiguously confirmed. In particular, the last model indicated a $G(0)$ linear dependence on temperature, while we have found $G(0)\propto T^{0.46}$, as can be seen in Fig. 6.

In conclusion, we have analyzed three different types of ZBA in HTS junctions. The first one develops at $T>T_c$ and appears as a conductance peak at zero bias. The be-

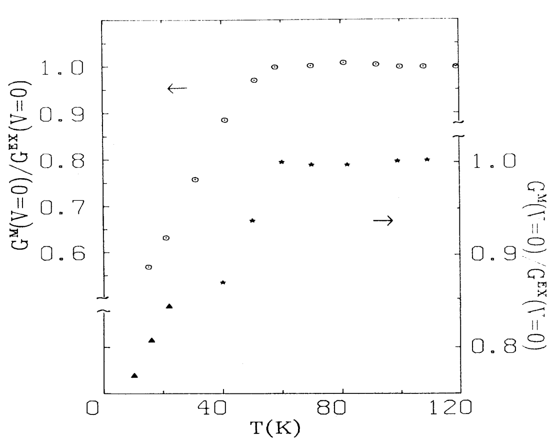

FIG. 4. $G^M(0)/G^{Ex}(0)$ vs temperature for the junctions of Fig. 2. Triangles refer to the $G^S(0)/G_0(0)$ quantity directly measured on the junction.

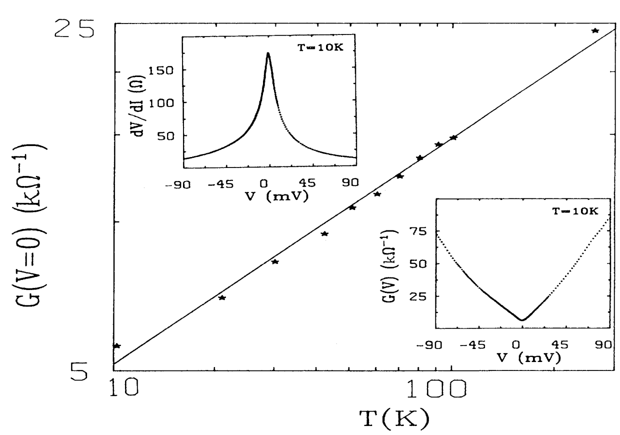

FIG. 6. Temperature dependence of the zero-bias conductance for a BSCCO/Pb junction. Right inset: dV/dI vs V at $T=10$ K. Left inset: dI/dV vs V at $T=10$ K.

havior of this anomaly is well described by the Anderson-Appelbaum model for magnetic interaction of the tunneling electrons at the interface. In HTS junctions that show this anomaly, evidence of electron condensation in the superconducting state is observed. We have found this ZBA in about 20% of YBCO/Pb junctions with Fe-doping concentrations of 3–5 % and in about 10% of 60-K-phase and oxygen-deficient YBCO/Pb junctions. In these systems Fe impurities and/or Cu moments associated to physical defects can be easily responsible for excitation processes near or in the barrier. As demonstrated for conventional junctions, the position of the impurities in the barrier and the fabrication conditions of the interface, are very critical,[14] so that a statistical observation of this effect in HTS junctions is not surprising.

The second kind of anomaly seems to be consistent with the magnetic origin supposed for the first one. However, it develops at $T < T_c$ so that normal or semiconducting regions at the junction interface can be supposed. We have found this anomaly in about 10% of 2:2:1:2 BSCCO-based junctions with Pb, Pb-Bi and Au counterelectrodes and in 5% of 60-K-phase YBCO/Pb junctions, indicating a "real" possibility of a nonsuperconducting surface, or surface regions, in these systems.

Unfortunately, the origin of the third giant resistance peak is not well understood in conventional junctions, making more difficult the interpretation of this effect in HTS's. We have found this type of anomaly in about 10% of 2:2:1:2 BSCCO/Pb and in 90-K-phase YBCO-based junctions with Al or Ag counterelectrodes.[24] For these junctions, from photoemission measurements,[25,26] interdiffusion and/or agglomeration of the first evaporated layers of the thin-film counterelectrode can be supposed, and it seems to us that no definitive elements exist so far to confirm a magnetic origin of this feature.

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