Tunnelling studies of $Eu_1Ba_2Cu_3O_7$ single crystals

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A tunnelling-effect method has been used to study the superconducting characteristics of $Eu_1Ba_2Cu_3O_7$ single crystals. Ratios $2\Delta/kT_c = 10$–11.6 have been found. The "phonon" structure on the curves of $-dV/dI(V)$ is compared with the phonon spectra of oxide superconductors. It is suggested that although the electron-phonon interaction is strong in $Eu_1Ba_2Cu_3O_7$, it can explain only 10–20% of the value of T_c.

Tunnelling studies of the new high-temperature superconductors may be of assistance in analyzing the mechanism for their superconductivity. Studies of this sort make it possible to directly measure not only the energy gap Δ but also the energy dependence of the one-particle tunnelling state density in the superconductor. From the latter we can extract information about the gap function $\Delta(\omega)$. Knowing this function and the ratio $2\Delta(0)/kT_c$, we are in a better position to answer the question of whether an electron-phonon interaction is capable of explaining the high values of T_c in oxide superconductors.

Previous tunnelling-method studies of polycrystalline samples of the compound $Y_1Ba_2Cu_3O_7$ in various laboratories have yielded values of the ratio $2\Delta(0)/kT_c$ ranging from 2.8 to 44 (Ref. 1). However, recent tunnelling[2] and NMR[3] experiments with an yttrium ceramic and also measurements of the optical reflection of $Y_1Ba_2Cu_3O_7$ single crystals with $T_c = 90$ K (Ref. 4) have yielded the values 8–11.2 for this ratio.

In the present letter we are reporting a tunnelling-method study of $Eu_1Ba_2Cu_3O_7$ single crystals. In terms of its structural and superconducting characteristics, this compound is essentially indistinguishable from the widely studied $Y_1Ba_2Cu_3O_7$, but single-crystal samples of $Eu_1Ba_2Cu_3O_7$ are relatively simple to synthesize.

The single crystals were wafers 0.2–1 mm long, 0.1–0.5 mm wide, and 30–50 μm thick. The single-crystal structure of the samples was determined from the data of x-ray and electron-microscopy studies. The c axis of the crystals was oriented perpendicular to the plane of the wafer. In the technological procedure used, these crystals were grown from the molten solution in a few seconds. They were next annealed in oxygen for 2 h and then slowly cooled. We studied "point" $Eu_1Ba_2Cu_3O_7$-Nb tunnel junctions. Since the theoretical papers link the superconductivity in these new superconductors with a high conductivity in the $(a$–$b)$ plane, the tip of a niobium needle was pressed against the edge of the single-crystal wafers, i.e., perpendicular to the c axis in most of our experiments. We recorded current-voltage $(I$–$V)$ characteristics and their derivatives over the temperature range 4.2–150 K. The error of the temperature measurements in the particular cryostat which we used was 0.5 K, as we estab-

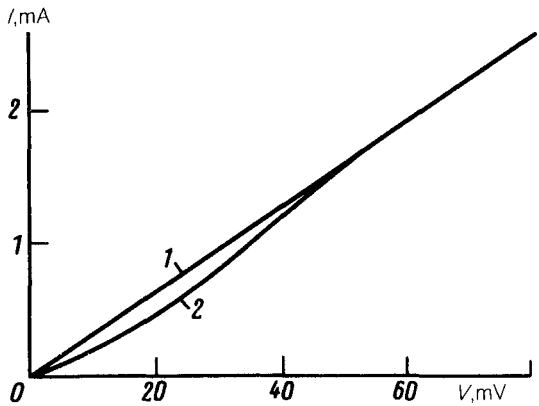

FIG. 1. I–V characteristics of a $Eu_1Ba_2Cu_3O_7$-Nb tunnel junction at (1) 100 K and (2) 4.2 K.

lished in a special check in which we used a second thermometer in place of the sample. We identified the superconducting transition temperature T_c as the temperature at which the energy gap of the compound, $\Delta_x(T)$, vanished. The values of T_c for the various samples lay in the range 85–91 K.

The gap feature on the I–V characteristics of the tunnel junctions, which corresponds to the sum $\Delta_x + \Delta_{Nb}$ (Fig. 1), was observed only for junctions with a resistance less than 150 Ω. As in earlier tunnelling experiments with polycrystalline $Y_1Ba_2Cu_3O_7$ samples, we observed a large "parasitic" current in our tunnel junctions at $eV < \Delta_x + \Delta_{Nb}$. This parasitic current was caused by a tunnelling of normal elementary excitations, which are present in the sample crystals even at $T \ll T_c$. The large background on the plot of the differential conductivity of the tunnel junction versus the voltage, $dI/dV(V)$, was also linked with this current. The value of Δ_x was determined from the maximum on the curves of $-dV/dI(V)$, whose position along the voltage axis ($T < T_c$ of Nb) corresponded to the sum $\Delta_x + \Delta_{Nb}$ (Fig. 2). It can be

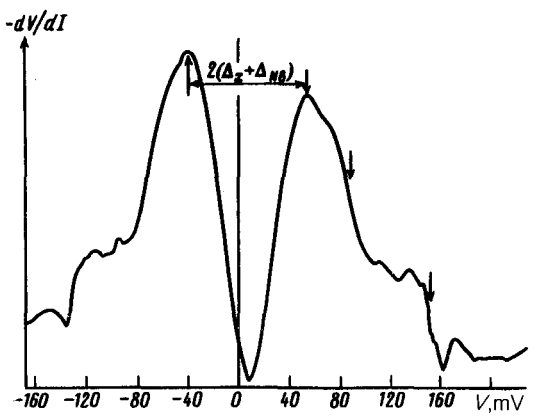

FIG. 2. The dependence $-dV/dI(V)$ for the tunnel junction whose characteristics are shown in Fig. 1, at $T = 4.2$ K. The arrows show the structure which results from the electron-phonon interaction in $Eu_1Ba_2Cu_3O_7$.

assumed—and the temperature dependence of Δ_x confirms this assumption—that we have $\Delta_x(4.2)\kappa \approx \Delta_x(0)$. We determined the value $\Delta_{Nb}(4.2\kappa)$ from the dependence $\Delta_{Nb}(T)$ which we found previously. For the various $Eu_1Ba_2Cu_3O_7$ single crystals we found $\Delta_x(4.2\kappa) = 36 - 45.5$ meV and corresponding ratios $2\Delta_x(0)/kT_c = 10 - 11.6$. Large values of this ratio correspond to large values of Δ_x and high values of T_c.

On the curves $-dV/dI(V)$ at $V > (\Delta_x + \Delta_{Nb})/e$ we observe an additional, and reproducible, structure (as marked by the arrows in Fig. 2), which is caused by the electron-phonon interaction in tunnelling studies of ordinary superconductors. Since the "phonon" structure of Nb is known to lie in the region $V < 25$ mV on the tunnelling characteristics, it is natural to associate the structural features marked by the arrows with the compound $Eu_1Ba_2Cu_3O_7$. This assignment seems particularly safe since these structural features disappear at temperatures $T > T_c$ of the crystal. Figure 3 shows the dependence $d^2I/dV^2(V)$; the minima on this dependence should coincide with the maxima in the phonon spectrum of the compound under study. Shown at the bottom are phonon spectra $F(\omega)$ of $La_{1.85}Sr_{0.15}CuO_4$ (the dotted line; Ref. 5) and $Y_1Ba_2Cu_3O_7$ (Ref. 6), which were found in experiments on neutron scattering by polycrystalline samples at 6 K and 12 K, respectively. The minima on the $d^2I/dV^2(V)$ curve essentially coincide with the principal maxima on the $F(\omega)$ curve for the compound $La_{1.85}Sr_{0.15}CuO_4$; the same cannot be said of the spectrum of $Y_1Ba_2Cu_3O_7$. If all three curves are accurate, then only phonon modes associated with atoms in the a–b plane participate in the electron-phonon interaction in $Eu_1Ba_2Cu_3O_7$.

Apparently because the coherence length along the c axis is nearly an order of

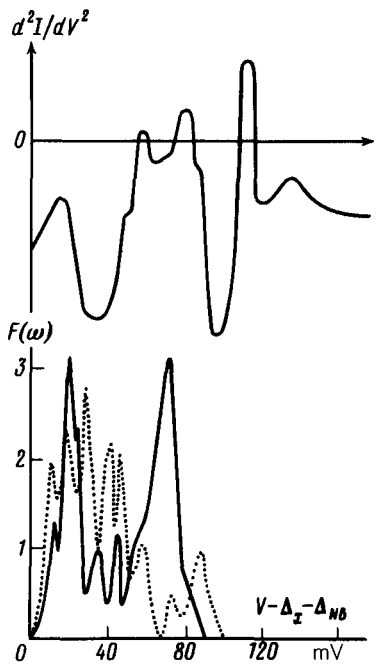

FIG. 3. The dependence $d^2I/dV^2(V)$ for a $Eu_1Ba_2Cu_3O_7$-Nb junction at $T = 4.2$ K; phonon spectra $F(\Omega)$ of (dotted line) $La_{1.85}Sr_{0.15}CuO_4$ and $Y_1Ba_2Cu_3O_7$, according to neutron studies.[5,6]

magnitude shorter than that in the a–b plane, we were not able to measure Δ_x along the direction of the c axis, although the characteristics of the tunnel junction reveal a gap structural feature which corresponds to Nb, and microwave irradiation of the junctions reveals a time-dependent Josephson effect.

A comparison of the amplitude of the "phonon" structure on the curves of $-dV/dI(V)$ with the corresponding amplitude for lead tunnel junctions and the value of the ratio $2\Delta_x(0)/kT_c$ provides evidence that $Eu_1Ba_2Cu_3O_7$ has a strong electron-phonon coupling, which is at least twice as strong as that in Pb. On the other hand, even a rough estimate shows that this structure leads to maxima in the function $\Delta(\omega)$ which are much smaller in amplitude than $\Delta[\Delta_x(0)]$ (in the case of lead, these quantities are on the same order of magnitude). The electron-phonon interaction thus contributes to the superconductivity of this compound, but it is not the governing mechanism; it could apparently explain only 10–20% of the values of T_c and $\Delta_x(0)$. Also in agreement with this conclusion is the small value of the isotopic effect in oxide superconductors.

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