Tunneling measurement of the energy gap in Y-Ba-Cu-O

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Superconductor-insulator-normal tunneling measurements have been performed on the high-$T_c$ superconductor YBa$_2$Cu$_3$O$_{6-\delta}$ at 4.2 and 77 K. The results indicate an energy gap of magnitude $2\Delta_0/k_BT_c=3.9$ at $T=0$, with a temperature dependence consistent with the Bardeen-Cooper-Schrieff theory of superconductivity.

The superconducting oxides La-$M$-Cu-O ($M=$Ba, Sr, Ca) and Y-Ba-Cu-O have recently attracted considerable interest, predominantly because of their very high superconducting transition temperatures $T_c$. In the lanthanum-based materials, La$_{1.85}$Sr$_{0.15}$CuO$_4$ has the highest transition temperature at $T_c=39$ K; the yttrium compound YBa$_2$Cu$_3$O$_{6-\delta}$ (which is presumably the active superconducting phase in Y$_{1.2}$Ba$_{0.8}$Cu$_4$O$_{6-\delta}$) has displayed $T_c$ above 90 K.

The exceptionally high superconducting transition temperatures in the oxides have raised questions as to the applicability of the Bardeen-Cooper-Schrieffer (BCS) theory of electron-phonon superconductivity to these materials. A number of new models have been proposed, in which, for example, important roles are played by low-dimensional effects or resonating valence-bond mechanisms. Both the BCS model and competing models remain largely untested in the superconducting oxides.

A feature common to nearly all BCS superconductors is the existence of an energy gap of magnitude $2\Delta$ in the density of states at the Fermi level $E_F$. In the weak-coupling limit, BCS predicts

$$2\Delta_0=3.5k_BT_c,$$

where $k_B$ is the Boltzmann constant and $\Delta_0=\Delta(T=0)$. For a strong coupling superconductor, the ratio $2\Delta_0/k_BT_c$ may exceed 3.5; ratios on the order of 4 are not uncommon.

Recent far-infrared and tunneling measurements on La$_{1.85}$Sr$_{0.15}$CuO$_4$ have demonstrated the existence of an energy gap, with $2\Delta_0/k_BT_c\approx 2.5$ from infrared data, and $2\Delta_0/k_BT_c$ ranging from 4 to 7 from point-contact tunneling. The reason for the discrepancy between the infrared and tunneling data is not well understood, but it may reflect proximity effects, or perhaps surface "contamination." The tunneling data are consistent with strong-coupling BCS superconductivity, and the temperature dependence of $\Delta$ as determined by infrared measurements is also in accord with the BCS prediction.

We here report point-contact tunneling measurements on the newly discovered high-$T_c$ superconductor YBa$_2$Cu$_3$O$_{6-\delta}$. Strong evidence for the existence of an energy gap is observed, and at 4.2 K we find $\Delta/e=15$ mV. At 77 K the gap lies near $\Delta/e=10$ mV. Our results suggest a maximum zero-temperature gap $2\Delta_0/k_BT_c=3.9$, a value consistent with the BCS strong-coupling theory. The full temperature dependence of the gap has not been determined; however, the ratio of the two points extracted from the tunneling data at 4.2 and 77 K are as expected from the BCS theory.

Polycrystalline single-phase samples of YBa$_2$Cu$_3$O$_{6-\delta}$ were prepared by grinding the starting materials Y$_2$C$_3$, BaCO$_3$, and CuO, pressing the powder into a pellet, and then sintering at 1050 °C in flowing oxygen. The samples were characterized by magnetic-susceptibility, x-ray, and dc-electrical-resistivity measurements. Figure 1 shows the dc resistance of Y-Ba-Cu-O as a function of temperature.

![Figure 1](https://example.com/Figure1.png)

**FIG. 1.** dc resistance vs temperature for YBa$_2$Cu$_3$O$_{6-\delta}$. $T_c=90$ K.
The onset of superconductivity is at 91 K, and zero resistance occurs at 89 K. The midpoint of the transition, which we identify as $T_c$, is at 90 K.

Point-contact tunneling measurements were performed with an experimental configuration similar to that described by Levinstein and Kunzler. A sharpened copper tip formed the normal side of the superconductor-insulator-normal (SIN) tunnel junction. Copper oxide, along with any nonconducting oxides on the surface of the YBa$_2$Cu$_3$O$_{y-6}$ sample, formed the insulating barrier. Conventional lock-in techniques were used to obtain the differential resistance, $dV/dI$, of the junction as a function of dc bias voltage $V_{dc}$. During the measurement, the sample and junction were fully immersed either in liquid helium or liquid nitrogen.

Figure 2(a) shows $dV/dI$ vs $V_{dc}$ for the SIN junction at 4.2 K. Numerous curves were measured, and all had the same general features. At $V_{dc}=0$, a finite resistance of approximately 750 Ω is observed, which we associate with leakage current due to defects in the barrier. With increasing $V_{dc}$, $dV/dI$ decreases, but displays a local minimum near ±15 mV. We also note a clear asymmetry of $dV/dI$ about the $V_{dc}=0$ axis; this feature was present in all of our tunneling measurements on Y-Ba-Cu-O, and has been seen by other workers. This indicates an asymmetrical barrier, probably due to differences in the barrier dielectric constant on either side of the junction. In Fig. 2(a), positive $V_{dc}$ corresponds to electrons tunneling from the superconducting sample into the copper tip.

Figure 2(b) shows the data of Fig. 2(a) numerically inverted and plotted as differential conductance $dI/dV$. The $V_{dc}=0$ conductance of the shunt resistance has been subtracted. The general form of the $dI/dV$ trace in Fig. 2(b) is that expected from SIN tunneling into a bulk superconductor, although the features are somewhat "smearred." From BCS theory, the differential conductance of a SIN tunnel junction may be expressed as an energy integral over the applied bias voltage and energy-gap parameter. At $T=0$, $dI/dV$ is finite, but diverges as $dI/dV$ at $V_{dc}=\Delta/e$. At finite temperatures, thermal excitations smear the sharp features. The dashed line in Fig. 2(b) is the prediction of $dI/dV$ from BCS theory, with $T=4.2$ K and $\Delta/e=15$ mV. It is apparent that the smearing of the experimental data is in excess of that predicted from simple thermal excitation and the BCS theory.

The smearing of the experimental data, both below and above $\Delta/e$, which may be due to quasiparticle lifetime effects or the granular nature of the Y-Ba-Cu-O superconductor, makes a precise determination of the magnitude of the energy gap difficult. However, the local maximum in $dI/dV$ at 15 mV may be taken as a good approximation to $\Delta/e$ at 4.2 K, and most certainly this value represents an upper limit to $\Delta/e$ at 4.2 K.

We have performed similar tunneling experiments on Y-Ba-Cu-O at $T=77$ K. Although a large amount of noise was present, $dV/dI$ traces at 77 K showed rough features similar to those apparent in Fig. 2(a). Dips in $dV/dI$ (corresponding to peaks in $dI/dV$) occurred approximately at 10 mV, suggesting $\Delta/e = 10$ mV as an estimate for the energy gap at 77 K.

Figure 3 shows $\Delta (T=4.2$ K) and $\Delta (T=77$ K) on a $\Delta$ vs $T$ plot for Y-Ba-Cu-O. Also shown is the BCS curve, with $2\Delta/k_BT_c = 3.9$. From Fig. 3, it is apparent that the tunneling data are adequately explained by BCS predictions. A more complete set of data points on the tempera-
ture dependence of $\Delta$ would be highly desirable. Because of the difficulties we have encountered in obtaining reliable tunneling measurements at high temperatures in the SIN junctions, we suggest that infrared measurements might be performed to extract the detailed behavior of the gap near $T_c$.\footnote{Note, however, that the functional form of the gap parameter near $T_c$ (square-root dependence on temperature) follows not only from BCS theory, but from mean-field theory in general.}

Finally, we note that we have made preliminary superconductor-insulator-superconductor tunneling measurements on Y-Ba-Cu-O at 4.2 K, using a niobium tunnel tip. The measurements indicate clear Josephson tunneling. Extension of these measurements to higher temperatures, employing Y-Ba-Cu-O/I/Y-Ba-Cu-O junctions, would be of interest because of important technological applications in the form of liquid-nitrogen Josephson devices, for example switches, mixers, and superconducting quantum interference devices.

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