RAPID COMMUNICATIONS

PHYSICAL REVIEW B VOLUME 35, NUMBER 16 1 JUNE 1987

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

M. F. Crommie, L. C. Bourne, and A. Zettl
Department of Physics, University of California, Berkeley, California 94720

Marvin L. Cohen
Department of Physics, University of California, Berkeley, California 94720
and Materials and Chemical Sciences Division of the Lawrence Berkeley Laboratory, Berkeley, California 94720

A. Stacy
Department of Chemistry, University of California, Berkeley, California 94720
and Materials and Chemical Sciences Division of the Lawrence Berkeley Laboratory, Berkeley, California 94720
(Received 24 March 1987; revised manuscript received 6 May 1987)

Superconductor-insulator-normal tunneling measurements have been performed on the high-T_c superconductor $YBa_2Cu_3O_{9-\delta}$ at 4.2 and 77 K. The results indicate an energy gap of magnitude $2\Delta_0/k_BT_c \approx 3.9$ at $T=0$, with a temperature dependence consistent with the Bardeen-Cooper-Schrieffer 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.[1-7] In the lanthanum-based materials, $La_{1.85}Sr_{0.15}CuO_4$ has the highest transition temperature at $T_c = 39$ K;[5] the yttrium compound $YBa_2Cu_3O_{9-\delta}$ (which is presumably the active superconducting phase[8,9] in $Y_{1.2}Ba_{0.8}CuO_{4-\delta}$) has displayed T_c above 90 K.[6,7]

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[10] to these materials. A number of new models have been proposed, in which, for example, important roles are played by low-dimensional effects[11] or resonating valence-bond mechanisms.[12] 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 2Δ in the density of states at the Fermi level E_F. In the weak-coupling limit, BCS predicts

$$2\Delta_0 = 3.5k_BT_c \ , \qquad (1)$$

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

Recent far-infrared[13-15] and tunneling[16-18] 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,[14,19] or perhaps surface "contamination." The tunneling data are consistent with strong-coupling BCS superconductivity, and the temperature dependence of Δ as determined by infrared measurements[13] is also in accord with the BCS prediction.

We here report point-contact tunneling measurements on the newly discovered high-T_c superconductor $YBa_2Cu_3O_{9-x}$. Strong evidence for the existence of an energy gap is observed, and at 4.2 K we find $\Delta/e \approx 15$ mV. At 77 K the gap lies near $\Delta/e \approx 10$ mV. Our results suggest a maximum zero-temperature gap $2\Delta_0/k_BT = 3.9$, 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 $YBa_2Cu_3O_{9-\delta}$ were prepared by grinding the starting materials Y_2C_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.

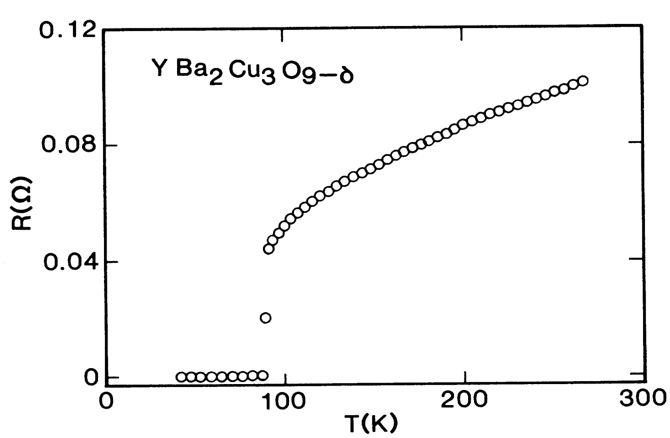

FIG. 1. dc resistance vs temperature for $YBa_2Cu_3O_{9-\delta}$. $T_c = 90$ K.

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.[20] 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 $YBa_2Cu_3O_{9-\delta}$ 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.[18] 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.

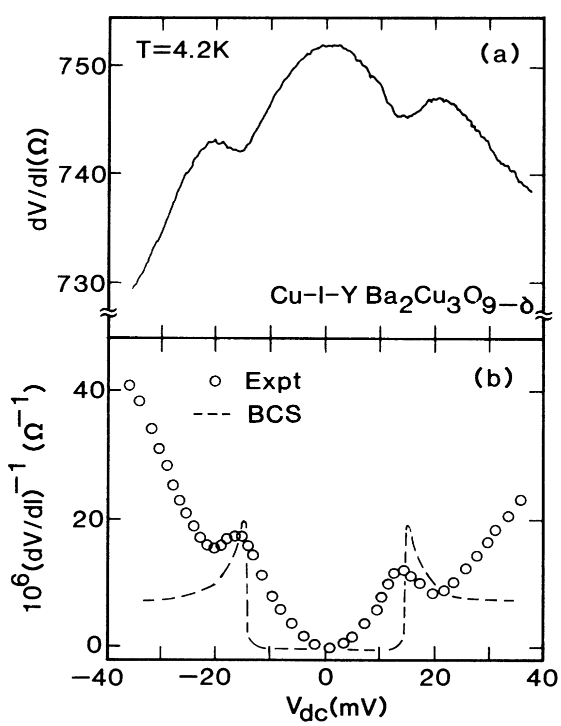

FIG. 2. (a) Differential resistance vs bias voltage for point-contact tunnel junction at 4.2 K. A copper tip is used to tunnel into $YBa_2Cu_3O_{9-\delta}$. (b) Differential conductance determined from data of (a). The $V_{dc}=0$ shunt conductance has been subtracted. The dashed line is the prediction of BCS theory, with $\Delta/e=15$ mV and $T=4.2$ K.

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 "smeared." 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.[21] At $T=0$, $dI/dV=0$ for $V_{dc}<\Delta/e$, and a divergence occurs in 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 Δ/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 Δ/e at 4.2 K, and most certainly this value represents an upper limit to Δ/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 $\Delta/e \approx 10$ mV as an estimate for the energy gap at 77 K.

Figure 3 shows Δ ($T=4.2$ K) and Δ ($T=77$ K) on a Δ vs T plot for Y-Ba-Cu-O. Also shown is the BCS curve, with $2\Delta_0/k_BT_c=3.9$. 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-

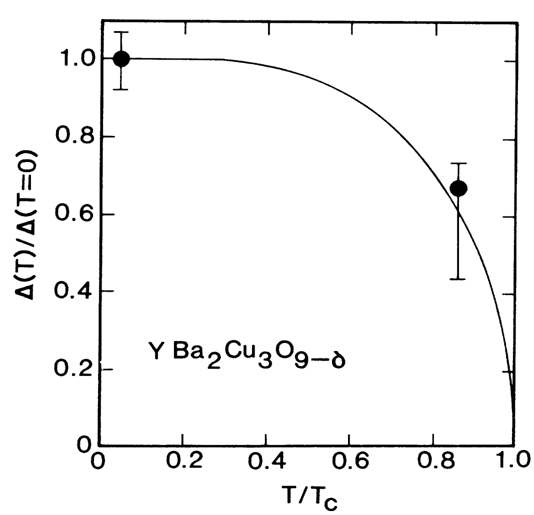

FIG. 3. Normalized gap at 4.2 and 77 K in $YBa_2Cu_3O_{9-\delta}$. The solid line is the BCS gap, with $2\Delta_0/k_BT_c=3.9$.

ture dependence of Δ 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.[22]

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.

We thank Professor J. Clarke for helpful discussions, and Mark Cohen, C. Mullin, S. Hoen, and W. Creager for assistance with sample preparation and resistivity measurements. This research was supported by National Science Foundation Grant No. DMR 84-00041. One of us (A.Z.) also received support from the Alfred P. Sloan Foundation.

[1]J. G. Bednorz and K. A. Müller, Z. Phys. B **64**, 189 (1986).

[2]S. Uchida, H. Takagi, K. Kitazawa, and S. Tanaka, Jpn. J. Appl. Phys. Lett. (to be published).

[3]H. Takagi, S. Uchida, K. Kitazawa, and S. Tanaka, Jpn. J. Appl. Phys. Lett. (to be published).

[4]C. W. Chu, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, and Y. Q. Wang, Phys. Rev. Lett. **58**, 405 (1987).

[5]R. J. Cava, R. B. van Dover, B. Batlogg, and E. A. Rietman, Phys. Rev. Lett. **58**, 408 (1987).

[6]M. K. Wu, J. R. Ashburn, C. J. Torng, P. H. Hor, R. L. Meng, L. Gao, Z. J. Huang, and C. W. Chu, Phys. Rev. Lett. **58**, 908 (1987).

[7]L. C. Bourne, M. L. Cohen, W. N. Creager, M. F. Crommie, A. M. Stacy, and A. Zettl, Phys. Lett. (to be published).

[8]R. J. Cava, B. Batlogg, R. B. van Dover, D. W. Murphy, S. Sunshine, T. Siegrist, J. P. Remeika, E. A. Rietman, S. Zahurak, and G. P. Espinosa, Phys. Rev. Lett. **58**, 1676 (1987).

[9]P. M. Grant, R. B. Beyers, E. M. Engler, G. Lim, S. S. P. Parkin, M. L. Ramirez, V. Y. Lee, A. Nazzal, J. E. Vazquez, and R. J. Savoy, Phys. Rev. B **39**, 7242 (1987).

[10]J. Bardeen, L. N. Cooper, and J. R. Schrieffer, Phys. Rev. **108**, 1175 (1957).

[11]V. Kresin (unpublished).

[12]P. W. Anderson (unpublished).

[13]U. Walter, M. S. Sherwin, A. Stacy, P. L. Richards, and A. Zettl, Phys. Rev. B **35**, 5327 (1987).

[14]P. E. Sulewski, A. J. Sievers, S. E. Russek, H. D. Hallen, D. K. Lanthrop, and R. A. Burhman, Phys. Rev. B **35**, 5330 (1987).

[15]Z. Schlesinger, R. L. Greene, J. G. Bednorz, and K. A. Müller, Phys. Rev. B **35**, 5334 (1987).

[16]T. Ekino, J. Akinitsu, M. Sato, and S. Hosoya (unpublished).

[17]S. Pan, K. W. Ng, A. L. de Lozanne, J. M. Tarascon, and L. H. Greene, Phys. Rev. B **35**, 7220 (1987).

[18]J. R. Kirtley, C. C. Tsuei, S. I. Park, C. C. Chi, J. Rosen, and M. W. Shafer, Phys. Rev. B **35**, 7216 (1987).

[19]M. S. Sherwin, P. L. Richards, A. Zettl, M. L. Cohen, and A. Stacy (unpublished).

[20]H. J. Levinstein and J. E. Kunzler, Phys. Lett. **20**, 581 (1966).

[21]See, for example, R. Heservey and B. B. Schwartz, in *Superconductivity,* edited by R. D. Parks (Dekker, New York, 1969), Vol. 1, p. 135.

[22]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.