Experimental Observation of Non-'S-Wave' Superconducting Behavior in Bulk Superconducting Tunneling Junctions of $YBa_2Cu_3O_{7-\delta}$

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ABSTRACT

Evidence of non-s-wave superconductivity from normal tunneling experiments in bulk tunneling junctions of $YBa_2Cu_3O_{7-\delta}$ is presented. The I-V and dI/dV characteristics of bulk superconducting tunneling junctions of $YBa_2Cu_3O_{7-\delta}$ have been measured at 77.0K and clear deviation from s-wave superconducting behavior has been observed. The result agrees with d-wave symmetry, and interpreting the data in this way, the magnitude of the superconducting energy gap, 2Δ, is found to be (0.038 ± 0.002) eV. Comparing this energy gap with T_c ($2\Delta/k_BT_c = 5.735$), indicates that these high-T_c superconductors are strongly correlated materials, which in contrast with BCS-superconductors are believed to be weakly correlated.

INTRODUCTION

More than a decade has passed after the discovery of high-temperature superconductivity in the compound $YBa_2Cu_3O_{7-\delta}$ (Bednorz & Muller, 1986). Since then, More and better superconductors with much higher superconducting transition temperatures (Poole & Creswick, 1995a, Table 2.1), better electrical and magnetic properties (Poole & Creswick, 1995b: Appendix A.1), and improved mechanical processing techniques for commercial applications (Applied Superconductivity Conference) have been discovered. However, as of this time, not one single theory has garnered major acceptance among the community to describe the underlying mechanism that makes these superconductors superconduct at such elevated temperatures (Clery, 1996). Clearly, an understanding of the superconducting mechanism in these superconductors is important in guiding the developments in commercial applications and in paving the way for future discoveries.

Such an understanding, nevertheless, can only be obtained from clear experimental evidence and a sound theoretical foundation. The renowned BCS theory of superconductivity was arrived at in this manner. It was only after a great deal of experimental work on the electronic and magnetic properties of superconductors that the theory was formulated in its final form.

At present, the community is divided between s-wave and d-wave superconductivity — two of the most prevalent theories of high-T_c superconductivity today (Clery, 1996). Each of these theories has its own separate following in the community with each group presenting new and compelling experimental evidences. The researches of interest at the moment are those that are specifically designed and implemented to disprove the one and consolidate convincing proof for the other.

Key words: s-wave, d-wave, tunneling, superconducting energy gap, $YBa_2Cu_3O_{7-\delta}$

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In this paper, we present experimental observations of d-wave superconductivity in $YBa_2Cu_3O_{7-\delta}$. Fully-oxygenated $YBa_2Cu_3O_{7-\delta}$-samples were prepared with Tc=78.4K (through resistivity measurements), from which normal tunneling experiments were performed at T=77.0 K. The I-V and dI/dV plots of the tunneling junctions show no evidence of a clear superconducting energy gap — a direct consequence of an s-wave superconducting mechanism approximation — but, cusps have been observed in the plots, which are a strong indication of d-wave superconductivity. Moreover, our theoretical calculations, based on a d-wave approximation, show good agreement to the experimental plots obtained.

METHODOLOGY

Bulk superconducting pellets of $YBa_2Cu_3O_{7+\delta}$ were prepared via the solid state reaction method based on an earlier research by Sarmago (1991). The pellets were cut into 2x20x2mm and 2x10x2mm rods and mounted on a PCB sample mount as a SIS (superconductor-insulator-superconductor) junction (Fig. 1) using the natural oxide that forms on the surface of these bulk superconductors as insulator. However, the thickness of this oxide layer was never measured.

The tunneling junction was then mounted on the sample holder of a locally fabricated tunneling head designed for break junction tunneling measurements at liquid nitrogen temperatures. Once mounted, the tunneling head was evacuated to rough vacuum conditions and was then filled with Helium gas. The gas would serve as a thermal conductor for the superconducting sample inside the chamber. Once filled with Helium, the tunneling head was cooled down to liquid nitrogen temperatures through an external liquid nitrogen bath. Fig. 2 is a schematic of the tunneling head used.

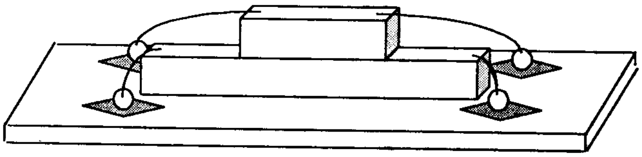

Fig. 1. The PCB sample mount showing how the bulk superconducting rods were mounted in a SIS configuration. Electrical connections to the superconducting sample consisted of gold wires with indium balls at the ends.

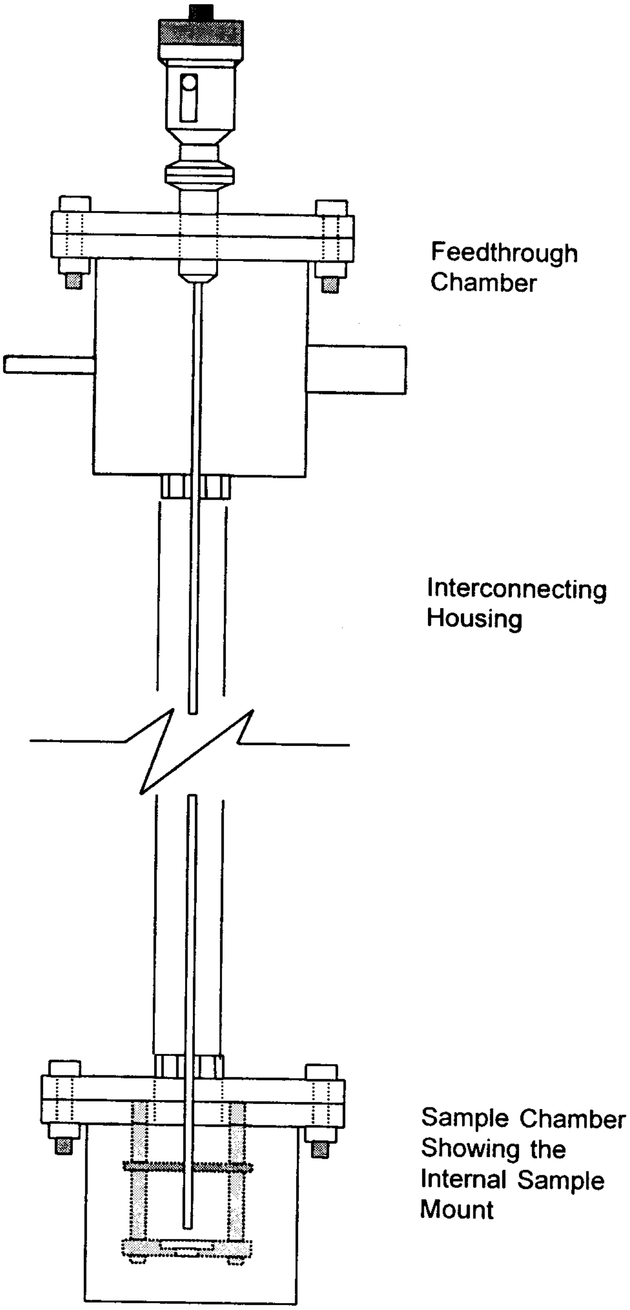

Fig. 2. Schematic diagram of the experimental tunneling head used in the measurement. The sample mount shown in Fig. 1 is mounted inside the sample chamber. Only the sample chamber is immersed in the external liquid nitrogen bath during cooldown to 77K.

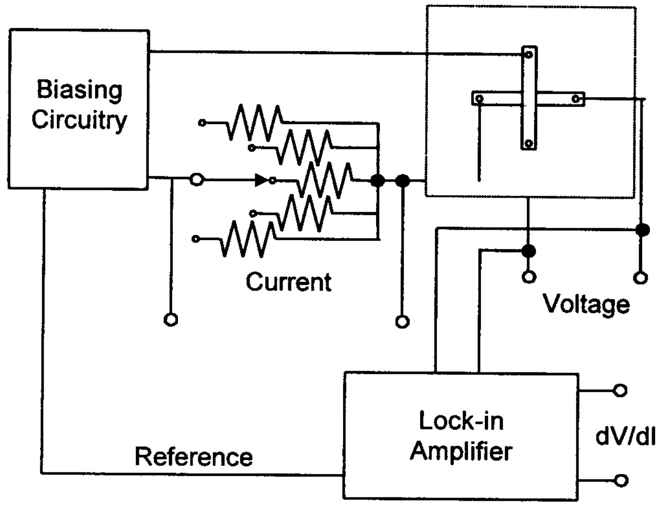

Fig. 3. Schematic of the measurement scheme implemented.

Once cooled to liquid nitrogen temperatures, the tunneling junction was biased by external circuitry, and plots of I-V and dI/dV-V were taken from a GPIB-based data acquisition program developed in Testpoint® and ran on an IBM-compatible personal computer. The program handles all initialization of measuring instruments, as well as acquisition of data from these measuring instruments. Fig. 3 shows the measurement scheme implemented based on an ac modulation technique employed by Thomas and Klein (1963).

In this technique, a small constant ac signal is applied to the tunnel junction. Harmonic detection is then employed directly to determine the dI/dV and other harmonics. Here, if the current modulation is kept constant, the voltage V developed across the junction may be written in terms of a Taylor series,

$$V(I) = V(I_o) + (dV/dI)\,\delta\cos\omega t + \tfrac{1}{2}\,(d^2V/d^2I)\,\delta^2\cos^2\omega t + \ldots \quad \textbf{(1)}$$

where $V(I_o)$ is the dc bias of the tunnel junction and ω is 2π times the modulating frequency. It then follows from Eqn. 1 that if δ is kept constant, then the component of the voltage across the junction at ω is proportional to (dI/dV) and at 2ω is proportional to (d^2V/d^2I). Circuit implementation of this technique utilized a ramp signal, obtained from a programmable voltage source, as the dc bias and a sine signal generated from a function generator as the modulation. All voltages, including the voltage proportional to the current being studied were measured from Keithley 2001 bench digital multimeters. The dI/dV signal on the other hand was obtained from the output of a lock-in amplifier locked on the sine signal input.

RESULTS AND DISCUSSION

The I-V characteristic of a tunneling junction consisting of identical superconductors at T=0 K may be calculated as follows:

$$I_{ss} \equiv \frac{G_{nn}}{e}\int n_s(E - eV)\,n_s(E)\,[f(E - eV) - f(E)]\,dE \quad \textbf{(2)}$$

$$I_{ss} \approx \frac{G_{nn}}{e}\int_0^{eV} n_s(E - eV)\,n_s(E)\,dE \quad \textbf{(3)}$$

For an s-wave (or BCS) superconductor, the energy dispersion relation is as follows:

$$E_k = \sqrt{\left(\frac{1}{2}k^2\right)^2 + \Delta^2} \quad \textbf{(4)}$$

By definition, the density of states(DOS), $n_s(E)$ is given by

$$n_s(E) = (2\pi)^{-2}\int d2k\,\delta(E - E_k) \quad \textbf{(5)}$$

Thus, for an s-wave superconductor, the expression for the density of states is as follows:

$$n_s(E) = \frac{E}{2\pi\sqrt{E^2 - \Delta^2}} \quad \text{when } (\,|E| \geq 2\Delta\,) \quad \textbf{(6)}$$

and zero otherwise.

Substituting Eqn. 6 with Eqn. 3, we obtain a theoretical plot of the I-V characteristic of a tunneling junction consisting of identical s-wave superconductors at absolute zero temperature, as shown in Fig. 4.

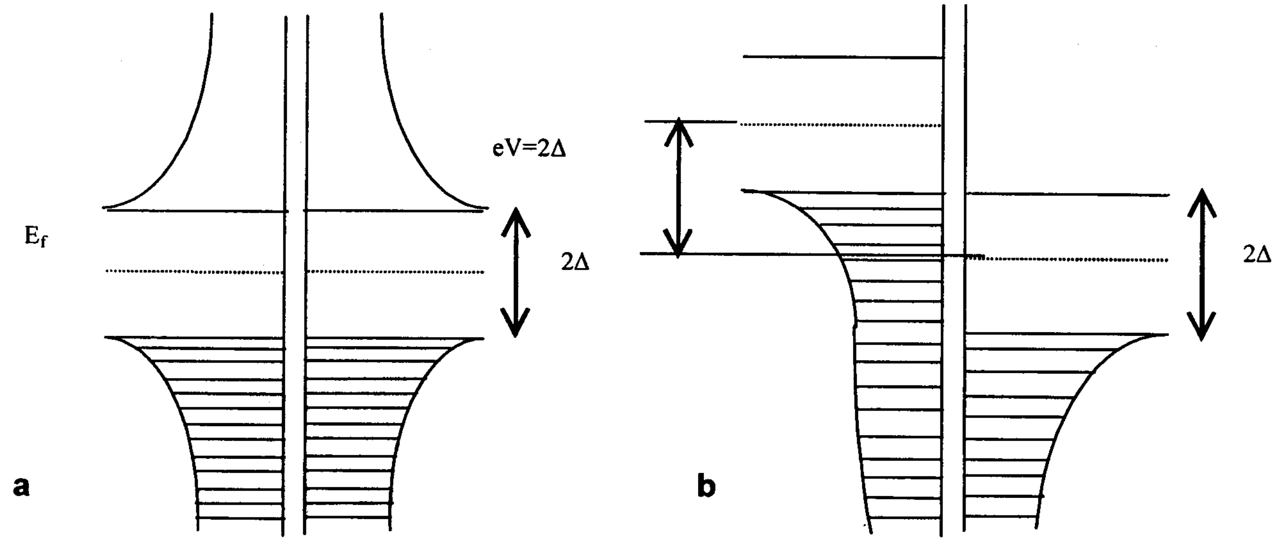

Fig. 4. Energy diagram of an SIS junction at absolute zero temperature. The one on the left is for the case of V=0, and the other is for the case of V=2Δ/e.

In the experiment, superconducting electron tunneling in SIS junctions was performed using bulk superconducting tunneling junctions of $YBa_2Cu_3O_{7-\delta}$. The abrupt decrease and plateau in the I-V characteristic as evidence of s-wave (or BCS) superconductivity (Fig. 4) is not observed. Instead a smooth nonlinear characteristic is observed, as in Fig. 5. Taking into account the effect of performing the measurement at 77.0K, the expected smearing of the data would only yield a rounding of the abrupt decrease and a finite slope at zero bias. However, the results that we obtained clearly deviate from what can be expected from an s-wave superconductivity standpoint.

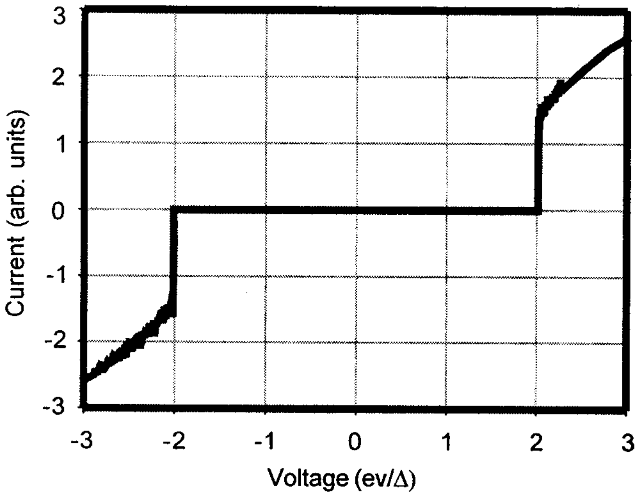

Fig. 5. Theoretical plot of the I-V characteristic of a superconductor obeying s-wave superconductivity. Note the abrupt decrease and plateau at small biases of the characteristic.

The results of the experiment strongly support the non-s-wave character of these superconductors. To prove the nature of the non-s-wave characteristic observed in this experiment, we study the differential conductance (dI/dV) of the tunneling junctions.

Fig. 6 is a typical experimental plot of dI/dV versus V plot obtained from the fabricated superconducting tunneling junctions of $YBa_2Cu_3O_{7-\delta}$. The plot shows distinct 'cusps' not ascertainable from the I-V plot presented earlier. From a d-wave superconductivity standpoint, these 'cusps' correspond to the magnitude of the superconducting energy gap 2Δ in these SIS junctions. A numerical plot of the dI/dV characteristic assuming the SIS junction consists of identical d-wave superconductors at T=0K is shown in Figure 7.

By considering the effect of temperature, the result of the experiment at T=77 Kelvin supports the result of a non-s-wave superconducting behavior in these superconductors. In fact, the results favor a d-wave character for these superconductors. To support this,

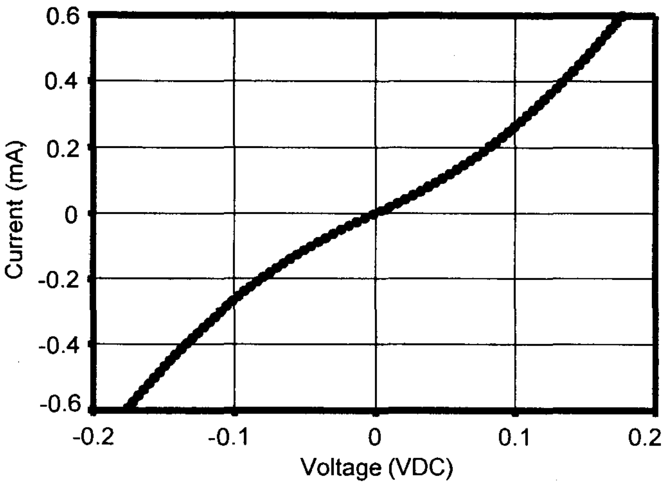

Fig. 6. A typical I-V plot of a SIS junction made from bulk superconducting $YBa_2Cu_3O_{7-}d$. The plot is characteristic of tunneling behavior in a d-wave superconductor. The plot was obtained at a temperature of 77.5K. Note the absence of any clear superconducting energy gap characteristic

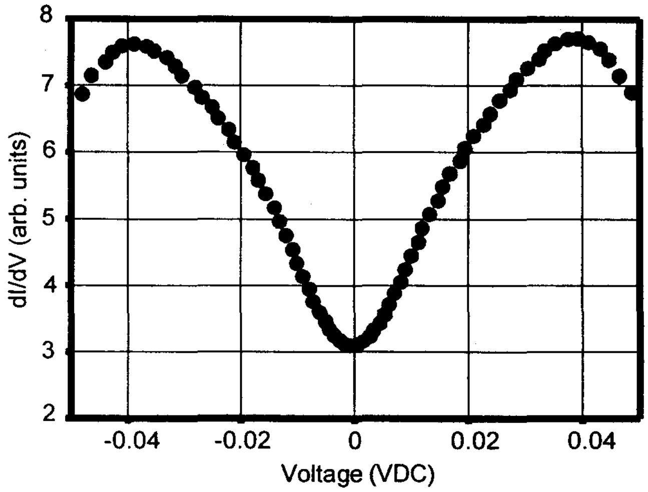

Figure 8. An experimental plot of dI/dV obtained from the output of the lock-in amplifier as described in the measurement scheme presented earlier. Note the presence of 'cusps' in the plot. These cusps correspond to the energy gap predicted in d-wave superconductivity.

we calculated the theoretical I-V characteristic of a SIS junction consisting of identical d-wave superconductors at T=0K and obtained a nonlinear characteristic as shown in Fig. 8. The nonlinearity of this theoretical plot is quite similar to the nonlinearity of the experimental traces we obtained in Fig. 4.

We thus proceeded to calculate the magnitude of the superconducting energy gap of these superconductors. The numerical derivative of Fig. 7 was taken and the zeroes of such a plot were averaged to arrive at a value of the superconducting energy gap, $2\Delta = (0.038 \pm 0.002)$ eV. Such a value of the energy gap would give rise to a value for the fraction $2\Delta/k_BTc$ of 5.735. This value is very much greater than the BCS prediction of 3.5 for such a fraction, indicating that these materials are strongly correlated materials (Tinkham, 1975).

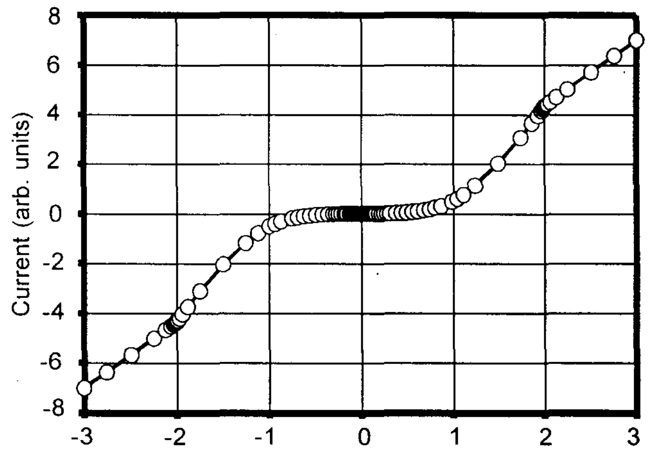

Fig. 7. A plot of the theoretical I-V curve of a superconductor, assuming the superconductor obeys d-wave superconductivity. The calculation assumes the temperature to be absolute zero (T=0).

The superconducting transition temperature, T_c, of the superconducting sample was obtained from resistivity measurements. From such a measurement, the T_c of the sample was found to be 78.4K.

It is evident in Figs. 6 and 7 that there is qualitative agreement between the experimental and the theoretical plots of the dI/dV characteristic. To further consolidate this point, the experimental plot was normalized to the value of the superconducting energy gap, 2Δ. The results of the normalization are shown in Fig. 9. In Fig. 9 we observe convincing qualitative agreement to the theoretical plot of the dI/dV characteristic of a SIS junction under d-wave superconductivity.

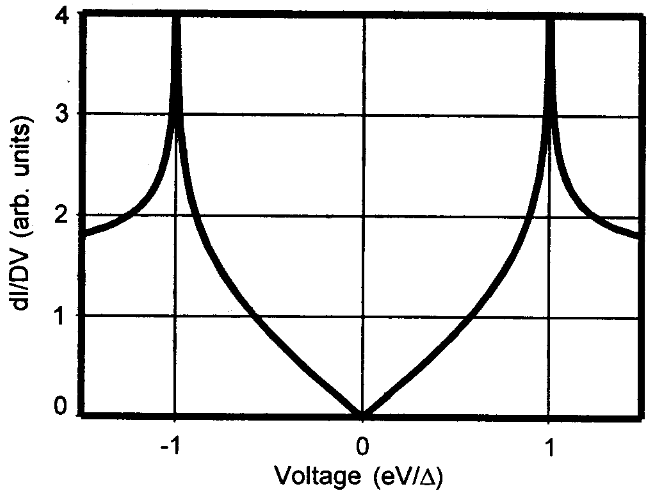

Fig. 9. Theoretical plot of dI/dV vs. V for SIS junction consisting of d-wave superconductors at absolute zero temperature.

CONCLUSION

We have performed normal electron tunneling into bulk superconducting SIS junctions of $YBa_2Cu_3O_{7-\delta}$. The measured I-V and dI/dV plots obtained experimentally deviated significantly from that predicted by s-wave superconductivity. Theoretical calculations based from a d-wave superconducting mechanism in these superconductors show good qualitative agreement to the data obtained. A value of the superconducting energy gap, $2\Delta = (0.038 \pm 0.002)$ eV was obtained theoretically from the experimental data for a value of $2\Delta/k_BT_c$ of 5.735. This value of $2\Delta/k_BT_c$ is very much greater than the BCS prediction of 3.5, indicating that these materials are strongly-coupled superconductors.

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