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Cooperative weak links in sintered Y-Ba-Cu-O superconductor

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The *I-V* characteristics of Y-Ba-Cu-O have been measured for several temperatures below T_c. A clear "footlike" structure is developed when the temperature goes down from T_c, strongly reminiscent of the case in superconducting weak links. The energy gap derived from the critical current and the "excess current" is about 18.4 meV at $T=0$ and with a roughly Bardeen-Cooper-Schrieffer-type of variation at $T>0$. The results are indicative of a kind of "cooperative" weak link behavior in sintered superconducting Y-Ba-Cu-O.

The first discovery of 35 K superconductivity in Ba-La-Cu-O by Bednorz and Müller[1] quickly spurred the observation of superconductivity above 90 K in Y-Ba-Cu-O.[2,3] In spite of the impressive high critical temperature T_c and the estimated very high upper critical field H_{c2} (Ref. 4) of the latter, its critical current is rather low when the material is prepared by solid reaction of fine powders. This is not surprising since the samples thus obtained are always ceramiclike and the susceptibility measurements often overestimate the volume of superconducting phase in the sample. In this paper we report the first observation of a "footlike" structure in current voltage (*I-V*) characteristics in sintered Y-Ba-Cu-O samples. The curves are strongly reminiscent of that found in some microbridge weak links.[5]

The preparation of the samples was described in Ref. 6. Resistivity measurement shows a superconducting transition of width 2 K and midpoint of 91 K. The volume of superconducting phase is about 80%, determined by susceptibility measurement. By keeping the temperature within ±0.1 K and sweeping the current in both positive and negative directions, a set of *I-V* curves for different temperatures was obtained by using the standard four-lead method. The results for two current directions were similar and consistent with the measurement of dV/dI when the current was modulated by a small ac current.

Figure 1 shows the results for sample 1. The curves below T_c are similar. Starting from $V=0$, we observe the supercurrent I_c followed by a finite voltage branch, up to V_1 of about several hundred microvolts, characterized by a small differential resistance R_{eff}. Then a steep rise in V takes place until $V \cong V_2$. Above V_2 the *I-V* curves enter a straight-line region with the differential resistance reaching about the value in the normal state, $R_n \cong 8$ mΩ. However, the intersection of the straight line with the abscissa yields an "excessive current" I_e. The footlike structure of these *I-V* curves is in all ways reminiscent of the case in microbridge weak links where the phenomenon was explained by the nonequilibrium occupation of quasiparticle states[7,8] or as a result of flux flow.[9] Here we will not judge the correctness of these models. We only want to stress the similarity of our case to the weak links.

For a weak line, Ref. 10 has given a relation of critical current with energy gap in the Bardeen-Cooper-Schrieffer (BCS) approximation. However, it was shown that for a short microbridge the experimental data $I_c(T)$ could be much larger than the theoretical value.[11] So, we simply write $I_c(T)$ as[10]

$$I_c(T) = b\frac{\Delta(T)}{2eR_n}\tanh\left[\frac{\Delta(T)}{2k_BT}\right] , \tag{1}$$

where b is a factor larger than 1 in the case of a short microbridge and R_n is the normal-state resistance of the bridge. At $T=0$, we have $I_c(0)=b\Delta(0)/2eR_n$. Thus (1) can be normalized by $I_c(0)$ as

$$\frac{I_c(T)}{I_c(0)} = \frac{\Delta(T)}{\Delta(0)}\tanh\left[\frac{c}{4}\frac{T_c}{T}\frac{\Delta(T)}{\Delta(0)}\right] , \tag{2}$$

where $c=2\Delta(0)/k_BT_c$. Assuming that $\Delta(T)/\Delta(0) = f(T/T_c)$ is a BCS-type function (we will show that this assumption is reasonable later), then formula (2) gives the relation of $I_c(T)/I_c(0)$ vs T/T_c, as shown in Fig. 2. By fitting the curve to experimental data, we can uniquely determine the ratio value $c=4.8\pm0.4$. This gives

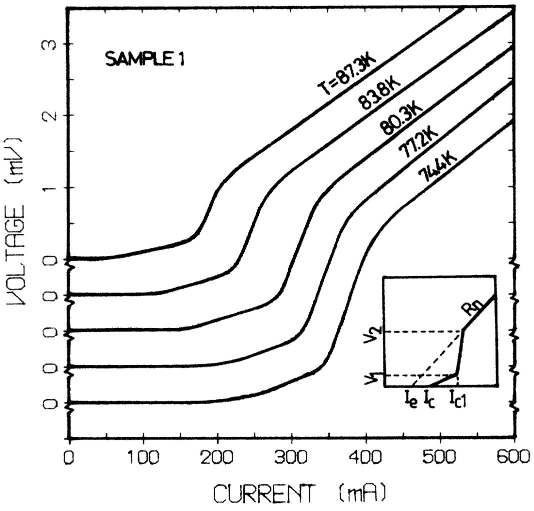

FIG. 1. *I-V* characteristic for sample 1 at several temperatures below T_c. The inset shows the definitions of characteristic values I_c, I_e, I_{c1}, V_1, V_2, and normal-state resistance R_n. A clear "footlike" structure can be seen.

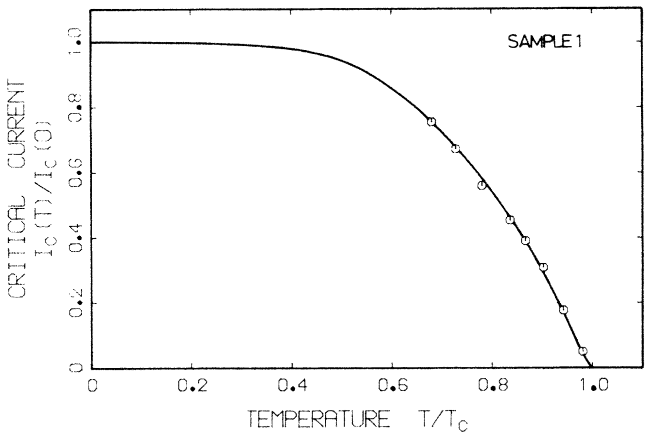

FIG. 2. Temperature dependence of critical current for sample 1. Circles represent the experimental values, and the solid line is plotted according to formula (2); $I_c(0)=397$ mA.

$\Delta(0)=18.4\pm1.5$ meV, $I_c(0)=397\pm15$ mA, and $b/R_n=13.74$ Ω^{-1} for the sample (taking $T_c=89$ K). The ratio value c and $\Delta(0)$ so obtained is in agreement with the values obtained by other methods.[12]

It was shown[7] that for a short microbridge with link length $L<\xi(T)(1-T/T_c)^{1/4}=\eta(T)$, where the $\xi(T)$ is the coherent length, the excess current is

$$I_e(T)=\left[\frac{\pi^2}{4}-1\right]\frac{\Delta(T)}{eR_n}\tanh\left[\frac{eV}{2k_BT}\right]. \tag{3}$$

Formula (3) is valid when $eV>\Delta$. Experiments on Nb-Nb point contacts have confirmed that formula (3) holds even for $L>\eta(T)$.[13] The excess current $I_e(T)$ for our Y-Ba-Cu-O sample as a function of T is plotted in Fig. 3 (circles). By fitting formula (3) to the experimental data, we get $R_n=0.147$ Ω and $I_e(0)=184$ mA in the BCS approximation and by taking $\tanh(eV/2k_BT)\cong1$. The solid line in Fig. 3 represents the prediction of formula (3).

The previous results $R_n=0.147$ Ω and $b/R_n=13.74$ Ω^{-1} yield $b=2.02$. Therefore, combining (1) and (3), we have

$$\Delta(T)=2k_BT\tanh^{-1}\left[0.462\frac{I_c(T)}{I_e(T)}\tanh\left[\frac{eV}{2k_BT}\right]\right]. \tag{4}$$

By using the experimental data of $I_c(T)$ and $I_e(T)$, and taking $\tanh(eV/2k_BT)\cong1$, we can determine $\Delta(T)$. Figure 4 shows $\Delta(T)$ thus obtained which is roughly consistent with the BCS-like temperature dependence. The fact that $\Delta(T)/\Delta(0)$ derived from experimental data is consistent with the assumption made in the deriving process implies that BCS theory might be still valid for this high-T_c superconductor.

If we consider V_1 in Fig. 1 as a measure of inelastic scattering time τ_E which is important in the nonequilibrium properties of weak links,[8] then the value of V_1 corresponds to about $\tau_E\sim10^{-12}$ sec, which is not unreasonable for a superconductor with high T_c.[14] Extrapolating the slope in the steep rise region after V_1 to $V=0$, one obtains the enhanced supercurrent I_{c1} (Fig. 1).[5] The ratio I_{c1}/I_c falls in the range of that given in Ref. 8. However, the

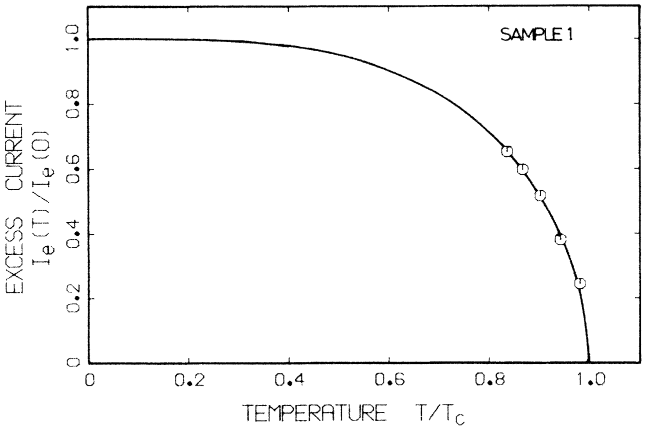

FIG. 3. Temperature dependence of excess current for sample 1. Circles are the experimental values and the solid line is plotted according to formula (3); $I_e(0)=184$ mA.

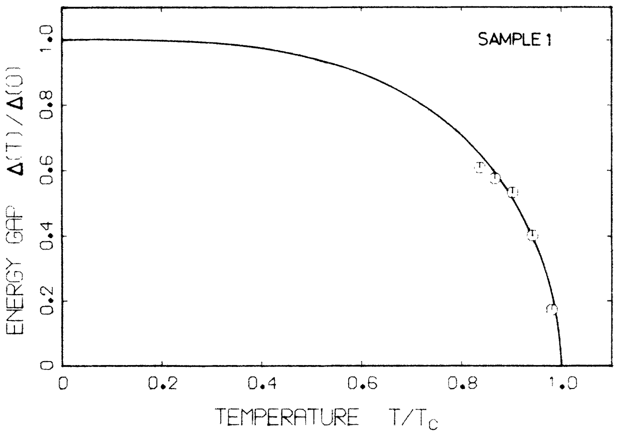

FIG. 4. Temperature dependence of energy gap for sample 1. Circles are derived from formula (4) by using the experimental data of I_c and I_e. Solid line is from BCS theory; $\Delta(0)=18.4$ meV.

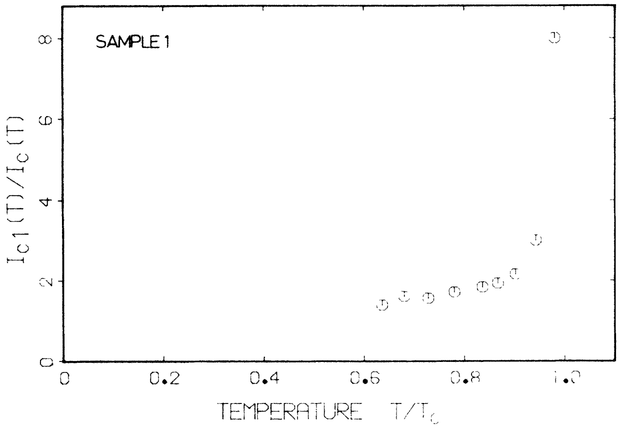

FIG. 5. The ratio I_{c1}/I_c vs temperature for sample 1.

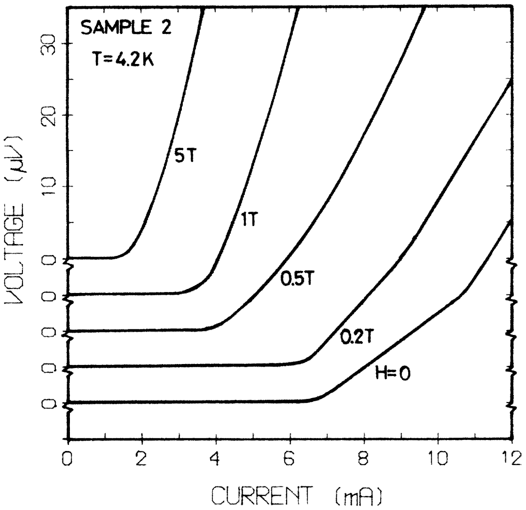

FIG. 6. I-V characteristics for sample 2 at 4.2 K in different magnetic fields.

temperature dependence of the ratio is not as expected (Fig. 5). The reason for this is not clear yet.

The equivalent resistance R_n derived above is $R_n = 0.147\ \Omega$. This value is about an order larger than the measured resistance in normal state. The result seems to imply that the superconducting weak links are shunted by a large amount of normal phase which never becomes superconducting and whose resistance dominates the whole sample. The picture is consistent with our recent work on the structure dependence of superconductivity in this material.[15]

The above analysis shows that I-V properties of the sintered Y-Ba-Cu-O compound are very similar to that observed in a single weak link. However, this similarity is very surprising. In the present case the sample is certainly not composed of a single weak link, but, most probably, contains a network of weak links randomly distributed in the sample. Associated with the structures of these links, there should be a distribution of R_n which would smear the footlike structure in I-V curves. On the contrary, the actual case is that the crossover between different regions is quite clear. Figure 6 shows the I-V characteristics for another sample (sample 2) at 4.2 K for which I_c, I_e, I_{c1}, and V_1 can be well defined at $H = 0$.

A possible explanation to this peculiar behavior is that the weak links in the sample are "cooperative." This "cooperative" effect can be decoupled by the application of an increasing magnetic field, which causes the rich structure of the curves to fade away (Fig. 6). At present we are not sure what mechanism is responsible for such a peculiar "cooperative" phenomena. It might be possible that this behavior is related to the so called "superconductive glass state" predicted recently in[16] and supported by the magnetic data on Ba-La-Cu-O systems.[17] We have measured the dependence of resistance R versus magnetic field H near T_c for sample 3, and we find a set of curves with some knee structure ended at some H_0 [Fig. 7(a)]. The temperature dependence of H_0 can be well-described by

$$\frac{H_0(T)}{H_0(0)} = \left[1 - \frac{T}{T_c}\right]^{\gamma} , \qquad (5)$$

near T_c with $\gamma = 1.5$ [Fig. 7(b)]; the same value is theoretically derived for the line separating ergodic and nonergodic regions.[18] However, more work is still needed to clarify the peculiar behavior presented here.

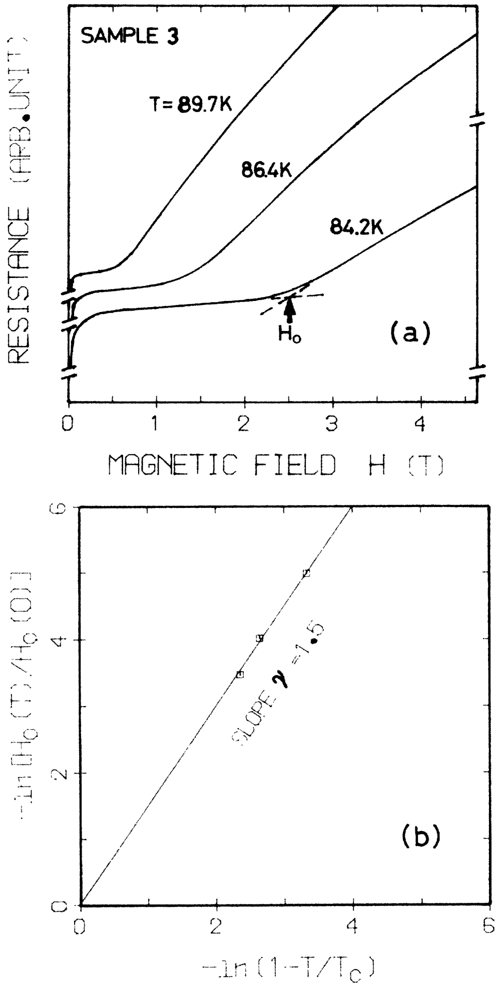

FIG. 7. (a) Dependencies of resistance on magnetic field for sample 3. At temperatures near T_c, zero voltage state can be easily destroyed by a field of less than 100 G. A "knee" structure is observed. A characteristic field H_0 can be well defined (see figure). (b) The data taken from Fig. 7(a) show agreement with formula (5) with $\gamma = 1.5$, taking $T_c = 93$ K and $H_0 = 82$ T.

In conclusion, the I-V characteristics of the sinter Y-Ba-Cu-O samples show a footlike structure similar to that observed in some superconducting weak links. This behavior is indicative of a network of cooperative weak links in the sample.

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