Critical current of $Y_1Ba_2Cu_3O_7$ in strong applied fields

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Critical currents of the new high-temperature superconductor $Y_1Ba_2Cu_3O_7$ have been measured in applied fields of up to 7 T and for temperatures down to 70 K. We find that the critical current is drastically reduced by the application of magnetic fields much smaller than the upper critical field of the samples, H_{c2}. This anomalous behavior might be due to very weak pinning, or to a very strong anisotropy of H_{c2}. H_{c2} is found to follow a linear temperature dependence that however extrapolates to a critical temperature higher than that measured directly. This might result from the existence of a percolative structure, or from the presence of a small volume fraction of high critical temperature, high critical field regions.

Since the discovery of the new high-temperature superconductors,[1,2] the problem of their low critical current density[3,4] has been one of the principal issues related to the practical application of these materials. Although important progress has been announced recently for singly oriented thin films of $Y_1Ba_2Cu_3O_7$, with critical current densities in the range of 10^5 A/cm^2,[5] it is clear that this problem will remain of primary importance in the foreseeable future.

We present in this letter critical current measurements on bulk $Y_1Ba_2Cu_3O_7$ in the presence of applied magnetic fields of up to 7 T. Compared to the behavior of ordinary type II superconductors, the data show an anomalous collapse of the critical current in the presence of applied fields much weaker than the upper critical field H_{c2} of the samples. The values of H_{c2} that we obtain follow a linear temperature dependence from 68 up to 81 K. Assuming that H_{c2} has the usual linear temperature dependence near the critical temperature T_c, the data imply $T_c = 97$ K, significantly higher than the directly measured $T_c = 87$ K. In any case, our measurements contradict previous work that reported an upward curvature for $H_{c2}(T)$ near T_c,[2,3] which we think is due to an inappropriate determination of H_{c2}. We propose that what we claim to be the correct behavior of $H_{c2}(T)$ might be due either to a percolative structure with a homogeneous T_c, or to a higher critical field and higher critical temperature in a small volume fraction of the sample, such as the grain boundaries.

Samples were prepared following the accepted procedure by grinding down Y and Cu oxides and Ba carbonate, reacting in a furnace at 900 K in a flow of O_2, grinding down again and forming pellets that were annealed in a flow of O_2 at 900 K, and then cooled down slowly (in about 6 h) to room temperature. The pellets were 6 mm in diameter and 1 mm in thickness. Four electrodes were formed at the edge of the samples by vacuum deposition of Cu through a mask, and then by In contacting the Cu film 1 mm dots. The critical current was defined as the value of the current producing a 1-μV voltage across the voltage electrodes. Critical currents in excess of 1 A could not be measured due to heating of the current contacts.

Figure 1 shows the critical current versus applied field data. The central feature of the data is that at all temperatures, the critical current shows a very sharp drop already for small applied fields. At 81 K for instance, the critical current is reduced down to 3.5 mA in a field of 500 G, while in zero field it exceeds 200 mA. This feature is quite extraordinary for a sample whose upper critical field is in excess of 10 T.

At least two possible interpretations can be proposed. The first is that the samples have essentially no pinning strength, so that their critical current is drastically reduced in fields in excess of H_{c1}. Although a definite possibility, this would be most unusual for a sample which is very far from being a single crystal and has certainly many impurities and grain boundaries that should provide a large number of pinning centers. Such an explanation, if correct, should therefore find its origin in some fundamental property of this high T_c compound, for instance, the fact that the size of its unit cell (11.5 A along the c axis) is not much smaller than the superconducting correlation length (about 20 A from the value of H_{c2}). Any defect may then lead to the local destruction of superconductivity, instead of providing a pinning center.

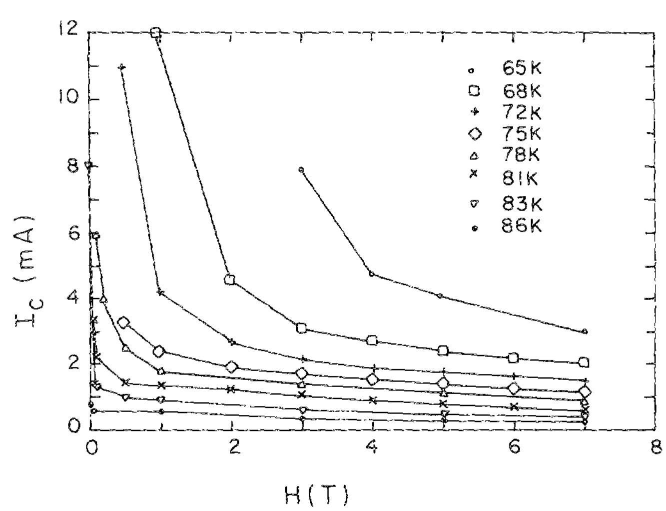

FIG. 1. Critical current as a function of the magnetic field at different temperatures.

Another interpretation could be based on the expected anisotropy of H_{c2}, due to the quasi-two-dimensional nature of superconductivity in this compound. Since the grains in the bulk samples are certainly randomly oriented, the applied field first destroys preferentially superconductivity in the grains where the c axis is perpendicular to the applied field. This interpretation is quite reasonable. We note, however, that our data would imply a very high anisotropy ratio, of the order of 100, which seems very high.

Finally, we note that the recently suggested model of superconducting perovskites proposed by de Gennes,[6] which implies the existence of a nearly antiferromagnetic order with two slightly canted sublattices, might have quite unusual properties in an applied magnetic field. In addition to the effect of the field on the pairs, there would also be an effect on the tilt angle of the two sublattices, which would prevent the system from reaching its lower energy state and would therefore lead to a weakening of the superconducting properties.

We now turn to a discussion of the upper critical field. A correct operational definition of H_{c2} is that it is the field at which the critical current vanishes. It is therefore best determined by measuring the critical current as a function of the applied field, and extrapolating to zero critical current. Due to the very small values of the critical current near T_c and to the small normal state resistance of the samples, this definition can, however, only be used in practice somewhat below T_c. We have found that for temperatures $68 < T < 81$ the critical current depends linearly on the field in a range of fields that is broad enough to allow a reasonable extrapolation to zero current. The values of H_{c2} thus determined follow a linear temperature dependence, as shown in Fig. 2. This is the usual behavior of H_{c2} near T_c. However, the extrapolated value of $T_c = 97$ K is significantly higher than that measured directly, which is 87 K (Fig. 3). In any case, our data are not compatible with the upward curvature of $H_{c2}(T)$ reported previously.[2,3] This discrepancy is due, we believe, to the inappropriate definition of $H_{c2}(T)$ used in Refs. 2 and 3 (midpoint of the temperature transition in a given applied field), particularly for a sample with a broad transition and presumably weak critical current.

It is known that in percolative samples the resistivity[7] and the temperature dependence[8] of $H_{c2}(T_c)$ may be anomalous. This occurs when the superconducting correlation length is smaller than the percolation correlation length, in which case the value of H_{c2} is not determined by the bulk value of the coefficient of diffusion but by its (anomalous) value on the scale of the superconducting correlation length.[9] It is then predicted that $H_{c2} \simeq (T_c - T)^{2/(2+\theta)}$, where $\theta = (\mu - \beta)/\nu$. Here μ is the percolation conductivity exponent, $\mu = 2$; β is the infinite cluster mass exponent, $\beta = 0.39$; ν is the correlation length exponent, $\nu = 0.89$; all indices are for the three-dimensional case. This then leads to $H_{c2} \simeq (T - T_c)^{0.52}$, which gives a reasonable, although not excellent fit to our H_{c2} data with $T_c = 87$ K. Hence a percolative structure could possibly reconcile our critical field data with the measured T_c.

Another possibility is of course that the upper critical field measured is that of a small volume fraction of the sample, which also has the higher critical temperature close to 100 K. For this small volume fraction to be interconnected throughout the sample almost requires that it consists of grain boundaries. It is clear that only measurements on good single crystals will allow reaching final conclusions.

In conclusion, we have reported in this letter on a very unusual dependence of the critical current on an applied field, characterized by a collapse in fields much weaker than the upper critical field. We propose that this behavior points out to a fundamental difference between the new high T_c superconductors and the classical ones. We suggest that an interesting avenue to be explored for the understanding of this behavior is the nearly antiferromagnetic model proposed by de Gennes, because it should have unusual properties in an applied field.

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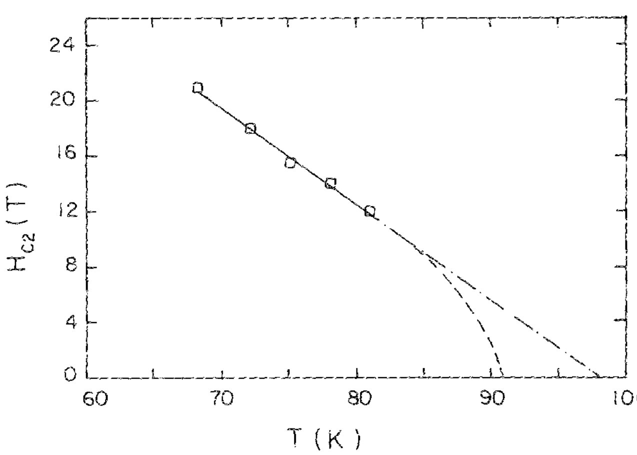

FIG. 2. Critical magnetic field H_{c2} as a function of the temperature. The critical field was obtained by extrapolating the curves in Fig. 1 to zero current. The dashed dotted line refers to the usual behavior of H_{c2} near T_c and the dashed line refers to the percolation case.

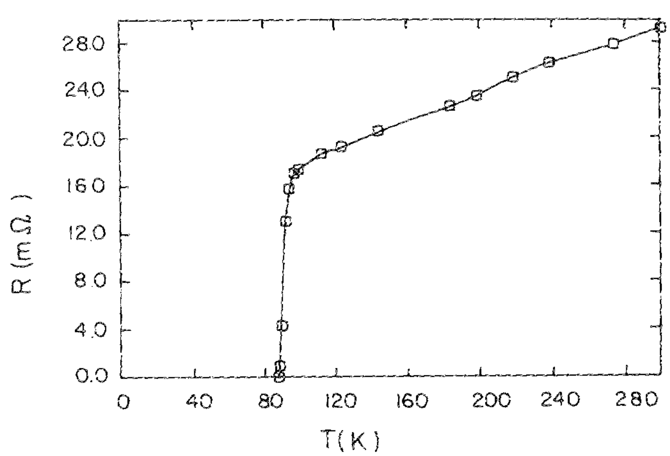

FIG. 3. Resistance as a function of the temperature. The onset is in $T = 97$ K and the zero resistance temperature is 87 K.

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