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High-magnetic-field study of superconducting $YBa_2Cu_3O_{7-\delta}$

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The resistance of single-phase samples of $YBa_2Cu_3O_{7-\delta}$ has been measured as a function of temperature in magnetic fields up to 23 T. The nearly linear temperature dependence of the resistivity characteristic of this high-T_c material was observed from room temperature down to about 120 K. Between 120 K and $T_{c0} \sim 92.5$ K the resistivity drops more quickly. Analysis shows this behavior to be consistent with the effect of three-dimensional superconducting fluctuations as was shown by Tsuei *et al.* for zero magnetic field. A critical-field slope of 3.2 T/K is obtained.

INTRODUCTION

The recently discovered high-T_c oxide superconductors[1] display unusual normal-state properties[2] and the possible absence of the isotope effect.[3] Considerable theoretical interest in these materials has been generated.[4] The dc resistivity of the sintered material shows a striking linear dependence on temperature from room temperature down to just above the superconducting transition. It has been noted[5] that if this dependence represents an intrinsic transport property of the material, that is, one not due to the granularity, then it implies an anomalously high inelastic scattering rate. In a temperature region above the bulk superconducting transition the resistivity deviates from this behavior. The resistivity decreases below an extrapolation of the linear behavior and resembles the effect of superconducting fluctuations. An examination of this decrease in fields up to 23 T shows that this decrease can be described by the three-dimensional (3D) Aslamazov-Larkin (AL) theory.[6] This result was found previously by Tsuei *et al.*[7] in zero field and is inconsistent with the suggested two-dimensional character of the crystallographic and electronic structure. Recent measurements on single crystals by Worthington, Gallagher, and Dinger[8] confirm the three-dimensional nature of the superconductivity in this material.

Although quantitative information has been difficult to extract, the temperature dependence of the superconducting critical magnetic field has in the past been used successfully to identify different electron scattering mechanisms in metals and to give a more complete description of the superconducting pairing in real metals.[9] Critical-field measurements on high-T_c oxide superconductors have been published,[10] but analysis is difficult due to two factors. First, the enormous critical field (hundreds of tesla) is beyond the magnetic field available for its measurement except in the temperature region close to T_{c0}. Second, the transition width broadens considerably with the application of a magnetic field making the position of the phase boundary uncertain. The broadening is universally seen in sintered material and is generally attributed either to a large critical-field anisotropy or to multiphase material. Indeed, studies of single crystals show critical field and critical current anisotropy.[8,11] Previous measurements of the magnetic-field behavior of sintered samples have been restricted to temperatures at and below the superconducting transition. We now have extended these measurements on independently fabricated samples to temperatures well above the transition and to higher fields.

EXPERIMENT

Samples of $YBa_2Cu_3O_{7-\delta}$ were made by the usual method of solid-state reaction of the oxide powders followed by an anneal at 900° C and a slow cooling in pure oxygen. The samples were cold-pressed under 1.4×10^5 psi before the oxygen anneal and were found to have a density 75% of that theoretically predicted. X-ray diffraction shows these samples to be single phase. The zero-field transition widths for the best samples are less than a degree as measured by both their resistive and diamagnetic response. The diamagnetism was measured using a SHE Superconducting quantum interface device magnetometer. Resistivity was approximately 800 $\mu\Omega$-cm. The resistance was measured with a dc four-point technique using connections anchored with silver paint. A variable temperature probe was provided by the facilities of the Francis Bitter National Magnet Laboratory for measurements in a liquid-nitrogen dewar which fit into the 1-in. bore of a water-cooled Bitter magnet. Temperature was measured with a Pt resistance thermometer which was corrected for its magnetoresistance.

RESULTS AND DISCUSSION

The resistance was measured as a function of field at constant temperature from 300 to 68 K (Fig. 1). Several features of the resistive transition appear to be common to the high-T_c oxide superconductors. The resistance does not rise from zero to the normal-state value in a narrow interval of field. The so-called "transition width" is essentially the size of the critical field. Within a few degrees below T_{c0} the resistance becomes nonzero for small applied fields; as the field is increased the resistance saturates at some small fraction of the normal-state resistance. This is shown most clearly in Fig. 2. As the field is increased further the resistance abruptly begins to rise again

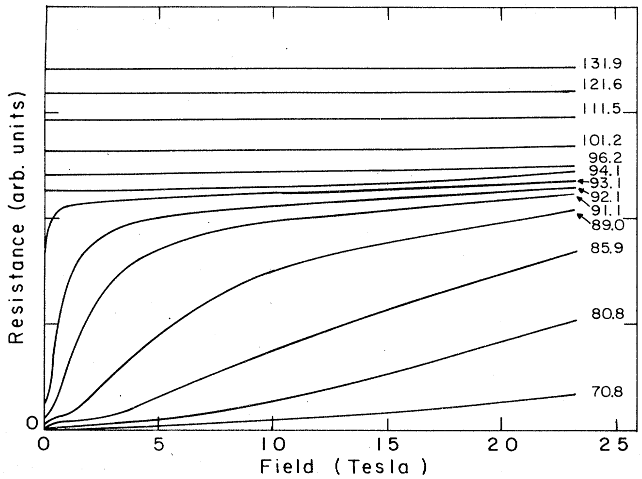

FIG. 1. Resistance vs magnetic field for constant temperature.

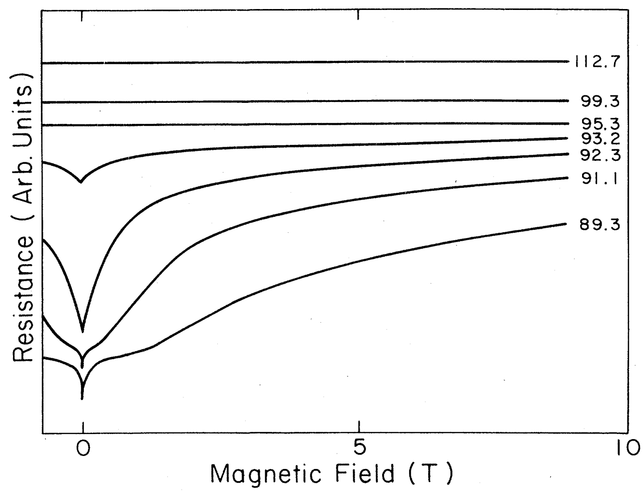

FIG. 2. Resistance at constant temperature as the magnetic field is swept through zero.

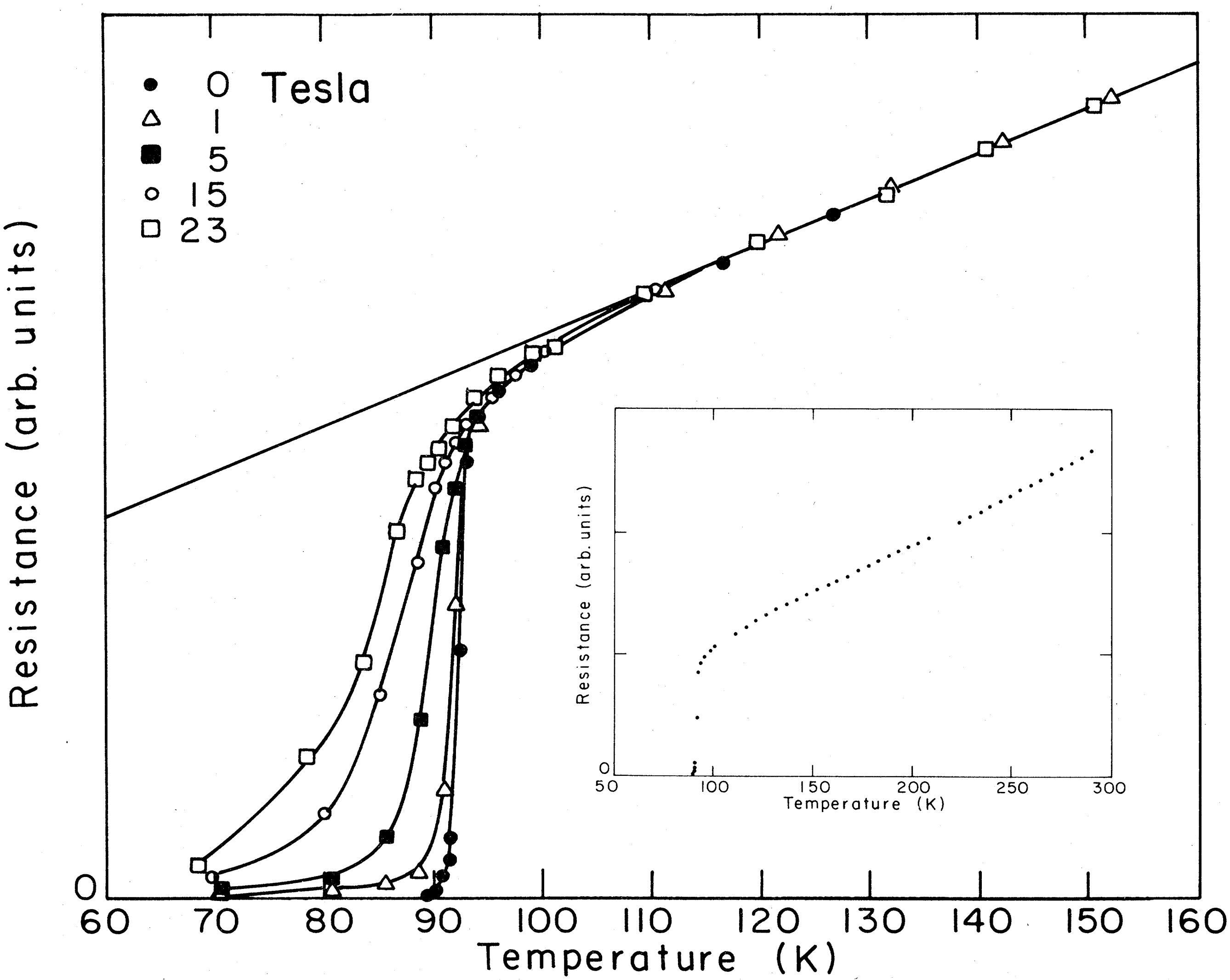

FIG. 3. Resistance vs temperature at constant applied magnetic field. The inset shows the nearly linear dependence of the resistance in zero field from room temperature down to the fluctuation region.

and the resistance then continues to rise toward the normal-state value. The low-field behavior, as exemplified by the cusplike resistance rise in Fig. 2, may be attributed to Josephson coupling between grains. The second field region, over which the sample regains most of its resistance, is where the resistance of the grains is recovered. In our most recent measurements on monolithic samples, the low-field behavior is absent; the resistance remains zero until the field corresponding to the second rise described above. These samples were $\sim 1\times1\times0$ mm^2 pieces of material with faceted faces picked out of the reacted powder before pelletizing.

The critical-field phase boundary is generally found by choosing for each temperature the field for which the resistance has risen to some fraction of the normal-state resistance. In this system the severe broadening casts doubt on the validity of this procedure. Therefore, we have looked toward an analysis of superconducting fluctuations to obtain critical-field information. In bulk superconductors, conductance fluctuations are usually a small fraction of the normal-state conductivity. However, due to the short coherence length and high normal-state resistance of this material, conductance fluctuations are significant. An additional consequence is the failure of the Ginzberg-Landau description within an observable temperature region ($\sim$0.1 K) about T_c.[12] The data presented here lie outside this region.

The data presented in Fig. 1 are replotted in Fig. 3 as a function temperature for constant applied field. The curve in Fig. 4 shows a comparison of the fluctuation conductivity to the three-dimensional AL term.

$$\sigma_{AL}=\frac{e^2}{32\xi}(T_c/T-T_c)^{1/2}\,.$$

A value for the coherence length of the order of the BCS value $\xi\sim1$ nm is obtainable from the critical-field slope.[11] The absence of the Maki-Thompson-type[13] contribution to the fluctuations is usually associated with strong pair-breaking.[14] The presence of this term would increase the magnitude of the conductance fluctuations by a factor of 5. A recent theory[5] proposes that the inelastic processes play an important role in the superconductivity of the high-T_c ceramic superconductors. As such, inelastic scattering may account for the absence of a contribution to the fluctuation conductivity from the anomalous (Maki) term.

Deviations from the AL expression at higher temperatures are characteristic of superconductors with very short mean free path.[15] Tsuei *et al.*[7] have suggested this to be the case for $YBa_2Cu_3O_{7-\delta}$. It is generally believed that the deviation at higher temperatures is the result of the unphysical emphasis the AL term gives to short wavelength fluctuations. This failure is particularly apparent in $YBa_2Cu_3O_{7-\delta}$, since the normal-state conductivity is decreasing as T^{-1}, that is, faster than the AL fluctuation conductivity at high temperatures. The AL result is equivalent to that obtained from the Ginzberg-Landau free-energy expansion to fourth order. Near T_{c0} the temperature-dependent coherence length serves as a lower cutoff to the wavelength of superconducting fluctuations. At higher temperatures the coherence length decreases introducing a contribution from smaller wavelength fluctuations, a contribution which would not be favorable in a higher-order Ginzberg-Landau free-energy expansion. A phenomenological modification of the AL expression which has been used previously introduces an *ad hoc* cutoff to the fluctuation spectrum at large wave number. With this modification, the fluctuation conductivity at high temperature decreases faster than the AL result. Ami and Maki[16] introduced expressions, somewhat more complicated and involving numerical integrations, based on the microscopic theory which reproduced the characteristic damping of the fluctuation conductivity at high temperature seen in the data. In Fig. 4 the modified AL term for a cutoff of wavelengths less than 10 times the coherence length is shown. In the past,[15] cutoffs of the order of the coherence length were found appropriate for

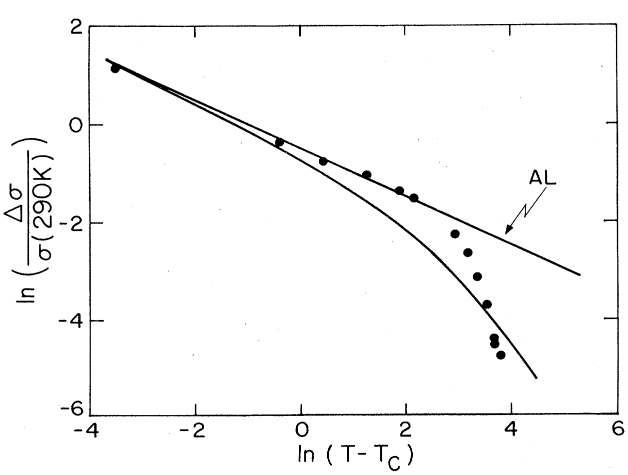

FIG. 4. Comparison of the fluctuation conductivity, measured in zero magnetic field, with the AL term and the AL term modified with a wavelength cutoff of ten times the coherence length.

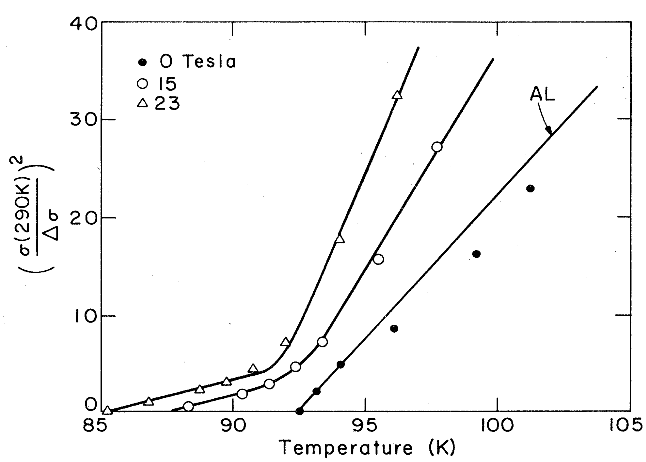

FIG. 5. The measured fluctuation conductivity plotted on axis for which the intercept with the temperature axis defines $T_c(H)$. The AL term corresponding to zero field is shown. The solid lines through the data measured in a field are guides to the eye.

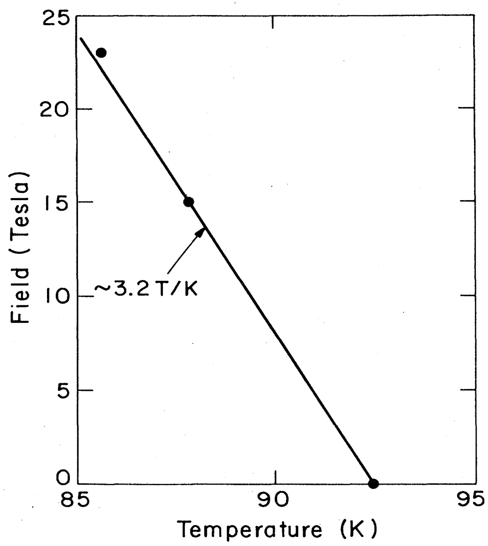

FIG. 6. The critical field as determined from the intersection of the curves in Fig. 5 with the temperature axis.

other materials.

In Fig. 5 the data near T_{c0} are plotted on axes for which the AL fluctuation conductivity plots linearly and intercepts the temperature axis at T_{c0}. The zero-field data are indeed linear in accord with Fig. 4 and intercept the temperature axis at T_{c0} of 92.4 K. The theoretical 3D fluctuation conductivity[17] in a field applied perpendicular to the current direction has a square-root singularity at $T_c(H)$. However, the coefficient of the singularity is temperature and field dependent and has a magnitude which is larger than that of the AL term. That is, the fluctuation conductivity is enhanced by a perpendicular applied field. This enhancement accounts for the decrease in slope near $T_c(H)$ of the curves in Fig. 5. The enhancement is readily seen in thin films and is a consequence of the fact that the energy spectrum in a field is discrete.[18] We have taken the intercept with the temperature axis to define $T_c(H)$ giving the critical-field slope of 3.2 T/K (Fig. 6). This value is intermediate between those values obtained by the conventional method of taking the field at which the resistance rises to 50% and 90% of the normal-state resistivity for each temperature. This suggests a critical field at zero temperature of just over 200 T as estimated from the Ginsberg-Landau theory. However, in the absence of spin-orbit scattering, the critical field would be limited to the Pauli limiting field $H_p = 1.84 \times T_{c0}$ T.[19]

CONCLUSION

The resistance of single-phase $YBa_2Cu_3O_{7-\delta}$ has been measured as a function of field from 300 to 68 K. Near T_{c0} the resistance becomes nonzero for very small fields indicating that at T_{c0} the grains become Josephson coupled. The fluctuation conductivity is adequately described by the three-dimensional AL term with a wavelength cutoff of 10 coherence lengths. The absence of the anomalous (Maki) contribution to the fluctuations indicates strong pairbreaking possibly due to inelastic scattering.

ACKNOWLEDGMENT

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