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Evidence from resistivity measurements along the c axis for a transition within the vortex state for H ∥ ab in single-crystal $YBa_2Cu_3O_7$

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The broadening of the resistive transition along the c axis of a $YBa_2Cu_3O_7$ single crystal in the presence of strong magnetic fields ($H > H_{c1}$) parallel to ab disappears below a well-defined line in the H-T phase diagram. Above this line, dissipation is Ohmic and field dependent. Below this line, a discontinuity appears in the resistivity curves, and the I-V behavior is strongly nonlinear. The shape of the resistive transition below the $T_m(H)$ line has a universal character, which remains unaffected by changes in the amplitude of the field. This unusual behavior contradicts any collective-flux-pinning model that predicts a field-dependent activation energy, and suggests a phase transition related to the depinning line.

The broadening of the superconducting transition of the high-T_c compounds in high magnetic fields ($H > H_{c1}$) has been the subject of intensive investigation.[1-7] The anisotropy of broadening phenomena is principally related to the orientation of the field with respect to the CuO planes because of anisotropic pinning forces. As a general rule, the width of the transition decreases with the angle between the field and the CuO planes.[4] The relevance of the Lorentz force is not clear, since the broadening persists even in the absence of macroscopic Lorentz force.

Giant fluctuations have been suggested in order to account for this feature,[8] but it is difficult to understand how the superconducting fluctuations are enhanced by the magnetic field, which should act as a pair-breaking mechanism. When the nature of the mixed state is considered an interesting physical situation arises. In these high-κ, high-T_c materials a melting transition of the vortex lattice is possible well below T_c.[9-11] For a low density of pinning centers the flux liquid will not be pinned; instead, the vortex lattice will be pinned. If the melting transition indeed occurs, one expects entanglement of the flux liquid.[12] This gives rise to a local Lorentz force even if the transport current flows parallel to the external applied field. In this case smooth resistivity curves are expected, with the resistivity decreasing continuously down to the solidification temperature where the flux liquid is disentangled. In contrast, when the external field is applied perpendicular to the transport current, the mean Lorentz force is independent of the local arrangement of the vortices and remains finite at the melting temperature. At this temperature, pinning forces increase abruptly with the formation of a flux lattice, and one expects a discontinuity of the resistivity at T_m. In a weak pinning regime the melting transition should remain of first order[13] and one should be able to define the "melting" line in the phase diagram from a sharp transition in the resistivity curves. The dissipation for a given point in the H-T diagram should then depend uniquely on the distance from this line.

Kwok *et al.*[2] reported a Lorentz force mechanism giving rise to a "kink" in the resistivity for $H = 1.5$ T∥ab, perpendicular to the current, whereas an unexplained resistive background was observed when the field was applied parallel to the current. This was confirmed by their later measurements, for a field parallel to the ab planes with a precision of better than 0.005°.[14] They observed pinning due to the twin planes only below the kink temperature, the regime above this temperature apparently being unpinned. Other groups have also reported the appearance of this kink only in the case where the current and the field are perpendicular.[4] The kink feature is smoother when the field is parallel to the c axis, and in this case is not related to non-Ohmic behavior.[6] To date this behavior has been interpreted as a crossover between a flux creep or a thermally activated flux flow (TAFF) regime to a flux-flow regime.

We provide evidence that in the H∥ab case the kink feature is related to a phase transition within the vortex state. We find strong non-Ohmic behavior which clearly coincides with a discontinuity of the resistance. This rules out a TAFF regime, which would be Ohmic. In the low current limit, the resistive transition is extremely sharp: $\Delta T = 20$ mK at 90 K. Furthermore, the shape of the transition has a universal character, unaffected by changes in the amplitude of the field. The only effect of increasing the field is to shift the transition temperature downwards. We believe that, because of anisotropy effects, the smooth kink feature that appears for H∥c is some residue of the very "clean" transition in the H∥ab case.

We studied the superconducting transition of a very small $YBa_2Cu_3O_7$ single crystal (dimensions $100\times80\times50$ μm^3) in magnetic fields of up to 8 T, applied parallel to the CuO planes (Fig. 1). The crystal was grown following Ref. 15. We developed a six-face lithography technique in order to realize contacts on very small crystals with a well-defined geometry (resolution 2 μm).[16,17] This ensures a unique direction for the current flow within the crystal and is very important because of the angle-dependent effects. The small size of the crystal favors good oxygen content homogeneity. The current was injected parallel to the c axis. The normal state ρ_c equals 8 mΩ cm at 300 K and shows a metallic temperature depen-

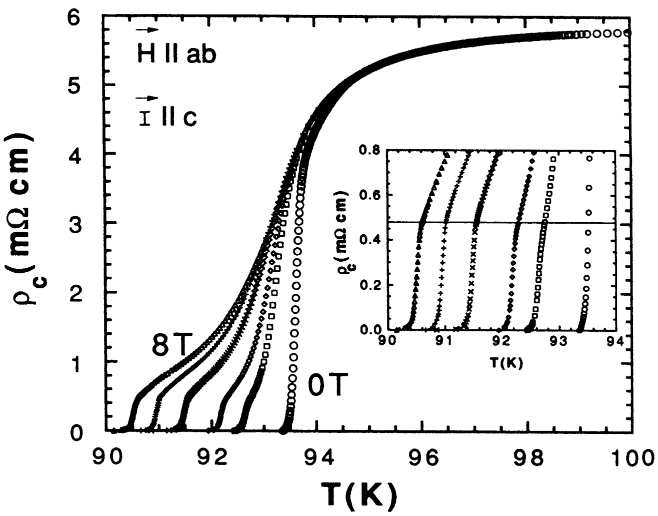

FIG. 1. ρ_c vs T for magnetic fields of 0, 1, 2, 4, 6, and 8 T parallel to the *ab* planes. Inset: Low-resistivity data for 0, 1, 2, 4, 6, and 8 T. Notice the similarity between the curves below the solid line.

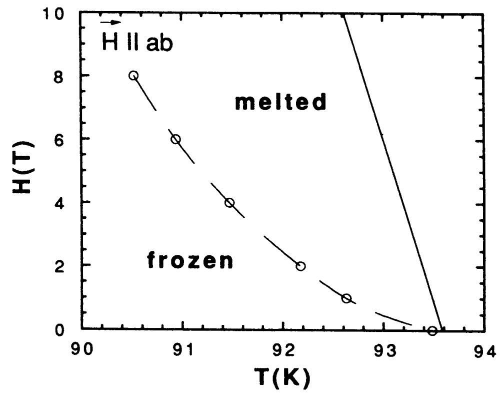

FIG. 3. An H-T phase diagram for the onset of non-Ohmic behavior in $YBa_2Cu_3O_7$. The field is applied parallel to the *ab* planes. Below the dashed line resistance drops very rapidly in the low current limit. Above this line the transition is broadened, in a way which is strongly dependent on the magnetic field. The estimated upper critical field (solid line) (Ref. 18) is also shown. Zero resistance would be indistinguishable from the $H(T_m)$ line in this scale.

dence. T_c in zero field is among the highest reported for $YBa_2Cu_3O_7$ single crystals ($T_c = 93.6$ K) and the transition width in zero field is very small ($\Delta T = 150$ mK). These are very convincing arguments in favor of the high quality of the sample. As expected, the shift of T_c (upper part of the resistivity curves Fig. 1) is quite small for $H \| ab$ (10 T/K from Ref. 18). The transition is broadened, but below an approximately constant resistivity level for all the applied fields ($\approx \rho_N/12$) the broadening phenomenon is frozen out and a sharp drop in the resistivity is observed.

This drop is shifted to lower temperatures for increasing fields, but its shape remains unaffected, being very similar to the zero-field transition (see the inset in Fig. 1). At the same temperature where the resistivity drop occurs, strongly non-Ohmic behavior is observed (Fig. 2). We identify the temperature at which the non-Ohmic behavior appears with a characteristic temperature T_m. Figure 3 shows the phase diagram for the onset of non-Ohmic behavior. The $H(T_m)$ line follows a power law $H(T_m) \propto (T_m - T_{m_0})^{1.7}$. The position of the sharp peak of the $d\rho/dT$ curves (inset in Fig. 4) coincides with T_m in the low-current limit.

For a given current density, we observe the same voltage drop at the same distance from T_m, independent of the amplitude of the magnetic field. As shown in Fig. 4, all the resistivity curves can be mapped onto one another by a simple shift in temperature, when measured with the

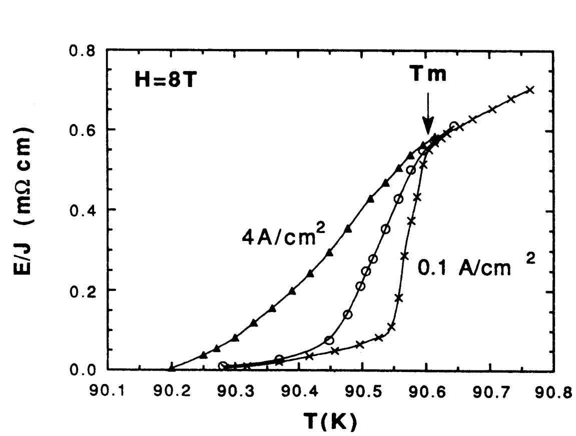

FIG. 2. Non-Ohmic effects in the low-resistivity region ($H = 8$ T). The current densities are 0.1, 1, and 4 A/cm^2. T_m denotes the onset of the nonlinear behavior. The sharp resistance drop coincides with T_m. The transition width for 0.1 A/cm^2 is 20 mK.

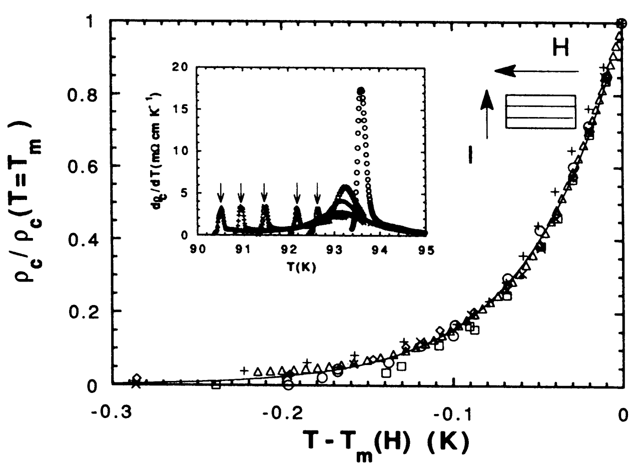

FIG. 4. A universal diagram of the ρ vs T and the ρ vs H data. Data for $H = 1,2,4,6,8$ T and magnetoresistance data for $T = 92.76$ K, all measured with a current density of 1 A/cm^2, are included. All of the data collapse on the same curve, when plotted as a function of the distance from the $T_m(H)$ line. Inset: Derivative of the ρ vs T curves. The position of the narrow peak coincides with T_m in the low current limit.

same current. For a current of 1 A/cm^2, we find an exponential drop, $\rho(T)/\rho(T_m)=\exp[(T_m-T)/T_d]$. T_d is the only fitting parameter, found to be extremely small ($T_d \approx 50$–60 mK) for a large range of fields from 0 up to 8 T (Fig. 4). This means that contrary to earlier reports[19] the logarithmic slopes of the ρ vs T curves are identical below T_m for all the fields. Furthermore, we find a resistivity prefactor which is quite small, $\rho(T=Tm)\approx\rho_N/12$, in contrast with the huge resistivity prefactors reported so far.[5] This is because the cutoff temperature of the exponential rise is T_m and not T_c, which means that the effective pinning force vanishes at T_m.

The very sharp peak in the $d\rho/dT$ curves at T_m, the appearance of strongly non-Ohmic behavior at the same temperature, and the universal shape of the curves below T_m clearly show that a drastic change occurs at T_m, distinct from T_c. The critical temperature T_c denotes a smooth crossover from the normal to the superconducting state, without any singular feature in the resistivity curves. A test for the significance of the $H(T_m)$ line in the phase diagram is the behavior of the magnetoresistance. In principle, whichever way one approaches this line, horizontally (ρ vs T) or vertically (ρ vs H) one should expect to observe the same scaling laws for the resistivity, if this line indeed denotes a phase transition. From the ρ vs T curves we find an exponential rise, depending only on $(T-T_m)/T_d$, with T_m shifting downwards with increasing field. We are able to map the experimental ρ vs H curve onto a ρ vs $T-T_m$ curve. We do this in the following way: We keep T fixed (equal to the temperature of the magnetoresistance measurement) and we vary T_m along the $T_m(H)$ line. The magnetoresistance data fall on the same line as the ρ vs T data, when measured with the same current (Fig. 4). The parameter T_d from the ρ vs H data equals 55 mK, in excellent agreement with the ρ vs T results. This provides very convincing arguments in favor of a dissipation mechanism entirely controlled by the distance from the $T_m(H)$ line.

The occurrence of a melting of the vortex lattice well below T_c in the CuO materials has been discussed by several authors.[9–11,13,20] However, the melting transition has not yet been identified with a sharp drop in the resistivity in high magnetic fields. Another possibility is that there exists a breakdown field which decouples the superconducting CuO layers, giving rise to a second-order phase transition far from T_c.[21] In this case the non-Ohmic effects would be related to an intrinsic Josephson critical current. On the other hand, thermal depinning (which is not a phase transition) has been extensively discussed,[22–24] but this mechanism, controlled by the distance from T_c, can hardly account for the very sharp variations observed close to T_m. The I-V curves at 8 T are shown in Fig. 5 in a log-log plot. Above T_m we observe a straight line with slope 1. Below T_m, a negative curvature appears which becomes positive on lowering the temperature. This is the typical behavior one expects for a flux creep to a flux-flow crossover very close to the critical current I_c. As shown in the inset in Fig. 5, one can observe, for a given window in the I-V curves, a crossover between negative curvature near the Ohmic flux-flow regime to positive curvature inside the flux-creep regime. We observe linear null, negative, and positive curvature in a narrow temperature interval of 200 mK. This means that the critical depinning current is changing extremely fast with temperature near T_m, vanishing at T_m, and increasing rapidly on cooling. We interpret this by vanishing effective pinning force at T_m and not at T_c.

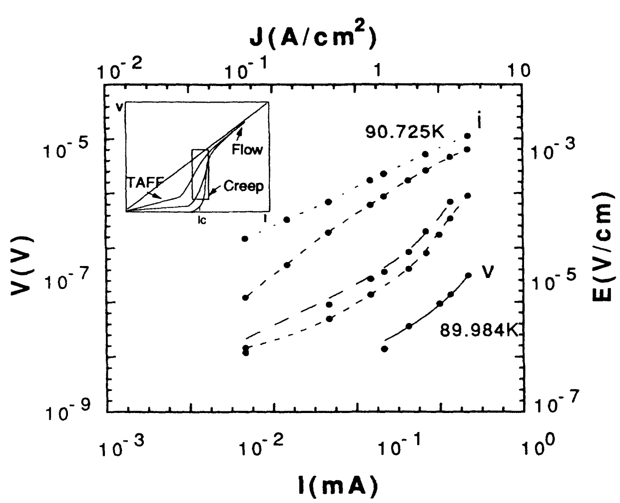

FIG. 5. I-V characteristics in a logarithmic scale. The temperatures are (i) 90.725, (ii) 90.428, (iii) 90.230, (iv) 90.182, and (v) 89.984 K. Curve (i) is Ohmic. Curve (ii) shows negative curvature. Curves (iii)–(v) show positive curvature and follow a flux creep law $V\propto\sinh(J/J_c)$. Inset: Voltage-current characteristics of a high-T_c superconductor (Ref. 20). Notice the change of curvature in the region of the rectangle.

We should point out that the vortex-glass model[25] predicts an Ohmic resistance above T_g which vanishes *continuously* at T_g, the glass temperature. Our results are not consistent with this model, since the Ohmic resistance exhibits a discontinuity at T_m. In this high-quality single crystal we expect weak disorder, and the glass transition may not occur. Fisher, Fisher, and Huse[13] predicted that in a weakly disordered regime, where the vortex-glass state is not expected, resistance will drop very rapidly just below the melting temperature T_m and the I-V curves will become strongly nonlinear. This is precisely the situation encountered here. However, it is difficult to understand how a collective effect like melting of the vortex lattice gives rise to a frozen state where the collective effects disappear. The remarkable feature of these data is that the scaling of the transition with temperature and current is independent on the amplitude of the magnetic field, apart from the shift in T_m. This contradicts any collective flux-pinning model which predicts a field-dependent activation energy, and raises questions about the collective nature of the transition. An independent vortex process, like a core transition inside a single vortex, related to quasiparticles effects, is an interesting possibility.[26]

In conclusion, we have shown that the dissipation mechanism for a field parallel to the *ab* planes is controlled by the $T_m(H)$ line, which sharply separates the phase diagram into two regions. The two regimes are qualitatively different: In the melted regime the resistance depends on temperature *and* magnetic field. In the frozen regime the resistance no longer depends on the field, but on temperature and transport current. The shape of the resistive transition below the $T_m(H)$ line has a universal character independent of the amplitude of the field. This implies that in the frozen regime the activation energy does not depend on the mean vortex distance, contrary to any collective flux-pinning model.

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