

Measurement of the Exponent μ in the Low-Temperature Phase of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Films in a Magnetic Field: Direct Evidence for a Vortex-Glass Phase

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Current-voltage (I - V) characteristics were measured for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ thin films in high magnetic fields and at temperatures well below the superconducting transition temperature. The functional form of the I - V curves is described by $E/J \propto \exp[-(J_0/J)^\mu]$, with E the electric field and J the current density. The exponent μ is 0.19 ± 0.05 for low values of current density and $\mu = 0.94 \pm 0.1$ at high values. The results at low current density are characteristic of a vortex glass and constitute the first direct evidence that the low-temperature phase of a disordered superconductor is a vortex glass.

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Recent experiments [1-4] on $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ in large magnetic fields have presented strong evidence for the existence of a true phase transition at a temperature $T_g(H)$. Static and dynamic properties of films, crystals, and ceramics were found to exhibit critical behavior near $T_g(H)$ with critical exponents in agreement with theoretical predictions [5] for a second-order phase transition from a vortex-liquid phase (having no long-range phase coherence nor any long-range order in the vortex-line positions) to a vortex-glass [5] (VG) phase (having long-range coherence in the phase of the superconducting wave function but no long-range translational order of the vortex positions). These experimental results have been widely viewed as evidence for the existence of such a VG phase. While the observation of critical scaling behavior provides strong evidence that a second-order phase transition does occur, *these observations, however, do not directly probe if the low-temperature state is a VG phase.* Whether the low-temperature phase is a vortex glass or a vortex lattice (having long-range translational order of the vortex-line positions) has remained a very controversial issue.

In this paper we directly address the question of whether the low-temperature state is a vortex-glass phase by carefully measuring the exponent μ which characterizes the low-temperature phase. We have measured the dissipation of $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films in a magnetic field well below T_g . Over a wide range of fields and temperatures, the functional form of the nonlinear current-voltage (I - V) characteristics is found to be well described by

$$\rho \equiv \frac{E}{J} = \rho_0 \exp \left[- \left(\frac{J_0}{J} \right)^\mu \right], \quad (1)$$

with ρ the nonlinear resistivity, E the electric field, J the current density, and J_0 and ρ_0 a characteristic current density and resistivity, respectively. The present experiments yield $\mu = 0.19 \pm 0.05$ at low current densities and $\mu = 0.94 \pm 0.1$ for high J . Equation (1) has been proposed by VG theory [5] and our results are consistent with the low-temperature phase being a vortex glass. Further, we have made an estimate of the spatial extent

of the translational order. The vortex structure appears to be highly disordered for our films, with the spatial extent of the translational order limited to only a few vortex spacings.

Epitaxial c -axis-up $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ films of thickness 3000 Å were grown by laser ablation on (100) SrTiO_3 (two films, denoted STO1 and STO2) and yttrium stabilized zirconia (one film, YSZ1). The films exhibited vanishing resistance near 90 K and 0 T. The critical current densities from a 1 $\mu\text{V}/\text{cm}$ criterion were about $10^{10} \text{ A}/\text{m}^2$ at 77 K and 0 T. Photolithography and Ar-ion milling techniques were used to define four-probe patterns with sample areas of typical width 2-4 μm and length 100-200 μm . Au contact pads that were $(200 \mu\text{m})^2$ in area yielded contact resistivities of $\ll 10^{-8} \Omega \text{ m}^2$ after annealing. The I - V curves were measured as previously discussed in Ref. [1] by averaging individual current and voltage characteristics typically 5000 times for each value of temperature. The current-induced heating of the sample, estimated from the increase in temperature of the sample with increased power, was estimated to be much less than 0.5 K. The system noise temperature was less than 1 K. Magnetic fields up to 5 T were applied perpendicular to the film, i.e., $\text{H} \parallel c$.

Figure 1(a) shows as an example some selected I - V curves for STO2. At high temperatures, the present findings reproduce the critical behavior reported in Ref. [1] (see [6]): For $T > T_g$, an Ohmic resistivity is found which changes to power-law behavior at $T = T_g$. For $T < T_g$, negative curvature on the $\log E$ - $\log J$ plot is obtained. The latter behavior appears to persist down to the lowest temperatures. To find μ , Eq. (1) can be recast as an equation for a straight line by taking its logarithm, $\ln \rho = \ln \rho_0 + m[-J^{-\mu}]$, where m , the slope, is given by J_0^μ . A fit of this form to the low-temperature ($T \ll T_g$) data was tested [7] by replotting the data as $\ln \rho$ vs $-J^{-\mu}$ for different values of μ ; see Fig. 1(b). Conformity of the data to a straight line on such a plot signifies a satisfactory fit of Eq. (1) and allows μ to be determined. Indeed, this equation was found to describe the data adequately for all T , B , and J [8]. Subsequently, J_0 and ρ_0 are directly found from the slope and the ordinate, re-

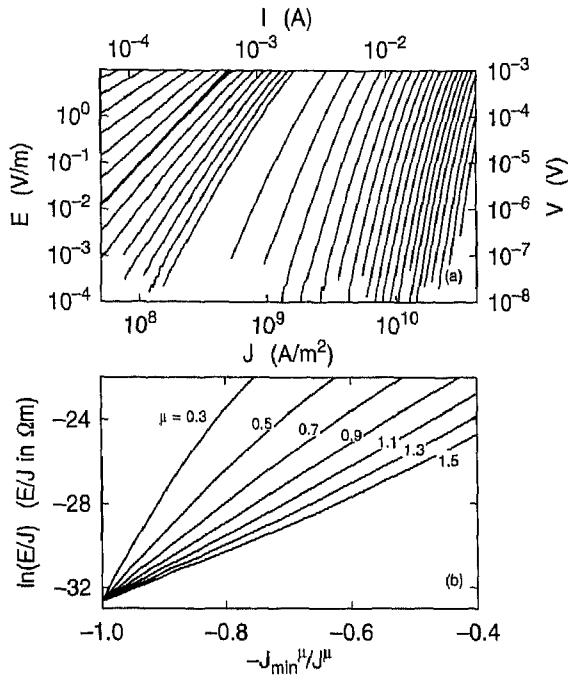


FIG. 1. (a) I - V curves for sample STO2 at $B=1$ T for selected temperatures from 88 K (upper left corner) to 18.5 K (lower right corner). The curves differ by 0.5 K near the transition temperature (thick solid line denotes $T_g=85$ K), and by 3 K below 81.5 K. (b) Example of the data analysis: Plot of $\ln(E/J)$ vs $-J_{\min}^{\mu}/J^{\mu}$ at various μ for STO2, $B=1$ T, $T=39$ K. The current densities are normalized to the minimum value J_{\min} to allow comparison for different μ . The experimental data conform to a straight line only near $\mu=0.9$, but show curvature for the different values.

spectively.

The temperature dependence of μ is given in Fig. 2(a). Two plateaus in the value of μ are found: $\mu \approx 0.19$ at high temperature, but, upon lowering the temperature, μ gradually increases until ultimately $\mu \approx 0.94$. Note that at the highest T/T_g , no values for μ have been extracted because the I - V curves evolve into power-law behavior as expected for the critical regime near T_g ($T/T_g \geq 0.85$ for 5 T). The crossover between the two plateaus can be illustrated in an even more compelling way with the magnetic field dependence of μ . Figure 2(b) shows $\mu(B)$ for STO2 for T/T_g between 0.3 and 0.85. We have chosen to measure $\mu(B)$ for constant T/T_g rather than for constant temperature in order to keep a constant relative distance to the superconducting transition line in the (H, T) plane. Also shown are some results for STO1 for $T/T_g=0.7$ which compare well with those for STO2 at a slightly higher T/T_g of 0.85. From the figure, it is seen that μ has two limiting values, 0.19 and 0.94, and a crossover from one limiting value to the other.

Why does μ depend on T and B ? It should be realized that a change in B or T always requires the current scale to be varied in order to observe the dissipation within our fixed voltage window. We have found that it is the current density which controls the value of μ . Figure 3

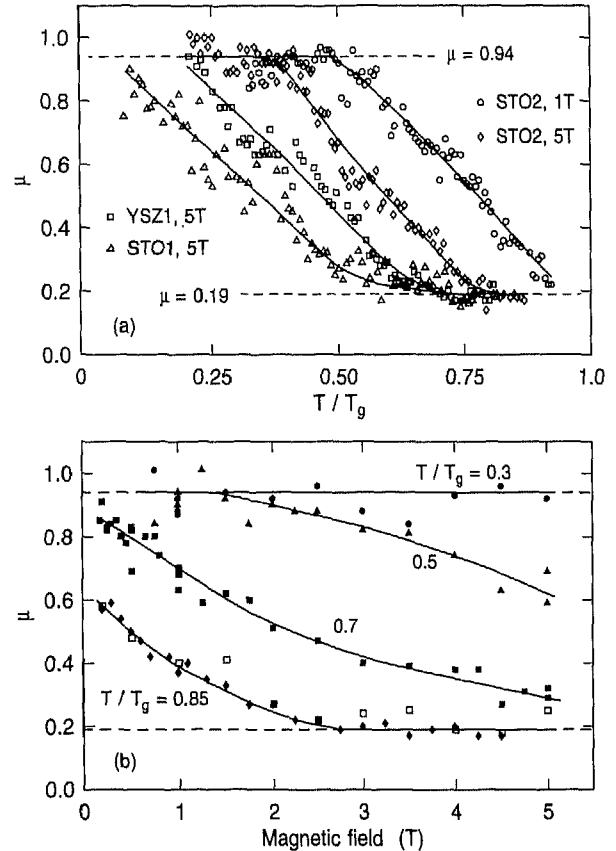


FIG. 2. (a) Temperature dependence of μ . The data are displayed vs reduced temperature T/T_g rather than T to account for small sample-to-sample variations in T_g (which is ≈ 73 K for 5 T as defined from the power-law behavior [1]). (b) Field dependence of μ for STO2 at various T/T_g (solid symbols), and for STO1 at $T/T_g=0.7$ (open squares). Solid lines are guides to the eye. Dashed lines denote the two μ plateaus.

shows a plot of μ vs J [9]. The figure contains *all* data of Figs. 2(a) and 2(b) for STO2. There is the substantial experimental scatter, but the data collapse convincingly shows that μ depends, at least primarily, on J rather than on T or B . We also note that while the limiting behavior for μ at high and low current densities is plausible from Fig. 3, it is by no means irrefutable. Our strongest evidence for the limiting behavior is the same data presented in Figs. 2(a) and 2(b). Finally, we note that the plateau for μ at low current density is found for all three samples, while the high- J plateau is observed clearly for sample STO2 only. Table I summarizes the μ values found at the plateaus. It comprises the results presented above as well as some more data not shown here.

The values of J_0 and ρ_0 were also extracted from the data. Both exhibit quite strong T and B dependences which can be explained by a crossover between rather different values in the two plateau regimes for μ found earlier. For high T and $\mu=0.19$, we find that $J_0(T)$ and $\rho_0(T)$ approach the critical behavior $J_0 \propto (1 - T/T_g)^{2\nu}$

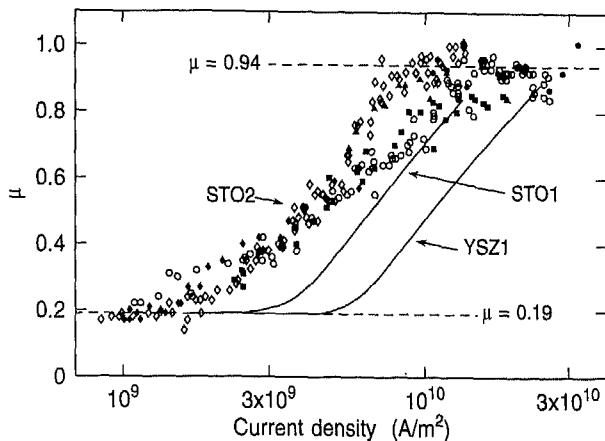


FIG. 3. μ vs the current density [9] for STO2. Symbols are as in Fig. 2. The data collapse indicates that μ depends on J rather than on T or B . Solid lines indicate similar data for STO1 and YSZ1.

and $\rho_0 \propto (1 - T/T_g)^{(z-1)\nu}$. The resultant exponents $\nu = 1.8 \pm 0.2$ and $z = 6 \pm 2$ compare excellently with previously reported values, $\nu = 1.7$ and $z = 4.9$, which were extracted above and at T_g , respectively [1-4]. For low T and $\mu = 0.94$, we obtain $J_0 \propto 1/T^{1.2 \pm 0.2}$. Such an approximate $1/T$ dependence is anticipated since Eq. (1) derives [5,10] from a thermally activated resistivity $\rho \propto \exp(-U/k_B T)$, with an energy barrier $U \propto J^{-\mu}$, and, correspondingly, J_0 should be proportional to $1/T^{1/\mu}$. In all cases, J_0 exceeds the experimental range of J substantially ($J_0/J \sim 10^7$ for $\mu = 0.19$, and ~ 20 for $\mu = 0.94$), validating the use of Eq. (1) for the analysis.

Equation (1) has been proposed by VG theory [5] as well as by the most commonly cited alternative explanation, collective flux creep [10]. The two theories, however, predict different values for μ . Both theories envision dissipation by jumps of vortex-bundle segments, forming vortex loops (i.e., the net addition of a closed loop of vortex line to the superconductor) of characteristic size l in a disordered Abrikosov lattice. Yet, they approach it from opposite limits: Whereas the VG theory considers long length scales ($l \gg l_{LO}$), the collective-creep theory considers the case where the randomness is weak enough (implying $l \leq l_{LO}$) to enable a description of the local vortex lattice in terms of elastic-media theory. Here, l_{LO} denotes the Larkin-Ovchinnikov length which is a mea-

sure for the finite short-range translational order [11], i.e., it characterizes the size of the "Abrikosov lattice domains." The length l_{LO} may be found at T_g from the deviations from critical scaling at high current density, i.e., $l_{LO} = (k_B T_g / \gamma \phi_0 J)^{1/2}$, with J the current density where deviations from power-law behavior occur, $\gamma \approx 0.2$ the anisotropy factor, and ϕ_0 the flux quantum. The results are listed in Table I. Remarkably small [12] values are found for l_{LO} : only ~ 400 Å, or 1-3 vortex spacings. Note that l_{LO} is expected to be nearly independent of T since the short-range translational order will freeze in near T_g . An important result of both theories is that the typical vortex-loop size l is larger for smaller applied current densities [5,10]. The collective-creep theory yields different μ for different regimes of l , with $\mu = \frac{7}{9}$ for the longest length scale considered [10], while a similar scaling approach [13] results in $\mu = \frac{1}{2}$. Both values are inconsistent with the present experimental result $\mu = 0.19 \pm 0.05$ at low J , i.e., large l . This small μ value, however, fits the VG picture particularly well since $0 < \mu \ll 1$ is expected, because the three-dimensional VG appears to be only slightly above its lower critical dimensionality [14] where $\mu = 0$. A consistent picture of an equilibrium VG phase thus appears from the present work together with the evidence for the phase transition.

It is important to realize that at high currents the signatures of the VG phase will be illegible. With increasing current density, the loop size l will shrink and eventually reach l_{LO} . At this point, the dissipation will become dominated by the relevant processes for $l < l_{LO}$ and not by the properties of the vortex glass. Experimentally, we indeed observe deviations from the small μ value at increasing current density, eventually leading to $\mu \approx 0.94$ at high current density. The current density and temperature for which this crossover occurs, J_{cr} and T_{cr} , appear at first glance to be rather different for different samples. To understand this behavior, we now will correlate l_{LO} to l_{cr} , the size of the vortex loops at the crossover point, for the three samples investigated. Within vortex-glass theory, the vortex-loop size is given by $l = l_0 (\gamma/J)^{\mu/\Psi}$, with Ψ an exponent, l_0 a constant, and γ a stiffness coefficient with an approximate $1 - (T/T_g)^4$ temperature dependence [5]. The ratio μ/Ψ is expected [5] to be $\approx \frac{1}{2}$. We employ the above definition to extract the loop size l_{cr} at crossover by inserting J_{cr} and T_{cr} which are taken at $\mu = 0.6$, i.e., at some value in between 0.19 and

TABLE I. Some results for the three samples investigated: $\mu_{low J}$ and $\mu_{high J}$ denote μ as deduced at low and high current density, respectively; J_{cr} is the crossover current density at $\mu = 0.6$; l_{LO} is the Larkin-Ovchinnikov length at T_g (5 T); $a = (2\phi_0/B\sqrt{3})^{1/2}$ is the Abrikosov lattice parameter at $B = 5$ T; and l_{cr} is the crossover length as defined in the text.

Sample	$\mu_{low J}$	$\mu_{high J}$	J_{cr} (10^9 A/m 2)	l_{LO}/a	l_{cr}/l_{LO} [$10^2 l_0/(1 \text{ m})$]
YSZ1	0.19 ± 0.03	1.0 ± 0.2	14 ± 2	1.4 ± 0.3	2.8 ± 0.6
STO1	0.21 ± 0.04	1.0 ± 0.2	8.0 ± 0.9	2.5 ± 0.3	2.1 ± 0.3
STO2	0.19 ± 0.02	0.94 ± 0.1	5.6 ± 0.5	2.4 ± 0.3	2.5 ± 0.4

0.94. With these approximations, we can compare I_{cr}/I_{LO} at $B=5$ T. The results for the three samples are listed in Table I. The results coincide satisfactorily, supporting the picture that crossover in μ reflects that current density where the size of the I_{cr}/I_{LO} is a particular value. In passing we note that VG behavior thus will be perceived more easily (i.e., at higher current density) in films than in crystals, or, generally, in the more strongly disordered materials with a small I_{LO} .

The dissipation encountered for $I < I_{LO}$, i.e., for high current density ($> J_{cr}$), will be nonuniversal and dependent on the microscopic details of the material. In crystals, which have a large I_{LO} [12], one might expect excitations involving flux bundles in the local lattice [10]. For the films, however, I_{LO} only amounts to a few lattice spacings, and the dissipation at high current density is likely to be dominated by loops involving single vortex lines only. For single vortex lines interacting with weakly pinning point defects, μ has been calculated [10] to equal $\frac{1}{7}$, which clearly is at variance with the experimental $\mu = 0.94 \pm 0.1$. We propose that the major source of pinning in the films instead involves linear or planar defects with some extent along c such as stacking faults, microtwins, dislocations, etc. A simple estimate for $U(J)$ shows that $\mu = 1$ for this case [15], which is in agreement with the experimental result.

In conclusion, we have found exponential I - V curves, as in Eq. (1), with an exponent μ which is current dependent. Whereas the results at low current density provide direct evidence for a vortex-glass phase, the findings at high current density signal the nonuniversal behavior at very short length scales. The crossover between these regimes is controlled by the size of the Abrikosov lattice domains, which in the films amounts to only a few vortex spacings. More generally, from the present work, a physical picture emerges which reconciles the existence of a VG phase at equilibrium, i.e., for $J \rightarrow 0$, with alternative descriptions of the dissipation in the mixed state which may be relevant at high current density.

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