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Scaling of thin-film $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ resistivity-current isotherms at low fields: Implications for vortex phase transitions and universality

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We have investigated a second-order phase transition of the vortex lattice in thin-film $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ from 1 mT to 1 T applied magnetic fields. The dc resistivity-current density data for each field exhibit critical scaling consistent with a second-order vortex-liquid to vortex-solid phase transition. The high-field data support the vortex-glass model and have the same critical exponents as thin-film $YBa_2Cu_3O_{7-\delta}$. At low fields we observe a change in the critical exponents and universal functions. The critical regime diminishes as the field is decreased but remains nonzero even at 1 mT. These results suggest that the universality class of the transition changes at low fields.

I. INTRODUCTION

Recently, an array of experiments on high-temperature superconductors (HTS) have supported the existence of a vortex-liquid to vortex-glass phase transition.[1] Evidence of these phases is expected in HTS because of the increased role of thermal fluctuations in the vortex dynamics. Thermal fluctuations are more important in high-T_c superconductors because these materials are more anisotropic, have shorter pair coherence lengths, larger penetration depths, and higher transition temperatures, than low-T_c type-II superconductors. According to the vortex-glass (VG) model of Fisher, Fisher, and Huse (FFH) a phase transition occurs from a vortex-liquid state to a vortex-glass state in HTS with point defects.[2] In contrast to the first-order melting transition observed in defect-free single crystals,[3] this transition is expected to be second-order, owing to impurities, and as a consequence critical scaling applies. The transition should be characterized by length ξ_{VG} and time τ scales which diverge at the vortex-glass transition temperature T_g as $\xi_{VG} \propto |1-T/T_g|^{-\nu}$ and $\tau \propto \xi_{VG}^z$. Here T is the temperature, ν the static, and z the dynamic critical exponent. A dimensional argument leads to the ansatz that the resistivity ρ versus current density J isotherms will scale according to

$$\rho(J) \propto \xi_{VG}^{d-2-z} F_{\pm}\left[\frac{J\xi_{VG}^{d-1}\phi_0}{k_B T}\right], \tag{1}$$

where the $F_{\pm}$ are universal scaling functions and d is the dimensionality.[4] The critical exponents are expected to be universal with $z \approx 4-7$ and $\nu \approx 1-2$ for $d=3$.[2,4]

Experiments which investigate the vortex-glass model have used $YBa_2Cu_3O_{7-\delta}$ (YBCO),[1] $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ (NCCO) films,[5] amorphous Mo_3Si films,[6] and $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi2223).[7,8] Studies of YBCO films have yielded reasonably consistent results which agree with the vortex-glass predictions. However, earlier NCCO film data[5] did not yield exponents which matched those of the YBCO film studies. The published data is almost exclusively limited to high fields, (0.5 T and above), and the only report of a systematic dependence of the critical exponents with field used thin film YBCO.[9] In this paper we present critical scaling of ρ-J isotherms for a NCCO film at fields from 1 mT to 1 T.[10]

Studying the ρ-J characteristics of NCCO gives insight into the relative importance of T_c and thermal fluctuations in HTS vortex dynamics. In many ways, NCCO is an anomaly within the family of copper oxide HTS; it has a modest T_c near 20 K which reduces the importance of thermal fluctuations. NCCO is also more anisotropic than YBCO ($\gamma=20-25$ versus $\gamma=5-7$ for YBCO),[11,12] and has a longer coherence length ($\xi=70-80$ Å versus $\xi=10-15$ Å).[11,13,14] [The mass anisotropy γ is defined as $\gamma \equiv (M_z/m_\perp)^{1/2}$.] These materials have strikingly different magnetoresistance characteristics, which is evident in the contrast between their resistivity-temperature curves. In YBCO the ρ-T curves exhibit dramatic fan-shaped broadening with increasing magnetic field. The broadening is not as pronounced in NCCO where the onset temperature decreases with increasing field.[15] Thus critical scaling of NCCO ρ-J characteristics helps isolate the primary factors which govern vortex dynamics.

II. PROCEDURE

Our experimental procedure for taking and analyzing dc ρ-J data has been described previously.[9] The NCCO

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film was made by pulsed-laser deposition onto a YSZ substrate in a nitrous-oxide atmosphere at the University of Maryland facility. The 180-nm-thick film is c-axis oriented and has been etched into a 200-μm-wide bridge. The $T_c(\rho < 10^{-3}\ \mu\Omega\,\text{cm})$ is 18.6 K at ambient field with a transition width of 1.4 K. The resistivity at T_c is 148 $\mu\Omega$ cm. The details of the film growth have been described in Ref. 16.

Contact to the film was made in a standard four-point configuration using the following method. First the film was etched in a dilute (1:10) solution of glacial acetic acid and deionized water. Next, gold pads were evaporated onto the film and annealed in air for 20 min at 190 °C. Finally, gold wires were attached to the gold pads using silver paint. This procedure yielded resistances of less than 1 Ω per contact. No evidence of heating was manifest for current densities below about 10^5 A cm^{-2}. The film was affixed to a copper block which was mounted in a variable temperature insert inside a liquid-helium cryostat. The c axis of the film was parallel to the axis of a 9-T superconducting magnet. The magnetic fields were calculated from the current in the magnet. Remnant fields and self-fields may change the absolute determination of the field by a few mT; this is significant only at the lowest fields. Temperature fluctuations in the cryostat were held to below 10 mK for each isotherm.

III. RESULTS

For each field, 30–100 resistivity-current density isotherms were taken around T_g. This glass-transition temperature is defined by a power-law dependence of ρ on J. Below T_g, isotherms display negative concavity while those above T_g show positive concavity on a logρ-log$J$ plot. These data were collapsed onto the two universal scaling functions $F_\pm$ by plotting $\rho_{\text{scale}} = \rho|1 - T/T_g|^{\nu(z-1)}$ versus $J_{\text{scale}} = JT^{-1}|1 - T/T_g|^{-2\nu}$. Figure 1 shows a typical set of data: (a) the ρ-J isotherms taken in an applied field of 30 mT and (b) the same data collapsed. The quality of the collapse is just as striking for all fields.[10] Figure 2 displays the field dependence of the critical exponents for the NCCO film described in this paper and for an YBCO film.[9] For high fields, the extracted exponents $z \cong 5.4$ and $\nu \cong 1.75$ are constant, approximately equal to those of YBCO, and consistent with the predictions of the vortex-glass model. Between 50 and 30 mT we find a sharp increase in z for the NCCO film, and a more gradual decrease in ν occurs between 0.25 T and 30 mT. At the lowest fields, (below 30 mT), z and ν become constant again with $z \cong 7.3$ and $\nu \cong 0.93$.

The H-T phase diagram resulting from this experiment appears in Fig. 3. The H_{c2} line is obtained by defining T_c as the temperature where the resistivity is half the normal-state value. Fitting the vortex-glass transition temperature T_g to the function $H \propto [T_g(0) - T_g(H)]^{2\nu_0}$ resulted in $\nu_0 = 0.65$. This function describes all the data, in contrast to YBCO where one value of ν_0 does not fit all fields.

It is important to set out the relevant length scales of the system. In this experiment, the vortex-glass correla-

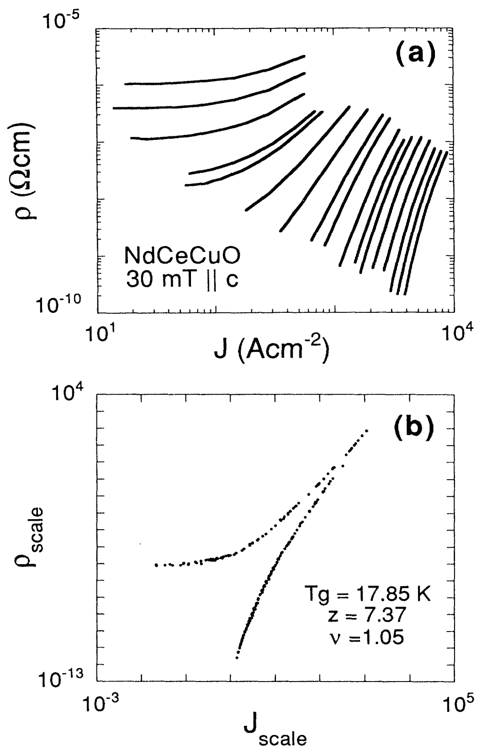

FIG. 1. (a) ρ-J isotherms for a NCCO film with a 30 mT field applied parallel to the c axis. The temperature range is 16.8 to 18.4 K, with the isotherms spaced by about 100 mK. (b) Data in (a) collapsed onto the two universal functions according to Eq. (1), where $\rho_{\text{scale}} = \rho|1 - T/T_g|^{\nu(z-1)}$ and $J_{\text{scale}} = JT^{-1}|1 - T/T_g|^{-2\nu}$.

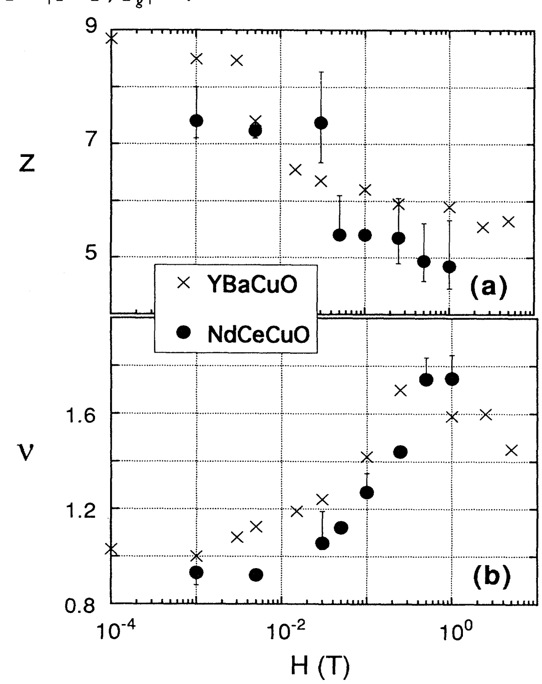

FIG. 2. Dynamic exponent z (a) and static exponent ν (b) as a function of applied field. Crosses are the values for the YBCO film, and the circles for the NCCO film. The uncertainty in T_g is the primary source of the error in the exponents; once T_g has been specified, the uncertainty becomes much smaller.

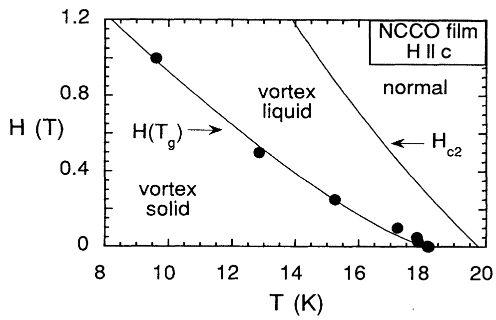

FIG. 3. *H-T* phase diagram for a NCCO thin film with $\mathbf{H}\|c$. The circles denote T_g values; the line is a fit to the function $H \propto [T_g(0)-T_g(H)]^{2\nu_0}$, giving $\nu_0=0.65$. For the H_{c2} line, T_c is defined as the temperature where the resistivity is 50% of the normal-state value.

tion length, penetration depth, average intervortex spacing, sample width and thickness lie approximately within two orders of magnitude, as displayed in Fig. 4. The vortex-glass correlation length ξ_{VG} can be roughly estimated from (assuming $d=3$)

$$\xi_{VG}^2 = C\frac{k_B T}{J_{nl}\phi_0} \ . \tag{2}$$

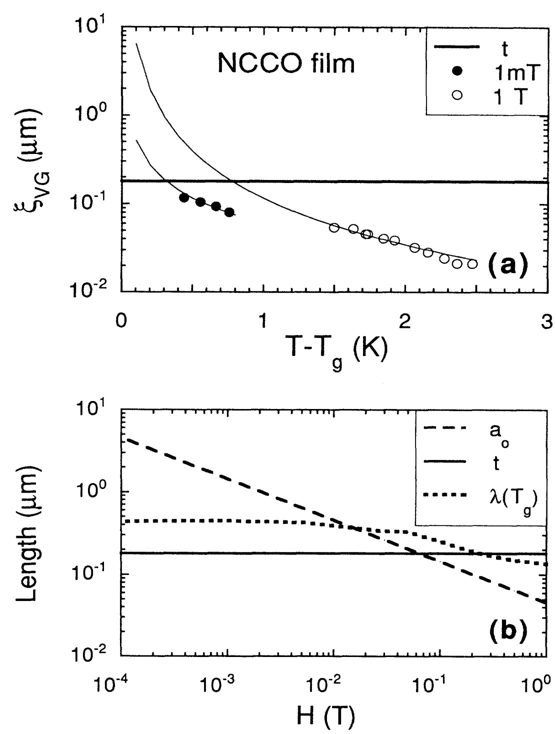

FIG. 4. (a) Estimated vortex-glass correlation length for 1 T (open circles) and 1 mT (solid circles); see text. The film thickness is depicted as a horizontal line. (b) Relevant lengths as a function of magnetic field. The solid line depicts the film thickness t, the dashed line represents the average intervortex spacing a_0, and the dotted line is the penetration depth λ evaluated at $T_g(H)$.

This gives the correct functional form of ξ_{VG}, but the dimensionless prefactor C (assumed of order unity) is not known. In addition, there are several ways of obtaining J_{nl}, the current density at which the resistivity is no longer current independent for isotherms with $T>T_g$. All reasonable methods give the same temperature dependence, $J_{nl}=J_0|1-T/T_g|^{2\nu}$, but result in different values of J_0. The solid curves in Fig. 4(a) result from defining J_{nl} as that current for which $F_+(J_{nl})\approx 3.5$ in the scaled plot, [e.g., Fig. 1(b)], and then extrapolating to low temperatures using $\xi_{VG}\propto|1-T/T_g|^{-\nu}$. The resulting temperature dependence for this film is consistent with finding J_{nl} by estimating the current on the ρ-J plot where ρ first deviates from linearity. These appear in Fig. 4(a) as points, (C was adjusted so that the points would lie on the solid curves). The same form for J_{nl} is obtained from using the criterion that J_{nl} is the current for which $\partial \ln E/\partial \ln J = 1.2$.[17] The latter two definitions of J_{nl} result in $\xi_{VG}>t$, which is unphysical and sets an upper bound on C in Eq. (2).

The penetration depth λ is 1300 Å at $T=0$ (Ref. 13) and assumed to have a temperature dependence given by the two-fluid model,[18] but is otherwise taken to be field independent. The penetration depth, evaluated at T_g, is only weakly field dependent. As shown in Fig. 4(b), it varies from 0.24 μm at low fields to 0.14 μm at 1 T. The average intervortex spacing $a_0=\sqrt{\phi_0/B}$ increases from 0.05 μm at 1 T to 1 μm at 1 mT. At 200 μm the film width (not shown) remains larger than all other lengths, but the film thickness, $t=0.18$ μm, is exceeded by both a_0 and ξ_{VG} in certain regimes.

IV. DISCUSSION

The critical exponents reported here for NCCO films, (in contrast to those previously published[5]), are very similar to those for YBCO films. The transition of the vortex liquid to a glassy state is the same for the two materials. Indeed, the exponents for YBCO films are closer to those of NCCO films than to those of YBCO single crystals.[19] This suggests that the defect structure, which is likely to be similar in all perovskite films, is more important than intrinsic differences in chemical composition, T_c, pair coherence length, and H_{c2}, in determining the nature of the phase transition. The high-field exponents lend support to the vortex-glass model of FFH.

The similarity of the exponents for the NCCO and YBCO films extends even to their field dependence. Such dependence is not predicted by scaling theory, where the scaling functions are determined only by the transition mechanism. If these data are to be interpreted as the signature of a phase transition, and not merely a convenient parameterization, the most likely explanation for the field dependence is a change in the mechanism driving the transition. Nevertheless, several interpretations deserve consideration.

One might argue that the critical region becomes immeasurably small at the lowest fields. However, we define the critical region consistently at all fields and it remains measurable down to at least 1 mT. The VG model predicts that the constant resistivity at low current density for isotherms above T_g varies as $\rho_{\rm lin} \sim |T-T_g|^s$ where $s=\nu(z-1)$. Figure 5(a) shows that $\log\rho_{\rm lin}$ versus $\log|T-T_g|$ is a straight line up to some field-dependent temperature, as predicted. This temperature can be used as an estimate of the critical region, which is displayed in Fig. 5(b) as a function of field. The critical region decreases from 5 K at 1 T to 1.5 K at 1 mT. We find $s \cong 6 \pm 1.5$ with considerable scatter but without systematic field dependence.

In a recent paper that presented the scaling of ρ-J isotherms for Bi2223 films, Yamasaki *et al.* suggested that the field-dependent exponents observed in YBCO could be explained by assuming a two-dimensional transition at low fields.[8] They noted that upon setting $d=2$ in the scaling analysis for the low fields, one could define two-dimensional (2D) scaling exponents z' and ν', which can be found from the 3D critical exponents using $\nu'=2\nu$ and $z'=(z-1)/2$; the resulting 2D critical exponents z' and ν' are closer to the high-field ($d=3$) values. Even if it were clear in what sense low field implies two dimensionality, one would not expect the critical exponents to be the same in two dimensions as in three. In most cases, a different dimensionality corresponds to a distinct universality class. For example, the Ising model calls for $\nu=1.0$ in 2D but $\nu=0.627$ in 3D. In dimensions above

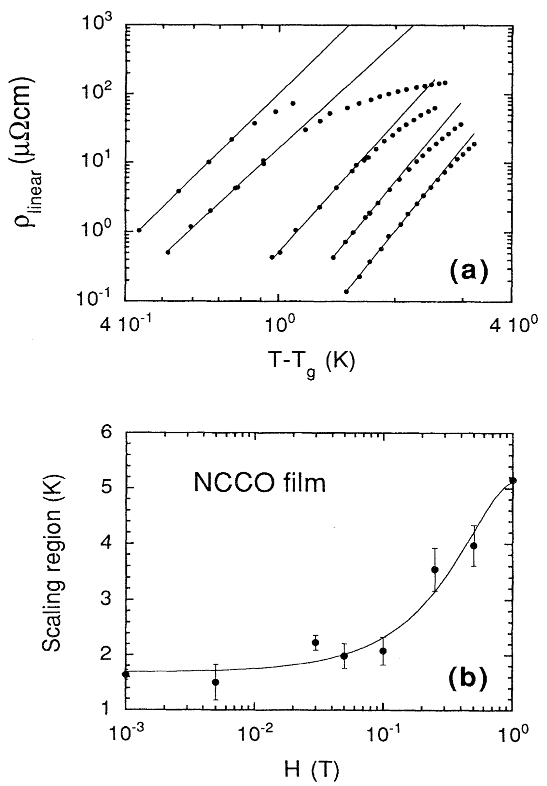

FIG. 5. (a) Linear resistivity $\rho_{\rm lin}$ versus $|T-T_g|$ for (from left to right) 1 mT, 0.1, 0.25, 0.5, and 1 T. The temperature at which $\log\rho_{\rm lin}$ is no longer a linear function of $\log|T-T_g|$ defines the critical region. (b) Critical region as a function of field.

the upper critical dimension $D_u=6$ of the glass transition, the exponents should converge to their mean-field values $z=4$ and $\nu=0.5$;[20] the exponents are expected to increase for dimensions less than D_u. In light of this, it is not reasonable to change the value of d merely to preserve the high-field values of the critical exponents.

However, the comparison between the Bi2223 films and the low-field data presented here is interesting. That experiment extracted 3D critical scaling exponents $z=12.2$, $\nu=0.69$ and 2D exponents $z'=5.61$, $\nu'=1.38$. Since Bi2223 is expected to be quasi-two-dimensional, they considered the latter more appropriate. While the 3D values of z and ν are not identical to our low-field values, they are similar in that the dynamic exponent is higher and the static exponent is lower than predicted by the VG model.

At low magnetic fields, several length scales in the system start to intersect. Finite-size effects should become relevant when the correlation length becomes comparable to the physical size of the system. A few Kelvin from T_g, $\xi_{\rm VG}$ can be directly determined from $J_{\rm nl}$ via Eq. (2), and it is well below the film thickness. Close to T_g, our experimental resolution prohibits us from directly measuring $J_{\rm nl}$, but $\xi_{\rm VG}$ can be determined by extrapolating the values far from T_g. Although Eq. (2) gives only an estimate of $\xi_{\rm VG}$, we do not observe $\xi_{\rm VG}$ leveling off as it would if t were limiting $\xi_{\rm VG}$, as demonstrated in Fig. 4(a) for 1 mT and 1 T.[17] The region where $\xi_{\rm VG}$ would be greater than t decreases with field. This makes it more difficult to see the effects of dimensionality at low fields and less likely that the different low-field exponents can be an artifact of a finite-size effect. Moreover, the scaling exponents are unaffected by the inclusion of the data in this narrow temperature region.

The field dependence of the critical exponents may have its origins in a field-induced change in the mechanism which drives the transition. If so, we should examine the relationship between the average intervortex spacing a_0 and the other lengths in the system. For data within the critical region as defined above, $\xi_{\rm VG}$ is smaller than a_0 for approximately half of the scaled data at high fields; at the lowest fields, $\xi_{\rm VG} < a_0$ for all the scaled data. A correlation length shorter than the intervortex spacing may suggest that dissipation is due to single-vortex movement.[21]

The intervortex spacing exceeds the penetration depth $\lambda(T_g)$ below about 30 mT for the NCCO film and 10 mT for the YBCO film, resulting in reduced vortex interaction. These fields are where the exponents have assumed their low-field values. The physics governing the transition could change for different vortex-interaction strengths. In the mid-range of the crossover region, a_0 equals the film thickness. The significance of this is not clear.

We are not aware of a theoretical model which both attempts to describe a second-order phase transition at low fields and is consistent with our data. FFH predict that a transition into the Meissner phase will be characterized by $z \approx 2$ and $\nu \approx \frac{2}{3}$. A Kosterlitz-Thouless (KT) transition, which applies in two dimensions at zero field, predicts a power-law isotherm $\rho \propto J^2$ at the KT transition temperature. At T_g we observe a power-law isotherm at all fields, but our low-field result is $\rho \propto J^{3.2}$.

This is the first consistent comparison of critical scaling in NCCO and YBCO thin films. Their dc ρ-J characteristics in a magnetic field closely resemble one another and can be similarly scaled in the context of a second-order normal-to-superconducting phase transition. Within error, we obtain the same critical exponents for the two materials. Hence the same transition occurs in NCCO as in YBCO. The high-field results, taken alone, support the VG hypothesis. A consistent analysis of the low-field data yields a well defined, though narrow, critical region and gives different critical exponents. If size effects do not cause the change in exponents (experiments on single crystals are underway to investigate this possibility), then the field dependence signifies that the universality class of the transition changes as the field is decreased.

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