

## Absence of a Finite-Temperature Vortex-Glass Phase Transition in Two-Dimensional $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ Films

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Nonlinear current-voltage characteristics are investigated for the high-magnetic-field state of ultrathin (down to  $\sim 1$  unit cell thick)  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  films. The current density where nonlinearity sets in,  $J_{nl}$ , exhibits a nontrivial power-law temperature dependence,  $J_{nl} \propto T^{3.0 \pm 0.3}$ , which quantitatively verifies a prediction from the vortex-glass theory for two dimensions (2D). Additionally, a critical scaling analysis of the  $I$ - $V$  data clearly manifests the differences between a 2D and 3D vortex glass. The results suggest that a 2D vortex glass does not order at finite temperatures.

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The fascinating possibility of a truly superconducting vortex-glass (VG) phase for the mixed state of disordered superconductors in a magnetic field has been intensely debated [1-5]. A crucial parameter for the existence of a VG phase is the dimensionality. It was predicted theoretically [1,2] that a VG phase is stable in three dimensions (3D), but not in 2D. Indeed, recent numerical simulations [3] seem to confirm that the lower critical dimensionality is in between 2 and 3. Experimental work [4] has focused on the VG phase transition in 3D. The 2D limit, on the other hand, has never been explored experimentally with regard to VG behavior. In the present Letter, such an investigation is presented.

We report on an experimental search for 2D VG correlations in ultrathin  $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (YBCO) films in a high magnetic field through a detailed examination of the nonlinear current-voltage ( $I$ - $V$ ) characteristics. The results turn out to be quite different from the 3D case, where a finite-temperature VG phase transition is observed [4], as well as from the 2D case at zero magnetic field, where a Kosterlitz-Thouless transition occurs [6]. The present findings verify predictions of the VG theory for the 2D limit. In particular, we find that the 2D current density where nonlinearity of the  $I$ - $V$  curves sets in,  $J_{nl}$ , has a nontrivial power-law temperature dependence, viz.,  $J_{nl} \propto T^{3.0 \pm 0.3}$ . This agrees well with the VG prediction  $J_{nl} \propto T^3$ . On the other hand, it cannot be understood from an Anderson-Kim-like flux-creep model [7], which yields  $J_{nl} \propto T$ . The result for  $J_{nl}(T)$  provides the first experimental evidence for the existence of a finite 2D VG correlation length which diverges at  $T_{g,2D} = 0$  K. Such a zero glass temperature is in direct contrast to the 3D case, where a phase transition occurs at a finite  $T_{g,3D}$  [4]. At the end of this paper, we will present a critical scaling analysis of the  $I$ - $V$  curves which clearly visualizes the essential differences between 2D and 3D.

Before turning to the experimental results, we briefly recapitulate the theory for the 2D VG and its conse-

quences for the transport properties [1,8]. Although no ordered VG phase is expected at finite temperatures for 2D, VG correlations will develop towards the "critical temperature"  $T_{g,2D} = 0$  K [1,8]. This may be described by a 2D VG correlation length

$$\xi_{2D} \propto 1/T^{\nu_{2D}}, \quad (1)$$

with  $\nu_{2D}$  the correlation-length exponent in 2D. The vortex dynamics involves collective motion of vortex bundles with a linear size  $\xi_{2D}$ . The VG correlations are anticipated to strongly modify the low-temperature transport properties [8]. Thermal activation over the relevant energy barriers for the collective vortex motion has been shown [1,8] to lead to an expression for the linear resistance, viz.,

$$R_{lin} \propto \exp \left[ - \left( \frac{T_0}{T} \right)^p \right], \quad (2)$$

with  $T_0$  a characteristic temperature, and  $p \geq 1$ . The same expression, but with  $p \approx 0.7$ , has been predicted if the vortex motion proceeds through quantum tunneling [8]. In the presence of an applied 2D current density  $J$ , the Lorentz force contributes an extra energy  $\phi_0 J \xi_{2D}$  for the creation of vortex excitations ( $\phi_0$  is the flux quantum). If this energy becomes comparable to the intrinsic thermal energy, nonlinearities arise in the  $I$ - $V$  curves.  $J_{nl}$ , the 2D current density at the onset of nonlinearity, is thus given by

$$J_{nl} = k_B T / \phi_0 \xi_{2D} \propto T^{1+\nu_{2D}}. \quad (3)$$

Below, we report an experimental test of these expressions.

Ultrathin YBCO films of thickness between 16 and 400 Å were studied. The epitaxial  $c$ -axis-up films were made by laser ablation at a low growth rate of about 0.3 Å/s. The thin YBCO films were sandwiched between two non-superconducting  $\text{PrBa}_2\text{Cu}_3\text{O}_{7-\delta}$  (PBCO) layers (see inset

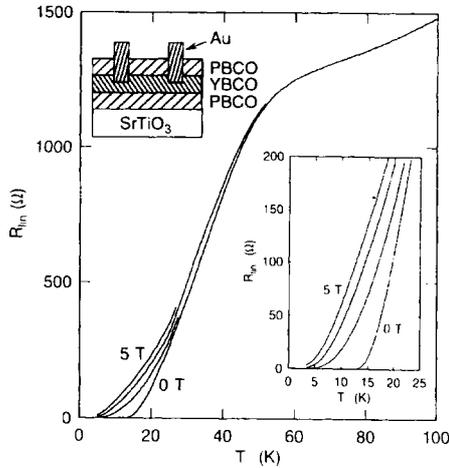


FIG. 1. Temperature dependence of the linear sheet resistance for a 16-Å YBCO film. Curves are for  $B=0, 0.5, 2,$  and  $5$  T (from bottom to top). Upper inset: The schematic layout (not to scale) of the film.

of Fig. 1). First, a PBCO buffer layer of about  $70 \text{ \AA}$  was deposited on a  $\text{SrTiO}_3$  substrate. Subsequently, the growth was interrupted for 3 min to improve the surface smoothness [9]. Then the thin YBCO film was deposited. After waiting another 3 min, a  $20\text{-\AA}$  top cover layer of PBCO was added. In this paper, we focus on the thinnest film with a nominal thickness of  $16 \text{ \AA}$  ( $\sim 1.3$  unit cell). Low-resistivity contacts were made by Ar-ion-milling away the top PBCO layer through a shadow mask, followed by deposition of  $500 \text{ \AA}$  of Au. By use of pulsed-laser lithography, a four-probe pattern was defined with a relevant YBCO area of  $\sim 150 \times 60 \mu\text{m}$ . Care was taken to minimize the laser power to prevent thermal damage to the film. The  $I$ - $V$  curves were measured as previously discussed in Ref. [4(a)] 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 less than  $0.2 \text{ K}$ . Magnetic fields were applied perpendicular to the film, i.e.,  $\parallel c$ .

In zero field, the  $16\text{-\AA}$  film becomes superconducting (i.e., attains zero linear resistance) near  $13 \text{ K}$ , as shown in Fig. 1. In magnetic fields of  $0.5$  to  $5 \text{ T}$ , however, the linear resistance does not completely vanish down to the lowest temperatures in our experiment ( $\approx 3.5 \text{ K}$ ). The results for the linear resistance agree reasonably well with reports on ultrathin films by other groups [9].

Figure 2 shows the nonlinear  $I$ - $V$  curves for the  $16\text{-\AA}$  film in a  $0.5\text{-T}$  field. Data at  $2$  and  $5 \text{ T}$  are very similar. Pronounced nonlinearities are apparent below about  $10 \text{ K}$ . At low temperatures, the  $I$ - $V$  curves exhibit a crossover from linear behavior at small  $J$  to nonlinear behavior at high  $J$ . Such a crossover is anticipated in the 2D VG model; cf. Eq. (3). The physical picture is that at low  $J$

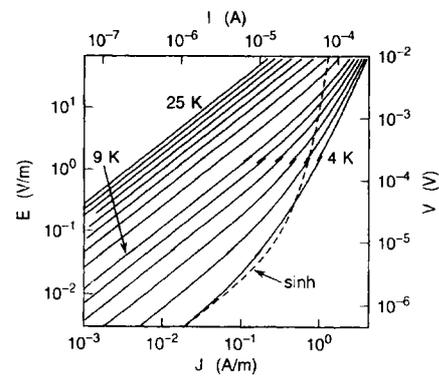


FIG. 2. Selected nonlinear  $I$ - $V$  curves for the  $16\text{-\AA}$  film at  $0.5 \text{ T}$  and various  $T$ . Temperatures range from  $25$  to  $4 \text{ K}$  in steps of  $2 \text{ K}$  (above  $9 \text{ K}$ ) and  $1 \text{ K}$  (below  $9 \text{ K}$ ). Dashed line denotes  $E = E_0 \sinh(J/J_0)$  for  $E_0 = 0.023 \text{ V/m}$  and  $J_0 = 0.15 \text{ A/m}$ . Note that variation of  $E_0$  or  $J_0$  changes the location of the dashed line on this log-log plot, but *not* its shape. Clearly, the sinh form does not fit the  $I$ - $V$  curves.

one probes the vortex dynamics at length scales larger than  $\xi_{2D}$  (where the system will look like a vortex liquid with a linear resistance), whereas at high  $J$ , by contrast, the excitations involve length scales smaller than  $\xi_{2D}$  and the associated glassy dynamics yield a nonlinear  $I$ - $V$  relation. Note that in Fig. 2, one does *not* observe the signatures of a finite-temperature phase transition such as is apparent in thick (3D) films [4].

Alternatively, one might try to interpret the results of Fig. 2 in the light of flux-creep-like models. Although qualitatively the shape of the  $I$ - $V$  curves is consistent with the flux-creep form  $E = E_0 \sinh(J/J_0)$ , quantitative comparison shows otherwise: It appears not possible to adjust the parameters  $E_0$  and  $J_0$  in such a way that a good fit of the sinh function to the shape of the experimental  $I$ - $V$  curves is achieved. An example of this is shown in Fig. 2 (dashed line). From a 2D collective flux-creep model [2], one expects  $E \propto \exp[-(J_0/J)^\mu]$ , which results in  $I$ - $V$  curves with a negative curvature on a log-log plot. Such behavior is not observed within the present temperature range.

In order to allow detailed comparison with the 2D VG theory, we quantify the onset of the nonlinearity in the  $I$ - $V$  curves. To this end, we define the crossover 2D current density  $J_{nl}$  by that value of  $J$  where  $\partial \ln E / \partial \ln J = 1.2$  [10]. In other words, we examine the point where the  $I$ - $V$  curves start to deviate from the low- $J$  linear behavior. The result for  $J_{nl}(T)$  is shown in Fig. 3. It is clear (dashed line in Fig. 3) that  $J_{nl}$  does not exhibit a linear  $T$  dependence such as is expected from a flux-creep picture [7]. The 2D VG model, however, works excellently:  $J_{nl}(T)$  is well described by a power law (solid lines in Fig. 3). Fits to Eq. (3) to the data at various fields yield  $\nu_{2D} = 2.0 \pm 0.3$  (see Table I). This value

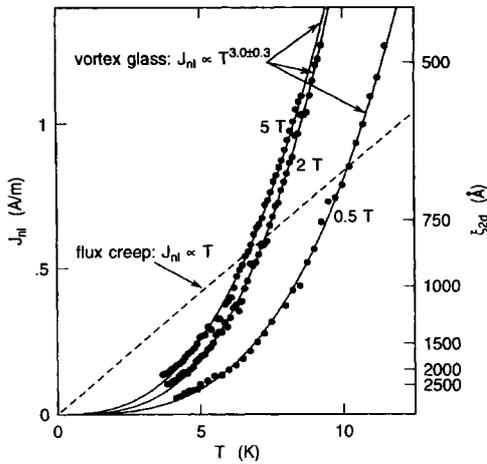


FIG. 3. Temperature dependence of  $J_{nl}$ , the 2D current density at the onset of nonlinearity in the  $I$ - $V$  curves. Solid lines denote the 2D VG power law, Eq. (3), while the dashed line denotes the flux-creep prediction,  $J_{nl} \propto T$ . Shown on the right-hand side is a rough estimate for  $\xi_{2D}$ , the 2D VG correlation length as deduced from Eq. (3) for the 2-T data.

agrees well with the estimate  $\nu_{2D} \approx 2$  which was deduced in various numerical simulations of simplified 2D VG models [3]. The 2D VG prediction is thus in quantitative agreement with the data. The power-law  $J_{nl}(T)$  provides evidence for a 2D VG correlation length which diverges at 0 K according to Eq. (1). By use of Eq. (3), the magnitude of  $\xi_{2D}$  may be calculated, although this will yield an order-of-magnitude estimate only since Eq. (3) in fact implies a proportionality constant of order unity. Also, the magnitude of  $J_{nl}$  depends somewhat on the criterion used to extract it [10]. As seen from Fig. 3 (scale on right-hand side), typical values of  $\xi_{2D}$  range from 500 to 2500 Å, i.e.,  $\sim 2$ -10 vortex spacings, which seems a reasonable number.

The remarkable power-law temperature dependence of  $J_{nl}$  may be contrasted with the 3D VG case, where  $J_{nl}$  vanishes at a finite  $T_g$  according to  $J_{nl} \propto (T - T_g)^{\approx 3.5}$  (Ref. [4]). The present findings also differ strongly from the results for the 16-Å film at zero magnetic field: A similar analysis of the data at zero field yields  $J_{nl} \propto T^{\approx 15}$ , and, accordingly,  $\nu_{2D} \approx 14$ , a dramatically different value. In fact, the results at zero field are consistent with a Kosterlitz-Thouless transition near  $\approx 10$  K,

and, consequently, a fit to  $J_{nl}$  should instead incorporate the finite Kosterlitz-Thouless transition temperature.

An alternative data analysis which shows the differences between 2D and 3D in an even more pronounced way concerns the investigation of critical scaling of the nonlinear  $I$ - $V$  curves. The idea of such a scaling analysis is that near a phase transition the nonlinear transport characteristics may be cast into a scaling form  $(E/J)/R_{lin} = \mathcal{F}(J/J_{nl})$ , with  $\mathcal{F}(x)$  some scaling function with an *a priori* unknown  $x$  dependence [1]. On a plot of  $(E/J)/R_{lin}$  vs  $J/J_{nl}$ , all  $I$ - $V$  curves taken near the phase transition then should merge into one single curve. We now show how this applies to YBCO films, and how the dimensionality effects this. For a 3D VG,  $R_{lin} \propto (T - T_{g,3D})^{\nu_{3D}(z_{3D}-1)}$  and  $J_{nl} \propto T(T - T_{g,3D})^{2\nu_{3D}}$ , and the 3D scaling form thus reads

$$(E/J)(T - T_{g,3D})^{-\nu_{3D}(z_{3D}-1)} = \mathcal{F}(J/[T(T - T_{g,3D})^{2\nu_{3D}}]). \quad (4)$$

The top curve in Fig. 4 shows 270  $I$ - $V$  curves for a 3000-Å YBCO film scaled according to Eq. (4). Clearly, the 3D scaling form with a finite critical glass temperature holds excellently for the parameters given in the figure [11].

For much thinner films, this is no longer true. As an example, we show data for a 100-Å film and a 16-Å film. It is *not* possible to adjust the parameters  $T_{g,3D}$ ,  $z_{3D}$ , and  $\nu_{3D}$  in such a way as to achieve a data collapse onto a single curve. However, if the scaling is limited to the high-current parts of the  $I$ - $V$  curves ( $J > 10^9$  A/m<sup>2</sup> for 100 Å, 2 T) only, the data again collapse onto a single curve without deviations for  $T_{g,3D} = 62.7$  K,  $z_{3D} = 4.8$ , and  $\nu_{3D} = 1.9$ , i.e., the 3D values. Adding the low-current parts then reveals deviations from scaling as is apparent in the middle curve in Fig. 4: From the 3D "backbone," the  $I$ - $V$  curves exhibit systematic deviations towards a linear resistance at low-current densities. This behavior fits the picture of a crossover from 3D to 2D very well: At high  $J$ , one probes length scales smaller than the film thickness, i.e., the 3D VG behavior, whereas at low  $J$ , the 2D VG behavior is encountered (i.e., a linear resistance at  $T \sim 60$  K for the 100-Å film).

For the 16-Å film, we find evidence for a new 2D VG scaling form. In view of Eqs. (2) and (3), we propose the 2D scaling form

$$\frac{E}{J} \exp \left[ \left( \frac{T_0}{T} \right)^p \right] = \mathcal{G} \left( \frac{J}{T^{1+\nu_{2D}}} \right). \quad (5)$$

TABLE I. Some results for the 16-Å YBCO film.

Field (T)	$T_g$ (K)	$\nu_{2D}$	$\rho$	$T_0$ (K)
0.5	0	$2.2 \pm 0.2^a$	$2.1 \pm 0.2^b$	$0.6 \pm 0.1^b$
2	0	$2.1 \pm 0.2^a$	$2.0 \pm 0.2^b$	$115 \pm 10^b$
5	0	$1.7 \pm 0.2^a$	$2.2 \pm 0.2^b$	$84 \pm 10^b$

<sup>a</sup>From power-law  $T$  dependence of  $J_{nl}$ ; cf. Eq. (3).

<sup>b</sup>From 2D scaling analysis; cf. Eq. (5).

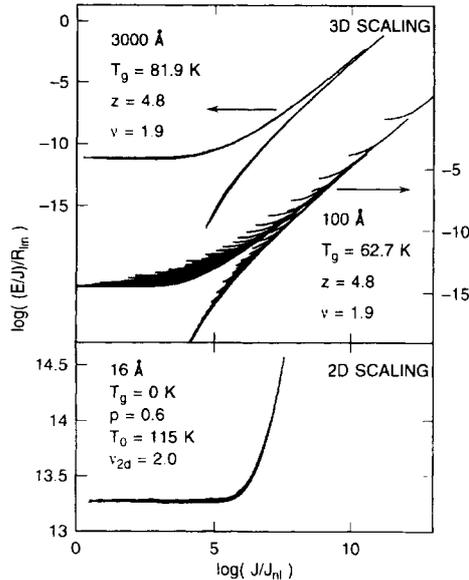


FIG. 4. Scaling collapse of  $I$ - $V$  curves for various YBCO films at 2 T. Top curve denotes 3D scaling for a 3000-Å film ( $T$  ranges from 77 to 86 K); middle curve displays an attempt of 3D scaling for a 100-Å film ( $T$  ranges from 53 to 78 K); and bottom curve shows the 2D scaling plot for a 16-Å film ( $T$  ranges from 3.7 to 18.0 K).

As shown in Fig. 4 (lower curve), the experimental data may indeed be scaled well on the basis of Eq. (5). Apparently, the relevant physics is captured with this scaling form. Note that the  $I$ - $V$  data again *cannot* be scaled onto a single curve according to the 3D form, Eq. (4). The 2D scaling that is observed provides further evidence for 2D VG correlations which diverge towards  $T_{g,2D} = 0$  K. It is gratifying that the 2D scaling analysis yields  $\nu_{2D} = 2.1 \pm 0.2$ , which agrees well with the estimate  $\nu_{2D} = 2.0 \pm 0.3$  obtained from  $J_{nl}(T)$ . Implicit in the 2D scaling form is the fact that the linear resistance has a temperature dependence according to Eq. (2). We find  $p \approx 0.6$  (see Table I). Presently, it is not yet fully clear whether the present experimental results call for a "classical" description (thermal activation of correlated bundles of vortices) or a quantum description (variable-range hopping of vortex bundles through tunneling). Fisher, Tokuyasu, and Young [8] have predicted  $p \geq 1$  and  $\nu_{2D} \approx 2$  for the classical case, whereas for the quantum case  $p \approx 0.7$  and  $\nu_{2D}$  is as yet unknown. For a definitive identification of the relevant model, further theoretical work and more experiments, especially at lower  $T$ , would be helpful.

While most of the previous work on VG was done on 3D YBCO [4], the  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  superconductors appear to show an interesting 2D-3D crossover [5]. Here, at high  $T$ , the superconducting  $\text{CuO}_2$  planes are effectively decoupled, and the system thus comprises a stack of independent 2D layers. At lower  $T$  ( $\sim 20$  K),

however, the planes couple, and a 3D VG phase transition occurs. Consequently, the  $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+\delta}$  system does not allow a study of 2D VG behavior at low temperatures such as presented here.

In conclusion, the nonlinear transport characteristics of ultrathin (2D) YBCO films in a high field appear to be rather different from those in a bulk (3D) system as well as from those at zero field. Strong evidence is obtained for a finite two-dimensional vortex-glass correlation length which diverge at a glass temperature at *zero* K. The present work thus indicates that the lower critical dimensionality for a vortex glass is larger than 2.

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- [10] The precise definition of  $J_{nl}$  is somewhat arbitrary. However, various other definitions of  $J_{nl}$  lead to essentially the same result for the temperature dependence of  $J_{nl}$ . For example, if we instead use the different criterion  $\partial \ln E / \partial \ln J = 2$  to define  $J_{nl}$ , we again obtain  $J_{nl} \propto T^{2.9 \pm 0.3}$ , or  $\nu_{2D} = 1.9 \pm 0.3$ , i.e., within errors the same result.
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