Do Superconductors Have Zero Resistance in a Magnetic Field?

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We show that dc voltage versus current measurements of a $YBa_2Cu_3O_{7-\delta}$ film in a magnetic field can be collapsed onto scaling functions proposed by Fisher *et al.* [Phys. Rev. B **43**, 130 (1991)] as is widely reported in the literature. We find, however, that good data collapse is achieved for a wide range of critical exponents and temperatures. These results strongly suggest that agreement with scaling alone does not prove the existence of a phase transition. We propose a criterion to determine if the data collapse is valid, and thus if a phase transition occurs. To our knowledge, none of the data reported in the literature meet our criterion.

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One of the more remarkable consequences of research on high-temperature superconductors is a new picture of the superconducting transition in a magnetic field. Contrary to understanding based on conventional superconductors, a consensus has emerged [1–6] that a transition occurs in high-temperature superconductors to a state where dc resistance vanishes as current density decreases. The most common and direct evidence for the transition comes from dc *voltage* vs *current* (I-V) data [7]. As proposed by Fisher *et al.* [8], these I-V curves should collapse onto two scaling functions on either side of the transition.

Despite a strong consensus that this data collapse implies the transition, some workers have suggested that the apparent agreement with scaling is misleading [9–11] because simulated I-V curves, based on models without a phase transition, have also collapsed onto scaling functions [9,10].

It has been countered [4] that the simulations invoke highly nonphysical parameters in order to obtain "scalable" data which resemble actual measurements. Moreover, the critical exponents found from the simulated data [9,10] differ drastically from the ones obtained experimentally. Fueling the debate still further are recent I-V measurements over larger voltage ranges, with exponents [5,12] approaching those from the controversial simulations [9,10].

Furthermore, it was recently proposed [13] that a true phase transition does not actually occur. This "window-glass" scenario is more like a conventional glass, where dynamics slow down considerably over a small temperature range, but correlation lengths do not diverge. If a superconductor behaves this way, the linear resistance should rapidly decrease upon lowering the temperature, but would not become zero. A small but nonvanishing linear resistance was also predicted by theoretical studies that incorporate screening [14].

Granting all this, we do not see how this issue can be resolved through the use of simulated I-V curves. Simply showing the simulated data from a model without a transition scale does not demonstrate that the measurements scale for the same reason. The scaling interpretation of measurements may still be valid.

What is needed is an unambiguous signature in the data that can be used to make a valid claim for a transition. We propose that a necessary criterion for determining whether I-V data supports a transition to vanishing resistance is that log (*voltage*) vs log (*current*) isotherms equally distanced [i.e., with equal $|(T - T_g)/T_g|$] from the critical temperature, T_g, must have opposite concavities at the *same* applied currents. This contrasts with previously published data where opposite concavity is seen, but *not* at the same currents.

We begin by showing the difficulties in experimentally demonstrating that a true phase transition exists in a superconductor. We start with a typical scaling analysis of I-V data taken on a 2200-Å-thick $YBa_2Cu_3O_{7-\delta}$ film laser ablated onto a $SrTiO_3$ substrate. This sort of film has previously been shown to have transport characteristics agreeing with vortex glass scaling in externally applied magnetic fields of about 4 T [1–6]. The exact nature of the film's defects, i.e., correlated or not, is irrelevant to our study since, in either case, one expects zero resistance below the glass (or Bose glass) transition temperature and scaling to hold, albeit with possibly different exponents [15]. The high quality of our film was verified with x-ray diffraction peaks of predominately c-axis orientation, from an ac susceptibility measurement transition width of 0.2 K in zero magnetic field, and through zero field $R(T)$ (inset of Fig. 1) which shows a $T_C \approx 91.5$ K and a transition width of about 0.5 K. The film was photolithographically patterned into a four-terminal bridge 8 μm wide by 40 μm long and etched using a dilute solution of phosphoric acid with no noticeable degradation of $R(T)$.

Figure 1 shows I-V measurements taken in a perpendicular magnetic field of 4 T. Scaling predicts [8]

$$V\xi^{2+z-D}/I = \chi_{\pm}(I\xi^{D-1}/T), \tag{1}$$

where D is the dimensionality, z is the dynamic critical exponent, ξ is the glass correlation length which is expected

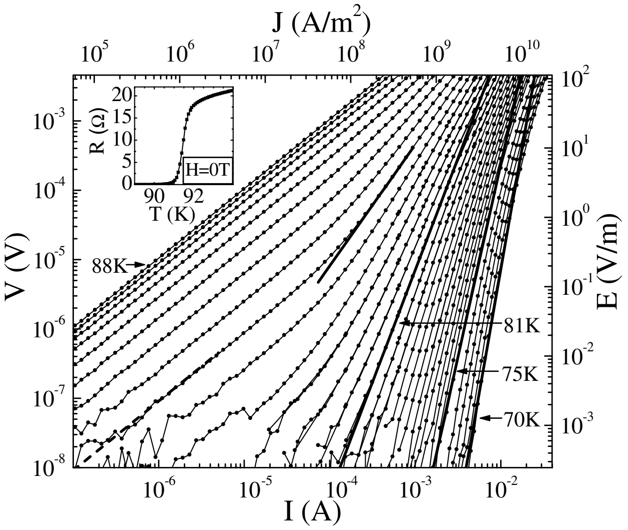

FIG. 1. I-V isotherms for a 2200 Å $YBa_2Cu_3O_{7-\delta}$ film in 4 T. The dashed line has a slope of 1, while the solid lines are linear fits to non-Ohmic power-law–like regions. The inset is $R(T)$ in ambient field.

to behave as $|(T - T_g)/T_g|^{-\nu}$, ν is the correlation-length exponent, and $\chi_\pm$ are the scaling functions for above and below the glass transition temperature T_g.

The parameters of Eq. (1) are found from experimental data in the standard way. Only I-V isotherms above T_g should show low-current Ohmic tails, where Ohmic behavior is represented in Fig. 1 by the dashed line with a slope of 1. At higher currents the isotherms are non-Ohmic, and it is typically presumed that they cross over to power-law behavior (i.e., straight lines on log-log plots with a slope greater than 1).

The thick solid line at 81 K is a power-law fit to the isotherm separating those with low-current Ohmic tails from the ones without. This is conventionally designated as T_g and the slope of the fitted line on this plot gives the dynamic exponent of $z = 5.46$, since $V \propto I^{(z+1)/2}$ is expected at T_g from Eq. (1) for $D = 3$ [16]. The exponent ν can be found from the low-current Ohmic tails which should behave as $R_L \propto (T/T_g - 1)^{\nu(z-1)}$. We make a log-log plot of this in the inset of Fig. 2(a) and use the z and T_g found above to determine ν. Since scaling predicts that this plot should be a straight line, deviations from this at about 87 K determine the extent of the critical region, which is ± 5.5 K from T_g. Only data within this temperature window will be used to test Eq. (1).

Data at high currents are also excluded because free flux flow occurs which is not described by scaling [1,5,6]. An upper cutoff is conventionally set to the voltage where the critical isotherm begins to deviate towards Ohmic behavior, which is seen as a slight decrease in slope at about 10^{-3} V in Fig. 1. By plotting all data in Fig. 1 below this voltage and within the ± 5.5 K range about 81 K, a conventional collapse is clearly demonstrated in Fig. 2(a) with the critical exponents in good agreement with those reported elsewhere, $z = 5.46$ and $\nu = 1.5$.

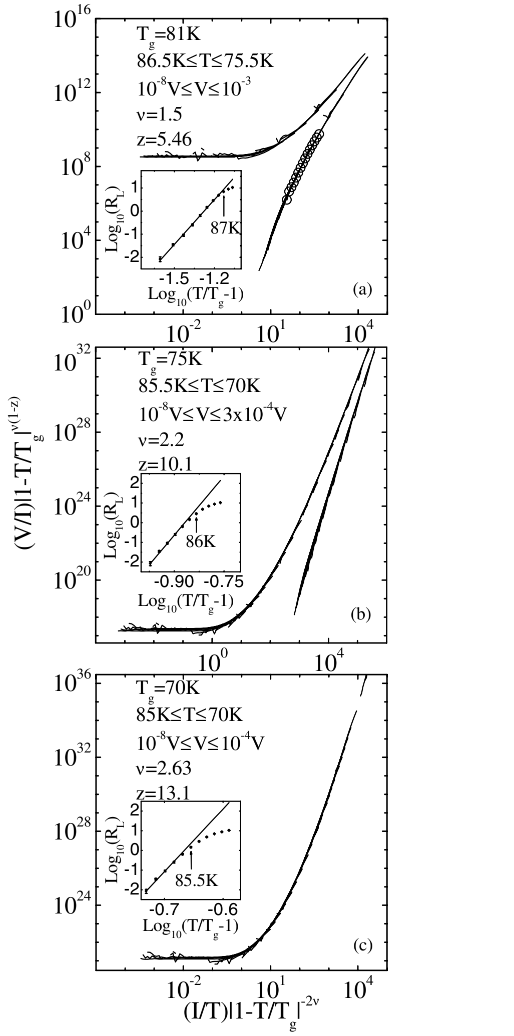

FIG. 2. Collapses of the Fig. 1 I-V curves using various critical parameters with experimental windows denoted. The conventional analysis is shown in (a).

There is a serious problem with the analysis outlined above. Following Repaci *et al.* [17], we demonstrate this by plotting the derivatives of the log (*voltage*) vs log (*current*) isotherms, which are shown in Fig. 3 as small solid dots [18]. The curve at T_g should correspond to a horizontal line in Fig. 3, at a value of $(z + 1)/2$. The data, however, *peak* at about 7×10^{-4} A. In fact, all isotherms seem to have a maximum slope at about this current with Ohmic tails developing to the left of the peaks. Apparently, the only difference between the isotherms above and below the conventionally determined T_g is that the ones at lower temperatures are truncated due to the resolution limit of the experiment before decreasing in slope towards Ohmic behavior. This truncation is evident in these derivative plots where the data at lower currents and voltages become noisier.

Since the conventionally chosen critical isotherm does not show any signs of unique power-law behavior, we now ask whether a scaling collapse could determine a unique transition temperature where the resistance vanishes. To

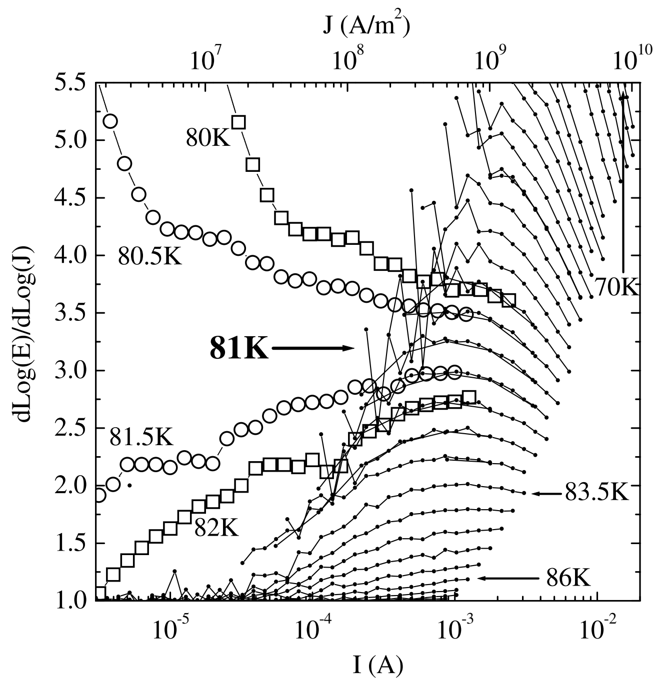

FIG. 3. The small solid dots are $[d\log(V)/d\log(I)]_T$. The open squares are extrapolated data 1 K from T_g, and the open circles are extrapolated data 0.5 K from T_g. Extrapolated data were extracted from the Fig. 2(a) collapse.

test this we note that non-Ohmic power-law–like behavior can be fit to *all* the $T < 81$ K isotherms over at least four decades of voltage data. This is shown in Fig. 1 for the isotherms at 75 and 70 K. By repeating the scaling analysis, assuming that these two temperatures are the critical isotherms, we again obtain excellent data collapses, as is shown in Figs. 2(b) and 2(c).

When we lower the defined T_g by 6 K, in going from Fig. 2(a) to Fig. 2(b), we need only readjust z and ν in order to maintain successful data collapse with an even larger critical region (greater than 15 K). As shown in Fig. 2(c), T_g can even be defined as the lowest temperature of our measurement, where χ_- is not shown because there is no data below 70 K.

Thus far, we find that (i) I-V scaling cannot determine a unique T_g where resistance vanishes (Fig. 2) and (ii) careful inspection of I-V data (Fig. 3) does not at all imply a vanishing resistance at T_g. Clearly we need some other signature in the I-V behavior implying a vanishing resistance at T_g.

Such a signature is suggested by the scaling functions found from the conventional vortex-glass analysis. To see this it is important to note that each isotherm in Fig. 1 collapses onto only small portions of the scaling functions of Fig. 2. We demonstrate this by plotting only the isotherm at 79 K as open circles in Fig. 2(a). In the low-current direction of the collapses the isotherms are truncated by the voltage sensitivity floor of the experiment.

We can, however, predict how data at lower voltages would behave if a data collapse is assumed to represent a real transition. We do this by using the temperature for the desired isotherm, a current, and the values of the parameters ν and T_g used in the collapse. This information can determine a position along the horizontal axis of Fig. 2(a) in the form of $(I/T)|1 - T/T_g|^{-2\nu}$ at a point on the collapse where measured data at this temperature does not reach. Now, by setting the vertical axis value of the scaling function at this point to $(V/I)|1 - T/T_g|^{\nu(1-z)}$, we can solve for the predicted voltage by employing the parameters z, ν, and T_g used in the collapse.

The results of the extrapolation are shown in Fig. 4, with the I-V curves displaying a property not seen in the measured data. For isotherms at equal temperatures away from T_g [i.e., equal to $|(T - T_g)/T_g|$], opposite concavities are clearly evident *at the same current level*. We demonstrate this in Fig. 4 with vertical lines representing constant currents drawn between isotherm pairs. Tangent lines to these isotherms at the intersections clearly show that both pairs have opposite concavity at the same applied currents. The reader can verify that this signature could restrict the assignment of T_g to within ± 0.5 K of 81 K whether the resolution of the experiment would be at 10^{-16} or 10^{-10} V [19] by covering the extrapolated data at low voltages.

We demonstrate the striking contrast to the real data by plotting the extrapolated ones as open squares and circles on the derivative plot of Fig. 3. Note that the actual data curves in Fig. 3 are all qualitatively the same. It is only in the extrapolated region that curves with equal $|(T - T_g)/T_g|$ show opposite concavity at the same applied currents.

To show that this signature is necessary for determining a transition to zero resistance, we consider an important feature of the measured data of Fig. 3. All isotherms for $T > 81$ K have a maximum slope at approximately

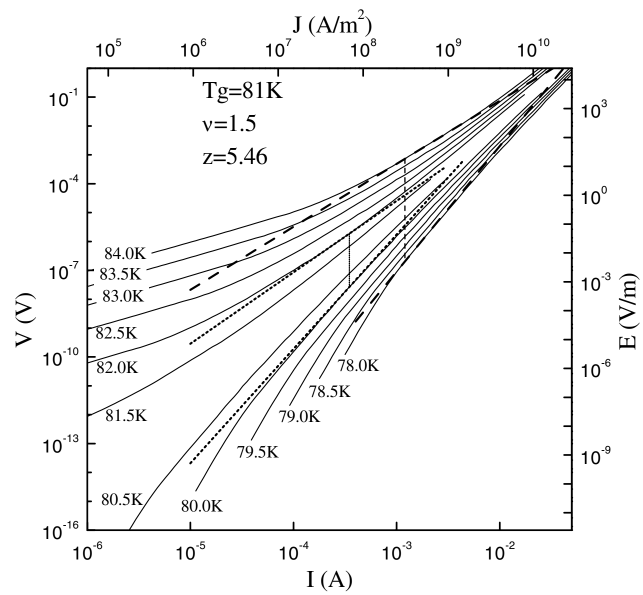

FIG. 4. Extrapolated I-V data from the Fig. 2(a) collapse. Dashed and dotted lines are tangents to isotherms demonstrating concavity.

7×10^{-4} A, which implies low-current Ohmic tails (nonzero resistance). For a vortex-glass transition to exist, this feature must cease at some temperature while the below-T_g isotherms maintain the expected negative concavity [8]. For this to occur, it is necessary to see negative concavity for an isotherm below T_g, while one above and with equal $|(T - T_g)/T_g|$ has a positive concavity [20]. Since the criterion is not satisfied by our data (nor are the ones we know of in the literature which scale), we argue that necessary evidence for a vortex-glass transition to zero resistance is not seen in these I-V characteristics.

In this paper we have focused on the absence of a vanishing dc resistance—the popular definition of a superconductor. One can also use ac measurements [21] to probe an Ohmic to inductive transition in complex linear impedance [22]. However, we are not aware of ac measurements that demonstrate the Ohmic to inductive transition in *both* magnitude and phase, which is necessary for agreement with scaling. A critical comparison between dc and ac on the same sample would be important for this issue.

In conclusion, we have found that a data collapse is not sufficient evidence for a transition to zero resistance since the critical temperature at which this occurs is not uniquely determined. In addition to obeying scaling, I-V data must also satisfy the opposite concavity signature we propose in order to determine a T_g below which the resistance vanishes. Since our I-V data plus many in the literature do not show this signature, a transition to zero resistance has not yet been demonstrated despite the fact that much of the data scales. Furthermore, this signature can be used as a criterion to judge future I-V data in order to help settle the controversy surrounding critical phenomena in the high-temperature superconductors.

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[16] $D = 3$ since the largest length scale, $L_c \approx (\gamma k_B T/\Phi_0 J)^{1/2}$ [6,8], probed along the film's c-axis at T_g is 330 Å, much less than the film thickness.

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[18] Derivatives are calculated from linear fits to successive data points. Other methods, e.g., fitting quadratics to three successive points, make no notable change to the results.

[19] This is an experimentally accessible voltage resolution. See, for example, Ref. [3].

[20] We require that the relevant temperature scale, $|(T - T_g)/T_g|$, be equal since both isotherms must be in the critical region, excluding the possibility of comparing critical to noncritical behavior.

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