Universal critical scaling of ac-vortex-transport properties in superconducting Y-Ba-Cu-O single crystals: From 1 to 90 kOe

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Transport measurements showing universal critical scaling behavior of the ac conductivity in superconducting twinned Y-Ba-Cu-O single crystals provide unambiguous evidence for a second-order vortex-solid melting transition. Critical exponents are found to be consistent for fields ranging from 1 to 90 kOe as well as with those found from dc-transport measurements. Additionally, the universal functions for both the resistivity amplitude and phase are identified.

Over the past several years, a great debate has arisen over the existence of a true vortex-solid melting phase transition. Previous dc-transport measurements[1] which support this phase transition can be be explained equally well by a more conventional flux creep model,[2] but the more difficult ac-transport measurements have no analogous explanation for their frequency dependence, thereby providing stronger evidence for a second-order melting transition. Previous ac-transport measurements[3] have only been made on one Y-Ba-Cu-O epitaxial film in a single magnetic field, insufficient for demonstrating the universality of the critical exponents and vortex transport functions. Although the single set of data measured in Ref. 3 permits an evaluation of the critical exponents, without demonstrating universality over a broad frequency and magnetic field range, the results cannot provide conclusive evidence for the existence of a second-order transition or the accuracy of the exponents obtained. Presented here is clear experimental evidence showing that the critical scaling relations apply to both the amplitude and the phase of the ac resistivity. The critical exponents ($\nu \approx \frac{2}{3}$, $z \approx 3$) and the vortex transport functions obtained from two decades of magnetic fields are found to be truly universal, lending strong support for a second-order melting phase transition.

The uniqueness of a second-order phase transition stems from its universality as described by the critical scaling relations. Within a limited critical regime about a transition, observed quantities should be given by a universal scaling form involving the coherence length[4,5] $\xi \sim |1-T/T_M(H)|^{-\nu}$, where ν is the static exponent. Since in the asymptotic limit, the relaxation frequency[5] scales as $\omega \approx \xi^{-z}$, where z is the dynamic exponent, it is convenient to define $\tilde{\omega} = \omega |1-T/T_M|^{-\nu z}$. For the case of frequency-dependent resistivity,[4,6] we expect the amplitude ρ and phase ϕ to follow the relations:

$$\rho = |1-T/T_M|^{\nu(2+z-d)} \tilde{\rho}_{\pm}(\tilde{\omega}) ,$$
$$\Phi = \tilde{\Phi}_{\pm}(\tilde{\omega}) , \quad (1)$$

where $d=3$ is the dimensionality of the transition, and $\tilde{\rho}_{\pm}$ and $\tilde{\Phi}_{\pm}$ are universal functions for $T < T_M$ $(-)$ and $T > T_M$ $(+)$. Further, all temperature dependence is contained in the coherence length, so that the temperature dependence can be removed by considering only $\tilde{\rho}_{\pm}(\tilde{\omega})$ and $\tilde{\phi}_{\pm}(\tilde{\omega})$. In order to give solid evidence to support the existence of a second-order phase transition, this independence of temperature in the universal functions must be shown. Additionally, the universal functions and exponents must be independent of applied field, experimental method, and any details of the sample itself.

The above scaling relations must not be applied too broadly as some important limitations apply.[7] In these relations, effects from a finite applied current have been ignored. The scaling relation in Eq. (1) can be justified only if thermal effects dominate the current effects, which will be true as long as the current is kept below a characteristic scaling current,[7] $J_T(H,T) = [k_B T/(\xi_0^2 \phi_0)] |1-T/T_M|^{2\nu}$. This J_T has been found from dc measurements on this sample,[7] and for the current density of $J = 2$ A/cm^2 used in this experiment, the requirement that $J < J_T(H,T)$ limits the temperature resolution near the melting transition to $|T-T_M| > \sim 0.04$ K at $H > 50$ kOe and $|T-T_M| > \sim 0.006$ K at $H \sim 1$ kOe. The limit corresponds roughly to the temperature interval used in this experiment at each of the respective fields so that, with the possible exception of one or two isotherms very close to T_M, the finite current effects should be insignificant. Another potential complication is the dominance of flux pinning in highly disordered samples.[7] This effect should be minimized in high-quality single crystals as opposed to films, permitting a better look at the more intrinsic property of melting.

Although technically more difficult, the experimental technique used in this work is conceptually much like dc-transport measurements since a current is applied uniformly through the entire sample. The direct ac transport measurement is in contrast to the more common ac-susceptibility measurements in which an ac-current is induced on the surface of the sample, so the measurements are strongly limited by the surface quality and the magnetic peneration depth. The sample used for these measurements is a twinned Y-Ba-Cu-O single crystal, with details of its preparation and electrical contacts published elsewhere.[8] To perform the measurements, the sample is held at a fixed temperature within ± 0.01 K and a constant magnetic field is applied along the c axis of the crystal. Using a standard four-point contact method, a sinusoidal current is passed through the sample and the resulting voltage measured. The applied current (I) is monitored by measuring the voltage across a 1 $k\Omega$ noninductive load resistor that is in series with the sample. 400 such measurements made at frequencies from 100 Hz to 2 MHz form each of the isothermal curves shown in Figs. 1 and 2. A series of isotherms covering the melting transition is repeated in a wide range of magnetic fields from 1 to 90 kOe to give solid evidence for the universality of the transition. The difficulties in this experiment arise from the small resistance of a single crystal and the need for small current density which require a measured voltage of 10 nV. The primary instrument used in these measurements is the HP 4194A impedance analyzer enhanced with an 80-dB low noise preamplifier, which with proper shielding and grounding provide a sufficiently low noise level. More information about the experimental setup has been published in Ref. 9.

Despite all precautions, it is never possible to eliminate all parasitic capacitance and inductance, which lead to some purely imaginary background signal Z_{back}. In addition, the preamplifier induces some phase delay $\theta(\omega)$ and a frequency-dependent gain $G(\omega)$. This gives a measured signal of the form[9] $Z_{\text{meas}}=[Z_{\text{signal}}+Z_{\text{back}}(\omega)]G(\omega)e^{i\theta(\omega)}$. $G(\omega)$ can be found by assuming that the amplitude of the normal state YBaCuO is independent of frequency for $\omega<2$ MHz, and $\theta(\omega)$ can be found by assuming that the total signal (Z_{meas}) well below the transition is purely imaginary. Measurement of a small length of gold wire (resistance $\approx 2\times 10^{-5}$ Ω corresponding to a voltage ≈ 10 nV) provides an effective short with a purely imaginary signal which is taken to be Z_{back}.

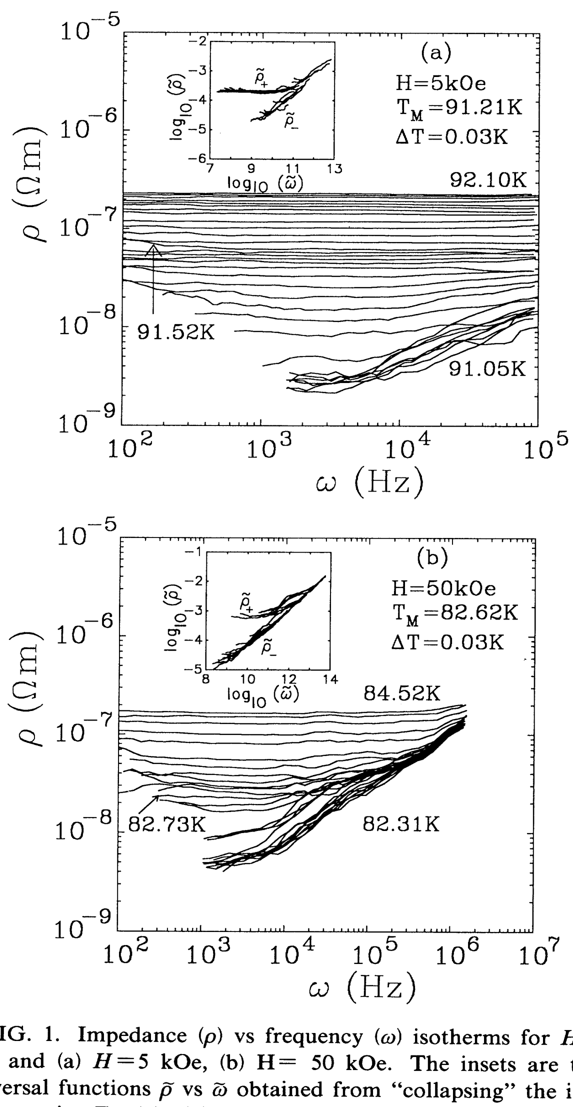

FIG. 1. Impedance (ρ) vs frequency (ω) isotherms for $H\parallel c$ axis and (a) $H=5$ kOe, (b) H= 50 kOe. The insets are the universal functions $\tilde{\rho}$ vs $\tilde{\omega}$ obtained from "collapsing" the isotherms using Eq. (1) with values of ν, z, and T_M shown in Table I. The temperature increment ΔT between successive traces is 0.03 K, and the critical regime is indicated by the temperature interval between the lowest temperature shown above and the arrow.

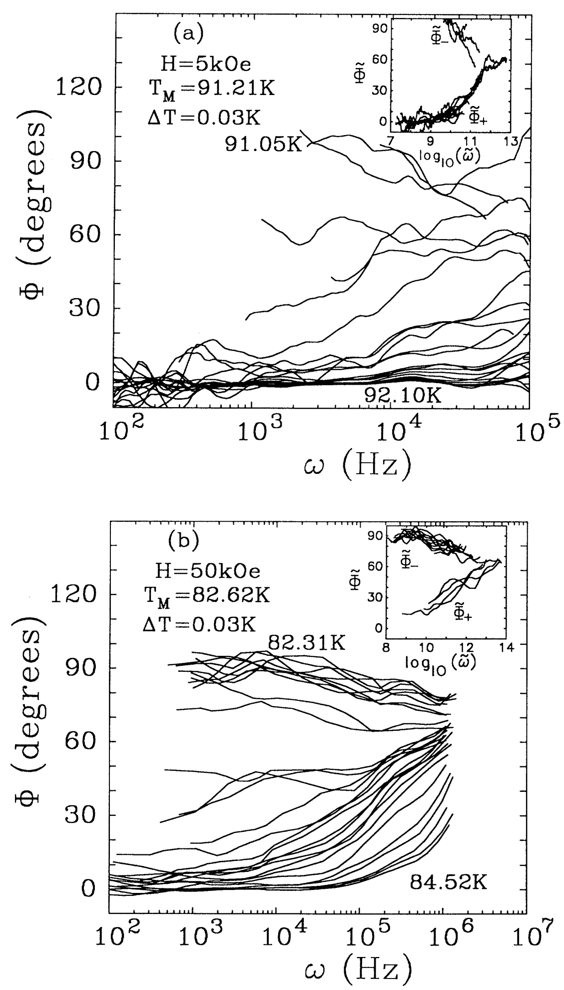

FIG. 2. Phase (Φ) vs frequency (ω) isotherms for $H\parallel c$ axis and (a) $H=5$ kOe, (b) $H=50$ kOe. The insets are the universal functions $\tilde{\Phi}$ vs $\tilde{\omega}$ obtained from "collapsing" the isotherms. The temperature increment ΔT is 0.03 K.

TABLE I. The critical exponents ν and z obtained from the "collapsing" of the amplitude (ρ), the phase (Φ) measured at $T_M(H)$, and the slope of the universal function $\tilde{\rho}(\tilde{\omega})$, for fields from 1 to 90 kOe.

		Amplitude		Phase		$\rho_-(\tilde{\omega})$	
H(kOe)	T_M (K)	ν	z	$\Phi(T_M)$	z	Slope (x)	z
1	92.51±0.04	0.70±0.1	3.4±0.2	50°±10°	2.4±0.6	0.70±0.05	3.3±0.5
3	91.77±0.01	0.80±0.2	3.0±0.3	55°±8°	2.6±0.6	0.68±0.04	3.1±0.4
5	91.21±0.01	0.70±0.03	3.0±0.2	55°±10°	2.6±0.7	0.62±0.05	2.6±0.3
6	90.93±0.01	0.60±0.10	3.0±0.2	59°±7°	2.9±0.7	0.67±0.05	3.0±0.4
10	90.04±0.01	0.60±0.10	3.0±0.5	59°±8°	2.9±0.7	0.67±0.03	3.0±0.3
30	85.98±0.01	0.70±0.10	2.8±0.5	60°±8°	3.0±0.7	0.66±0.02	2.9±0.2
50	82.62±0.01	0.70±0.05	3.0±0.2	58°±5°	2.8±0.4	0.66±0.03	2.9±0.3
70	79.34±0.05	0.65±0.20	2.8±0.8	60°±7°	3.0±0.7	0.61±0.04	2.6±0.3
90	75.85±0.03	0.80±0.20	3.0±0.5	59°±9°	2.9±0.8	0.65±0.01	2.9±0.1

The consistency of the data in all magnetic fields compensated with exactly the same parameters gives confirmation that this method is correct. In addition, we note that at given H and T, the amplitude of the applied current is independent of the frequency despite a finite capacitance (C) between the sample and the ground. This is because the sample impedance is so small ($\sim 10^{-3}\Omega$ at $T\sim T_M$ and $\omega \sim 10^6 Hz$) that $(\omega C)^{-1} \gg 10^{-3}\Omega$ is easily satisfied as long as $C \ll 10^{-3} F$. (typically $C < \sim 10^{-10}$ F).

The data presented here are composed of measurements made in nine different magnetic fields as indicated by Table I, with 5 and 50 kOe data selected as representative of all fields. Figure 1 shows the resistivity amplitude versus frequency along isothermal curves ranging from 91.05 to 92.10 K and 82.31 to 84.52 K, for 5 and 50 kOe, respectively. The phase of these data is shown in Fig. 2. The insets of Fig. 1 show that by removing the temperature dependence in $\rho(\omega)$ as described above, the curves can be collapsed to a single universal function $\tilde{\rho}_\pm(\tilde{\omega})$. The inset of Fig. 2 shows the same type of collapsing to obtain $\tilde{\Phi}_\pm(\tilde{\omega})$. Table I shows the values obtained for ν and z that most accurately collapse all curves to a single function. To show the universality of $\tilde{\rho}$, the lower branch of these collapsed curves $\tilde{\rho}_-$ is fit to $\tilde{\rho}_- \sim \tilde{\omega}^x$, the form predicted in Refs. 4 and 6 with $x = 1 - 1/z$. Table I lists the values obtained for x and z, which agree well for all magnetic fields. Another important result is that the phase at the melting temperature[6] should be constant across all frequencies with a value $\Phi(T_M) = [1-(1/z)](\pi/2)$. While this can be seen in Fig. 2, it is illustrated more dramatically in Fig. 3, where the 50 kOe data are converted to phase versus temperature for different frequencies from 1 kHz to 2 MHz. This clearly shows the phase at all frequencies merging to the same value at the melting temperature. The phase evaluated in this way for other fields is listed in Table I, all of which are consistent within experimental error. The exponents obtained here are also consistent with results of dc current-voltage transport measurements which give[7] $\nu = 0.67$ and $z = 3.0$.

As the data are brought together over a broad range of experimental situations, a clear consistency with the scaling predictions begins to emerge. The universal scaling analysis covers nearly two decades in magnetic field and two independent parameters, the amplitude and phase,

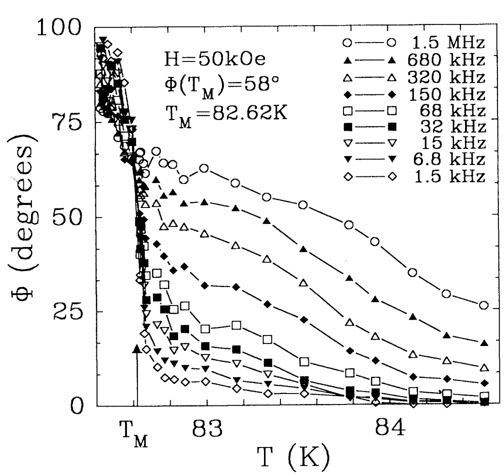

FIG. 3. Phase (Φ) vs temperature (T) data converted from Fig. 2(b) for several frequencies by averaging points of each isotherm in a small interval about the indicated frequency.

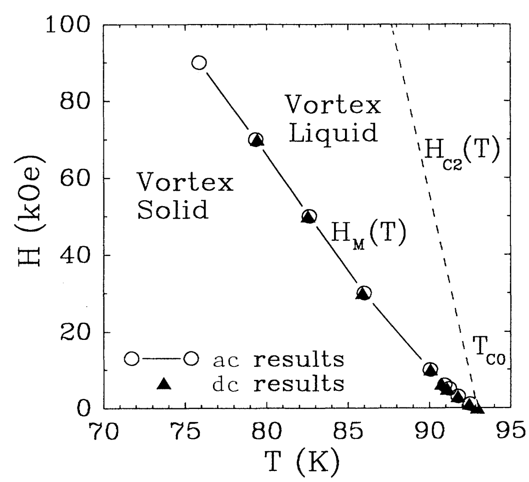

FIG. 4. The vortex phase diagram for $H \| c$. The line $H_M(T)$ is derived from the scaling fits in Fig. 1. The previously published dc data (Ref. 7) are shown to emphasize the consistency between two different types of measurement techniques. The dashed line $H_{C2}(T)$ is the upper critical field.

which are not only consistent in their scaling to universal functions, but each gives nearly identical values of the critical exponents. Combining the ac measurements with the same result from dc current-voltage characteristics and absence of any alternative theoretical explanation, it lends very strong support for a second-order vortex-solid melting transition. Therefore, Fig. 4 shows the vortex melting in its rightful place as a true phase transition on the magnetic phase diagram for twinned Y-Ba-Cu-O superconducting single crystals.

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