Evidence of a Bose-Glass Transition in Superconducting $YBa_2Cu_3O_7$ Single Crystals with Columnar Defects

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Experimental evidence of a Bose-glass transition in the vortex state of $YBa_2Cu_3O_7$ single crystals with *columnar defects* along the c axis is manifested by the *universal* critical exponents $\nu_\perp$, $\nu_\parallel$ ($\equiv\zeta\nu_\perp$), and z' derived from the $(d'+1)$-dimension critical scaling of the frequency-dependent ac resistivity from 10^2 to 2.5×10^6 Hz. The Bose-glass transition temperature (T_{BG}) is found to *decrease* with the increasing angle (θ) between the applied magnetic field and the c axis. The finding that $\zeta=\nu_\parallel/\nu_\perp=1.1\pm0.1<d'=2$ suggests an *incompressible* Bose glass at temperatures below T_{BG}.

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Nelson and Vinokur [1] recently proposed a "Bose-glass" to "superfluid" transition [2] in the vortex state of high-temperature superconductors with columnar defects. In the case that the density of vortices is smaller than that of the columnar defects (or, equivalently, if the applied magnetic field H is smaller than the "matching field" B_φ), it is argued [1] that strong pinning of the artificially created columnar defects [3] results in an equivalent "Bose localization" effect on vortices at low temperatures. At high temperatures, vortices could "hop" into neighboring empty columns via the formation of "superkinks," thereby resulting in an entangled vortex liquid [1] which resembles a superfluid state [2]. The theoretically well-defined Bose-glass transition differs from the vortex-glass transition for $YBa_2Cu_3O_7$ single crystals with random point defects [4–9] in that the tilt modulus in the former is infinite. Furthermore, for columnar defects along the sample c axis, the Bose-glass transition temperature (T_{BG}) is predicted to *decrease* with the increasing angle (θ) between the applied magnetic field and c axis [1,10], in sharp contrast to the increasing vortex-glass melting temperature (T_M) due to the sample anisotropy [6–8].

Despite its sound theoretical foundation, experimental verification of a Bose-glass transition may be complicated by large electronic anisotropies as well as by the presence of point defects or twin boundaries which would compete with the effect of columnar defects on vortices [10]. It is therefore important to select superconducting single crystals with minimal defects and smaller anisotropies before creating columnar defects in them. In this Letter, we provide the first experimental evidence for a second-order Bose-glass transition by demonstrating *universal* (2+1)-dimension critical scaling of the ac resistivity (ρ_{ac}) taken on $YBa_2Cu_3O_7$ single crystals irradiated with 0.9 GeV Pb ions. We find that for $\theta<45°$, *universal* scaling functions for the amplitude and phase of ρ_{ac} taken at frequencies from 10^2 to 2.5×10^6 Hz can be achieved with a single set of critical exponents, $\nu_\perp\approx1.0$, $\nu_\parallel\equiv\zeta\nu_\perp=1.1\pm0.1$, and $z'=2.2\pm0.2$, independent of the magnitude and orientation of the magnetic field. In addition, the Bose-glass transition temperature T_{BG} is found to *decrease with the increasing angle θ for $\theta<45°$, following* the predicted "cusp" shape [1,10]. The different critical exponents and the sharp contrast in the angular dependence of T_{BG} for $YBa_2Cu_3O_7$ single crystals with columnar defects distinguish the Bose-glass transition [5] from the vortex-glass transition [6–8]. Finally, we show that the finding of $\zeta<2$ suggests a long-range Bose interaction [11] in the *incompressible* Bose-glass phase at $T<T_{BG}$, which is consistent with recent numerical simulation results [12].

The sample used for the heavy-ion irradiation in this work is a $YBa_2Cu_3O_7$ single crystal of dimensions $0.65\times0.50\times0.020$ mm^3, with 100% superconducting volume and low twin boundary densities averaging ~10 μm separation. The 0.9 GeV Pb ion irradiation was performed at liquid nitrogen temperature, with the ion beam aligned along the sample c axis. The total fluence was $\sim5\times10^{10}$ ions/cm^2 which corresponds to a matching field $B_\varphi\approx10$ kG and an average column separation ≈490 Å. The creation of amorphous columnar defects is confirmed by high-resolution electron microscopy which reveals the formation of continuous tracks extending throughout the entire thickness of the sample with diameters ~70 Å. Measurements on two other $YBa_2Cu_3O_7$ single crystals, one an as-grown crystal and the other irradiated with 3 MeV protons with a fluence of 1×10^{16} protons/cm^2 were also performed for comparison. Details of the preparations and characterizations of these crystals have been given in Refs. [6–8].

To study the frequency (f) dependent ac resistivity, four-probe ac transport measurements are carried out by using the technique described in Ref. [7]. An HP4194 impedance analyzer is used to supply a uniform ac current to the entire thickness of the sample through a

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serial 1 kΩ noninductive resistor. The resulting voltage is enhanced by an 80-dB low noise amplifier. Impedance versus frequency isotherms are taken in various applied dc magnetic fields with the field direction tilted at an angle θ of 0° to 90° from the c axis of the sample. Each isotherm constitutes 400 frequencies from 10^2 Hz to 2.5×10^6 Hz, and the temperature stability is better than 10 mK. For three different magnetic fields $H=3$, 6, and 15 kOe, two below and one above the matching field $B_\varphi=10$ kG, an average of 50 such isoterms are taken in each field and at a given angle. The angular dependence is investigated at $\theta=0$, 7.5° (9.4°), 15°, 22.5°, 30°, 45°, 60°, 75°, and 90°.

To find the Bose-glass to superfluid transition temperature ($T_{\rm BG}$) and the corresponding critical exponents, we follow the discussion in Ref. [1] that the transverse and longitudinal correlation lengths of vortex dislocations both diverge at $T_{\rm BG}$ with the temperature dependence $\xi_\perp\sim|1-T/T_{\rm BG}|^{-\nu_\perp}$ and $\xi_\parallel\sim|1-T/T_{\rm BG}|^{-\nu_\parallel}$, where $\nu_\parallel$ and $\nu_\perp$ are the static exponents. The dynamic exponent z' may be defined by $\tau\xi_\perp^{z'}$, where τ is the characteristic thermal relaxation time [1]. Assuming $\nu_\parallel\equiv\zeta\nu_\perp$ and a $(d'+1)$-dimensional phase transition with $d'=2$ [1,2], the generalized scaling form for the ac resistivity $\rho_{\rm ac}$ is given by [5]

$$\rho_{\rm ac}(f;T;H)=\delta^{\nu_\perp(z'-\zeta)}\tilde\rho(f\xi_\perp^{z'};\delta\xi_\perp^{1/\nu_\perp};h_\perp\xi_\perp\xi_\parallel/\Phi_0)\,,\qquad \delta\equiv|1-T/T_{\rm BG}|\,,\tag{1}$$

where $h_\perp\approx H\sin\theta$ is the local transverse magnetic field [1], and Φ_0 is the flux quantum. For a constant field H (we have assumed the induction $B\approx H$), and in the limit that $\theta\ll90°$, Eq. (1) yields the following frequency-dependent scaling relations for $|\rho_{\rm ac}|$ and ϕ_ρ [5]:

$$|\rho_{\rm ac}(f,T,H)|\sim\delta^{\nu_\perp(z'-\zeta)}|\tilde\rho\pm(\tilde f)|\,,\qquad \phi_\rho(f,T,H)=\tilde\phi\pm(\tilde f)\,,\quad \tilde f\equiv f|1-T/T_{\rm BG}|^{-\nu_\perp z'}\,,\tag{2}$$

where $|\tilde\rho_+|$ ($\tilde\phi_+$) and $|\tilde\rho_-|$ ($\tilde\phi_-$) are the universal scaling functions for the amplitude (phase) at $T>T_{\rm BG}$ and $T<T_{\rm BG}$, respectively. Defining $|\tilde\rho|\equiv|\rho_{\rm ac}|\delta^{-a}$ and $\tilde f\equiv f\delta^{-b}$, where $a\equiv\nu_\perp(z'-\zeta)$ and $b\equiv\nu_\perp z'$, we find that $|\rho_{\rm ac}(f)|$ and $\phi_\rho(f)$ isotherms for *all* data taken at $H<B_\varphi$ and $\theta<45°$ can be simultaneously scaled into universal functions $\tilde\rho_\pm$ and $\tilde\phi_\pm$ with the *same* set of parameters $a=1.1\pm0.1$ and $b=2.2\pm0.2$, and with the $T_{\rm BG}(H,\theta)$ value as a fitting parameter, as shown in the insets of Figs. 1(a), 1(b), 2(a), and 2(b). In addition, since scaling analysis asserts that $|\tilde\rho_\pm|\to\tilde f^{(1-\zeta/z')}$ and $\tilde\phi_\pm\to\phi_c=(\pi/2)(1-\zeta/z')$ if $\tilde f\to\infty$ [5], the data $|\tilde\rho_\pm|\sim\tilde f^{0.5}$ in the insets of Fig. 1 and the phase $\phi_c=45°\pm5°$ in the insets of Fig. 2 both confirm the finding that $\zeta/z'=1-a/b\approx0.5$. This demonstration of universality provides strong support for a second-order phase transition at $T_{\rm BG}$. The values of $T_{\rm BG}$ have been determined to 30 mK accuracy by using Eq. (2), and are shown in Fig. 3 as a function of θ and for $H=3$ and 6 kOe. We note that the drastic cusp feature at $\theta=0$ is the signature of the Bose-glass transition [1,10], and is in sharp contrast to the smooth *increase* of the vortex-glass melting temperature (T_M) with increasing θ in as-grown and proton-irradiated $YBa_2Cu_3O_7$ single crystals [5–8].

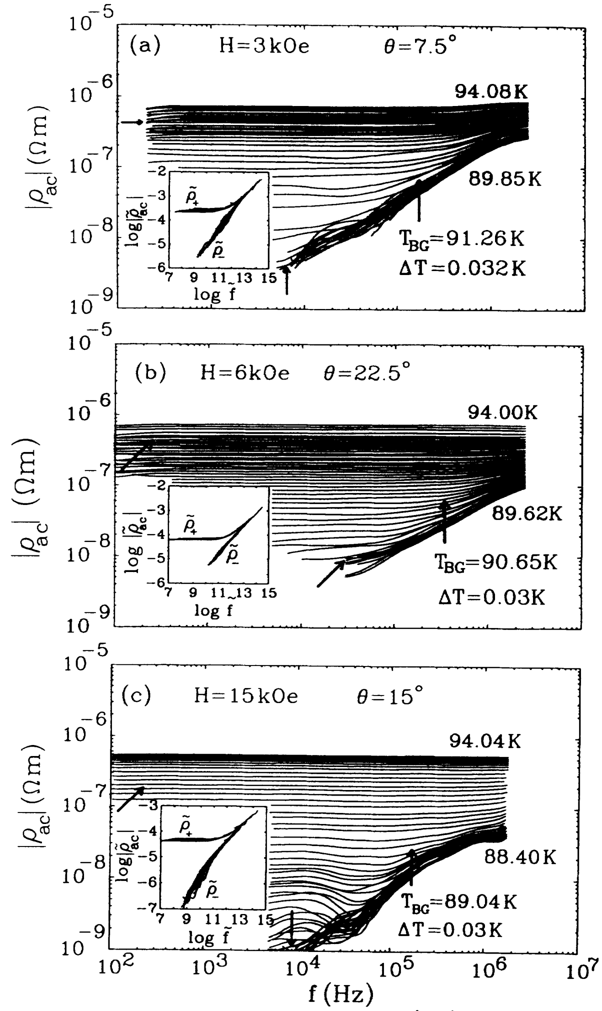

FIG. 1. Amplitude of the ac resistivity $|\rho_{\rm ac}|$ vs frequency (f) isotherms taken at (a) $H=3.0$ kOe, $\theta=7.5°$; (b) $H=6.0$ kOe, $\theta=22.5°$; and (c) $H=15.0$ kOe, $\theta=15°$. The arrows indicate the isotherms in the critical regime which are scaled into universal functions $|\tilde\rho_\pm(\tilde f)|$ in the insets by using Eq. (2). The temperature increment in the critical regime is $\Delta T\approx0.03$ K.

Although the ratio of $\zeta/z'\approx0.5$ has been obtained, additional information is still needed in order to find the values for $\nu_\perp$, ζ, and z'. If the Bose-glass phase were *compressible* as suggested in Ref. [1], so that the compression modulus $C_{11}\sim\xi_\perp^{d'}/\xi_\parallel$ approached a finite value at $T_{\rm BG}$, the necessary condition would be $\zeta=d'=2$ [2], yielding the exponents $\nu_\perp\approx0.5$ and $z'\approx4.0$ as reported previously [5]. However, the value $\nu_\perp\approx0.5$ violates the theoretical constraint $\nu_\perp\geq2/d'=1$ [2,13], thereby implying that the assumption $\zeta=2$ is incorrect. In fact, theoretical evidence shows that $\zeta\to1$ can be realized in the limit of a long-range Bose interaction [11].

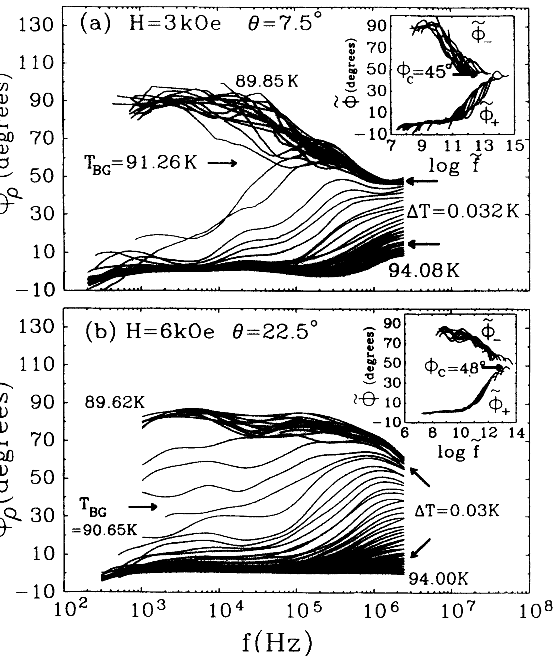

FIG. 2. Phase of the ac resistivity ϕ_p vs frequency (f) isotherms taken at (a) $H=3.0$ kOe, $\theta=7.5°$; and (b) $H=6.0$ kOe, $\theta=22.5°$. The arrows indicate the isotherms in the critical regime which are scaled into universal functions $|\tilde{\phi}_\pm(\tilde{f})|$ in the insets by using Eq. (2). the temperature increment in the critical regime is $\Delta T \approx 0.03$ K.

Since the magnetic penetration depth (~ 1400 Å at $T=0$) in our sample is much larger than the separation of the columnar defects, it is not surprising that the vortex interaction is long ranged and that ζ may differ from 2 even if $H < B_\varphi$. Recent numerical simulations [12] have also shown evidences supportive of $\zeta \to 1$.

To find an additional scaling relation to determine the absolute values of ζ, $\nu_\perp$, and z', consider Eq. (1) in the limit of $f \to 0$. The angular dependence of the ac resistivity becomes

$$|\rho_{ac}| \sim \delta^{\nu_\perp(z'-\zeta)} |\tilde{\rho}_\pm(\tilde{\theta})|, \quad \tilde{\theta} \equiv \delta^{-\nu_\perp(1+\zeta)} \sin\theta, \qquad (3)$$

so that $\tilde{\rho}_\pm \sim \tilde{\theta}^{(z'-\zeta)/(1+\zeta)}$ at $T \to T_{BG}$. Figure 4 shows the real part of the resistivity versus temperature curves taken at various angles for $H=6$ kOe and $f \to 0$. We find that for $\theta < 45°$, the ρ_{ac} vs T data at various angles near $T_{BG}(\theta)$ can be scaled into universal functions $\tilde{\rho}_\pm(\tilde{\theta})$, as shown in the inset of Fig. 4 for both $H=3$ and 6 kOe. The power-law dependence $\tilde{\rho}_\pm \sim \tilde{\theta}^{0.53}$ yields $(z'-\zeta)/(1+\zeta) = 0.53 \pm 0.03$. Knowing that $\zeta/z' = 0.50 \pm 0.03$ and $b \equiv \nu_\perp z' = 2.2 \pm 0.2$, we obtain $\zeta = 1.1 \pm 0.1$, $\nu_\perp = 1.0 \pm 0.1$, and $z' = 2.2 \pm 0.2$.

In the case of $H=15$ kOe ($H > B_\varphi$) and $\theta < 45°$, the same scaling functions $|\tilde{\rho}_\pm|$ and $\tilde{\phi}_p$ can be obtained with the same set of exponents $\nu_\perp = 1.0$, $\zeta \approx 1.1$, and $z' \approx 2.2$, as shown in the inset of Fig. 1(c). The angular dependence of the phase transition temperatures (which we also call T_{BG}) is also similar to that for $H < B_\varphi$ and $\theta < 45°$, as shown in Fig. 3. Since an effective Bose-glass to superfluid transition is also possible for $H > B_\varphi$ [1,2], we speculate that the critical phenomena observed for both $H > B_\varphi$ and $H < B_\varphi$, and for $\theta < 45°$, are governed by the same type of phase transition.

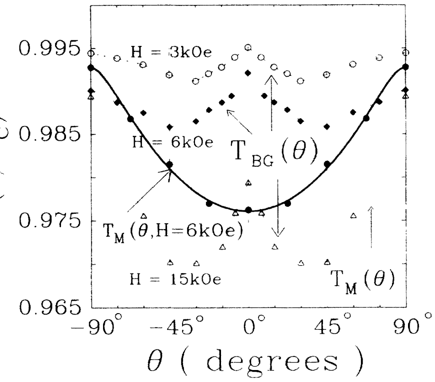

FIG. 3. The reduced Bose-glass transition temperature (T_{BG}/T_c) for a $YBa_2Cu_3O_7$ single crystal with columnar defects ($T_c = 91.77$ K) and the reduced vortex-glass temperature (T_M/T_c, thick solid line) for an as-grown $YBa_2Cu_3O_7$ single crystal ($T_c = 92.95$ K) are shown as functions of the angle (θ).

Next, we consider the scaling behavior for $\theta > 45°$. For all three fields we find that neither $|\rho_{ac}(f)|$ nor $\phi_p(f)$ isotherms at $\theta > 45°$ can be scaled with the critical exponents derived from the low-angle ($\theta < 45°$) scaling analysis. Rather, different scaling functions $|\tilde{\rho}_\pm|$ and $\tilde{\phi}_\pm$ can be achieved for all data taken at $\theta > 45°$ by using a different set of exponents $\nu_\perp = \nu_\parallel \approx \frac{2}{3}$ and $z = z' \approx 3$, which is consistent with the three-dimensional XY model predicted in Ref. [1] for $\theta \to 90°$ in systems with c-axis columnar defects. The difference between the scaling behavior for $\theta < 45°$ and that for $\theta > 45°$ can be further contrasted by considering the critical phases ϕ_c at the transition temperatures. We find that for $\theta > 45°$, the

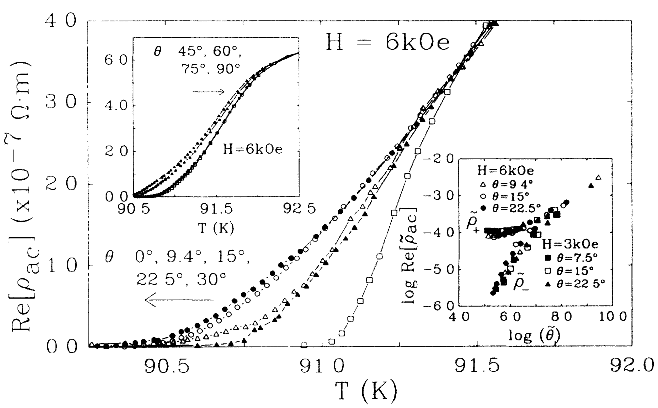

FIG. 4. The angular dependence of the resistivity Re[ρ_{ac}] vs temperature (T) curves at $H=6.0$ kOe are shown for the $YBa_2Cu_3O_7$ single crystal with columnar defects and for $\theta < 45°$. The upper inset shows Re[ρ_{ac}] vs T for $\theta \geq 45°$. The lower inset shows that $\rho_{ac}(T,\theta)$ data near $T_{BG}(H,\theta)$ can be scaled into universal functions $\tilde{\rho}_\pm(\tilde{\theta})$ by using Eq. (3).

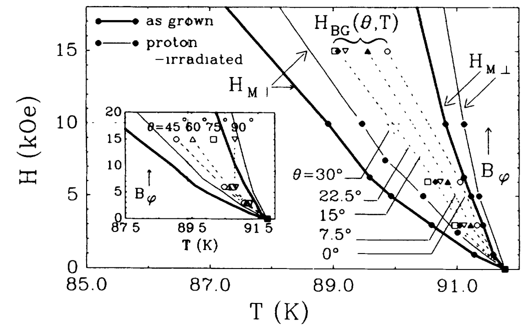

FIG. 5. The low-angle ($\theta < 45°$) H vs T vortex phase diagram for a $YBa_2Cu_3O_7$ single crystal with columnar defects ($T_c = 91.77$ K). The inset shows the high-angle ($\theta > 45°$) phase diagram. The thick solid lines denote the vortex-glass melting lines $H_{M\parallel}(T)$ and $H_{M\perp}(T)$ for an as-grown $YBa_2Cu_3O_7$ single crystal ($T_c = 92.95$ K), and the thin solid lines are those for a $YBa_2Cu_3O_7$ single crystal irradiated with 3 MeV protons ($T_c = 91.62$ K). The data for all samples have been scaled to the same T_c for comparison.

critical phase $\phi_c(T = T_M) = (\pi/2)(1 - 1/z) \approx 60°$ is consistent with $z \approx 3.0$ for the XY model [7]. In contrast, $\phi_c(T = T_{BG}) \approx 45°$ is found for *all* data taken at $\theta < 45°$, as shown in the insets of Figs. 2(a) and 2(b). Furthermore, the phase transition temperatures obtained for $\theta > 45°$ (see Fig. 3) are found to *increase* with increasing θ, resembling the angular dependence in samples with point defects.

The differences in the angular-dependent transition temperatures between the data for $\theta > 45°$ and those for $\theta < 45°$ may be understood by the following argument. At sufficiently small angles, columnar defects become less efficient in confining vortices when the applied field is tilted away from the c axis, thereby resulting in a *decreasing* transition temperature T_{BG} with increasing θ. On the other hand, at sufficiently high angles intrinsic electronic anisotropies in $YBa_2Cu_3O_7$ become dominant, giving rise to an increasing T_M with increasing θ. The anisotropic phase transitions for the sample with columnar defects are delineated in the H vs T phase diagram in Fig. 5. For comparison, we also show the anisotropic vortex-glass melting lines $[H_{M\parallel,\perp}(T)]$ for $\theta = 0°$ and $90°$ in samples with random point defects. At $\theta < 45°$, the Bose-glass to superfluid transition line $H_{BG}(\theta,T)$ moves to lower temperatures with increasing θ. In contrast, the effective "vortex-glass" transition line at $\theta \gtrsim 45°$ (see the inset of Fig. 5) shifts towards higher temperatures with increasing θ.

Finally, we emphasize that the result $\zeta < d' = 2$ suggests a diverging compression modulus C_{11} at T_{BG}, indicating that the Bose interaction is long ranged and the Bose-glass *incompressible*. However, it is likely that ζ is a parameter dependent on both the density of columnar defects (i.e., the matching field) and the strength of the other types of defects. We speculate that a compressible Bose-glass transition with $\zeta = 2$ may be achieved in superconducting samples nearly free of point and twin defects and with columnar defects of separations greater than the magnetic penetration depth.

In summary, we have demonstrated the first experimental evidence of a second-order Bose-glass transition in $YBa_2Cu_3O_7$ single crystals with columnar defects by showing *universal* critical scaling of frequency-dependent ac resistivity data from 10^2 to 2×10^6 Hz. The signature of the transition, that the Bose-glass transition temperature T_{BG} *decreases* with the increasing angle (θ) between the applied magnetic field and the c axis, has been confirmed and is in sharp contrast to the smooth *increase* of the vortex-glass temperature (T_M). For $\theta < 45°$, the static and dynamic exponents $\nu_\perp \approx 1.0$, $\nu_\parallel \equiv \zeta\nu_\perp \approx 1.1$, and $z' \approx 2.2$ are found to be *independent* of the magnitude and orientation of the magnetic field. The different set of critical exponents distinguishes the Bose-glass transition from the universality class of the vortex-glass transition. The diverging compression modulus at T_{BG} suggests an *incompressible* Bose glass with long-range interaction at temperatures below T_{BG}.

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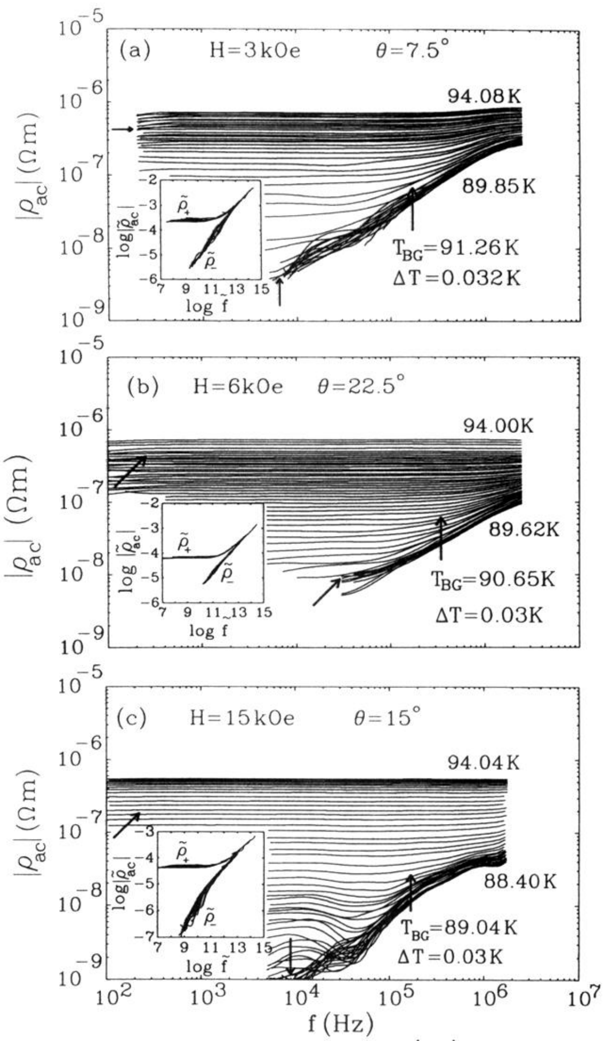

FIG. 1. Amplitude of the ac resistivity $|\rho_{ac}|$ vs frequency (f) isotherms taken at (a) $H=3.0$ kOe, $\theta=7.5°$; (b) $H=6.0$ kOe, $\theta=22.5°$; and (c) $H=15.0$ kOe, $\theta=15°$. The arrows indicate the isotherms in the critical regime which are scaled into universal functions $|\tilde{\rho}_{\pm}(\tilde{f})|$ in the insets by using Eq. (2). The temperature increment in the critical regime is $\Delta T \approx 0.03$ K.

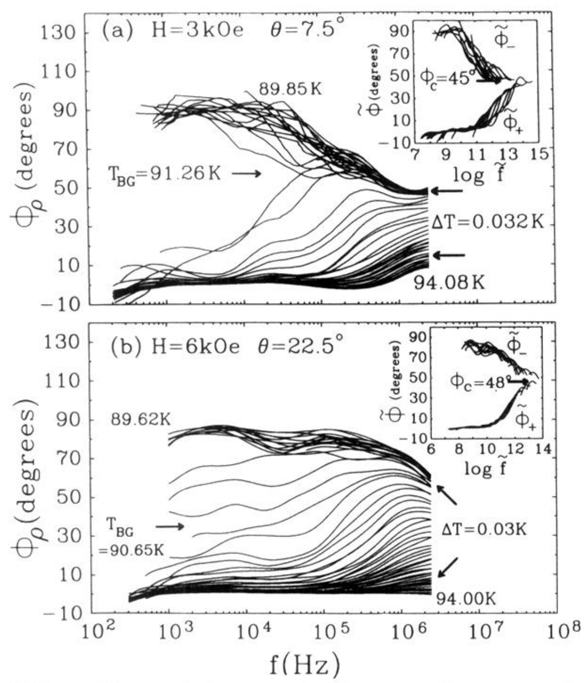

FIG. 2. Phase of the ac resistivity ϕ_ρ vs frequency (f) isotherms taken at (a) $H=3.0$ kOe, $\theta=7.5°$; and (b) $H=6.0$ kOe, $\theta=22.5°$. The arrows indicate the isotherms in the critical regime which are scaled into universal functions $|\tilde{\phi}_{\pm}(\tilde{f})|$ in the insets by using Eq. (2). the temperature increment in the critical regime is $\Delta T \approx 0.03$ K.