Bose-Glass Melting in YBaCuO Crystals with Correlated Disorder

L. Krusin-Elbaum,[1] L. Civale,[1,*] G. Blatter,[2] A. D. Marwick,[1] F. Holtzberg,[1] and C. Feild[1]

[1]*IBM Research, Yorktown Heights, New York 10598-0218*

[2]*Eidgenössiche Technische Hochschule Zürich-Hönggerberg, CH-8093 Zürich, Switzerland*

(Received 8 October 1993)

We report a *sharp* melting transition of the Bose glass in YBaCuO crystals with columnar defects installed by the irradiation with 1 GeV Au ions. The melting $B_{BG}(T)$ is tracked at low fields by the irreversibility line, which undergoes a remarkably abrupt crossover at a field B_{cr} for the vortices aligned with columns along the c axis. Below B_{cr}, the upward curvature of $B_{BG} \propto (1-T/T_c)^{\alpha}$ increases with the pin density (the exponent α grows from the clean value of $\sim 4/3$ to ~ 2 at the highest irradiation doses), in quantitative agreement with the theory of melting in the presence of correlated disorder. Above B_{cr}, the linear in T irreversibility line is consistent with a transition into a (super)entangled vortex liquid.

PACS numbers: 74.72.Bk, 74.60.Ge, 74.60.Jg

The pinning and melting of the vortex matter in high-T_c superconductors is decidedly controlled by disorder, both dynamic, caused by large thermal fluctuations, and static, caused by material defects [1,2]. The presence of strong static disorder is technologically relevant. It also can lead to novel thermodynamic phases, such as vortex glass for the case of *random* quenched disorder [3,4]. Another situation arises with *correlated* (or *mesoscopic*) disorder, such as, for example, twin boundaries [5] or columnar defects engineered with an irradiation with swift heavy ions [6], which dominate at high fields and temperatures.

Recently, Nelson and Vinokur [7] considered a system of vortex lines in the presence of a columnar defect structure. By mapping such a system onto a system of 2D bosons subject to static disorder [8], they predict a new "Bose-glass" phase at low temperatures, with vortex lines localized on columnar pins, an infinite tilt modulus, and zero linear resistivity. At low fields all vortex lines will be anchored on the pins. The melting of such stiffened vortex array into a viscous liquid (which eventually entangles) will occur at a critical field $B_{BG}(T)$, when the transverse localization length of the vortex lines will diverge [7]. At low fields, where the pins outnumber the vortices, $B_{BG}(T)$ will be shifted to higher temperatures from the melting line of a clean lattice $B_m(T)$, and progressively elevated with the increase in the pin density [7]. At high fields, where the vortices outnumber the pins and all the pins are occupied, the vortex array is polycrystalline on the scale of the correlated pinning potential, and eventually T_{BG} is expected to approach T_m (Ref. [7]).

In this Letter we report the observation of a *sharp Bose-glass melting transition*, $B_{BG}(T)$, in YBaCuO crystals with *continuous* columnar defects introduced by the bombardment with 1 GeV Au. We show that, for the field aligned with columns along the c axis, and below a dose-dependent crossover field B_{cr}, the Bose-glass melting is tracked by the irreversibility line $H_{irr}(T)$. We associate B_{cr} with the *accommodation field* below which the vortices are pinned independently. For $B \leq B_{cr}$, $B_{BG}(T)$ becomes *more upwardly curved* with the increase in the defect density as expressed by a *larger effective power-law exponent* α, which grows from the pre-irradiation value of $\sim 4/3$ to ~ 2 at the highest doses. We show this behavior to be in *quantitative agreement* with the predicted shift in $B_{BG}(T)$ to higher temperatures [7]. Above B_{cr}, the observed *dose-independent linear behavior* of $H_{irr}(T)$ is consistent with the entanglement transition in the vortex liquid [2].

Several YBaCuO single crystals [9] of nearly millimeter size and ~ 20 μm thick along the c axis were irradiated with 1.08 GeV $^{197}Au^{23+}$ ions at the Tandem Accelerator Superconducting Cyclotron (TASCC) facility at the Chalk River Laboratories in Canada. Irradiation doses (expressed in terms of a matching field B_Φ, the field at which the density of vortices and defects were equal) were $B_\Phi = 0.6$, 1.1, 2.4, 4.7, and 9.5 T. The incident beam was tilted away from the c axis by 2° to minimize channeling and the dose rate was less than 8×10^8 ions/cm^{2}sec to avoid heating. The resulting damage consists of a random array of amorphous columns, about 60–70 Å in diameter and *continuous* throughout the thickness of the crystal [10].

Figure 1(a) shows the line determined from the maximum in the out-of-phase component χ'' for $YBa_2Cu_3O_7$ irradiated with dose equivalent to $B_\Phi = 4.7$ T, measured at 1 MHz with the ac excitation amplitude $H_{ac} = 3.0$ Oe and in dc fields $H \| c$ axis up to 6 T. We observe a well defined *crossover* at a field $B_{cr} \sim \frac{1}{2} B_\Phi$ from a nearly *parabolic* behavior in $1-t$ below B_{cr} to a *linear* above, where $t = T/T_c$. The relation between the maximum in χ'' and $H_{irr}(T)$ is a nontrivial issue, and we have discussed it extensively in our previous work [11,12]. We define $H_{irr}(T)$ from the *onset of nonlinear* response, which manifests itself through the onset of amplitude dependence of χ. In general, this does not coincide [11,12] with the maximum in χ''. In fact, with $H_{ac} = 3.0$ Oe the maximum in χ'' occurs well into the nonlinear response regime [12], i.e., below $H_{irr}(T)$. We can now approach $H_{irr}(T)$ *from below* by reducing H_{ac}. By doing so, we find that the remarkable crossover *persists to the smallest measurable level of* H_{ac}. As an example, the data for $H_{ac} = 0.3$ Oe

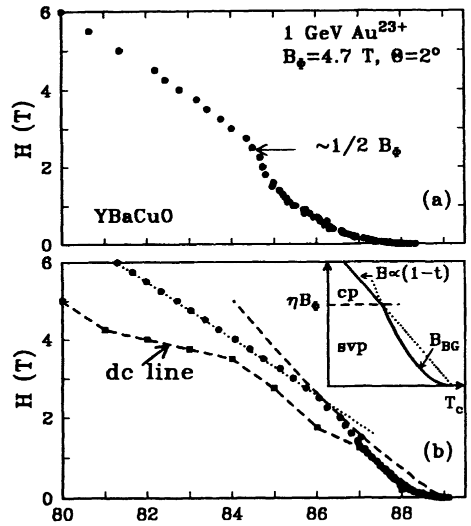

FIG. 1. The line in the H-T plane obtained from the maximum in $\chi''(T,H)$ measured at 1 MHz (solid dots) with (a) $H_{ac}=3.0$ Oe ($J \sim 2750$ A/cm^2) and (b) $H_{ac}=0.3$ Oe ($J \sim 200$ A/cm^2) in a single crystal of YBaCuO irradiated to a dose of $B_\Phi=4.7$ T for $H \|$defects. A clear crossover is seen at $B_{cr} \sim 0.5 B_\Phi$ from nearly parabolic behavior in T/T_c below B_{cr} to a linear above [dotted line in (b)]. The dc line (connected filled squares) obtained from $M(H)$ and corresponding to $J_c \sim 200$ A/cm^2 coincides with ac line only below the crossover. The dashed line below B_{cr} is the calculated $B_{BG}(T)$ for this dose (see text). The accommodation field ηB_Φ separates single-vortex (svp) and collective (cp) pinning regimes as shown in the inset (see text).

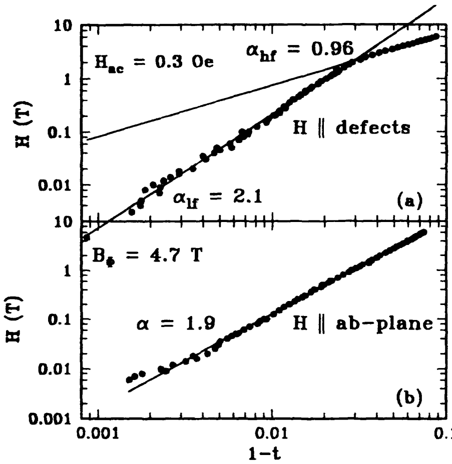

FIG. 2. (a) Same as in Fig. 1(b) in a log-log plot. This line is a good estimate of $H_{irr}(T)$. The field B_{cr} of the parabolic-to-linear crossover is independent of the amplitude of ac excitation. (b) $H_{irr}(T) \propto (1-t)^{\alpha}$ measured with dc field$\|a$-b plane; here $\alpha = 1.9 \pm 0.06$ over the entire field range.

are shown on a linear plot in Fig. 1(b) and in a log-log plot in Fig. 2(a), where the high- and low-field power laws are described by the exponents $\alpha_{hf}=0.96 \pm 0.05$ and $\alpha_{lf}=2.10 \pm 0.06$, respectively [13]. We take the maximum in χ'' at low H_{ac} as a good approximation to $H_{irr}(T)$ (Ref. [14]).

We now proceed to establish the relationship between $H_{irr}(T)$, determined as described above, and the melting line of the Bose glass. The crossover at B_{cr} is obviously due to columnar defects being aligned with the field. Indeed, the effect disappears when the field is tilted away from the defects; for $H \|$ a-b plane, $\alpha = 1.9 \pm 0.06$ over the entire field range [see Fig. 2(b)], similar to unirradiated crystals for this field orientation [11]. The linearity above B_{cr} is preserved for all values of B_Φ in this study, but the behavior at low fields is dose dependent. The log-log plot of $H_{irr}(T)$ of a crystal irradiated with a dose $B_\Phi=2.4$ T is shown in the lower inset of Fig. 3; where, $\alpha_{lf}=1.72 \pm 0.06$, less than 2. This inset also shows $H_{irr}(T)$ of the same crystal before the irradiation; there α is 1.33 ± 0.05 ($\sim 4/3$), as we invariably see at high fields in all unirradiated YBaCuO crystals for $H \|$ c axis [11]. At low doses, α_{lf} is also close to 1.3, but increases with dose and settles at about 2 for higher doses as shown in Fig. 3. B_{cr} remains just below $\frac{1}{2} B_\Phi$ for all doses (upper inset of Fig. 3). This is true even at $B_\Phi=9.5$ T, although there the irradiation damage causes already a several degree shift in T_c and smearing of the crossover.

To identify the crossover field B_{cr}, we consider $B^*(T)$, a boundary in the Bose-glass phase which separates a strong single-vortex and a weaker collective pinning re-

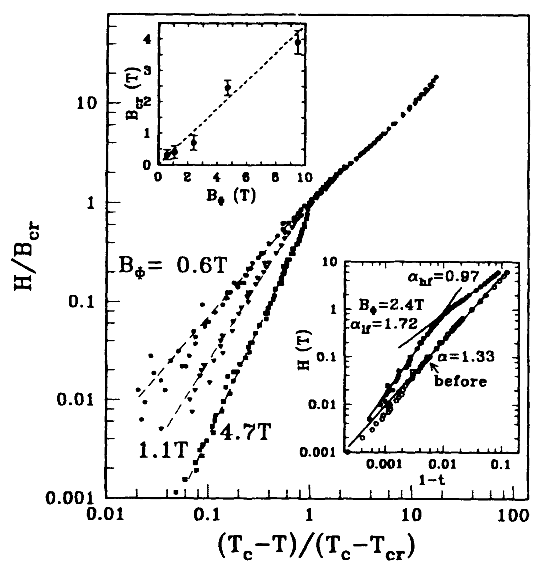

FIG. 3. Log-log plot of the irreversibility lines for several values of B_Φ (several irradiation doses) scaled to their respective values of the crossover fields and temperatures. The linear behavior above B_{cr} is independent of the dose. Below B_{cr} at small doses, the power law is similar to that seen in unirradiated crystals; for $B_\Phi=0.6$ T (solid dots), α_{lf} is 1.3 ± 0.05. It increases with dose; for $B_\Phi=1.1$ T (solid triangles), α_{lf} is 1.6 ± 0.06 and for $B_\Phi=4.7$ T (solid squares), α_{lf} is 2.1 ± 0.06. The crossover field scales with dose as shown in the upper inset. Lower inset shows the comparison of the lines before and after irradiation with $B_\Phi=2.4$ T.

gimes [7]. At low fields the vortex lattice spacing $a_0 > d$, where $d = \sqrt{\Phi_0/B_\Phi}$ is the mean distance between the tracks. In order to accommodate to the random array of columnar defects, the vortex line should be shifted over a distance d. While the energy gain in this shift is the pinning energy $U_p(T)$, it costs $C_{66}d^2$ in elastic energy, where C_{66} is the shear modulus of the vortex lattice. At low T the comparison of the two energies yields [7] $B^* = B^*(0) \simeq \eta B_\Phi$. Here, we have introduced the pinning efficiency η, which for core pinning is ≤ 1. It describes the fractional suppression of the superconductivity in the track such that $U_p = \eta U_0 = \eta(H_c^2/8\pi)\pi\xi^2$. We estimate η from the field dependence of the critical current density $J_c(H)$ at low temperatures (below 30 K) [6] to be 0.52 at the lowest doses and gradually decreasing with increasing B_Φ to ~ 0.25 at $B_\Phi = 9.54$ T, consistent with the material damage as seen by the reduction of T_c. Thus, we take the crossover field $B_{cr} \sim 0.5 B_\Phi$ to indicate B^*, which separates low- and high-field regimes.

For $B \leq B^*$, all vortices are localized on tracks and the Bose-glass melting temperature T_{BG} will depend on the defect density [1,7] as

$$T_{BG} \simeq T_m[1 + (c_L a_0/d)(T^*/T_m)^2] . \tag{1}$$

The effect of thermal fluctuations is contained in the *energy scale* $T^*(t) = \frac{1}{4}[b_0/2\xi(0)](T_c/\sqrt{\mathrm{Gi}})(1-t)(1-b_t)$, which separates strongly localized and weakly localized regimes [1,7]. Here Gi is the Ginzburg number [1], b_0 is the defect diameter, and, for completeness, we include the high field correction [1] $b_t = b/(1-t)$, with $b = B/H_{c2}(0)$. The melting temperature T_m obtained with the Lindemann criterion can be written as [1,7] $T_m \simeq c_L^2[a_0/\xi(0)](T_c/\sqrt{\mathrm{Gi}})(1-t)(1-b_t)$, where c_L is the Lindemann number ($4c_L \sim 1$). With the above expressions for T_m and T^* we can rewrite Eq. (1) as an implicit equation for T_{BG},

$$T_{BG} \simeq T_m + \frac{b_0}{8d}\frac{b_0}{2\xi(0)}\frac{T_c}{\sqrt{\mathrm{Gi}}}(1-t-b) . \tag{2}$$

Dividing both sides of Eq. (2) by T_c and evaluating it self-consistently at $t = t_{BG}$ we obtain a compact expression for t_{BG}:

$$t_{BG}(B) \simeq [t_m(B) + \gamma(1-b)]/(1+\gamma) , \tag{3}$$

where both the thermal ($\sqrt{\mathrm{Gi}}$) and static ($b_0^2/d\xi$) disorder enter via a single parameter $\gamma = (b_0^2/16d)/\xi(0)\sqrt{\mathrm{Gi}}$. This expression behaves correctly in both limits; for a clean system as $\gamma \to 0$, $t_{BG} \to t_m$, as it should, and as $\gamma \to \infty$, t_{BG} approaches $1 - b = t_{c2}$, the upper critical temperature. From Eq. (3) (*valid only below* B^*) for a finite γ the Bose-glass line will be shifted up and will have a *steeper upward curvature* than the melting line, as indicated schematically in the inset of Fig. 4(b). The *steeper curvature*, of course, *will appear as a larger exponent* [15] in a log-log plot of B vs $1-t$, as is clearly demonstrated in Fig. 3.

We test the above expression for $t_{BG}(B)$ in the following way. We start with a clean unirradiated crystal and take the preirradiation irreversibility line as a good estimate of $t_m(B)$. We then obtain $t_{BG}(B)$ from Eq. (3) for one specific defect density B_Φ by taking the experimental $t_m(B)$, $\mathrm{Gi} \simeq 4\times10^{-3}$, $\xi(0) \simeq 12.0$ Å, and using the diameter of the track as the *only fitting parameter*. For $H \leq 3$ T, $b \leq 0.01$, and the high-field correction can be ignored. This is shown in Fig. 4(a) for $B_\Phi = 2.4$ T ($d = 294$ Å). The best fit is obtained with $b_0 = 80$ Å, in remarkable agreement with the diameter of $\sim$60–70 Å directly imaged with high resolution transmission electron micrograph [10]. With the effective track diameter established, we can now *calculate* the Bose-glass melting line for any dose, as shown, for example, for $B_\Phi = 1.1$ T in Fig. 4(b). The dashed line going through all the data points below B_{cr} *is not a fit* now and the agreement is astonishing. At the highest values of B_Φ, the sample degradation (as seen in the reduction of T_c and η) has a clear effect to cause deviations from the behavior prescribed by Eq. (3). This is seen in Fig. 1(b) for $B_\Phi = 4.7$ T, for which T_c is suppressed by about 3 K.

We now consider the high field regime above B_{cr}. In this regime the pinning is expected to be collective and weaker [7] and clearly is, as is apparent from the dc line obtained with a J_c criterion [16] of $\sim$200 A/cm^2 [see Fig. 1(b)]. At low fields, the dc line is remarkably near $H_{irr}(T)$ obtained from ac absorption and corresponding to roughly the same current density at the maximum of χ''. Thus, below B_{cr}, the large drop in resistivity which

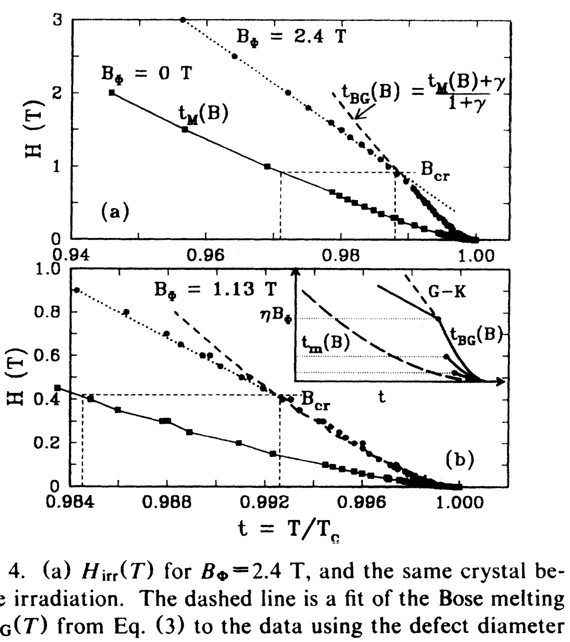

FIG. 4. (a) $H_{irr}(T)$ for $B_\Phi = 2.4$ T, and the same crystal before the irradiation. The dashed line is a fit of the Bose melting line $B_{BG}(T)$ from Eq. (3) to the data using the defect diameter b_0 as the only fitting parameter. (b) The b_0 from this fit is used to calculate $B_{BG}(T)$ for $B_\Phi = 1.1$ T, shown as dashed line. Inset schematically shows the progressive increase in the curvature of $B_{BG}(T)$ with the increase in B_Φ. It also shows the GK decoupling line.

we sense by ac absorption nearly coincides with the onset of J_c, indicating that the *transition is very sharp.* But, above B_{cr}, the ac line is well *above* the dc line, indicating that the onset of nonlinear behavior occurs well above the temperature where finite J_c first appears. This implies that the transition is *broad,* and that the *linear* portion of ac $H_{irr}(T)$ is in the *liquid regime.*

The linear temperature dependence has been suggested for a *clean* layered superconductor in the 3D melting regime [17]. Glazman and Koshelev (GK) [17] argue that the melting occurs in two stages. First, the vortex array melts into a line liquid with a finite tilt modulus c_{44}. Close to T_c, c_{44} vanishes at $B^{GK}(T) \cong v\Phi_0^3(1-t)/T_c(4\pi\lambda_c)^2 s$, where s is the spacing between the CuO layers and λ_c is the penetration depth for currents crossing the layers [18]. In a continuous anisotropic material this boundary is equivalent [17] to the vortex entanglement transition or crossover in the liquid, i.e., a decoupling on some length scale [2,19].

We suggest a modification of this scenario in the presence of correlated disorder. Columnar pins stabilize c_{44} (i.e., promote disentanglement), but this stabilization depends on the pin density and on the strength of pinning. It has been shown *rigorously* that at low fields c_{44} is significantly enhanced by the presence of columns and hence the entangled phase is unlikely to form [20]. Above B_{cr} the pinning is weaker, the lattice is less rigid, and, as temperature is increased, vortices first melt at $B_{BG}(T)$ into a line liquid. Upon further heating the liquid entangles and the lines break up along $B^{GK}(T)$ due to decoupling of CuO planes. For YBaCuO the 3D regime should persist to about 20 T [21] with the slope $dB^{GK}/dT \sim 1$ T/K (Ref. [17]), in reasonable agreement with the value of ~ 0.8 T/K obtained from the high-field slope of $H_{irr}(T)$ in Fig. 1(b). Not surprisingly, the *linearity* of this transition is *dose independent.* There are no theoretical predictions as of yet as to the behavior of the B_{BG} above B_{cr}, only an expectation that B_{BG} should approach B_m at sufficiently high fields [7]. From the experiment, we conclude that the high-field Bose-glass melting line will lie below $B^{GK}(T)$, consistent with the above expectation.

We are pleased to acknowledge our many useful discussions with V. M. Vinokur, D. Nelson, and M. P. A. Fisher, L.K.-E. especially wants to thank V. M. Vinokur for valuable suggestions. This work was partly sponsored by the Division of Material Sciences, U.S. Department of Energy, under Contract No. DE-AC-05-84OR21400 with Martin Marietta Energy Systems, Inc. We thank J. Hardy and J. Forster at TASCC (Chalk River) for their help and the provision of irradiation facilities. The operation of TASCC is supported by AECL Research.

*Present address: Centro Atomico Bariloche, 8400 Bariloche, Argentina.

[1] For a review see G. Blatter *et al.* (to be published).

[2] D. R. Nelson, Phys. Rev. Lett. **60**, 1973 (1988); J. Stat. Phys. **57**, 511 (1989); D. R. Nelson and H. S. Seung, Phys. Rev. B **39**, 9153 (1989).

[3] D. S. Fisher, M. P. A. Fisher, and D. A. Huse, Phys. Rev. B **43**, 130 (1991); M. P. A. Fisher, Phys. Rev. Lett. **63**, 1511 (1989).

[4] R. H. Koch, V. Foglietti, W. J. Gallagher, G. Koren, A. Gupta, and M. P. A. Fisher, Phys. Rev. Lett. **63**, 1511 (1989).

[5] W. K. Kwok, S. Fleshler, U. Welp, V. M. Vinokur, J. Downey, and G. W. Crabtree, Phys. Rev. Lett. **69**, 3370 (1992).

[6] L. Civale, A. D. Marwick, T. K. Worthington, M. A. Kirk, J. R. Thompson, L. Krusin-Elbaum, Y. Sun, J. R. Clem, and F. Holtzberg, Phys. Rev. Lett. **67**, 648 (1991).

[7] D. R. Nelson and V. M. Vinokur, Phys. Rev. Lett. **68**, 2398 (1992); Phys. Rev. B **48**, 13060 (1993).

[8] M. P. A. Fisher, P. B. Weichman, G. Grinstein, and D. S. Fisher, Phys. Rev. B **40**, 546 (1989).

[9] F. Holtzberg and C. Feild, Eur. J. Solid State Inorg. Chem. **27**, 107 (1990).

[10] A. D. Marwick, L. Civale, L. Krusin-Elbaum, R. Wheeler, J. R. Thompson, T. K. Worthington, M. A. Kirk, Y. R. Sun, H. R. Kerchner, and F. Holtzberg, Nucl. Instrum. Methods Phys. Res., Sect. B **81/81**, 1143 (1993); R. Wheeler *et al.* (unpublished).

[11] L. Krusin-Elbaum, L. Civale, F. Holtzberg, A. P. Malozemoff, and C. Field, Phys. Rev. Lett. **67**, 3156 (1991).

[12] L. Civale, T. K. Worthington, L. Krusin-Elbaum, and F. Holtzberg, in *Magnetic Susceptibility of Superconductors and Other Spin Systems*, edited by R. A. Hein, T. L. Francavilla, and D. H. Liebenberg (Plenum, New York, 1992), and references therein.

[13] The quoted uncertainties are standard deviations of least-square fits with T_c taken at the location of the maximum in χ'' at $H=0$.

[14] We observe the position of the maximum in χ'' to be essentially frequency independent; less than 1 K between 1 and 0.1 MHz.

[15] We note that although extracting a power-law exponent from a log-log plot is a compact way to show the data, there is no obvious significance in the absolute value of the exponent, only in the relative change in the curvature.

[16] dc line was determined from closing of the hysteresis loop $M(H)$ with the criterion of $\sim 10^{-5}$ emu, measured with a SQUID magnetometer.

[17] L. I. Glazman and A. E. Koshelev, Phys. Rev. B **43**, 2835 (1991); L. I. Glazman (private communication).

[18] In a strongly layered material the second step will transform the line liquid into a point liquid and it is yet unclear, whether this is a true phase transition (with $c_{44} \rightarrow 0$) or merely a crossover (with a sharp drop in c_{44}).

[19] D. R. Nelson, in *Phenomenology and Applications of High Temperature Superconductors*, edited by K. S. Bedell, M. Inui, D. Meltzer, J. R. Schrieffer, and S. Donaich (Addison-Wesley, Reading, MA, 1992).

[20] P. LeDoussal, T. Hwa, D. R. Nelson, and V. M. Vinokur (to be published); V. Vinokur (private communication).

[21] M. V. Feigel'man, V. B. Geshkenbeing, and A. I. Larkin, Physica (Amsterdam) **167C**, 177 (1990).