Evidence for Scaling Invariance and Universality of the Irreversibility Line of High Temperature Superconductors

C. C. Almasan,[1] M. C. de Andrade,[1] Y. Dalichaouch,[1] J. J. Neumeier,[1],[a] C. L. Seaman,[1] M. B. Maple,[1] R. P. Guertin,[2] M. V. Kuric,[2] and J. C. Garland[3]
[1]*Department of Physics and Institute for Pure and Applied Physical Sciences, University of California, San Diego, La Jolla, California 92093*
[2]*Department of Physics, Tufts University, Medford, Massachusetts 02155*
[3]*Department of Physics, Ohio State University, Columbus, Ohio 43210*
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Measurements of the irreversibility line $H(T^*)$ of $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$, a system in which the superconducting transition temperature T_c can be varied from 0 to 92 K, show that $H(T^*)$ obeys a universal scaling relation characterized by an $m=\frac{3}{2}$ power law near T_c, with a crossover to a more rapid temperature dependence below $T/T_c \approx 0.6$. The applicability of the scaling formula to other high T_c superconductors is tested, with the results suggesting that both the crossover phenomenon and the power law temperature dependence are ubiquitous, scale-invariant properties of high temperature superconductors.

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One of the more interesting and controversial developments in the study of the irreversibility line $H(T^*)$ in high temperature superconductors is the observation in some materials of a crossover from an approximate $(1-T^*/T_c)^{3/2}$ temperature dependence near $T/T_c \approx 1$ to a more rapid dependence at lower reduced temperatures. Such a crossover was first seen in the electron-doped superconductor $Sm_{1.85}Ce_{0.15}CuO_{4-y}$ [1] and has subsequently been observed in both electron-doped [2–5] and hole-doped compounds, the latter including oxygen-deficient $YBa_2Cu_3O_x$ [6,7] and $Bi_2Sr_2CaCu_2O_{8+\delta}$ [8].

That the crossover phenomenon has a fundamental origin is suggested in part by the large number of cuprate materials in which it has been observed (in both polycrystalline and single-crystal samples), and also because of corroborating measurements from several experimental techniques. [For brevity, in this Letter, we refer to $H_M(T^*)$, $H_R(T^*)$, and $H_\chi(T^*)$ as the irreversibility line inferred from measurements of the dc magnetization $M_{dc}(T,H)$, the magnetoresistance $R(T,H)$, and the real component of the ac magnetic susceptibility $\chi_{ac}(T,H)$, respectively [9].] Despite this body of evidence, the question still remains as to whether the crossover phenomenon is truly an intrinsic property of cuprate superconductors (e.g., whether it is related to some universal dynamical process involving flux line mobility or to a dimensional crossover in the vortex glass or liquid) or whether it is a material-dependent effect (e.g., resulting from a sample-dependent distribution of pinning potentials). Advocates of the latter point of view note that no crossover phenomenon has been reported for some important classes of cuprate superconductors, most notably fully oxygenated specimens of $YBa_2Cu_3O_{7-\delta}$. It is important that this issue of possible universality be resolved, since the physics of the irreversibility line appears to underlie the ultimate current-carrying capability of high temperature superconductors.

In our experiments, we address this issue through measurements of the irreversibility line $H_R(T^*)$ in $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$, a system in which T_c can be systematically reduced from 92 to 0 K by varying the Pr concentration. Our principal finding is that $H_R(T^*)$ in this system obeys a scaling relation in which the data from different Pr concentrations collapse onto a single universal curve. For $T^*/T_c \gtrsim 0.6$, this curve exhibits power-law behavior with an exponent $m \approx \frac{3}{2}$, while at lower temperatures, the curve displays a more rapid variation with temperature. The scaling variable is a characteristic magnetic field, designated $H^\dagger(x)$, which corresponds to the value of $H_R(T^*)$ at $T^*/T_c = 0.6$.

Having established the scaling relation for $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$, we then test the universality of the scaling conjecture by applying it to previously published results on other cuprate systems, notably $Sm_{1.85}Ce_{0.15}CuO_{4-y}$ [2,3], oxygen-deficient $YBa_2Cu_3O_x$ [6], and $Bi_2Sr_2CaCu_2O_{8+\delta}$ [8]. In all cases, we find virtually identical scaling behavior, with a crossover feature in the universality line occurring at $T^*/T_c \approx 0.6$. This result also suggests that the absence of the crossover in the irreversibility line of fully oxygenated $YBa_2Cu_3O_{7-\delta}$ is merely a consequence of measurements having not been performed at sufficiently strong magnetic field for that system.

We believe that this collective evidence indicates that the crossover phenomenon is likely to be an intrinsic microscopic property of the flux line dynamics of all high temperature superconductors. As discussed subsequently, this conclusion is consistent with a recent phenomenological model by Garland, Almasan, and Maple [10], which attributes the crossover to the onset of strong correlations in the flux line lattice at high magnetic fields.

In the measurements reported here, polycrystalline samples of $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ with $0 \le x \le 0.55$ and $13.5 \le T_c \le 92.2$ K were prepared as described in Ref. [11]. Low-frequency four-wire electrical resistance $R(T,H)$ measurements were performed in applied magnetic fields H up to 23 T. Data for $10 \le H \le 23$ T were

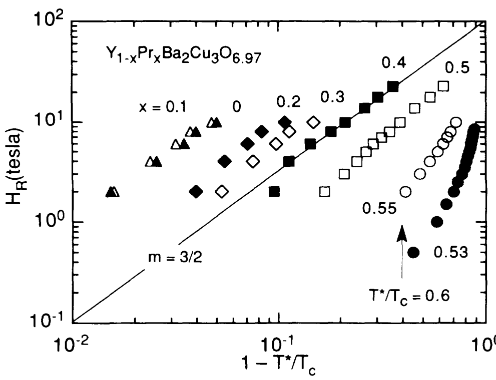

FIG. 1. Log-log plot of H_R vs $1-T^*/T_c$ for polycrystalline samples of $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ with $0 \leq x \leq 0.55$. The solid line represents power law behavior with exponent $m = \frac{3}{2}$.

obtained at the Francis Bitter National Magnet Laboratory. On the various curves, $T^*(H)$ is taken to be the temperature at which $R(T,H)$ drops to 50% of its extrapolated normal-state value. The resulting $H_R(T^*)$ curves obtained from the $R(T,H)$ data of $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ with $0 \leq x \leq 0.55$ are displayed in Fig. 1 in the form of log-log plots of $H_R(T^*)$ vs $1-T^*/T_c$. For low Pr concentrations, the $H_R(T^*)$ data exhibit a power law dependence of the form

$$H_R(T^*) = H_0(1-T^*/T_c)^m \quad (1)$$

with $m \approx \frac{3}{2}$. It is evident from the figure that a departure from this behavior is observed for $T^*/T_c \lesssim 0.6$ for those higher Pr concentrations in which the relevant H-T regime is attainable.

The data shown in Fig. 2(a) were obtained by applying a scaling procedure to the data of Fig. 1; for each specimen, $H_R(T^*)$ was normalized by the crossover field $H^\dagger(x)$, defined to be the value of $H_R(T^*)$ at $T^*/T_c = 0.6$. $H^\dagger(x)$ was obtained directly from the data for the $x = 0.5$ and 0.55 samples, and by extrapolation [using Eq. (1) with $m = \frac{3}{2}$] for the other specimens, except for the $x = 0.53$ sample, in which $H^\dagger(x)$ was an adjustable parameter. The values of $H^\dagger(x)$ are given in Table I. It is evident that the normalized $H_R(T^*)$ data for all x values collapse onto a single curve. The data in the low field and high temperature regime follow a power law dependence with $m \approx \frac{3}{2}$ (the solid line represents the $m = \frac{3}{2}$ power law). In the high field regime and for $T^*/T_c \lesssim 0.6$, there is a clear departure of the data from the low field power law; $H_R(T^*)/H^\dagger(x)$ varies more rapidly than $m = \frac{3}{2}$ in this regime, although it is not possible to deduce an explicit power law dependence. A narrowing of the superconducting transition was also observed in this field and temperature regime [12], as is consistent with the higher value of m and the thermally activated flux creep models. The value of the crossover field decreases with increasing x or, equivalently, increasing magnetic penetration depth λ [13], which is consistent with the model proposed in

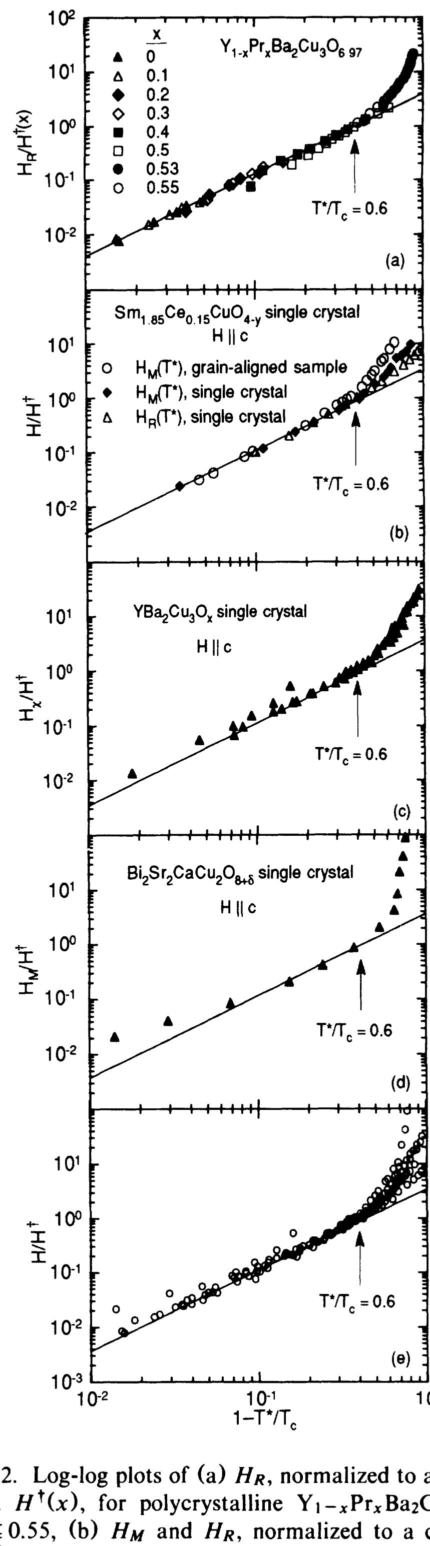

FIG. 2. Log-log plots of (a) H_R, normalized to a characteristic field $H^\dagger(x)$, for polycrystalline $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ with $0 \leq x \leq 0.55$, (b) H_M and H_R, normalized to a characteristic field $H^\dagger$, for a grain-aligned sample and two single crystals of $Sm_{1.85}Ce_{0.15}CuO_{4-y}$ with **H**||**c** (the data are from Refs. [2] and [3]), (c) $H_\chi/H^\dagger$ for a $YBa_2Cu_3O_x$ single crystal with tunable T_c (data from Ref. [6]), and (d) $H_M/H^\dagger$ for $Bi_2Sr_2CaCu_2O_{8+\delta}$ (data from Ref. [8]), all vs $1-T^*/T_c$; (e) composite plot of all the data from Figs. 2(a)-2(d). The solid lines in all four figures represent power law behavior with exponent $m = \frac{3}{2}$.

TABLE I. Superconducting transition temperature T_c, penetration depth λ (from Ref. [13]), and crossover field $H^\dagger(x)$ for different x values for $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$. The uncertainty in $H^\dagger(x)$ is the standard deviation of the data from fits to Eq. (1).

x	T_c (K)	λ (nm)	$H^\dagger(x)$ (T)
0	91.9	143	237 ± 17
0.1	88.5	172	260 ± 15
0.2	73.3	193	76.0 ± 8.0
0.3	62.5	219	47.3 ± 4.5
0.4	45.3	293	26.7 ± 0.7
0.5	31.1	⋯	10.4
0.55	22.1	⋯	1.8
0.53	12.7	⋯	0.4

Ref. [10].

Although the 50% criteria for defining $T^*(H)$ was arbitrarily chosen in the above analysis, we obtained similar results by defining $T^*(H)$ at $R/R_n = 10\%$ and 90%, where R_n is the extrapolated normal-state resistance. Indeed, Tinkham has shown [14] that $T^* - T_c \propto H^{2/3}$ at any R/R_n level and, hence, that the power law dependence of the H-T phase boundary is the same ($m \approx \frac{3}{2}$) regardless of the R/R_n level at which it is extracted. The irreversibility line extracted from dc magnetization measurements corresponds to the choice of a R/R_n level sufficiently low to allow persistent currents to flow.

We were not able to compare the temperature dependence of $H_R(T^*)$ with the temperature dependence of $H_M(T^*)$ for $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$. For samples having $x \geq 0.3$, the determination of the irreversibility line from the dc magnetization is limited to low fields ($H < 0.8$ T) because the Pr ions carry localized magnetic moments and are strongly paramagnetic. At higher fields, the strong paramagnetic contribution of the Pr ions dominates the superconducting diamagnetic response, decreasing the sensitivity and making it difficult to extract the small diamagnetic signal from the large paramagnetic background. Thus, the high field, low temperature portion of the irreversibility line $H_M(T^*)$ in the H-T plane becomes inaccessible.

In Figs. 2(b)–2(d), we apply the scaling procedure to previously published measurements on other cuprate superconductors. In each figure, the magnetic field is normalized by a characteristic field $H^\dagger$, which is defined to be the value of H_M (or H_R or H_χ) at $T^*/T_c = 0.6$. Figure 2(b) shows a log-log plot of $H_M(T^*)/H^\dagger$ and $H_R(T^*)/H^\dagger$ (all with $\mathbf{H} \parallel \mathbf{c}$) as a function of $1 - T^*/T_c$ for a grain-aligned sample and two single crystals of the electron-doped superconductor $Sm_{1.85}Ce_{0.15}CuO_{4-y}$ [2, 3]. Figure 2(c) shows an analogous plot of a compilation of measurements taken by Seidler *et al.* [6] on a single crystal of $YBa_2Cu_3O_x$ in which T_c was varied over a range of 7–17 K by progressively annealing the single-crystal specimen at room temperature.

Figure 2(d) shows scaled data of $H(T^*)/H^\dagger$ (for $\mathbf{H} \parallel \mathbf{c}$) of a single crystal of $Bi_2Sr_2CaCu_2O_{8+\delta}$, from measurements taken by Kadowaki and Mochiku [8]. Interestingly, this specimen also shows a crossover in the value of the exponent m at $T^*/T_c \approx 0.6$, even though the two highest temperature data points suggest that m is closer to 1.2 than to 1.5 for $T^*/T_c > 0.6$.

Figure 2(e) is a composite plot of all the data from Figs. 2(a)–2(d). This figure suggests that the crossover of the irreversibility line from $m \approx \frac{3}{2}$ to a stronger dependence at $T^*/T_c \approx 0.6$ is a fundamental property of the cuprate superconductors. It is evident from the figure that the detailed temperature dependence of $H(T^*)/H^\dagger$ in the region of rapid variation (below $T^*/T_c \approx 0.6$) is not characterized by simple power law behavior. Furthermore, in this region, there are clear differences in the temperature dependences among the families of cuprate superconductors.

Although it is still an open question as to whether the scaling invariance of the irreversibility line applies also to noncuprate superconductors, there is limited evidence for a crossover phenomenon in selected noncuprate materials. Rossel *et al.* [15] have reported a crossover in $H_M(T^*)$ from a $m \approx \frac{3}{2}$ to an exponential behavior at $T^*/T_c \approx 0.8$ in the more "conventional" superconductor $PbMo_6S_8$. Further, Visani *et al.* [16] have observed a crossover in $H_\chi(T^*)$ from a $m \approx 1.3$ to $m \approx 4.2$ power law at $T^*/T_c \approx 0.9$ in the heavy-fermion superconductor URu_2Si_2.

On the basis of the observations summarized in Fig. 2 and Table I it seems reasonable to draw the following conclusions: (i) The presence of the crossover effect at the same reduced temperature of $T^*/T_c \approx 0.6$ in $H_R(T^*)$, $H_M(T^*)$, and $H_\chi(T^*)$ indicates that $H_R(T^*)$ probes the H and T dependence of the irreversibility line, even in the lower T_c electron-doped cuprates [17]. (ii) The breakdown of the $m \approx \frac{3}{2}$ power law below $T^*/T_c \approx 0.6$ is most likely a scale-invariant universal characteristic of high T_c superconductors, independent of the superconducting copper oxide material, the value of T_c, and the experimental procedure employed to measure $H(T^*)$. (iii) The value of the crossover magnetic field $H^\dagger$, which marks the onset of the more rapid temperature dependence, is lower for superconductors with larger transverse magnetic penetration depth.

According to the flux creep model of irreversibility behavior, the value of the exponent m is governed by the physics of the pinning potential [18], with the existence of the crossover implying two regimes in which the pinning potential displays different temperature and/or magnetic field dependencies. Two models have been invoked to explain such a crossover. The first model [10] accounts for the crossover by postulating a characteristic vortex separation distance denoted a^*. When the flux line spacing $a_0 \approx (\Phi_0/H)^{1/2}$ exceeds a^*, the flux line bundles are found to be weakly correlated, with pinning-induced fluctuations in the local flux density smoothed over the entire bundle. This regime leads to an irreversibility exponent of $\frac{3}{2}$. At stronger fields, characterized by $a_0 < a^*$, the flux lines harden into rigid bundles, so that pinning effects become truly collective; in this regime the exponent $m \approx 3$. The crossover point between the two regimes occurs at a field H^* in which the flux line space is equal to a^*, i.e.,

$$a^* = (2\Phi_0/\sqrt{3}H^*)^{1/2}. \quad (2)$$

Comparing a^* to λ (transverse to the field), the crossover field extracted from magnetization measurements corresponds to a flux line spacing of about $\lambda/4$ for $Sm_{1.85}Ce_{0.15}CuO_{4-y}$ [10] and $\lambda/8$ for oxygen-deficient $YBa_2Cu_3O_x$ [7]. This difference might originate in the error introduced by using different methods to estimate λ. The small value of λ ($\lambda_{ab} \approx 1400$ Å [19]) in $YBa_2Cu_3O_7$ suggests that the onset of strong correlations should occur at much higher fields ($H \geq 2$ T for **H**$\|$c).

The second model invokes the presence of a transition in the vortex lattice from rigid three-dimensional vortex lines to two-dimensional independent pancakelike vortices that move in the CuO_2 planes [20]. A high degree of anisotropy implies weak interplane coupling, which produces thermally activated decoupling of the pancakelike vortices in the adjacent CuO_2 layers. Hence, this model predicts the crossover behavior to occur in highly anisotropic systems like Bi- and Tl-based materials, as well as oxygen-deficient $YBa_2Cu_3O_x$. The dimensional crossover in $YBa_2Cu_3O_7$ is not predicted to occur below H_{c2} because of the lower anisotropy of this material. Similarly, one would not expect to observe a dimensional crossover in the electron-doped compound $Sm_{1.85}Ce_{0.15}CuO_{4-y}$, which also has a relatively low anisotropy [21]. However, since we report crossover behavior in $Sm_{1.85}Ce_{0.15}CuO_{4-y}$, this model does not seem to be applicable to this system.

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[a]Present address: Sektion Physik, Universität München, Schellingstrasse 4, D-8000 München 19, Germany.

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