High-Field Scaling Behavior of Thermodynamic and Transport Quantities of $YBa_2Cu_3O_{7-\delta}$ near the Superconducting Transition

U. Welp, S. Fleshler, W. K. Kwok, R. A. Klemm, V. M. Vinokur,[a] J. Downey, B. Veal, and G. W. Crabtree

Science and Technology Center for Superconductivity, Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439

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The superconducting contribution to the magnetization and resistivity of twinned and untwinned $YBa_2Cu_3O_{7-\delta}$ crystals which are presented here, as well as to the specific heat (Inderhees *et al.*) and Ettinghausen coefficient (Palstra *et al.*), displays scaling behavior in the variable $[T-T_c(H)]/(TH)^{2/3}$. This is consistent with Ginzburg-Landau fluctuation theory for a 3D system in a high magnetic field. The scaling property allows for a consistent way of determining the mean-field transition temperature $T_c(H)$.

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The transition into the superconducting state in zero field of bulk low-T_c materials is well described by mean-field theory. Fluctuation effects are usually small and have been accounted for in the Gaussian approximation [1]. The region ΔT around T_c where the Gaussian approximation breaks down and critical phenomena occur is given by the Ginzburg criterion $G=\Delta T/T_c$, which is very small: $G\approx 10^{-5}$ [2]. In contrast, for the high-T_c materials the very short coherence lengths, the large anisotropies, and the high values of T_c greatly enhance the effects of fluctuations, $G\approx 10^{-3}$, as seen in measurements of the specific heat [3], normal-state susceptibility [4], or resistivity [5].

In a magnetic field H sufficiently strong that the paired quasiparticles are effectively limited to being in their lowest Landau level, the superconducting fluctuations in bulk low-T_c as well as in high-T_c materials acquire an effective one-dimensional (1D) character along the field direction [6], and the usual sharp second-order phase transition accompanied by a divergent part in the free energy is not expected [7–12]. This reduction of the effective dimensionality increases the importance of fluctuations, resulting in a fluctuational region around $T_c(H)$ which grows with increasing field according to the field-dependent Ginzburg criterion $G(H)=(8\pi\kappa^2 k_B T_c H/\Phi_0\xi_c H_{c2}^2)^{2/3}$ [10], where Φ_0 is the flux quantum, κ is the Ginzburg-Landau (GL) parameter, ξ_c is the c-axis coherence length, and H_{c2} is the upper critical field, both at zero temperature and for fields applied parallel to the c axis. The temperature and field dependence of physical quantities in this fluctuational region show scaling behavior in the variable $t_G=(T_c/T)^{2/3}[T-T_c(H)]/G(H)T_c$, where $T_c(H)$ is the mean-field transition temperature. The high-T_c materials are characterized by broad, "fan"-shaped resistive and magnetic transitions into the mixed state. Two mechanisms have been considered responsible for this behavior, namely, dissipative flux-line motion [13] and/or thermodynamic fluctuations of the order parameter [10] as discussed above. The study of these effects is important for the understanding of the nature of the superconducting transition and of the vortex structure in the mixed state.

Here we present high-precision measurements of the magnetization and resistivity of three $YBa_2Cu_3O_{7-\delta}$ crystals near the superconducting transition in magnetic fields applied perpendicular to the CuO layers. Both quantities are found to show scaling behavior in the variable t_G near $T_c(H)$. For purposes of data presentation, we write $t_G=A[T-T_c(H)]/(TH)^{2/3}$, where

$$A=\frac{(T_cH)^{2/3}}{T_cG(H)}=\left(\frac{\Phi_0\xi_cH_{c2}^2}{8\pi k_B\kappa^2T_c^{3/2}}\right)^{2/3}$$

is a field- and temperature-independent coefficient. This scaling behavior is expected on the basis of the 3D GL theory in a high magnetic field [7–12]. The values of the mean-field transition temperature $T_c(H)$ determined from a fit of the experimental data by the GL scaling form are in good agreement with earlier determinations [14,15]. The same values of $T_c(H)$ produce optimal fits for both the conductivity and the magnetization on the *same* crystal. Analysis of published specific-heat [3] and Ettinghausen-effect [16] data indicates that this scaling is a *general* property of $YBa_2Cu_3O_{7-\delta}$.

Two crystals, one with mass 1.94 mg, (magnetic) $T_c=89.9$ K, and $\Delta T_c=0.2$ K (crystal No. 1) and the other with mass 4.2 mg, (magnetic) $T_c=92.1$ K, and $\Delta T_c=0.25$ K (crystal No. 2), were selected for the magnetization experiments. Crystal No. 1 was detwinned by annealing under uniaxial stress [17]. The resistivity was measured on crystal No. 1 and a third crystal which had a (resistive) $T_c=92.2$ K. Electrical contacts were made by sintering silver paste pads to the sample surface. The magnetization was measured in a commercial SQUID in fields up to 5 T.

Figure 1 shows the temperature dependence of the magnetization of crystals No. 1 (top panel) and No. 2 (bottom panel) in different fields parallel to the c axis. The normal-state magnetization, obtained from a least-squares fit to the data for $T>170$ K, has been subtracted. For crystal No. 1, the normal-state background is temperature independent, $\chi_c=6.1\times10^{-7}$ cm^3/g, whereas for crystal No. 2 an additional strong Curie-Weiss-like

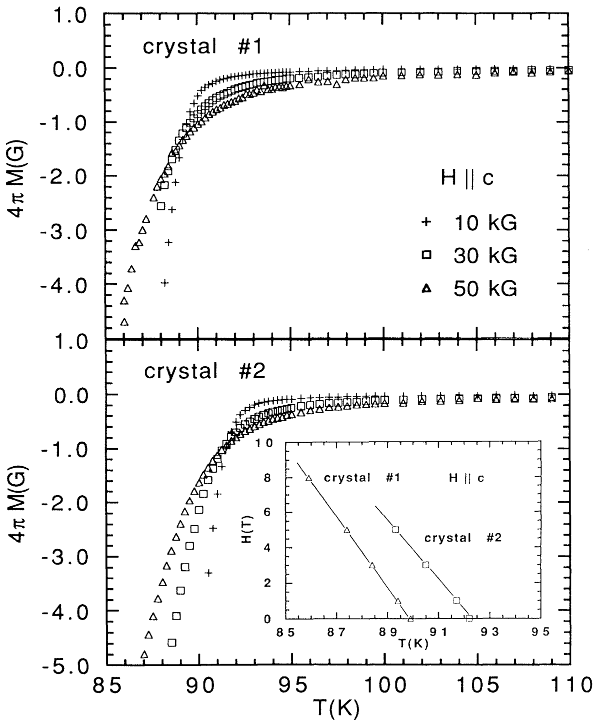

FIG. 1. Temperature dependence of the magnetization of crystals No. 1 (top) and No. 2 (bottom) in different fields parallel to **c**. Inset: $H_{c2}(T)$ for both crystals as determined from the scaling.

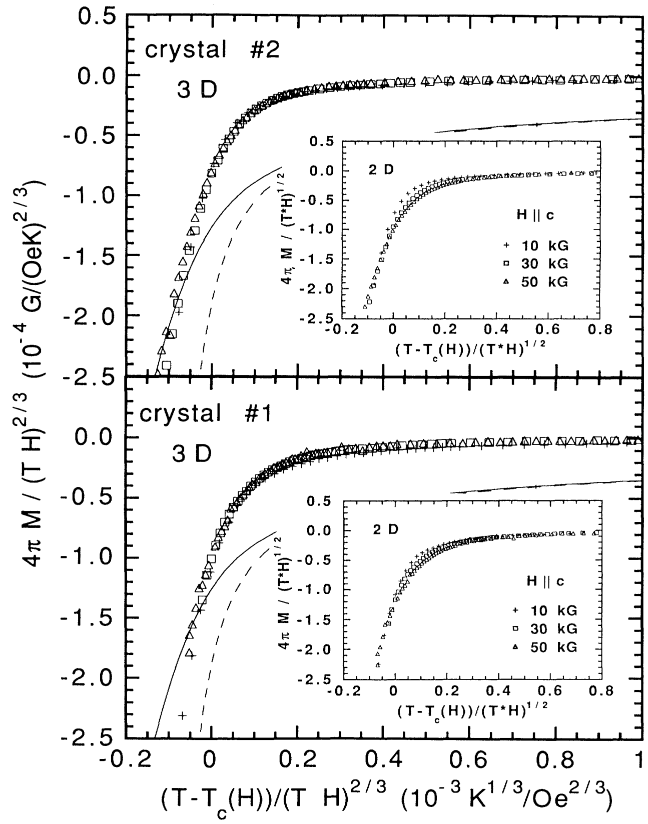

FIG. 2. 3D scaling of the magnetization for crystals No. 1 and No. 2. Insets: The 2D scaling behavior.

contribution (probably due to growth flux inclusions) is observed, and is likewise subtracted. However, the superconducting signals for both crystals are very similar. This indicates that the results of this study are not artifacts of a specific form of the normal-state background.

Critical phenomena and scaling properties of thermodynamic quantities at the transition into the mixed state have been studied by Bray [7], Thouless [8], and Ruggeri and Thouless [9], who find scaling in the variable t_G for a system which is 3D in zero field. Ikeda *et al.* [10] have extended this theory to the description of the resistivity, specific heat, and the flux-line correlations in high-T_c superconductors. Recently, Ullah and Dorsey [12] obtained expressions for the scaling functions of various thermodynamic and transport quantities within the Hartree approximation. The magnetization M, conductivity σ, Ettinghausen coefficient U_ϕ, and specific heat C scale as

$$\Xi_i = \left(\frac{T^2}{H}\right)^{\varepsilon_i} F_i\left(A\frac{T-T_c(H)}{(TH)^{2/3}}\right). \qquad (1)$$

The Ξ_i represent the measured quantities: $\Xi_1 = M/H$, $\Xi_2=\sigma$, $\Xi_3 = U_\phi/H$, $\Xi_4 = C/T$, $\varepsilon_1=\varepsilon_2=\varepsilon_3=\frac{1}{3}$, and $\varepsilon_4=0$. The F_i are the scaling functions which are not known precisely (they depend on the approximations used to solve the GL equation), but which are universal for all materials. For large negative $T-T_c(H)$ they reduce to the mean-field behavior. The coefficient A [or equivalently $G(H)$] determines the transition width. Note that $A \propto H_{c2}/T_c\gamma^{2/3}\kappa^{4/3}$, showing how large anisotropies $\gamma=\xi_{ab}/\xi_c$, a large κ, and a high transition temperature increase the fluctuational region as compared to conventional superconductors. If the quantities $\Xi_i(H/T^2)^{\varepsilon_i}$ are plotted versus t_G, then single curves, independent of H, are expected.

The results for the fluctuation magnetization and conductivity scaled in this way are shown in Figs. 2 and 3, respectively. The fluctuation conductivity shown in the insets of Fig. 3 has been obtained by subtracting the normal-state resistivity ρ_n (assumed linear in T) from the data, where ρ_n was obtained at temperatures above 170 K. For crystal No. 1 $\rho_n = 113.8 + 2.33T$ $\mu\Omega$ cm, and for crystal No. 3 $\rho_n = -14.4 + 3.24T$ $\mu\Omega$ cm. For each measurement, all the data can be collapsed onto a single curve, consistent with Eq. (1). The only free parameters in this scaling are the values of $T_c(H)$ at the measured fields. These were determined by optimizing the scaling fit using linear and nonlinear $T_c(H)$ curves. The optimum fit resulted from a linear $T_c(H)$ form with an uncertainty in the slopes dH_{c2}/dT of approximately 0.2 T/K (inset of Fig. 1). For the magnetization and resistivity data of crystal No. 1, the *same* set of $T_c(H)$ values has been used. The results of $dH_{c2}/dT = -1.7$ and -1.9

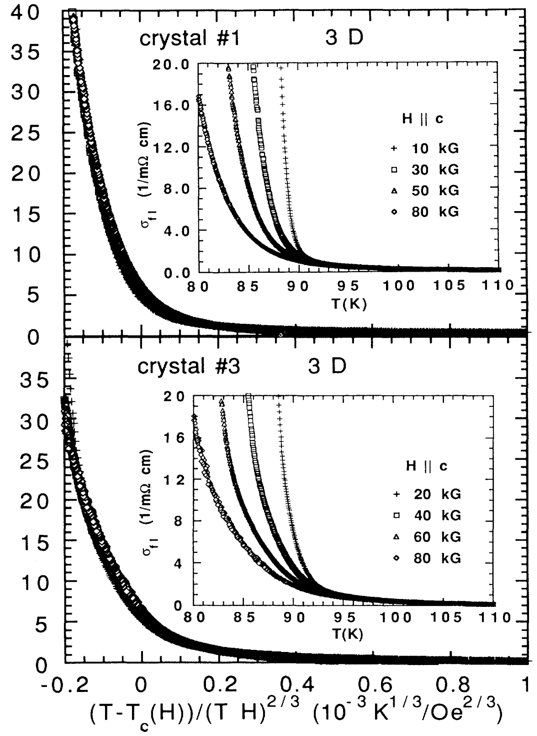

FIG. 3. 3D scaling of the fluctuation conductivity of crystals No. 1 and No. 3. Inset: The temperature dependence of the fluctuation conductivity.

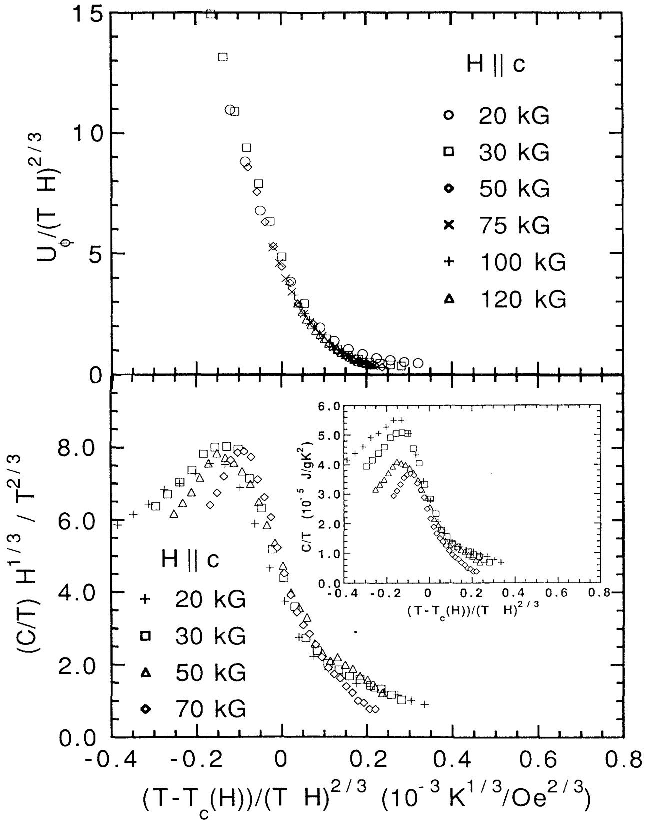

FIG. 4. Scaled representation of the Ettinghausen effect [16] and specific heat [3]. The units for the Ettinghausen effect and the specific heat are 10^{-17} (J/m)/(Oe K)$^{2/3}$ and 10^{-5} (J/g K^2)Oe$^{1/3}$/K$^{2/3}$, respectively. Inset: C/T as a function of $[T-T_c(H)]/(TH)^{2/3}$.

T/K for crystals No. 1 and No. 2, respectively, are in good agreement with earlier values obtained from magnetization measurements [14,15]. A slope of $dH_{c2}/dT = -7$ T/K [16] would not be compatible with the scaling of our data. The insets in Fig. 2 show fits by an assumed 2D scaling form, for which universal curves of the form $M/(TH)^{1/2}$ vs $[T-T_c(H)]/(TH)^{1/2}$ are expected. The 2D scaling form does not work as well as the 3D scaling near the transition, but it might work better at temperatures well above $T_c(H)$. This demonstrates that the superconducting transition of $YBa_2Cu_3O_{7-\delta}$ is 3D in nature.

The expressions for the fluctuation conductivity have been derived [12] in linear-response theory, and contain the orbital free-energy derivable contributions, i.e., the Aslamazov-Larkin terms [18]. The Maki-Thompson [19] and Zeeman [20] corrections are not included. These corrections are expected to be small in a 3D system near $T_c(H)$, although they might be responsible for the small deviations from scaling observed near the transition. We observe additional deviations from the scaling in other crystals with imperfections such as cracks or holes.

Thermodynamic considerations suggest that such scaling behavior should be evident in other measurements as well. It is therefore instructive to reanalyze published data of the Ettinghausen effect and the specific heat. The top panel of Fig. 4 shows that the Ettinghausen-coefficient data [16] scale nicely according to Eq. (1) for $H \geq 2$ T, with $dH_{c2}/dT = -1.9$ T/K. The specific-heat data [3] scaled according to Eq. (1) are shown in the inset of the bottom panel of Fig. 4. Using $dH_{c2}/dT = -1.9$ T/K, we observe scaling of the data on the high-temperature side of the peak around $T_c(H)$, as well as of the peak positions of $H \geq 2$ T. This indicates that t_G is also the proper scaling variable of the specific heat. The deviations from the other scaled data of the 7-T data at high temperatures may be related to a different normal-state behavior in this field as compared to the other field values (see Fig. 2 of Ref. [3]). But, as has been mentioned before [3], Eq. (1) does not account for the field dependence of the height of the specific-heat peak. By phenomenologically introducing in Eq. (1) a nonvanishing exponent $\varepsilon_4 = \frac{1}{3}$, good scaling of the high-temperature side of the peak around $T_c(H)$, of the peak position, and of the peak height as well can be achieved, as shown in the bottom panel of Fig. 4. A similar analysis has been presented earlier [21]. Thus, the peak height decreases roughly like $H^{-1/3}$ and the transition width grows like $H^{2/3}$.

The reasons for the poor scaling of the height of the specific-heat peak according to Eq. (1) in its original form ($\varepsilon_4=0$) are not yet completely understood. It has been interpreted [3] as evidence for the breakdown of GL theory and the onset of finite-size effects. Alternatively, the vortex structure, which has not yet been included in the calculation of the scaling functions, can influence the specific heat below $T_c(H)$. In the high-field limit ($H \approx H_{c2}$) it has been shown [22] that the vortex structure suppresses the specific-heat anomaly of high-κ superconductors in a magnetic field. This has been observed experimentally on Ti-Mo and V-Ta alloys [23]. For intermediate fields ($H_{c1} \ll H \ll H_{c2}$) the effect of the vortex structure on the specific heat can be estimated using the Maxwell relation and the expression for the mean-field magnetization valid in this field range [15]: $4\pi M = -\alpha H_{c1} \ln(\beta H_{c2}/H)/(2\ln\kappa)$ with $\alpha=0.77$ and $\beta=1.44$. Assuming linear $H_{c1}(T)$ and $H_{c2}(T)$, this yields $(1/T)\,\partial C/\partial H \approx -2\times10^{-4}$ mJ/g K^{2}kG. In 5 T, this is a substantial fraction of the peak height, and therefore has to be included. In addition, entropy contributions due to the elasticity of the flux lines have been considered [24]. These corrections may be more important for the specific heat, which is a second derivative of the free energy, than for the magnetization conductivity and Ettinghausen coefficient, which are proportional to first derivatives.

The results presented here show that near $T_c(H)$, the superconducting magnetization, conductivity, specific heat, and Ettinghausen coefficient display scaling behavior in the variable $[T-T_c(H)]/(TH)^{2/3}$ predicted [7-12] on the basis of Ginzburg-Landau fluctuational theory for a 3D superconductor in a high magnetic field. These results support the interpretation [10] that the field independence of the onset temperature and the development of the characteristic fan-shaped magnetic and resistive transitions are primarily caused by thermodynamic fluctuations of the superconducting order parameter. The region where the scaling holds is roughly given by $T-T_c(H) \leq 2\times10^{-4}(TH)^{2/3}$, and corresponds to approximately the top 50% of the resistive transitions. The nature of the crossover from this fluctuation-dominated regime to the regime at lower temperatures, where the properties of the mixed state are determined by the vortex structure, remains unclear. The observation of scaling allows a self-consistent determination of $T_c(H)$ from a fit by the scaling form. These results suggest that $YBa_2Cu_3O_{7-\delta}$ behaves similarly to the low-T_c materials in a large magnetic field, but with stronger fluctuation effects. Because of their larger anisotropy and larger value of κ, the Bi- and Tl-based CuO superconductors are expected to show even more pronounced fluctuations, which could cause critical phenomena beyond GL theory.

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[a] Also at The Institute of Solid State Physics, Chernogolovka, Moscow District, U.S.S.R.

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