Magnetic-Field-Induced Finite-Size Effect in the High-Temperature Superconductor $YBa_2Cu_3O_{7-\delta}$: A Comparison with Rotating Superfluid ^4He

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(Received 16 April 2003; published 11 November 2003)

The effect of strong magnetic fields (11 T) on superconductivity in $YBa_2Cu_3O_{7-\delta}$ is investigated using high-resolution thermal expansion. We show that the field-induced broadening of the superconducting transition is due to a finite-size effect resulting from the field-induced vortex-vortex length scale. The physics of this broadening has recently been elucidated for the closely related case of rotating superfluid ^4He [R. Haussmann, Phys. Rev. B **60**, 12 373 (1999)]. Our results imply that the primary effect of magnetic fields of the order of 10 T is to destroy the phase coherence; the pairing, on the other hand, appears to be quite insensitive to these fields.

DOI: 10.1103/PhysRevLett.91.207001 PACS numbers: 74.72.Bk, 05.70.Jk, 74.25.Bt

In classical mean-field type-II superconductors there exists a well-defined upper critical field, $H_{c2}(T)$, above which superconductivity is fully destroyed by the applied magnetic field. The value of H_{c2}, which is an important fundamental parameter of a superconductor and provides a measure of both the Ginzburg-Landau (GL) coherence length ξ_{GL} and the strength of the pairing, can reliably be determined by, for example, resistive, magnetic, or calorimetric experiments. In contrast, in high temperature superconductors (HTSC) the superconducting transition is significantly broadened by a magnetic field, hindering a straightforward determination of H_{c2} and/or ξ_{GL}. The physics of this broadening has received considerable experimental [1–4] and theoretical [5,6] attention, and experimental data have been controversially analyzed using the scaling approaches of the 3D XY and/or lowest-Landau-level (LLL) fluctuation models.

In a recent theoretical paper [7], Haussmann showed that a similar broadening is expected for rotating superfluid ^4He, in which the rotational frequency is analogous to the magnetic field in a superconductor. A simple explanation of this broadening was given in terms of a finite-size effect due to the additional vortex-vortex length scale, which prevents the correlation length from diverging resulting in a broadened transition. Superfluidity in ^4He and superconductivity both belong to the 3D XY universality class [8]. The calculations of Ref. [7], however, go beyond the usual 3D XY scaling approach which has been applied to HTSC because they provide an explicit scaling function for the specific heat and the degree of broadening is directly given in terms of the correlation length. A sketch of this finite-size scaling applied to superconductors has recently been reported by Schneider [9].

In this Letter, using high-resolution thermal expansion data of a $YBa_2Cu_3O_{7-\delta}$ single crystal in magnetic fields up to 11.4 T, we show that the broadening of the thermodynamic transition in an optimally doped HTSC is identical to that calculated by Haussmann for superfluid ^4He. (We note that this effect has not been observed in ^4He because of the large extrinsic rotationally induced broadening due to pressure gradients [7].) This finding has strong implications for the understanding of the H-T phase diagram of HTSC. First, it shows that T_c is essentially a 3D XY phase-ordering transition and that magnetic fields on the order of 10 T affect only the phase coherence. Second, our results suggest that a much higher field scale must exist where the pairing amplitude is reduced.

The thermal expansivity measurements have been performed on a nearly optimally doped ($\delta = 0.05$; $T_c = 91.4 \pm 0.15$ K) detwinned $YBa_2Cu_3O_{7-\delta}$ single crystal from the same batch as used in previous studies [10,11]. A high-resolution capacitance dilatometer with a relative resolution of $\Delta L/L = 10^{-9}$ was used at a constant heating rate of 15 mK/s and in fields up to 11.4 T.

The thermal expansivity is directly proportional to the specific heat close to a phase transition and, as shown previously [10,11], for $YBa_2Cu_3O_{7-\delta}$ it is of great advantage to examine the expansivity instead of the specific heat due to the much larger superconducting-signal to phonon-background ratio—especially if one considers the difference in the linear expansivities of the a and b axes, α_{b-a}. Figure 1(a) shows the electronic part of α_{b-a}, which is obtained by subtracting the phonon background as shown previously [11]. In a magnetic field the λ-shaped zero-field anomaly, which has been analyzed in detail [10,11], is broadened as it is known from various thermodynamic and transport measurements [1,3,12–15]. At lower temperatures additional sharp peaks appear in α_{b-a}, which are not of electronic origin but are rather due to irreversible magnetostrictive effects at the irreversibility line [16].

The first important result, which directly follows from an inspection of the data in Fig. 1(a), is that 11.4 T have no visible effect on the quite sizable fluctuation

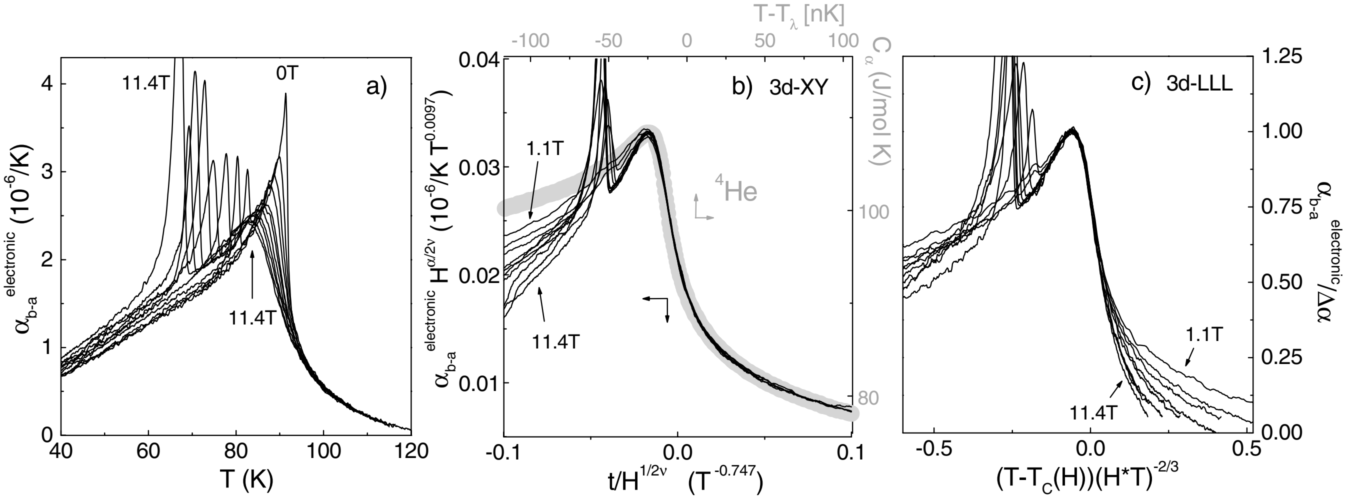

FIG. 1. Electronic thermal expansivity, $\alpha_{b-a}^{\text{electronic}}$, of $YBa_2Cu_3O_{6.95}$ in magnetic fields of 0, 1.1, 2.3, 3.4, 4.6, 5.7, 6.8, 8, 9.1, 10.2, and 11.4 T ($H \| c$ axis). (b) 3D *XY* and (c) 3D LLL scaling of the data in (a). The thick gray curve in (b) represents the specific heat of rotating ($\omega = 2\pi/\text{s}$) ^{4}He at the λ transition from Ref. [7].

contribution extending to about 30 K above T_c suggesting that "T_c" is not shifted by the field. This is in strong contrast to the behavior of a classical superconductor with fluctuations in which T_c, and thus also the temperature at which the fluctuations should diverge, decreases with applied field [17]. The above behavior is, however, expected in the 3D *XY* approach; in the following we show that our data exhibit excellent 3D *XY* scaling and match the scaling function for the specific heat of ^{4}He from Ref. [7].

In Fig. 1(b) the expansivity data near T_c are plotted using the 3D *XY* scaling variables ($\alpha H^{\alpha'/2\nu}$ vs $t/H^{1/2\nu}$), where $t = (T - T_c)/T_c$ and $\nu = 0.669$ and $\alpha' = -0.013$ (not to be confused with the expansivity α) are values for the 3D *XY* critical exponents. Very good scaling is observed over a wide range of values of $t/H^{1/2\nu}$ extending from the peak in alpha to $t/H^{1/2\nu} = 0.1$ [18]. The appropriately scaled specific heat data for rotating ^{4}He (thick gray curve) from Ref. [7] also scales perfectly with our expansivity data suggesting a similar broadening mechanism for both cases. The data do not scale below the peak in the expansivity—we attribute this to the temperature dependence of the "jump" component, which also affects the scaling below T_c in zero field [10]. It is interesting to note that the peaks of the expansivity at the irreversibility temperature also scale quite well suggesting that the irreversibility/melting transition also obeys 3D *XY* scaling, as has been noted previously [12–14,19].

We also tried to scale our data using the 3D LLL approach [20,21], in which one plots $\alpha/\Delta\alpha(H)$ vs $[T - T_c(H)](HT)^{-2/3}$ as shown in Fig. 1(c). $\Delta\alpha(H)$ is the field-dependent mean-field component of the anomaly and $T_c(H)$ is the field-dependent mean field T_c, which was chosen to be constant and equal to $T_c(H = 0)$. To obtain any kind of scaling close to T_c we have to set $\Delta\alpha(H)$ equal to the anomaly height at the peak. For this case we get reasonably good scaling close to T_c. Actually this is not unexpected because close to T_c the 3D *XY* and 3D LLL approaches are mathematically nearly identical and have scaling exponents too similar to be experimentally distinguishable [1]. However, a clear lack of scaling is observed for $[T - T_c(H)](HT)^{-2/3}$ greater than about 0.05. This is not improved by replacing the constant T_c by a $T_c(H)$. The reason we are able for the first time to clearly distinguish between 3D *XY* and 3D LLL scaling is because we are able to check for scaling over a much larger interval of the respective scaling variables due to a better knowledge of the background.

In Fig. 2 we show the correlation length in the vicinity of T_c obtained by scaling the width of the broadening seen in the thermal expansivity data to the results for ^{4}He [7,22]. $YBa_2Cu_3O_{7-\delta}$, in contrast to ^{4}He, is anisotropic, and a field parallel to the c axis probes the in-plane correlation length, ξ_{ab} [9]. The dotted lines represent the zero-field behavior with $\xi_{ab}^- = 12 \pm 1$ Å and $\xi_{ab}^+ = 4.5 \pm 1$ Å, and the solid line the approximate behavior expected in a field of 5 T in analogy to ^{4}He [7,23]. As can be seen, the correlation length is cut off by the length scale ℓ (dashed line), which for a superconductor is given by [7,9]

$$\ell = \sqrt{\Phi_o/2\pi H}. \tag{1}$$

In the 3D *XY* approach the correlation lengths above, ξ_{ab}^+, and below, ξ_{ab}^-, T_c follows a power law of the form $\xi^{\pm} = \xi_0^{\pm}|t|^{-\nu}$. *Two-scale-factor universality* [23,24] provides an explicit relation between ξ_{ab}^+ and ξ_{ab}^- and the specific heat amplitudes $A^+/A^- \cong 1.054$,

$$\left(\frac{\xi_0^-}{\xi_0^+}\right)^3 = \frac{A^+}{A^-}\left(\frac{R_\xi^-}{R_\xi^+}\right)^3 \approx (2.7)^3, \tag{2}$$

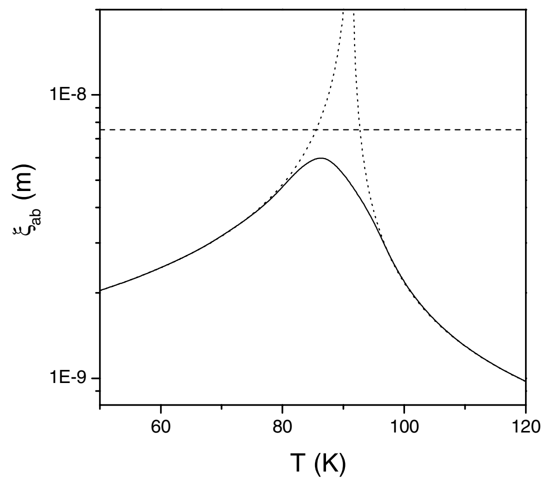

FIG. 2. In-plane correlation length, ξ_{ab}, of $YBa_2Cu_3O_{7-\delta}$ around T_c derived from a comparison with the ^{4}He data of Ref. [7]. The horizontal dashed line represents the cutoff length scale ℓ in a field of 5 T and the dotted line the zero-field divergence.

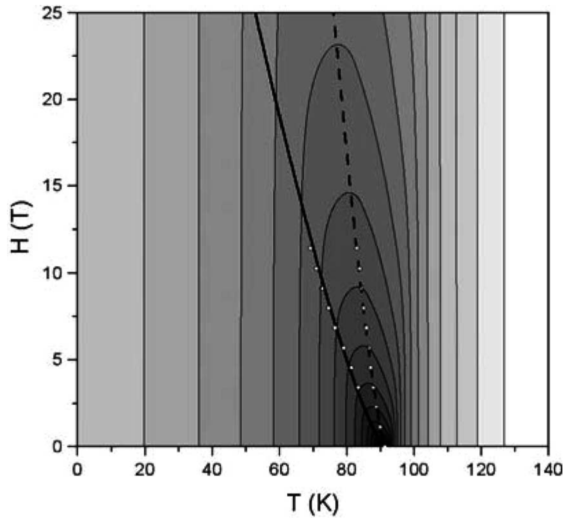

FIG. 3. Contour plot of ξ_{ab} in the H-T plane. Values of ξ_{ab} are represented using a logarithmic gray scale with white ($\log\xi = -9.2$) and black ($\log\xi = -7.5$) separated by steps of 0.1. The solid and dashed lines represent the vortex melting line, T_m, and the peak in the expansivity T_{peak}, respectively.

where $R_\xi^- \cong 0.95$ and $R_\xi^+ \cong 0.36$ are universal as well. The ratio $\xi_0^-/\xi_0^+ = \xi^-/\xi^+ \approx 2.7$ is responsible for the asymmetry in the temperature dependence of ξ relative to T_c. Values of the correlation length can be derived directly from the fluctuation amplitude of the specific heat using Eq. (2), and these values ($\xi_{ab}^- = 13$ Å [24]; $\xi_{ab}^- = 9$ Å [25]) agree very well with ours. This agreement together with the excellent scaling shown in Fig. 1 provides strong evidence that the field-induced broadening in $YBa_2Cu_3O_{6.95}$ is due to the same "finite-size" effect as in rotating ^{4}He.

Our results are summarized in the H-T phase diagram shown in Fig. 3. The contour lines, which represent constant values of the correlation length ξ_{ab}, show virtually no field effect below the vortex melting line (solid line) and above T_c(0 T). The dashed line represents the peak in the expansivity, T_{peak}. Both of these lines nicely follow the expected 3D XY scaling behavior, in which scaling assures that the ratio ξ/a is constant. Here a is the vortex spacing in an hexagonal lattice given by

$$a = \sqrt{2\Phi_o/\sqrt{3}B} \approx 2.7 \cdot \ell. \tag{3}$$

T_{peak} occurs near the maximum in the correlation length and is approximately given by the condition $\xi/a \approx \ell/a \approx 0.37$. This criterion is very similar to the one for classical superconductors at H_{c2} [17],

$$\frac{\xi_{\text{GL}}}{a} = \frac{\sqrt{\Phi_o/2\pi H_{c2}}}{\sqrt{2\Phi_o/\sqrt{3}H_{c2}}} = 0.371, \tag{4}$$

which suggests that T_{peak} represents a sensible criterion for "H_{c2}" in HTSC and shows that H_{c2} in classical superconductors in a sense is also due to a finite-size effect (overlapping of vortex cores). Physically, T_{peak} corresponds to the broadened remains of the zero-field phase-ordering transition—true phase coherence occurs only at T_m. Equations (3) and (4) suggest a close relationship between the correlation and coherence lengths and also provides a justification for the "classical" determinations of H_{c2} and ξ in HTSC using magnetization measurements ($\xi_{\text{GL}} = 16.4$ Å [26], $\xi_{\text{GL}} = 10.9$ Å [27]).

The previous discussion concentrated on the H_{c2} of the 3D XY phase-ordering transition, $H_{c2}^{3D\,XY}$. Our results suggest that a much higher field scale, H^{pairing}, might exist where the pairing correlations are destroyed. This is in analogy to the clear separation at zero field of T_c and the pairing at T^* in the preformed-pairs scenario of HTSC. $H_{c2}^{3D\,XY}$ and H^{pairing} can thus be viewed as the field dependencies of T_c and T^*, respectively. We observe no field effect on the 3D XY phase fluctuations above T_c(0 T) which demonstrates that fields on the order of 10 T have a negligible effect on the pairing amplitude. A similar conclusion was obtained by recent measurements of the Nernst signal by Wang *et al.* [28], and their Nernst contour lines are very similar to our Fig. 3. This suggests that H^{pairing} is much larger than $H_{c2}^{3D\,XY}$, in agreement with recent experimental [29] and theoretical [30] results, which find that this field scale is on the order of 100–200 T. Finally, in agreement with Ref. [31], we point out that this shows that a negligible magnetic-field effect (for $H = 10$–20 T) on the pseudogap [32,33] does not rule out superconducting pairing correlations as the origin of the pseudogap.

We acknowledge helpful discussions with A. Junod, T. Schneider, and G. A. Williams, and we thank W. Goldacker for the use of the high-field magnet system.

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