

Vortex lattice melting and H_{c2} in underdoped $\text{YBa}_2\text{Cu}_3\text{O}_y$ B. J. Ramshaw,¹ James Day,¹ Baptiste Vignolle,² David LeBoeuf,² P. Dosanjh,¹ Cyril Proust,^{2,3} Louis Taillefer,^{3,4} Ruixing Liang,^{1,3} W. N. Hardy,^{1,3} and D. A. Bonn^{1,3}¹*Department of Physics and Astronomy, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z1*²*Laboratoire National des Champs Magnétiques Intenses, UPR 3228, Centre National de la Recherche Scientifique, Institut National des Sciences Appliquées, Université Joseph Fourier, Université Paul Sabatier, Toulouse, France*³*Canadian Institute for Advanced Research, Toronto, Canada*⁴*Département de Physique and Regroupement Québécois sur les Matériaux de Pointe, Université de Sherbrooke, Sherbrooke, Québec, Canada J1K 2R1*

(Received 7 September 2012; published 1 November 2012)

Vortices in a type-II superconductor form a lattice structure that melts when the thermal displacement of the vortices is an appreciable fraction of the distance between vortices. In an anisotropic high- T_c superconductor, such as $\text{YBa}_2\text{Cu}_3\text{O}_y$, the magnetic field value where this melting occurs can be much lower than the mean-field critical field H_{c2} . We examine this melting transition in $\text{YBa}_2\text{Cu}_3\text{O}_y$ with oxygen content y from 6.45 to 6.92, and we perform a quantitative analysis of this transition in the cuprates by fitting the data to a theory of vortex-lattice melting. The quality of the fits indicates that the transition to a resistive state is indeed the vortex lattice melting transition, with the shape of the melting curves being consistent with the known change in penetration depth anisotropy from underdoped to optimally doped $\text{YBa}_2\text{Cu}_3\text{O}_y$. We establish these fits as a valid technique for finding $H_{c2}(T = 0)$ from higher-temperature data when the experimentally accessible fields are not sufficient to melt the lattice at zero temperature (near optimal doping). From the fits we extract $H_{c2}(T = 0)$ as a function of hole doping. The unusual doping dependence of $H_{c2}(T = 0)$ points to some form of electronic order competing with superconductivity around 0.12 hole doping.

DOI: [10.1103/PhysRevB.86.174501](https://doi.org/10.1103/PhysRevB.86.174501)

PACS number(s): 74.72.-h, 74.25.Uv

I. INTRODUCTION

Cuprate high- T_c superconductors are of great interest not only because of their high transition temperatures, but also because strong-correlation physics gives rise to peculiar normal-state properties. Ironically, however, the strength of the superconductivity in these high- T_c materials is what interferes with measurement of the normal-state properties at low temperature. Applying high magnetic fields can overcome this and has led to the discovery of a small Fermi surface in underdoped $\text{YBa}_2\text{Cu}_3\text{O}_y$ via quantum oscillation measurements in pulsed fields.¹ This discovery prompted a large experimental survey of the transport and thermodynamic properties of $\text{YBa}_2\text{Cu}_3\text{O}_y$ in high fields. The questions remain as to whether the high fields are revealing the normal-state properties of $\text{YBa}_2\text{Cu}_3\text{O}_y$, or are instead exposing a qualitatively different field-induced ground state, or whether one might still be in a regime dominated by superconducting pairing and the presence of vortices.

The idea of high magnetic fields revealing the normal state in cuprate superconductors is a contentious one, in part because the phase diagram of the cuprates differs qualitatively from that of conventional type-II superconductors. Owing to the short coherence length, low superfluid phase stiffness, and strong anisotropy, fluctuations play a dominant role in the phase diagram. There is evidence for three-dimensional (3D) XY critical fluctuations below and above T_c .²⁻⁴ Previous transport measurements on several cuprate compounds have shown that reaching the resistive state requires very high magnetic fields, and that the onset of resistivity as a function of field and temperature does not follow the conventional H_{c2} curve derived from Ginzburg-Landau theory, as it does in more conventional type-II superconductors.^{5,6} Instead, as is expected for a superconductor governed by strong thermal fluctuations,

a vortex melting transition occurs,^{5,7,8} with an extensive crossover regime to the normal state. Some Nernst effect experiments have been taken as evidence for the presence of superconducting pairing far above T_c , even in strong magnetic fields.⁹ With this in mind, it is important to consider at which field scale is superconductivity completely suppressed and the normal state recovered, especially with regard to quantum oscillation experiments, which are purported to probe the “normal-state” Fermi surface. In this paper we present, in the cuprates, a detailed comparison of the melting transition in $\text{YBa}_2\text{Cu}_3\text{O}_y$ with the theory of vortex-lattice melting.

II. THEORY

The thermodynamic critical field H_c is the field at which superconductivity is destroyed in a type-I superconductor, and is directly related to the condensation energy of the superconducting ground state. In a type-II superconductor the magnetic field can penetrate the sample at a field lower than H_c . At this field, H_{c1} , the magnetic field penetrates the superconductor in the form of vortices, with each vortex being supercurrent running around a normal-state core and containing a quantum of magnetic flux. The cores of these vortices, whose size is of order the superconducting coherence length ξ_0 , are in the normal state; outside of the vortex cores, the strength of the magnetic field decays over the length scale of the penetration depth λ , which, for strongly type-II superconductors such as the cuprates, is much larger than the coherence length. These vortices can form a two-dimensional lattice perpendicular to the applied field (a “vortex lattice”),¹⁰ and the lattice spacing shrinks in size as the magnetic field is increased. As long as the vortices remain pinned, the zero-resistance

property is maintained in the material. When the vortex cores overlap at a second field scale H_{c2} , superconductivity is destroyed. In an isotropic, low- T_c type-II superconductor, such as Nb₃Sn, resistivity sets in at H_{c2} and the diamagnetic signal of superconductivity completely disappears. In terms of the mean-field Ginzburg-Landau coherence length ξ_0 , this field scale is

$$\mu_0 H_{c2}(T=0) = \frac{\Phi_0}{2\pi\xi_0^2}, \quad (1)$$

where Φ_0 is the flux quantum in SI units [$H_{c2}(T=0)$ will henceforth be $H_{c2}(0)$].¹¹

The situation is more complicated in high- T_c materials, where the vortex lattice can melt into a vortex liquid well below H_{c2} . The Lindemann criterion for melting requires the thermal displacement of a lattice to be some fraction (defined c_L) of the average lattice constant. Using the Lindemann criterion for a vortex lattice, Houghton *et al.*¹² have shown that, because of the large anisotropy in the cuprates, the vortex lattice in a strongly type-II superconductor with a high T_c can melt at field values B_m well below H_{c2} for intermediate temperatures (away from 0 K and T_c).¹³ In these materials, H_{c2} represents a crossover from a vortex-liquid to the normal state. In the traditional picture the melting field B_m and $\mu_0 H_{c2}$ are equal at zero temperature, since there are no thermal fluctuations at zero temperature to melt the vortex lattice. The presence of strong quantum fluctuations could result in a vortex liquid persisting down to zero temperature. However, in order to compare our experimental data with the theory of vortex lattice melting, we use the assumption made by Houghton *et al.*,¹² Blatter *et al.*,¹³ and others that $B_m(0) = \mu_0 H_{c2}(0)$.

Using the notation of Blatter *et al.*,¹³ the melting transition field B_m is given implicitly by

$$\frac{\sqrt{b_m(t)}}{1 - b_m(t)} \frac{t}{\sqrt{1-t}} \left[\frac{4(\sqrt{2}-1)}{\sqrt{1-b_m(t)}} + 1 \right] = \frac{2\pi c_L^2}{\sqrt{Gi}}. \quad (2)$$

The reduced field variable is $b_m = B_m/\mu_0 H_{c2}$, and $t = T/T_c$ is the reduced temperature.

The Ginzburg number Gi , on the right hand side of Eq. (2), is given by

$$Gi = \frac{1}{2} \left(\frac{k_B T_c \gamma}{\frac{4\pi}{\mu_0} [(\mu_0 H_c(T=0))^2 \xi_0^3]} \right)^2 \quad (3)$$

$$\approx [9.225 \times 10^8 (\text{Wb}^{-1} \text{K}^{-1}) \times \mu_0 H_{c2}(0) T_c \lambda_{ab} \lambda_c]^2, \quad (4)$$

where γ is the anisotropy ratio $\gamma \equiv \frac{\lambda_c}{\lambda_{ab}}$, and the definition $H_{c2}(0) \equiv \frac{4\pi \lambda_{ab}^2 [\mu_0 H_c(T=0)]^2}{\Phi_0}$ has been used (λ_{ab} and λ_c are the penetration depths parallel and perpendicular to the \hat{a} - \hat{b} plane at zero temperature). As emphasized by Blatter *et al.*,¹³ this Ginzburg number should be thought of as a useful collection of parameters, and not as a number describing the width of fluctuations around T_c as it is in more three-dimensional superconductors. The Lindemann number c_L appearing on the right hand side of Eq. (2) represents the fraction of the vortex lattice parameter, $a_v \equiv \sqrt{\frac{\Phi_0}{B}}$, that the thermal displacement must reach in order for the vortex lattice to melt.^{7,12,13} Attempts have been made to calculate c_L , with values between 0.2 and 0.4 obtained for the cuprates, depending on the specific model

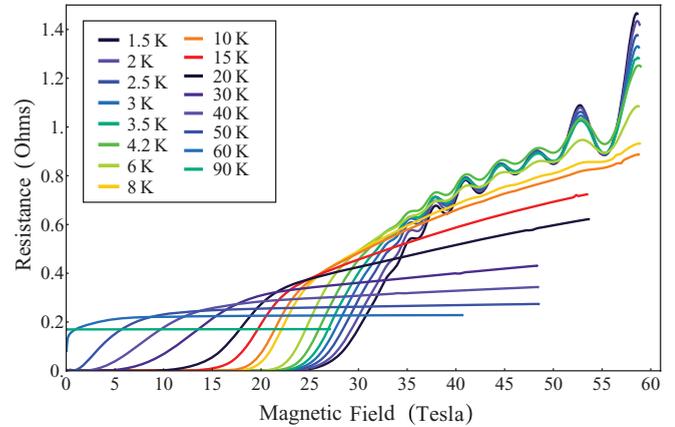


FIG. 1. (Color online) The \hat{c} -axis resistance of YBa₂Cu₃O_{6.59} as a function of magnetic field, from 1.5 to 200 K. The onset of resistivity as field is increased marks the vortex lattice melting transition. At low temperatures, quantum oscillations are seen above this melting field.

(see Blatter *et al.*¹³ for a review), but c_L is probably better left as a fit parameter.¹⁴

III. EXPERIMENT

All of the samples used in this study were fully detwinned, single-crystal YBa₂Cu₃O_y, grown in barium zirconate crucibles and annealed in oxygen to the desired concentration.¹⁵ Gold contacts were evaporated onto the a - b faces for a four-point c -axis resistivity geometry, and the gold was partially diffused into the sample near 500 °C to obtain subohm contacts.¹⁶ The chain oxygen was then ordered into superstructures (ortho-II for YBa₂Cu₃O_{6.45} through YBa₂Cu₃O_{6.59}, ortho-VIII for YBa₂Cu₃O_{6.67}, ortho-III for YBa₂Cu₃O_{6.75}, and ortho-I for YBa₂Cu₃O_{6.86} and YBa₂Cu₃O_{6.92}) by annealing the samples just below the superstructure transition temperature.¹⁷ Figure 1 shows a typical set of \hat{c} -axis resistivity curves up to 60 Tesla, from 1.5 to 200 K for YBa₂Cu₃O_{6.59}. We define the resistive vortex-melting transition as the magnetic field where the resistance is 1/100 of its value at 60 Tesla. The definition of B_m from resistivity curves is somewhat uncertain because of the width of the resistive transition (see upper panel of Fig. 2). An alternative definition would be the intersection of a line tangent to the steepest part of the resistive transition with the temperature axis. This would lead to small offsets (one Tesla at most) in B_m , but would not otherwise affect the conclusions of this paper. However, it is important that a consistent definition across different doping levels be used.

The upper panel of Fig. 2 shows the vortex lattice melting transition from 1.2 K up to T_c for YBa₂Cu₃O_{6.59}, one of the underdoped samples in which the melting transition is accessible even at low temperatures. The concave upwards shape is characteristic of a vortex melting transition, as seen before in YBa₂Cu₃O_y and in other cuprates,^{6,14} and differs qualitatively from the concave downwards curvature of $H_{c2}(T)$ in conventional superconductors. This form has been observed in a number of cuprates,^{6,18,19} but a systematic comparison to Eq. (2) across the underdoped regime of the cuprates has not been performed. Here we present data for

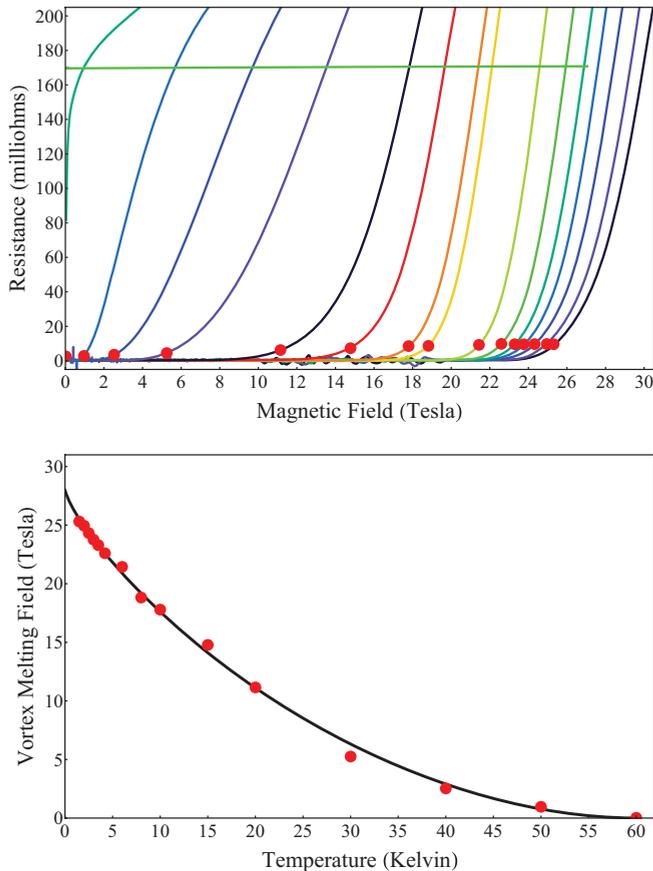


FIG. 2. (Color online) Top: A magnified plot of the resistive transitions shown above in Fig. 1. The red dots are where the resistance is $1/100$ of its value at 60 T (extrapolated for high temperatures where resistance was not measured to the highest fields). Bottom: The same data points as highlighted in red in the top panel, now plotted as a function of temperature. The black line is a fit to Eq. (2), using the known parameters given in Table I, and gives $\mu_0 H_{c2}(0) = 28 \pm 0.3$ T, and $c_L = 0.37$.

$\text{YBa}_2\text{Cu}_3\text{O}_y$ from oxygen content 6.45 to 6.92, with T_c s ranging from 44.5 to 93.5 K, and identify trends that arise as a function of doping. Characteristic curves for several other dopings are shown in Fig. 3, all with an upwards curvature, although that shape becomes less pronounced for the higher T_c samples.

Equation (2) can be expanded about T_c and solved for B_m as shown in Blatter *et al.*,¹³ but if the full temperature range from 1.5 K to T_c is to be used then it is more accurate to fit to the full implicit expression for B_m . The use of Eq. (2) requires both the in-plane and out-of-plane zero-temperature penetration depths, as well as the T_c : these values are also listed along with the hole doping (estimated using Liang *et al.*²⁰) in Table I. The in-plane penetration depth values, λ_{ab} , come from electron-spin resonance (ESR) measurements²¹ and from muon-spin rotation experiments,²² both performed on comparable $\text{YBa}_2\text{Cu}_3\text{O}_y$ crystals grown at the University of British Columbia (UBC). In the case of the ESR values, the geometric mean of λ_a and λ_b was taken. Out-of-plane penetration depth values, λ_c , come from infrared reflectance measurements,²³ also performed on UBC crystals. Interpolated

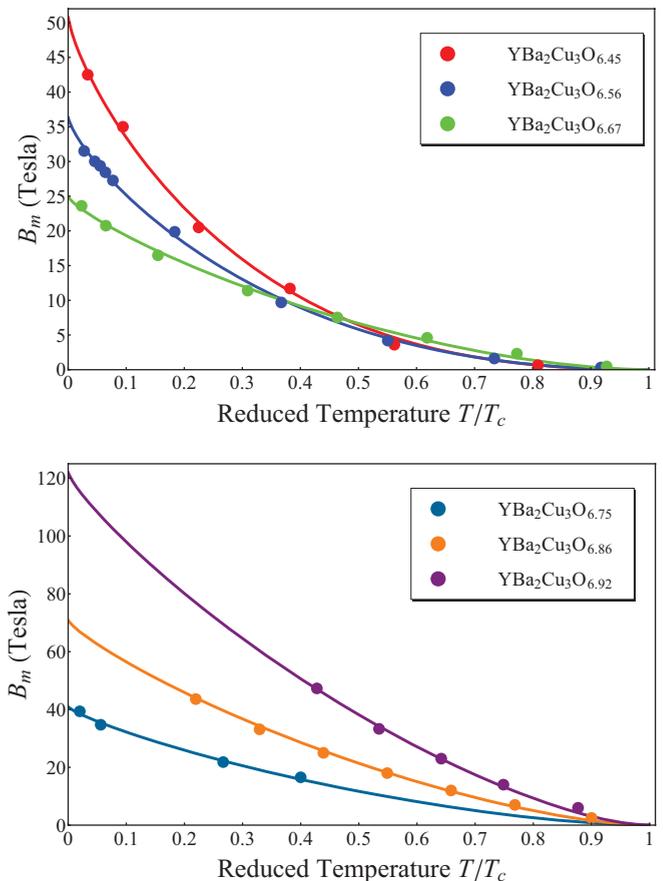


FIG. 3. (Color online) The vortex lattice melting transition for several different oxygen concentrations. The temperature axis has been scaled by T_c , and the lines are best-fit lines to Eq. (2). All of the data points were acquired in the same manner as described in the caption of Fig. 2.

values for the penetration depth were used when the exact doping values were not available. The penetration depth values and the interpolation are shown in the upper panel of Fig. 4.

With λ_c , λ_{ab} , and T_c experimentally determined, the data at each doping can be fit using only two parameters: c_L and $H_{c2}(0)$. The fits in the lower panel of Fig. 2 and in Fig. 3 clearly show that three-dimensional vortex melting describes the in-field resistive transition in $\text{YBa}_2\text{Cu}_3\text{O}_y$ from $y = 6.45$ to 6.92. The penetration depth anisotropy, $\gamma = \frac{\lambda_c}{\lambda_{ab}}$, changes from ~ 50 at 6.45 to ~ 16 at 6.92; this results in decreased curvature of the melting line as oxygen content (and hole doping) increases. This is the same behavior seen in several different cuprates of varying anisotropy, reported in Ando *et al.*⁶ The c_L and $H_{c2}(0)$ values extracted this way are given in Table I for all of the dopings measured. The fact that the Lindemann number remains relatively constant as a function of doping means that the shape of the melting curve is determined primarily by the penetration depths, which are becoming less anisotropic as hole doping increases. The Lindemann number and the penetration depths appear only as the ratio $\frac{c_L^2}{\lambda_{ab}\lambda_c}$ in Eq. (2), and we plot this ratio in the lower panel of Fig. 4. The increase of $\frac{c_L^2}{\lambda_{ab}\lambda_c}$ with hole doping is what is controlling the changing curvature as a function of doping. With this parameter setting

TABLE I. $H_{c2}(0)$ and c_L as obtained by fitting the vortex lattice melting curves to Eq. (2). ξ_0 is calculated from $H_{c2}(0)$ using Eq. (1). The uncertainties come from the width of the resistive transition and the proximity of the lowest data point to $T = 0$ K. The hole doping is obtained from the T_c , using Fig. 3 of Liang *et al.*²⁰

| Oxygen Content y | Hole Doping p | T_c (K) | λ_{ab} (nm) | λ_c (μm) | ξ_0 (\AA) | $\mu_0 H_{c2}(0)$ (T) | c_L |
|-----------------------|--------------------|--------------|------------------------|----------------------------------|-----------------------------|--------------------------|-------|
| 6.45 | 0.078 | 44.5 | 208 | 10.2 | 25.4 ± 0.5 | 50.8 ± 2.0 | 0.37 |
| 6.47 | 0.089 | 51 | 189 | 8.8 | 26.9 ± 0.5 | 45.2 ± 1.6 | 0.41 |
| 6.56 | 0.104 | 59 | 165 | 7.0 | 29.9 ± 0.4 | 36.9 ± 1.0 | 0.31 |
| 6.59 | 0.111 | 61.5 | 155 | 6.3 | 34.3 ± 0.3 | 28.0 ± 0.3 | 0.37 |
| 6.67 I | 0.116 | 64.7 | 147 | 5.6 | 36.6 ± 0.5 | 24.5 ± 0.7 | 0.41 |
| 6.67 II | 0.120 | 66 | 144 | 5.3 | 36.1 ± 1.5 | 25.2 ± 2.0 | 0.31 |
| 6.75 | 0.132 | 75.3 | 130 | 4.1 | 27.9 ± 0.5 | 42.1 ± 1.5 | 0.37 |
| 6.80 | 0.137 | 80.5 | 125 | 3.7 | 27.0 ± 0.9 | 45.0 ± 3.0 | 0.34 |
| 6.86 | 0.152 | 91.1 | 111 | 2.4 | 21.5 ± 0.6 | 70.9 ± 2.0 | 0.39 |
| 6.92 | 0.162 | 93.5 | 104 | 1.7 | 16.4 ± 0.8 | 121.9 ± 10.3 | 0.38 |

the shape, $H_{c2}(0)$ corresponds to the $T = 0$ intercept of the melting curve.

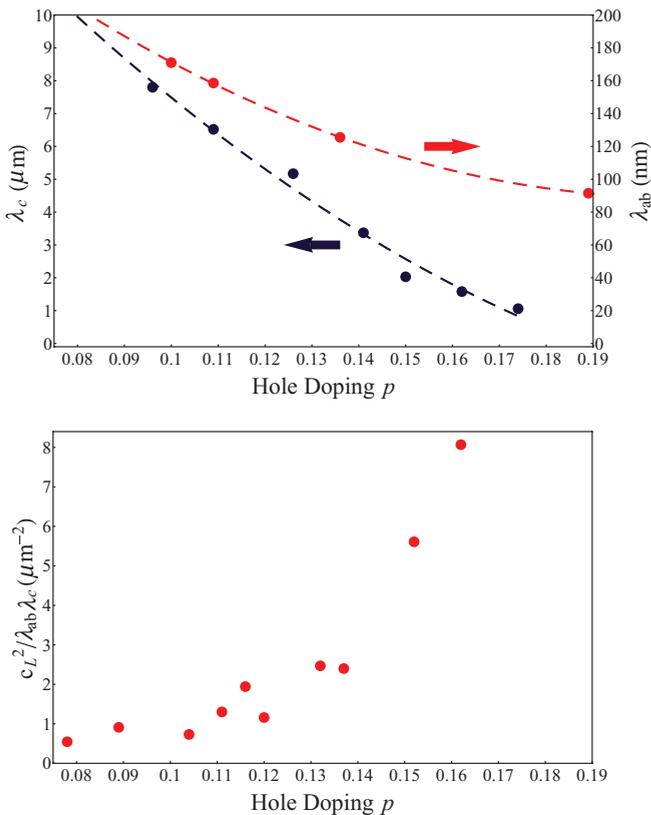


FIG. 4. (Color online) Top: The in-plane and out-of-plane penetration depths of $\text{YBa}_2\text{Cu}_3\text{O}_y$, as measured by muon-spin rotation (λ_{ab} at 0.11 holes), electron-spin resonance (the other λ_{ab} points), and infrared reflectance (λ_c).^{21–23} Note the difference in scale for the left- and right-hand axes: the anisotropy is actually decreasing with increased hole doping. The dashed lines are parabolic fits to the data, which are used to obtain interpolated values for doping levels not measured, and should be viewed as purely phenomenological. Bottom: The ratio of the Lindemann number squared to the product of the in-plane and out-of-plane penetration depths. This quantity, appearing on the right-hand side of Eq. (2), controls the curvature of B_m vs T .

It should be emphasized that in Eq. (2)

$$\lim_{T \rightarrow 0} B_m(T) = \mu_0 H_{c2}(0), \quad (5)$$

and so the values of $H_{c2}(0)$ derived from fits to Eq. (2) are determined mostly by the zero-temperature intercept of the data for B_m vs T , and are essentially independent of the penetration depth values chosen. The penetration depths and the Lindemann number always enter Eq. (2) as the ratio $\frac{c_L^2}{\lambda_{ab}\lambda_c}$, and so errors in the penetration depth values (which arise because we use interpolated values from the upper panel of Fig. 4) are absorbed into the fit value of c_L .

In using Eq. (2), we have ignored the possibility that the onset of finite resistivity is due to the lattice depinning, and not actually melting. This assumption is probably justified, as the depinning transition is distinct from the melting transition in $\text{YBa}_2\text{Cu}_3\text{O}_y$ only for temperatures very close to T_c and in samples with extremely low disorder.⁵ The fits shown in Figs. 2 and 3 show data up to near T_c when available, but only data at temperatures less than $0.8 \times T_c$ were used in the fits (which also avoids any possible effects of XY-critical phenomena near T_c).⁷ Additionally, all of the samples in this study (except for possibly the $\text{YBa}_2\text{Cu}_3\text{O}_{6.92}$ sample) have more disorder than the $\text{YBa}_2\text{Cu}_3\text{O}_{6.95}$ sample used in Liang *et al.*⁵ This is because the ortho-II, -III, -V, and -VIII states are not perfectly ordered,¹⁷ and have more disorder than ortho-I ordered $\text{YBa}_2\text{Cu}_3\text{O}_{6.95}$, which is close to stoichiometry. This disorder pushes the depinning transition closer to T_c .

The extracted values for $H_{c2}(0)$ are plotted with the phase diagram of $\text{YBa}_2\text{Cu}_3\text{O}_y$ in Fig. 5, and show an anomaly around 0.12 hole doping. The solid blue line in Fig. 5 is the function

$$1 - T_c/T_c^{\text{max}} = 82.6(p - 0.16)^2, \quad (6)$$

where T_c^{max} is the maximum T_c of the material (equal to 94.3 K for $\text{YBa}_2\text{Cu}_3\text{O}_y$).²⁰ This function has been found to describe T_c as a function of p in the cuprates, except for the suppression of T_c around 1/8 hole doping.²⁰ The green circles in Fig. 5 are the absolute difference between the actual T_c and Eq. (6), and the suppression of T_c is clearly correlated with a suppression of $H_{c2}(0)$. Suppression of the melting transition in this region was reported for a few different doping levels in LeBoeuf *et al.*¹⁹

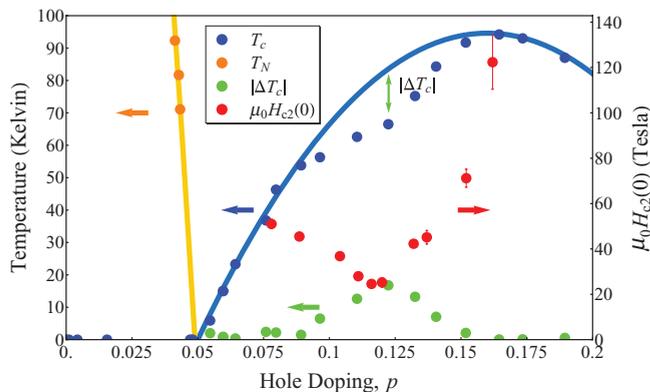


FIG. 5. (Color online) The superconducting phase diagram of $\text{YBa}_2\text{Cu}_3\text{O}_y$. $H_{c2}(0)$ is suppressed in the same region that T_c deviates from the parabolic form—a clear sign of the weakening of superconductivity around 0.12 hole doping. The T_c values are taken from Liang *et al.*²⁰

IV. DISCUSSION

The suppression of T_c in the underdoped region of the phase diagram was mapped in detail by Liang *et al.*²⁰ In the same work, Liang *et al.*²⁰ correlated the \hat{c} -axis lattice parameter with the hole doping of the copper-oxygen planes, showing a smooth evolution of hole doping with increased oxygen content. This demonstrates that the suppression of T_c is not due to some peculiarity of the copper-oxygen chain doping mechanism in $\text{YBa}_2\text{Cu}_3\text{O}_y$, but is in fact inherent to the electronic properties of the material. It was supposed that the suppression of T_c may be due to a competition of superconductivity with stripe formation, as has been demonstrated explicitly in the lanthanum cuprates.²⁴

The phase diagram in Fig. 5 shows a clear correlation between the suppression of T_c near 0.12 hole doping and a suppression in the $T = 0$ melting field and hence a suppression of $H_{c2}(0)$. This further strengthens the case that the anomaly in T_c is related to a weakening of superconductivity. The corresponding maximum in coherence length—recall that $\xi_0 \propto [H_{c2}(0)]^{-1/2}$ —has also been seen in μSR ²⁵ and in the fluctuation-magnetoconductance.^{26,27}

Recent NMR²⁸ and x-ray diffraction^{29–31} experiments have indicated the possibility of charge order in underdoped $\text{YBa}_2\text{Cu}_3\text{O}_y$. In all three x-ray diffraction experiments, the charge order was seen to drop in intensity below T_c . Additionally, Chang *et al.*³⁰ found that the intensity of the charge-order

peaks could be increased with an applied magnetic field below T_c . These experiments give further evidence for a close competition between superconductivity and the charge-ordered state. This is in agreement with the minimum in $H_{c2}(0)$ we observe near 0.12 hole doping.

V. CONCLUSION

The onset of finite resistivity in a magnetic field coincides with the vortex melting transition in $\text{YBa}_2\text{Cu}_3\text{O}_y$. This melting transition can be substantially below mean-field H_{c2} at temperatures between 0 K and T_c .¹² Using a Lindemann criterion for melting produces good agreement between theory and experiment, with a Lindemann number c_L between 0.3 and 0.4. These values are consistent with theoretical predictions, which vary between 0.2 and 0.4 for highly anisotropic materials.¹³ Because this model agrees well with the data across such a wide range of dopings (and anisotropies) where $H_{c2}(0)$ is experimentally accessible, it is reasonable to assume that the extrapolations to zero temperature at higher doping levels gives a reasonable determination of $H_{c2}(0)$.

Within the framework we used for flux-line-lattice melting,^{7,12,13} B_m is required to approach $\mu_0 H_{c2}$ as $T \rightarrow 0$. The agreement between our data and this theory suggests that $\mu_0 H_{c2}(0) = B_m(0)$, in contrast to previous suggestions.^{9,32–34} This means that the quantum oscillations seen in underdoped $\text{YBa}_2\text{Cu}_3\text{O}_y$ would occur in a state free of vortices (superconducting fluctuations may still be present,³⁵ of course, as detected in the Nernst signal,³⁶ for example.) This absence of vortices is consistent with the lack of a field-dependent scattering term needed to fully describe the quantum oscillations.³⁷

Below optimal doping, $H_{c2}(0)$ is rapidly suppressed with decreasing hole doping, reaching a minimum of 24.5 T at $p = 0.116$ holes. At lower hole doping $H_{c2}(0)$ recovers—even as T_c continues to decrease—indicating the presence of a phase that competes with superconductivity, a phase which is strongest between 0.11 and 0.13 holes.

ACKNOWLEDGMENTS

The authors acknowledge support from the Canadian Institute for Advanced Research, the Natural Sciences and Engineering Research Council of Canada, the Canada Foundation for Innovation, and Euromagnet II. L.T. acknowledges support as a Canada Research Chair and from Fonds Québécois de la Recherche sur la Nature.

¹N. Doiron-Leyraud, C. Proust, D. LeBoeuf, J. Levallois, J.-B. Bonnemaison, R. Liang, D. A. Bonn, W. N. Hardy, and L. Taillefer, *Nature (London)* **447**, 565 (2007).

²S. Kamal, D. A. Bonn, N. Goldenfeld, P. J. Hirschfeld, R. Liang, and W. N. Hardy, *Phys. Rev. Lett.* **73**, 1845 (1994).

³V. Pasler, P. Schweiss, C. Meingast, B. Obst, H. Wühl, A. I. Rykov, and S. Tajima, *Phys. Rev. Lett.* **81**, 1094 (1998).

⁴H. Xu, S. Li, S. M. Anlage, C. J. Lobb, M. C. Sullivan, K. Segawa, and Y. Ando, *Phys. Rev. B* **80**, 104518 (2009).

⁵R. Liang, D. A. Bonn, and W. N. Hardy, *Phys. Rev. Lett.* **76**, 835 (1996).

⁶Y. Ando, G. S. Boebinger, A. Passner, L. F. Schneemeyer, T. Kimura, M. Okuya, S. Watauchi, J. Shimoyama, K. Kishio, K. Tamasaku, N. Ichikawa, and S. Uchida, *Phys. Rev. B* **60**, 12475 (1999).

⁷D. S. Fisher, M. P. A. Fisher, and D. A. Huse, *Phys. Rev. B* **43**, 130 (1991).

⁸H. Safar, P. L. Gammel, D. A. Huse, D. J. Bishop, J. P. Rice, and D. M. Ginsberg, *Phys. Rev. Lett.* **69**, 824 (1992).

⁹Y. Wang, L. Li, and N. P. Ong, *Phys. Rev. B* **73**, 024510 (2006).

¹⁰A. A. Abrikosov, *Sov. Phys. JETP-USSR* **5**, 1174 (1957).

- ¹¹All formulas in this paper have been converted to SI units. Factors of μ_0 that may seem redundant, such as in Eqs. (3) and (4), have been left uncanceled in order to keep the conversion to SI units transparent.
- ¹²A. Houghton, R. A. Pelcovits, and A. Sudbø, *Phys. Rev. B* **40**, 6763 (1989).
- ¹³G. Blatter, M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, *Rev. Mod. Phys.* **66**, 1125 (1994).
- ¹⁴G. C. Kim and Y. C. Kim, *Appl. Supercond.* **4**, 151 (1996).
- ¹⁵R. Liang, D. A. Bonn, and W. N. Hardy, *Physica C* **304**, 105 (1998).
- ¹⁶B. J. Ramshaw, Ph.D. thesis, University of British Columbia, 2012.
- ¹⁷M. Von Zimmermann, J. Schneider, T. Frello, N. Andersen, J. Madsen, M. Kall, H. Poulsen, R. Liang, P. Dosanjh, and W. Hardy, *Phys. Rev. B* **68**, 104515 (2003).
- ¹⁸B. Lake, H. M. Rønnow, N. B. Christensen, G. Aeppli, K. Lefmann, D. F. McMorrow, P. Vorderwisch, P. Smeibidl, N. Mangkorntong, T. Sasagawa, M. Nohara, H. Takagi, and T. E. Mason, *Nature (London)* **415**, 299 (2002).
- ¹⁹D. LeBoeuf, N. Doiron-Leyraud, B. Vignolle, M. Sutherland, B. J. Ramshaw, J. Levallois, R. Daou, F. Laliberté, O. Cyr-Choinière, J. Chang, Y. J. Jo, L. Balicas, R. Liang, D. A. Bonn, W. N. Hardy, C. Proust, and L. Taillefer, *Phys. Rev. B* **83**, 054506 (2011).
- ²⁰R. Liang, D. A. Bonn, and W. N. Hardy, *Phys. Rev. B* **73**, 180505 (2006).
- ²¹T. Pereg-Barnea, P. J. Turner, R. Harris, G. K. Mullins, J. S. Bobowski, M. Raudsepp, R. Liang, D. A. Bonn, and W. N. Hardy, *Phys. Rev. B* **69**, 184513 (2004).
- ²²J. E. Sonier, J. H. Brewer, R. F. Kiefl, D. A. Bonn, S. R. Dunsiger, W. N. Hardy, R. Liang, W. A. MacFarlane, R. I. Miller, T. M. Riseman, D. R. Noakes, C. E. Stronach, and M. F. White, *Phys. Rev. Lett.* **79**, 2875 (1997).
- ²³C. Homes, T. Timusk, D. Bonn, R. Liang, and W. Hardy, *Physica C: Supercond.* **254**, 265 (1995).
- ²⁴J. Tranquada, B. Sternlieb, J. Axe, Y. Nakamura, and S. Uchida, *Nature (London)* **375**, 561 (1995).
- ²⁵J. E. Sonier, S. A. Sabok-Sayr, F. D. Callaghan, C. V. Kaiser, V. Pacradouni, J. H. Brewer, S. L. Stubbs, W. N. Hardy, D. A. Bonn, R. Liang, and W. A. Atkinson, *Phys. Rev. B* **76**, 134518 (2007).
- ²⁶In both of these experiments, the peak in coherence length was reported near oxygen 6.70, which would appear to be above where the peak occurs in Fig. 5. However, the oxygen content values reported may be shifted due to the different standards used for determining zero chain oxygen content, so that T_c is a better indicator of the hole doping.²⁰ The peak in Fig. 5 of Ref. 27 appears at $T_c = 60.5$ K, with the next data point at $T_c = 69.5$ K. The peak in Fig. 5 of the current work occurs near $T_c = 64.5$ K: these peaks are therefore consistent with each other. Similarly for Sonier *et al.*,²⁵ using T_c as a means of computing hole doping reveals that their peak in ξ_0 corresponds to the same doping as our minimum in $H_{c2}(0)$.
- ²⁷Y. Ando and K. Segawa, *Phys. Rev. Lett.* **88**, 167005 (2002).
- ²⁸T. Wu, H. Mayaffre, S. Kraemer, M. Horvatic, C. Berthier, W. N. Hardy, R. Liang, D. A. Bonn, and M.-H. Julien, *Nature (London)* **477**, 191 (2011).
- ²⁹G. Ghiringhelli, M. Le Tacon, M. Minola, S. Blanco-Canosa, C. Mazzoli, N. B. Brookes, G. M. De Luca, A. Frano, D. G. Hawthorn, F. He, T. Loew, M. M. Sala, D. C. Peets, M. Salluzzo, E. Schierle, R. Sutarto, G. A. Sawatzky, E. Weschke, B. Keimer, and L. Braicovich, *Science* **337**, 821 (2012).
- ³⁰J. Chang, A. T. Blackburn, N. B. Holmes, J. Christensen, J. Larsen, J. Mesot, R. Liang, D. A. Bonn, W. N. Hardy, A. Watenphul, M. v. Zimmerman, E. M. Forgan, and S. M. Hayden, *Nat. Phys.* (2012), doi:10.1038/nphys2456.
- ³¹A. J. Achkar, R. Sutarto, X. Mao, F. He, A. Frano, S. Blanco-Canosa, M. Le Tacon, G. Ghiringhelli, L. Braicovich, M. Minola, M. Moretti Sala, C. Mazzoli, R. Liang, D. A. Bonn, W. N. Hardy, B. Keimer, G. A. Sawatzky, and D. G. Hawthorn, *Phys. Rev. Lett.* **109**, 167001 (2012).
- ³²Y. Wang, N. P. Ong, Z. A. Xu, T. Kakeshita, S. Uchida, D. A. Bonn, R. Liang, and W. N. Hardy, *Phys. Rev. Lett.* **88**, 257003 (2002).
- ³³Y. Wang, S. Ono, Y. Onose, G. Gu, Y. Ando, Y. Tokura, S. Uchida, and N. P. Ong, *Science* **299**, 86 (2003).
- ³⁴S. C. Riggs, O. Vafek, J. B. Kemper, J. B. Betts, A. Migliori, F. F. Balakirev, W. N. Hardy, R. Liang, D. A. Bonn, and G. S. Boebinger, *Nat. Phys.* **7**, 332 (2011).
- ³⁵J. Chang, N. Doiron-Leyraud, O. Cyr-Choinière, G. Grissonnanche, F. Laliberté, E. Hassinger, J.-P. Reid, R. Daou, S. Pyon, T. Takayama, H. Takagi, and L. Taillefer, *Nat. Phys.* **8**, 751 (2012).
- ³⁶J. Chang, R. Daou, C. Proust, D. LeBoeuf, N. Doiron-Leyraud, F. Laliberté, B. Pingault, B. J. Ramshaw, R. Liang, D. A. Bonn, W. N. Hardy, H. Takagi, A. B. Antunes, I. Sheikin, K. Behnia, and L. Taillefer, *Phys. Rev. Lett.* **104**, 057005 (2010).
- ³⁷B. J. Ramshaw, B. Vignolle, J. Day, R. Liang, W. N. Hardy, C. Proust, and D. A. Bonn, *Nat. Phys.* **7**, 234 (2011).