Melting line with quantum correction in a melt-textured $YBa_2Cu_3O_{7-\delta}$ sample

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The irreversibility line for a high quality melt textured $YBa_2Cu_3O_{7-\delta}$ sample was determined in two orientations of the field H relative to the sample c axis. In both orientations we obtain good fits using a melting equation with quantum correction to describe the Abrikosov-lattice melting. The angular-scaling rule for uniaxially anisotropic materials is verified, giving additional support for the melting hypothesis. Our results are similar to those found in the literature for very clean untwinned samples. We suggest that the Abrikosov-lattice melting is weakly affected by quenched disorder, at least in the relatively low fields ($H \leq 50$ kOe) and high temperatures ($T/T_c > 0.8$) probed in this work.

The existence of an irreversibility line (IL) that separates a magnetically irreversible from a reversible state in the $H \times T$ plane is a very well-documented experimental fact for the high-T_c superconductors. However, the physical interpretation for the IL has aroused some issues. In order to describe the IL, simple power laws of the type $H_m(T) = H_0(1 - T/T_c)^n$ have been suggested, where H_0 is a model-dependent fitting parameter. The exponent $n = 3/2$ is predicted by a quasi–de Almeida–Thouless behavior[1] as well as by the giant flux creep model.[2,3] The exponent $n = 4/3$ is expected from a vortex-glass formation,[4,5] as well as from Tinkham's giant flux creep model.[3] An exponent which is dependent on the pinning strength can be found in a collective flux creep model.[6] In a more general approach the IL is identified with a depinning line, whose solution comes from an equation describing the constant diffusivity $D_0(H, T)$ of the flux lines.[7] Finally, the interpretation of the IL as the melting transition line of the Abrikosov lattice[8–11] has received enough confirmation, and nowadays the melting hypothesis seems to be a well-established matter.[12–14] The basic idea is that the Abrikosov lattice becomes unstable and melts, when the mean displacement amplitude of the flux lines, $\sqrt{\langle u^2 \rangle}$, reaches an appreciable fraction of the lattice parameter a_0. This latter condition is usually expressed in terms of the Lindemann criterion $\sqrt{\langle u^2 \rangle} = c_L a_0$, with the Lindemann number c_L varying between 0.1 and 0.3.

Recently, Blatter and Ivlev[13] discussed the relevance of quantum fluctuations ($\sqrt{\langle u^2 \rangle_q}$) that, combined with thermal fluctuations ($\sqrt{\langle u^2 \rangle_{\rm th}}$),[10] produce an effective mean displacement amplitude of the flux lines which may correct the melting line position in some cases. For instance, thermal fluctuations are known to be dominant in the strongly anisotropic Bi-Sr-Ca-Cu-O compounds, making quantum corrections vanishingly small.[13] However, in the less anisotropic $YBa_2Cu_3O_{7-\delta}$ (YBCO) compound the correction due to quantum fluctuations becomes important, as has been discussed by Schilling *et al.*[15] and Blatter and Ivlev,[13] using data from single-crystalline samples.

In this work we present results that provide further confirmation for the relevance of adding quantum correction in the calculation[13] of the melting line for YBCO. Our study was done in a melt-textured YBCO sample, in contrast with the very clean single crystals analyzed before.[15,13] Hence, we conclude that the occurrence of quenched disorder (pinning centers) in the melt-textured sample has little influence on the relative weight of quantum and thermal fluctuations that are required to interpret the IL as a melting line. We measured the IL in two angular directions ($\alpha = 0°, 60°$) of the field H with respect to the c axis of the textured sample, and found that these results obey the anisotropy-induced angular dependence predicted for the melting line.[16,17]

The melt-textured YBCO sample studied here was obtained by the partial-melt-growth method.[18] It was cut into a parallelepiped having dimensions 2.7 × 2.5 × 1.1 mm^3 and contains long crystalline grains, well aligned with the c-axis direction. Figure 1 presents the x-ray diffractogram for the c-axis-oriented geometry, showing essentially the occurrence of (00ℓ) peaks. A rocking curve for the (005) peak was also measured and shows an angular spread around 2° for the grain orientations along the c direction.

dc magnetization measurements $M(T)$ were made using a commercial superconducting quantum interference device (SQUID) magnetometer (Quantum Design, model MPMS5). The magnetic transition of the sample measured under $H = 5$ Oe gives $T_c = 91.0$ K at the transition onset and $\Delta T \approx 1.3$ K between 10% and 90% of

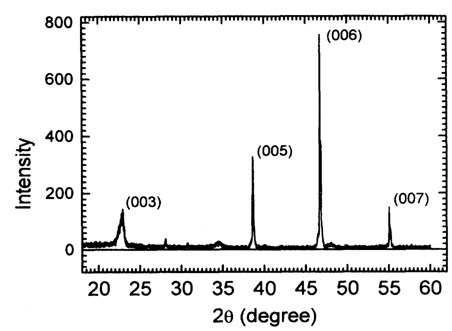

FIG. 1. X-ray diffraction pattern in the c-axis-oriented geometry for the melt-textured YBCO sample.

the maximum shielding. Each point $M(T)$ corresponds to an average over two scans in a length of 3 cm. We employed in this work a magnetic and thermal history similar to that reported by Schilling *et al.*,[19] aiming at the IL determination through conventional M vs T measurements. First, a remanent magnetization curve $M_{\rm rem}$ was obtained (Fig. 2) by cooling the sample from 100 K (normal state) to 10 K under an applied field $H = 50$ kOe. Then, a measuring field H was set and the sample warmed up to 70 K, from which the $M_{\rm rem}(T)$ curve was measured by slowly increasing the sample temperature in steps $\Delta T = 0.4$ K. Following, a field-cooled curve $M_{\rm FC}(T)$ was obtained by cooling the sample from 100 K to 70 K, in a measuring field H. From that point the $M_{\rm FC}(T)$ curve was measured by slowly increasing the sample temperature in steps $\Delta T = 0.4$ K, like before. For each chosen field H, the curves $M_{\rm rem}(T)$ and $M_{\rm FC}(T)$ merge at an irreversibility temperature $T_i(H)$ as shown in the inset of Fig. 2 for $H = 30$ kOe. A practical criterion was applied to define $T_i(H)$ where the difference $\Delta M = M_{\rm rem} - M_{\rm FC}$ becomes less than the standard deviation of the measurements. The upper critical field $H_{c2} = H(T_{c2})$ is associated with the temperature T_{c2} (see the inset of Fig. 2) where the linear extrapolation of the reversible region meets the normal base line of the magnetization curve. It can be noted that our data did not show a consistent feature like a break in the slope of the magnetization curve at a temperature $T^* > T_i$, as reported by Schilling *et al.* in their study with YBCO single crystals.[19]

As shown by Houghton *et al.*[10] the melting line due to thermal fluctuations, for H parallel to the c axis of an anisotropic material, is

$$\frac{t}{(1-t)^{1/2}}\frac{b^{1/2}}{(1-b)}\left[\frac{4(\sqrt{2}-1)}{\sqrt{1-b}}+1\right] \approx \frac{2\pi}{\sqrt{N_{\rm Gi}}}\epsilon c_L^2, \quad (1)$$

where $t = T/T_c$ and $b = B/H_{c2}$, with $H_{c2}(t) = H_{c2}(0)(1-t)$. In the above Eq. (1) appears the Ginzburg number $N_{\rm Gi} = 16\pi^3\kappa^4(k_BT_c)^2/\Phi_0^3H_{c2}(0) \approx 1.06\times10^{-9}T_c^2\kappa^4H_{c2}(0)$, where κ is the Ginzburg-Landau factor, Φ_0 is the flux quantum, and k_B the Boltzmann constant. The sample anisotropy is described by the effective mass ratio $\epsilon = \sqrt{m_{ab}/m_c}$, whose value is $\epsilon = 1/5$ for YBCO.[10,13]

Equation (1) does not admit a closed form solution for the melting line $B(T)$; therefore it has to be solved in a self-consistent way when fitting the experimental data. However, close to T_c and taking up to linear terms in $\sqrt{b}$ for the expansion of Eq. (1), one gets

$$B(T) \approx \beta_{\rm th}H_{c2}(0)\frac{c_L^4\,\epsilon^2}{N_{\rm Gi}}\left(\frac{1-t}{t}\right)^2 , \quad (2)$$

where $(1-t)/t$ appears as the natural variable,[13] instead of the commonly used form $(1-t)$. The numerical constant is $\beta_{\rm th} = \{2\pi/[4(\sqrt{2}-1)+1]\}^2 \approx 5.6$.

Figure 3 shows the best fits to our IL data ($H \parallel c$), for the complete thermal equation [Eq. (1)] and for its simplified form [Eq. (2)], both using the Lindemann number $c_L = 0.20$. Equation (1) gives a reasonable fit (dotted line) only for $H \leq 20$ kOe while the quadratic form, Eq. (2), fits only very close to T_c (dashed line), for $H \leq 10$ kOe. Figure 3 also shows the H_{c2} line, fitted by the linear form $H_{c2}(T) = H_{c2}(0)(1 - T/T_c^*)$ with $H_{c2}(0) = 1.72 \times 10^6$ Oe and the extrapolated critical temperature $T_c^* = 90.6$ K. These figures produce a slope $dH_{c2}/dT \approx -1.9 \times 10^4$ Oe/K which is comparable to the commonly quoted values for high quality YBCO crystals.[12,15] A $T_c = 91.8$ K was employed in all three melting equation forms fitted to the IL data (Fig. 3). This latter T_c value is fairly close to the measured value of 91.0 K. Using these quoted figures and the Ginzburg-Landau factor $\kappa = 80$, which is representative for YBCO,[14,20] we get the Ginzburg number $N_{\rm Gi} \approx 5.3 \times 10^{-3}$. This $N_{\rm Gi}$ number is about six orders of magnitude larger than what is found in conventional superconductors, thus stressing the relevance of thermal

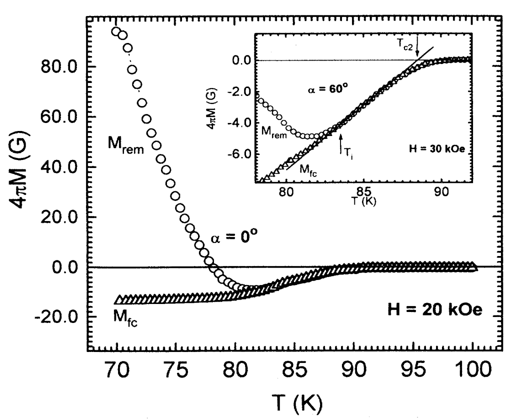

FIG. 2. Typical magnetization curves $M_{\rm rem}$ and $M_{\rm FC}$ (see text) of the melt-textured YBCO sample. Two angles $\alpha = 0°$, $60°$ between the applied field H and the c-axis direction were employed. The inset displays a magnified view of the reversible region for $\alpha = 60°$ where the temperatures T_i and T_{c2} (see text) are indicated.

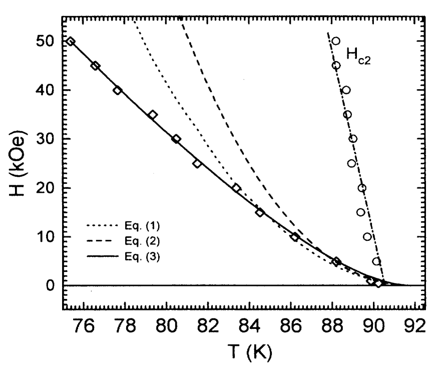

FIG. 3. Magnetic phase diagram of the melt-textured YBCO sample. The data points define the irreversibility line ($\diamond$) and the H_{c2} line ($\circ$). The solid, dotted, and dashed lines represent fits of the melting equation, respectively, with quantum correction [Eq. (3)], without quantum correction [Eq. (1)], and in the approximated quadratic form [Eq. (2)]. A linear fit of the H_{c2} line, $H_{c2} = H_{c2}(0)(1 - T/T_c^*)$, is also represented by the dot-dashed line.

fluctuations in the high-T_c material.[13]

The combined effect of thermal and quantum fluctuations lead to the following compact equation for the melting line, according to Blatter and Ivlev:[13]

$$b(t) = \frac{4\theta^2}{\left(1+\sqrt{1+\frac{4S\theta}{t}}\right)^2}\,, \tag{3}$$

with the temperature variable

$$\theta = c_L^2\sqrt{\frac{\beta_{\rm th}}{N_{\rm Gi}}}\left(\frac{T_c}{T}-1\right) \tag{4}$$

and the suppression parameter

$$S \approx 2.4\frac{\nu}{\xi K_F} + c_L^2\sqrt{\frac{\beta_{\rm th}}{N_{\rm Gi}}}\,, \tag{5}$$

where K_F is the Fermi wave vector [$K_F \approx 0.15-0.20$ Å^{-1} (Ref. 13)] and ν is a fittting parameter, which relates a cutoff frequency Ω with the superconducting gap energy Δ, $\nu = \hbar\Omega/\Delta$. As pointed by Blatter and Ivlev[13] only part of the suppression parameter S appearing in Eq. (5) can be attributed to the effect of quantum fluctuations, while the larger contribution actually arises from the suppression of the order parameter Ψ close to the H_{c2} line. Indeed, an increase of the magnetic penetration depth $\lambda \to \lambda/\langle|\Psi|^2\rangle \approx \lambda/(1-b)^{1/2}$ follows from Ginzburg-Landau theory.[21]

Equation (3) fits very well to our data as shown by the solid line in Fig. 3, producing $c_L \approx 0.24$ and $\nu \approx 4$ in quantitative agreement with the analysis of Blatter and Ivlev[13] for untwinned single crystals of YBCO. However, the melting line in our case is shifted to lower temperatures, as would be expected in the presence of quenched disorder.[13,22] For instance, at $H = 50$ kOe we have $T_i \approx 75.5$ K, instead of $T_i \approx 81.0$ K which was observed in untwinned single crystals.[23] These results suggest that the occurrence of quenched disorder in the melt-textured sample has a negligible influence on the determination of c_L and ν appearing in Eq. (3). This probably means that the melting of the Abrikosov lattice is weakly affected by quenched disorder, at least in the relatively low-field and high-temperature region studied here.

Figure 4 shows the IL shifted to higher temperatures when the field H makes an angle $\alpha = 60°$ ($\pm 2°$) with the c-axis direction. The dashed line represents the new position of the melting line $B(\alpha, t)$ when the effect of anisotropy is corrected by the scaling rule.[14,16,17]

$$B(\alpha,T) = \frac{B(0,T)}{\sqrt{\epsilon^2\sin^2\alpha\ + \cos^2\alpha}}\,, \tag{6}$$

where α is the angle between the c axis and H. The dashed line in Fig. 4 is obtained using $\epsilon = 1/5$, the same mass anisotropy factor employed in the melting equations [Eqs. (1)–(3)]. Similar to the conclusion of Beck *et al.*,[17] we believe that the verification of the scaling rule given by Eq. (6) is a strong point in favor of the melting hypothesis. The manifestation of other phenomena, like a giant flux creep or a thermal depinning, would be strongly dependent on the sample geometry[21] and nonequilibrium effects, thus having eventually different angular dependences.

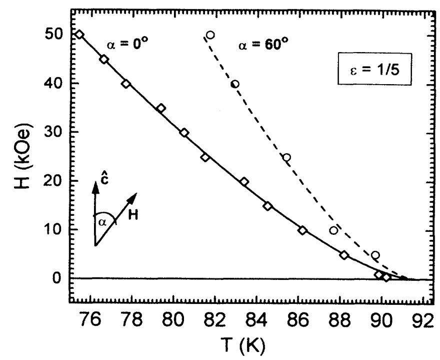

FIG. 4. Magnetic phase diagram of the melt-textured YBCO sample, showing the effect of anisotropy on the irreversibility line for $\alpha = 0°$ ($\diamond$) and $\alpha = 60°$ ($\circ$). The solid line represents a fit of the melting equation taking into account thermal and quantum fluctuations [Eq. (3)] for $\alpha = 0°$. The dashed line represents that same fit corrected by the angular scaling rule $B(\alpha,T) = B(0,T)/(\epsilon^2\sin^2\alpha\ +\ \cos^2\alpha)^{1/2}$.

In conclusion, the irreversibility line for a high quality melt-textured YBCO sample was determined in two orientations of the field H relative to the sample c axis. The hypothesis based on Abrikosov lattice melting is strongly corroborated by the good fit to the data (Fig. 3) of the melting equation with quantum correction, Eq. (3), as well as by the verification of the angular scaling rule (Fig. 4) predicted for the melting line, Eq. (6). Although the sample studied here might contain much more quenched disorder (pinning centers) than a single crystal, we found similar values for the Lindemann constant ($c_L \approx 0.24$) and for other parameters. Thus, we conclude that Abrikosov lattice melting is probably weakly affected by the quenched disorder, at least in the relatively low fields ($H < 50$ kOe) and high temperatures ($t > 0.8$) probed in this work.

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