Flux-line-lattice melting in $Bi_2Sr_2Ca_2Cu_3O_{10}$

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We have performed dc magnetization studies in the c-axis-oriented bulk $Bi_2Sr_2Ca_2Cu_3O_{10}$ compound. The penetration depth $\lambda_{ab}(T)$ is extracted from reversible magnetization data $M(H)$ taking into account fluctuations of the vortices. An "irreversibility line" is quantitatively compared with predictions of flux-line-lattice (FLL) melting models. The results strongly suggest that the "irreversibility line" near T_c is associated with melting of FLL caused by thermal fluctuations.

It is now widely accepted that thermal fluctuations play an important role in the thermodynamic and transport properties of high-temperature superconductors. The large fluctuations are caused by the high transition temperature T_c, the short coherence length ξ, and strong anisotropy of these materials. The fluctuations are responsible for the "anomalous" behavior of reversible magnetization $M(H,T)$.[1-6] Here the magnetization becomes independent of field at some temperature T^*, which is several degrees below the mean-field transition temperature T_{c0}, i.e., all $M(T)$ curves for different H cross at the temperature T^*. The experimental results have been well described in the model of a three-dimensional (3D) XY critical point[7] and in terms of the Ginsburg-Landau fluctuation theory, using the lowest Landau-level approximation.[8] Bulaevskii, Ledvij, and Kogan[9] have shown that in the London regime where the magnetization logarithmically changes with field, the existence of the crossing temperature T^* is a result of thermal fluctuations of vortices. They also argue that the superconducting transition temperature T_{SC} in layered superconductors is the analog of the Kosterlitz-Thouless vortex–antivortex dissociation temperature which lies below T_{c0}. Thus, the resistivity approaches zero at T_{SC}. For $T>T_{SC}$, the motion of dissociated vortex–antivortex pairs give rise to dissipation. Further Kogan *et al.*[10] have demonstrated from magnetization measurements in $Bi_2Sr_2CaCu_2O_8$ that vortex fluctuations have a strong influence on the London penetration depth $\lambda(T)$. On the other hand, strong fluctuations can lead to melting of the flux-line lattice.[11-19] In the high-temperature region where the London penetration depth $\lambda(T)\propto(1-T/T_c)^{-1/2}$, 3D FLL melting models predict a power law for the "melting line" (ML) of the form $H_m\propto(1-T/T_c)^{\alpha}$, with $\alpha=2$.[11-16] In Josephson-coupled layered superconductors like Bi- and Tl-based compounds, the thermal vortex fluctuations are enhanced due to weak coupling between CuO_2 superconducting planes. At the same time, for these strongly anisotropic superconductors, "irreversibility lines" (IL's) near T_c have been shown to fit the power-law relationship $H_i\propto(1-T/T_c)^{\alpha}$ with α substantially smaller than 2 (e.g., Refs. 20 and 21 reported values of an exponent α close to 1), where the T_c used is the measured superconducting transition temperature. These results imply that IL in the vicinity of T_c is not a 3D ML (here we discuss dc IL's which are suitable for comparison with predictions of melting models[16]).

In the present paper, evidence of vortex fluctuations in $Bi_2Sr_2Ca_2Cu_3O_{10}$ as well as quantitative comparison of IL inferred from dc magnetization measurements, with predictions of the FLL melting models are given. We show that IL close to T_c can be identified with a 3D ML, taking into account correction to the $\lambda(T)$ due to thermal vortex fluctuations and that it has a parabolic shape in $(l-t)$ with a relevant reduced temperature $T=T/T_{c0}$, where T_{c0} is the mean-field transition temperature.

The results are obtained from magnetization measurements $M(H,T)$ in a single-phase c-axis oriented $Bi_2Sr_2Ca_2Cu_3O_{10}$ compound with a superconducting quantum interference device (SQUID) magnetometer (Quantum Design-MPMS5) technique in a magnetic field parallel to the c axis. We used the specimen preparation method as reported in (Ref. 22). The high quality of the sample was confirmed from careful x-ray $[(\Theta-2\Theta)$ geometry and rocking curve], scanning electron microscopy, and metallographic analysis. Indexing the $(\Theta-2\Theta)$ scans according to an orthorhombic structure yielded the lattice parameters $a=5.51\pm0.01$ Å, $b=5.19\pm0.01$ Å, and $c=37.28\pm0.03$ Å. The platelet-like grains have average dimensions of 5×5 μm^2 in the (ab) plane and 0.6 μm along the c axis. The high quality of the measured sample was also confirmed by the zero-field resistive transition of the $T_c=109$ K midpoint and $\Delta T_c(10\text{–}90\%)\approx3$ K. The set of irreversibility data (H,T) was obtained by the points where the hysteresis in $M(H)$ disappears and where the $M_{FC}(T)$ curve starts to depart from the $M_{ZFC}(T)$ curve.

Figure 1 shows the isotherms of the reversible magnetization in a logarithmic field scale for temperature close to T_c after subtracting the normal-state background signal measured at 200 K. The vortex fluctuation effect is clearly demonstrated by the existence of the crossover temperature $T^*\approx106$ K. Let us verify the fluctuation effect on the penetration depth. According to Refs. 9 and 10, the reversible magnetization for intermediate fields $\phi_0/d^2\gamma^2\ll H\ll H_{c2}$ is

$$-M=\frac{\phi_0}{32\pi^2\lambda_{ab}^2(T)}\ln\frac{\eta H_{c2}}{eH}-\frac{k_BT}{\phi_0 d}\ln\frac{16\pi k_BT^2\kappa^2}{\alpha\phi_0 dH\sqrt{e}}\ , \quad (1)$$

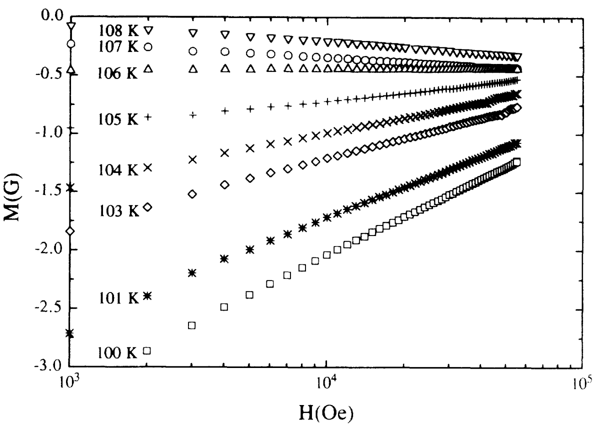

FIG. 1. Reversible magnetization M vs magnetic field H applied parallel to the c axis at different temperatures in the vicinity of T_c.

where γ^2 is the effective-mass ratio m_c/m_{ab}, d is the distance between weakly coupled superconducting CuO_2 planes, λ_{ab} is the in-plane penetration depth, $\kappa=\lambda_{ab}/\xi_{ab}$, $H_{c2}(T)=\phi_0/2\pi\xi_{ab}^2$ is the upper critical magnetic field, α and η are parameters of the order unity, $e=2.718\ldots$. The second term in Eq. (1) is associated with fluctuations and it leads to correction of the slope of the linear $M(\ln H)$ dependence which is given by

$$\frac{\partial M}{\partial \ln H}=\frac{\phi_0}{32\pi^2\lambda_{ab}^2(T)}[1-g(T)] , \tag{2}$$

where the correction term $g(T)$ is

$$g(T)=\frac{32\pi^2 k_B}{\phi_0^2 d}T\lambda_{ab}^2(T) . \tag{3}$$

The magnetic-field-independent magnetization at the crossover temperature is

$$-M(T^*)=(k_B T^*/\phi_0 d)\ln(\eta\alpha/\sqrt{e}) ,$$

where $\ln(\eta\alpha/\sqrt{e})\approx 1$ (Refs. 9 and 10). Using the experimental value of $M(T^*)\approx -0.4$ G (Fig. 1) we find $d\approx 18$ Å. This value is in very good agreement with our x-ray result ($c/2\approx 18.6$ Å) and others[23–25] and it can be considered as the average distance between Josephson-coupled CuO_2 planes (see also Ref. 26).

Evaluating the slopes $\partial M/\partial \ln H$ of Fig. 1 and using Eqs. (2) and (3), we determine $\lambda_{ab}(T)$ for both neglecting and taking into consideration the correction term $g(T)$. These results are shown in Fig. 2(a). Here the fluctuation contribution to $\lambda_{ab}(T)$ is very clear, particularly in the vicinity of T_c. This strong influence of vortex fluctuations on $\lambda_{ab}(T)$ in $Bi_2Sr_2Ca_2Cu_3O_{10}$ is similar to the result obtained for $Bi_2Sr_2CaCu_2O_8$.[10] From the temperature dependence of $\lambda_{ab}(T)$ at $T_{c0}-T \ll T_{c0}$,

$$\lambda_{ab}(T)=\lambda_{ab}(0)[T_{c0}/2(T_{c0}-T)]^{1/2} , \tag{4}$$

one can derive[9]

$$1-\frac{T^*}{T_{c0}}=\frac{16\pi^2 k_B T_{c0}\lambda_{ab}^2(0)}{\phi_0^2 d} . \tag{5}$$

Using Eq. (5) and $g(T^*)=1$, we find for our sample $\lambda_{ab}(0)=1240\pm 10$ Å and $T_{c0}=111.6\pm 0.1$ K. Figure 2(b) displays λ_{ab} data as a function of $(1-T/T_{c0})$ in a double logarithmic scale. The dashed line in Fig. 2(b) is obtained from Eq. (4) with $\lambda_{ab}(0)=1240$ Å and $T_{c0}=111.6$ K. As can be seen, Eq. (4) without any fitting parameter, describes very well the experimental $\lambda_{ab}(T)$ data for high temperatures when vortex fluctuations are taken into account.

It is interesting to estimate T_{SC}, which is shown to be[9]

$$T_{SC}=T_{c0}\left[1-\frac{(1-T^*/T_{c0})}{2(\ln\kappa+0.5)}\times\ln\frac{(1-T^*/T_{c0})(\lambda_J/\xi_{ab})^2}{\alpha\pi\ln(\lambda_J/\xi_{ab})}\right] , \tag{6}$$

where $\lambda_J=\gamma d$ is the Josephson length. Using $\gamma=31$ (Ref. 27) and $d=18$ Å, we have $\lambda_J=558$ Å. From experimental values for $T^*\approx 106$ K, $\lambda_{ab}(0)=1240$ Å and considering $\xi_{ab}(0)=10$ Å (Ref. 4), one can calculate $T_{SC}=110.3$ K and $T_{c0}-T_{SC}=1.3$ K. The obtained $T_{c0}-T_{SC}$ difference in $Bi_2Sr_2Ca_2Cu_3O_{10}$ is smaller when compared with more anisotropic compounds, $Bi_2Sr_2CaCu_2O_8$ [$T_{c0}-T_{SC}=2.1$ K (Ref. 28) or 3 K (Ref.

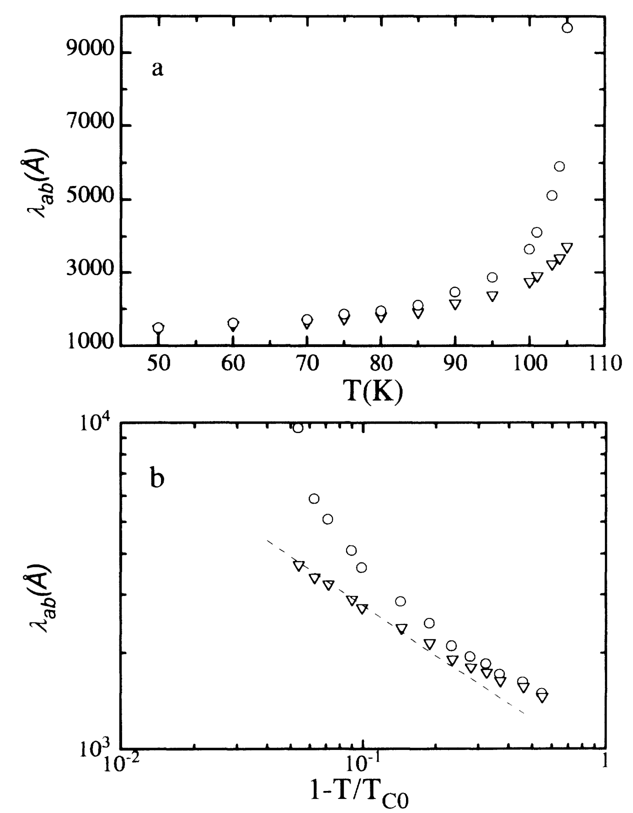

FIG. 2. (a) Temperature dependencies of the in-plane penetration depth λ_{ab} obtained from the slopes $\partial M/\partial \ln H$ neglecting (○) and taking vortex fluctuations into account (▽). (b) The same results in a double logarithmic scale λ_{ab} vs $(1-T/T_{c0})$; the dashed line is obtained from Eq. (4) with determined parameters $\lambda_{ab}(0)=1240$ Å and $T_{c0}=111.6$ K.

29)] and $Tl_2Ba_2CuO_6$ [$T_{c0}-T_{SC}=2.6$ K (Ref. 6)]. This result is consistent with the theoretical expectation.[9]

The penetration depth data of Fig. 2 allow us to make a quantitative comparison of the IL with a theoretical ML. Below a crossover field $H_{2D\text{-}3D}\approx\phi_0/\gamma^2 d^2$, the melting phase transition is of a 3D nature and for magnetic fields applied parallel to the c axis, ML is given by the following expression:[12-16]

$$H_m(T)=\frac{\phi_0^5 c_L^4}{16\pi^4 k_B^2 \mu_0^2 \gamma^2 \lambda_{ab}^4(T) T^2}\ , \qquad (7)$$

where c_L is the Lindemann number. Using the experimental data of $\lambda_{ab}(T), \gamma=31$, and c_L as a free parameter, we can calculate $H_m(T)$. In Fig. 3(a) the calculated values of $H_m(T)$ using Eq. (7) are presented. As seen in this figure, $H_m(T)$ values, taking into account fluctuation corrections for $\lambda_{ab}(T)$ and using $c_L=0.28$, match perfectly our experimental low-field and high-temperature irreversibility points.[30] At the same time, it is not possible to fit the experimental data using $\lambda_{ab}(T)$ without the fluctuation corrections. The dashed line in Fig. 3(a) corresponds to the best approach to the IL for this case. Substituting Eq. (4) in Eq. (7) one can have for temperatures $1-T/T_{c0}\ll 1$,

$$H_m(T)=A(1-T/T_{c0})^2\ , \qquad (8)$$

where

$$A=\frac{\phi_0^5 c_L^4}{4\pi^4 k_B^2 \mu_0^2 \gamma^2 \lambda_{ab}^4(0) T_{c0}^2}\ .$$

Taking $\lambda_{ab}(0)=1240$ Å, $T_{c0}=111.6$ K, $\gamma=31$, and $c_L=0.28$, we obtain $A\approx 0.6$ T. In order to further test the melting models we have plotted H_m as a function of $(1-T/T_{c0})$ in a double logarithmic scale [Fig. 3(b)]. The agreement of the experimental IL data with Eq. (8) is excellent [solid line in Fig. 3(b)]. Here we have also plotted the dc irreversibility data from (Ref. 20) for $Bi_2Sr_2Ca_2Cu_3O_{10}$, assuming the same value of T_{c0}. They coincide with our IL. The inset of Fig. 3(b) presents the same data now replotted in terms of $(1-T/T_c)$ with $T_c=109$ and 108 K as obtained in the present work and in Ref. 20, respectively. The dashed line corresponds to the relationship $H\propto(1-T/T_c)^2$. As seen, the behavior of IL's in this case is qualitatively inconsistent with the 3D melting result and thus illustrates the importance of using the relevant reduced temperature $T=T/T_{c0}$ when testing melting hypotheses, particularly in strongly anisotropic superconductors where the $(T_{c0}-T_c)$ difference can be sufficiently large. The Josephson coupling changes the dimensionality of the FLL with field. Above the crossover field $H_{2D\text{-}3D}\approx 0.64$ T, the FLL has 2D character and different mechanisms can be responsible for defining the IL in this region.[14,31] The deviation of experimental IL from 3D ML with increasing field is clearly seen in Fig. 3. The large field and low-temperature part of IL can be approximated by the power law $H_i(T)\propto(1-t)^{\alpha}$ with an exponent $\alpha\geq 4$. Discussion of this regime is not within the scope of the present work.

In summary, the results for $Bi_2Sr_2Ca_2Cu_3O_{10}$ presented here show that the behavior of the magnetization curves $M(H)$ in the fully reversible regime above IL can be consistently described by the vortex fluctuation theory of Bulaevskii, Ledvij, and Kogan.[9] The system parameters are determined. They are crossover temperature $T^*\approx 106$ K, mean-field transition temperature $T_{c0}=111.6\pm0.1$ K, superconducting or vortex unbinding temperature $T_{SC}=110.3$ K, London penetration depth

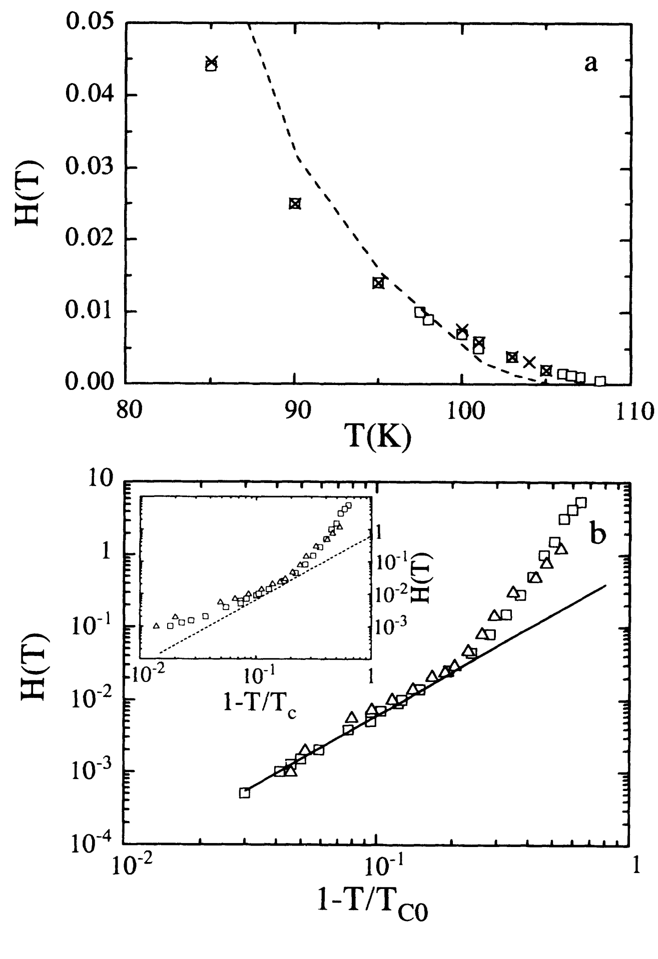

FIG. 3. (a) (□) Our irreversibility data points in the low-field limit; (×) calculated melting line data using Eq. (7) with experimental values of $\lambda_{ab}(T)$, taking into consideration vortex fluctuations and the Lindemann number $c_L=0.28$. The dashed line corresponds to the best approach to the IL, using Eq. (7) with $\lambda_{ab}(T)$ neglecting fluctuations ($c_L=0.34$). (b) (□) Our irreversibility data in the whole measured range of the (H-T) plane in double logarithmic scale H vs $(1-T/T_{c0})$; (△) irreversibility data points of Ref. 20, assuming the same value of $T_{c0}=111.6$ K. The solid line is the calculated melting line $H_m=A(1-T/T_{c0})^2$, with $A=0.6$ T (see text). Inset: the same data replotted in terms of $(1-T/T_c)$; the dashed line corresponds to $H\propto(1-T/T_c)^2$.

$\lambda_{ab}(0)=1240\pm10$ Å, and the distance between weakly coupled CuO_2 planes $d\approx18$ Å. The results give evidence for a strong fluctuation effect on $\lambda_{ab}(T)$ similar to that observed in $Bi_2Sr_2CaCu_2O_8$.[10] The IL is quantitatively compared to predictions of 3D FLL melting models,[11–16] using the determined system parameters. From this we conclude that IL close to T_c is associated with 3D melting of FLL caused by thermal fluctuations.

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