Irreversibility Line of Monocrystalline $Bi_2Sr_2CaCu_2O_8$: Experimental Evidence for a Dimensional Crossover of the Vortex Ensemble

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The irreversibility line $B_m(T)$ of monocrystalline superconducting $Bi_2Sr_2CaCu_2O_8$ has been measured in magnetic fields H parallel to the c axis of the crystal. For low inductions B near T_c, we find a parabolic temperature dependence, $B_m \approx B_0(T_c/T-1)^2$, while for larger inductions, B_m grows exponentially with T^{-1}. We argue that the two regimes reflect the three- and the quasi-two-dimensional character of the respective vortex fluctuations. In both regimes, a Lindemann-type melting criterion yields quantitative expressions for $B_m(T)$ which reproduce the experimental data very well.

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Numerous experiments probing the mixed state of cuprate superconductors have established the presence of a boundary in the magnetic phase diagram, which separates a magnetically irreversible, zero-resistance state from a reversible state with dissipative electrical transport properties [1-5]. This boundary has been suggested to be due to either depinning [2,6], to a vortex-glass formation [7], or to flux-lattice melting [8]. It has been recently suggested that the temperature dependence of the irreversibility field $H_{irr}(T)$ obeys a scaling relation universal for all high-T_c superconductors [5]. Although such a scaling may hold within one class of compounds (e.g., Pr-substituted or oxygen-depleted $YBa_2Cu_3O_{7-\delta}$ [5,9]), it is unlikely that it is also valid for more anisotropic compounds such as $Bi_2Sr_2CaCu_2O_8$ [10]. There, a crossover from essentially three-dimensional to quasi-two-dimensional vortex fluctuations is predicted to occur at $B_{cr} \approx 4\phi_0/s^2\gamma^2$ [10,11], where s is the interlayer distance, $\gamma = \lambda_c/\lambda_{ab}$ is the anisotropy parameter, and ϕ_0 is the magnetic flux quantum. At inductions $B \ll B_{cr}$, the vortices are expected to form an ensemble of vortex strings with 3D-like fluctuations. For $B \gg B_{cr}$, the interaction between vortex objects within one particular layer is stronger than the coupling between these 2D objects belonging to adjacent layers. This leads to a quasi-2D behavior of the thermal vortex fluctuations. Our experimental results on the irreversibility boundary $B_m(T)$ presented below strongly suggest that such a dimensional crossover occurs indeed in $Bi_2Sr_2CaCu_2O_8$.

The experiments were performed on a high-quality single crystal of $Bi_2Sr_2CaCu_2O_8$, prepared from the melt in a temperature gradient. In an external dc field of $H=4$ Oe, diamagnetism was observed to sharply develop below $T_c = 89.7$ K. After demagnetization corrections, the field-cooling susceptibility is 87% of $-1/4\pi$. For such corrections, the demagnetization factor N of the crystal had been previously determined by measuring the apparent zero-field cooling susceptibility χ at $T=6$ K in small external fields, $H \leq 1$ Oe. Assuming complete magnetic screening, i.e., $\chi_{eff} = -1/4\pi$, we obtained $N = 0.965$, which is consistent with a corresponding estimate from an ellipsoid approximation for the shape of the crystal. The irreversibility boundary $T_{irr}(B)$ was measured using a quasistatic technique described in Ref. [4]. The method is based on the measurement of the reduction of trapped magnetic flux with increasing temperature by a SQUID probe. *The remanent magnetization, i.e., the critical-current density j_c, vanishes at $T_{irr}(B)$.* For determining the irreversibility temperature, the detection of the disappearance of trapped flux of an *immobile* sample is, according to our experience, more reliable than the use of critera based on resistivity, ac susceptibility, or moving-sample magnetization measurements [12]. Since the sample is not exposed to variable magnetic fields, we reach a very low frequency scale of the measurement, an upper limit of which ($\omega_m \lesssim 10^{-2}$ Hz) we estimate from the period of the temperature oscillation with an amplitude $\Delta T \approx 0.2$ K, superimposed on the underlying warming rate (≈ 6 mK s^{-1}) [4]. This frequency is 1 order of magnitude lower than what has been claimed to be sufficiently small to detect a vortex-lattice melting in mechanical-oscillator measurements [13]. In a comparable ac susceptibility experiment probing dissipative behavior, a peak in the imaginary part of the complex susceptibility would occur at $\omega_m \approx (c^2/d^2)\rho$, where d is the sample diameter, ρ the sample resistivity, and c the speed of light [14]. Assuming the general equivalence of such experiments, our measurements on a crystal with dimension $d \approx 3$ mm and at a frequency $\omega_m \lesssim 10^{-2}$ Hz indeed probe irreversibility on a level of sensitivity of the order of $\rho \lesssim 10^{-12}$ Ω cm $\approx 10^{-8}$ ρ_n at most, where ρ_n is the normal-state resistance.

Representative observed signals for H parallel to the c axis of the crystal are shown in Fig. 1. The monitored voltage changes V_S at the analog output of the SQUID system correspond to magnetization variations $\Delta M/\Delta V_S \approx 0.2$ G/V. The remanent magnetization does not vanish abruptly in our experiments with $Bi_2Sr_2CaCu_2O_8$, particularly for $H \approx 1$ kOe, in distinct contrast to respective measurements on $YBa_2Cu_3O_7$ [4]. Therefore, we chose to use the minimum in $V_S(T)$ as a criterion defining $T_{irr}(B)$ for $\omega = \omega_m$, accepting an uncertainty in T_{irr} as in-

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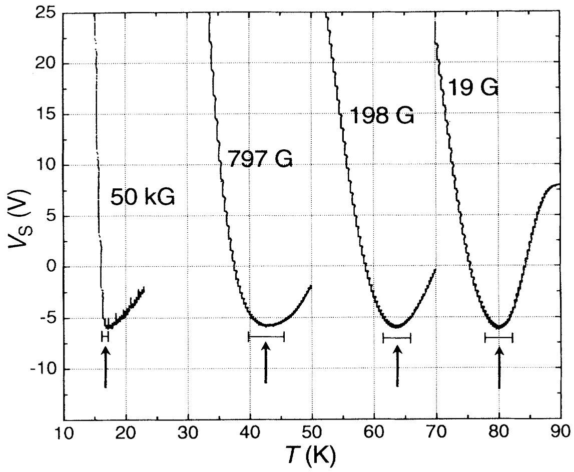

FIG. 1. Selected observed $V_S(T)$ curves used to determine the irreversibility temperatures $T_{\text{irr}}(B)$. The voltage V_S is approximately linearly related to magnetization changes ΔM of the crystal. Arrows indicate $T_{\text{irr}}(B)$, while solid error bars illustrate the estimated error in $T_{\text{irr}}(B)$ (see text and Refs. [4] and [15]).

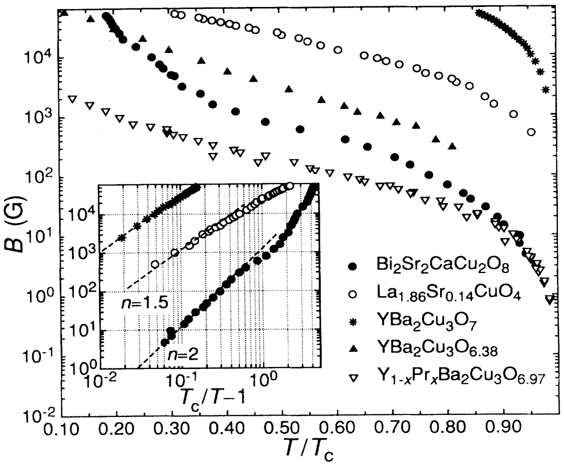

FIG. 2. Irreversibility inductions B_m as a function of T/T_c for $Bi_2Sr_2CaCu_2O_8$, $La_{1.86}Sr_{0.14}CuO_4$ [20], $YBa_2Cu_3O_7$ [4], $YBa_2Cu_3O_{6.38}$ (data of a sample with $T_c \approx 17$ K, taken from Ref. [9]), and $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ ($0 \leq x \leq 0.55$, scaled $10^2 B_m/B^\dagger$ data from Ref. [5]). The inset displays our data of $Bi_2Sr_2CaCu_2O_8$, $La_{1.86}Sr_{0.14}CuO_4$, and $YBa_2Cu_3O_7$, as a function of $\log_{10}(T_c/T-1)$ to demonstrate the approximate power-law behavior (6) near T_c.

dicated by the error margins drawn in Fig. 1 [15]. The demagnetization-corrected irreversibility inductions $B_m(T)$ are presented in Fig. 2.

At temperatures $T/T_c \lesssim 0.5$, we observe a distinct upturn in $\log_{10}B_m(T)$. Previous reports on the irreversibility line in $Bi_2Sr_2CaCu_2O_8$ included the observation of this upturn [16–19]. Such a feature is clearly absent in our data for $La_{1.86}Sr_{0.14}CuO_4$ [20] as well as in corresponding published data for oxygen-depleted $YBa_2Cu_3O_{7-\delta}$ [9] and $Y_{1-x}Pr_xBa_2Cu_3O_{6.97}$ [5], respectively (see Fig. 2). As we argue below, this upturn of $\log_{10}B_m(T)$ at low temperatures manifests the peculiar vortex dynamics expected only in highly anisotropic materials such as $Bi_2Sr_2CaCu_2O_8$.

In the limit of a thin-film type-II superconductor of thickness s, the melting of the flux-line lattice in fields $H \ll H_{c2}$ of the bulk material has been calculated to occur at [21]

$$T_m^{2D} = \frac{A}{8\pi\sqrt{3}} \frac{\phi_0^2 s}{k_B(4\pi\lambda_{ab})^2}, \tag{1}$$

where $0.4 \leq A \leq 0.75$, k_B is the Boltzmann constant, and λ_{ab} is the in-plane penetration depth. For weakly interacting vortices in adjacent layers of a layered superconductor with layer thickness s, the melting line $B_m(T)$ for $B \gg B_{\text{cr}}$ was calculated to asymptotically approach T_m^{2D} as

$$B_m(T) \approx B_{\text{cr}} \exp\{b[T_m^{2D}/(T-T_m^{2D})]^v\}, \tag{2}$$

where $v = 0.37$ and b is a constant of order 1 [10]. There, $T_{\text{irr}}(B)$ is regarded as a melting line independent of measuring frequency, an interpretation which we shall use in the following. In our calculations, we use $\lambda_{ab}(0) = 2100$ Å, determined on the same crystal of $Bi_2Sr_2CaCu_2O_8$ by a technique described in Ref. [22], and $s = 15$ Å, the distance between two CuO_2 double layers, found to be a reasonable estimate for the effective layer thickness s in the framework of Josephson-coupled layered superconductors (JCLS) [22]. The physical essence of the following analysis is, however, not seriously affected if these input parameters are varied within reasonable limits. For the melting temperature T_m^{2D}, we calculate $6 \lesssim T_m^{2D} \lesssim 11$ K. The order of magnitude of B_{cr} is mainly determined by the choice of the parameter γ. Early estimates of B_{cr}, with $\gamma \approx 50$ for $Bi_2Sr_2CaCu_2O_8$, are in the range $1 \lesssim B_{\text{cr}} \lesssim 10$ kG [10,23,24]. However, we find that for a reasonable choice of T_m^{2D} and B_{cr}, Eq. (2) in no way fits our data at lower temperatures [25].

As an alternative, we consider the mean-squared thermal vortex fluctuation displacement $\langle u^2 \rangle_{\text{th}}$ for $B \gg B_{\text{cr}}$ in Josephson-coupled layers for moderate anisotropy ($\xi_{ab} \ll \gamma s \ll \lambda_{ab}$) [10],

$$\langle u^2 \rangle_{\text{th}} = \frac{8\pi\lambda_{ab}^2 k_B T}{\phi_0 s B} \ln\left(\frac{B s^2 \gamma^2}{\phi_0}\right). \tag{3}$$

If $\langle u^2 \rangle_{\text{th}}$ dominates possible quantum fluctuations, likely to be true in $Bi_2Sr_2CaCu_2O_8$ [26], we may use the phenomenological Lindemann melting criterion [27], considered to quantitatively describe experimentally observed irreversibility boundaries in terms of a vortex-lattice melting [8,26,28,29]. From $\langle u^2 \rangle_{\text{th}} \approx \langle u^2 \rangle = c_L^2 a^2 \approx c_L^2 \phi_0/B$, where a is the intervortex distance and c_L is the Lin-

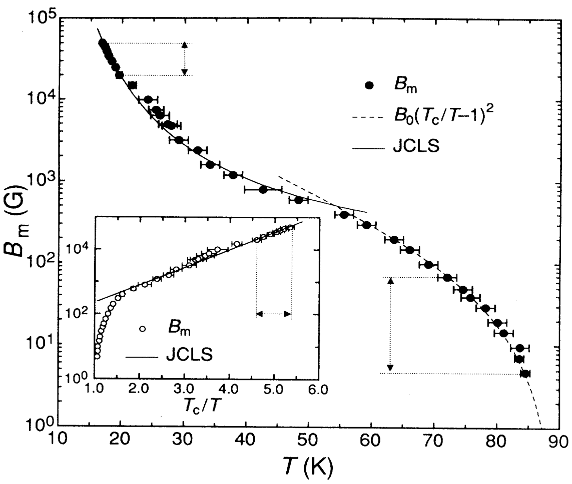

FIG. 3. Vortex-lattice melting temperatures $B_m(T)$ for $Bi_2Sr_2CaCu_2O_8$ on a logarithmic field scale. The arrows indicate the temperature ranges used to fit the data according to Eqs. (4) and (6). The solid lines correspond to a fit according to a description in terms of a Josephson-coupled layered superconductor (JCLS) with $c_L=0.16$ and $\gamma=370$. The dashed line is a quadratic fit to the data near T_c. The inset illustrates the large validity range of the T^{-1} dependence of $\log_{10}B_m(T)$.

demann number, we obtain

$$B_m(T) \approx \frac{\phi_0}{s^2\gamma^2}\exp\left(\frac{\phi_0^2 c_L^2 s}{8\pi\lambda_{ab}^2(0)k_B T}\right). \tag{4}$$

We assumed here that in the temperature region of interest ($T \lesssim 30$ K), the exponent in Eq. (4) is dominated by the T^{-1} term, since $\lambda_{ab}(T) \approx \lambda_{ab}(0)$ is expected to be weakly temperature dependent there. We note that Eq. (4) does not account for a limiting temperature T_m^{2D}.

In Fig. 3, we present the fit of Eq. (4) to our low-temperature data for $B_m(T)$. At first we accept a large estimate for B_{cr} and restrict the fit to the data $B_m(T) > 10$ kG. We obtain $c_L \approx 0.16$, well within expected limits, $0.1 \lesssim c_L \lesssim 0.4$ [30]. For the anisotropy parameter, however, we obtain $\gamma \approx 370$, which is larger than the widely used value $\gamma \approx 55$ [31]. Considering the results of recent resistivity data [32] $[\gamma \approx (\rho_c/\rho_{ab})^{1/2} \approx 200]$ and high-precision torque results [33] ($\gamma > 150$), our value is a reasonable order-of-magnitude estimate for γ. This leads to a reevaluation of $B_{cr} \lesssim 1$ kG and consequently, the validity range of Eq. (4) extends to higher temperatures. Indeed, we find that the exponential behavior of B_m in T^{-1} (with the same choice of c_L and γ, respectively) extends down to $B \approx 1$ kG, which we now consider to be a reasonable estimate of B_{cr} for our crystal.

Despite the remarkable quantitative agreement of the above analysis with experimental data, it should not be ignored that the condition of moderate anisotropy is not really fulfilled in $Bi_2Sr_2CaCu_2O_8$ since $\gamma s \approx \lambda_{ab}$. If we consider the seemingly more appropriate limit of vanishing Josephson coupling, $\gamma s \gg \lambda_{ab}$, we need to replace Eq. (3) by $\langle u^2\rangle_{th} = 16\pi\lambda_{ab}^2 k_B T \ln[2\pi B\lambda_{ab}^2/\phi_0 \ln(\phi_0/4\pi B s^2)]/\phi_0 s B$ [34]. Using the Lindemann criterion, we again obtain an implicit expression for $B_m(T)$, which does not, however, reproduce at all the observed T dependence of B_m at low temperatures within reasonable limits of $\lambda_{ab}(0)$, s, and c_L. We conclude therefore that Eqs. (3) and (4) are, at least from a *phenomenological* point of view, good approximations to describe the melting of the vortex ensemble in $Bi_2Sr_2CaCu_2O_8$ within the above given limits.

For $B \ll B_{cr}$, nearly 3D-like vortex fluctuations are expected [10], and thus [8,35]

$$\langle u^2\rangle_{th} \approx 4\pi k_B T \gamma \lambda_{ab}^2 (4\pi/B\phi_0^3)^{1/2}. \tag{5}$$

For the respective melting line, according to the Lindemann criterion, one obtains for $T \to T_c$

$$B_m(T) \approx B_0(T_c/T - 1)^n, \qquad B_0 \approx \frac{\phi_0^5 c_L^4}{16\pi^3\lambda_{ab}^4(0)\gamma^2(k_B T_c)^2}, \tag{6}$$

with $n=2$ [36], using $\lambda_{ab}^{-2}(T) \approx 2\lambda_{ab}^{-2}(0)(1-T/T_c)$. If we allow the exponent n in Eq. (6) to be a parameter in a fit to the data for $T \gtrsim 72$ K, we obtain $n = 1.8 \pm 0.1$ and $B_0 = 860 \pm 120$ G. For $n=2$, we find $B_0 = 1160 \pm 40$ G. Figures 2 and 3 suggest that a fit according to Eq. (6) with $n=2$ is indeed a good approximation to the experimental results near T_c. If we use our low-temperature estimate $\gamma \approx 370$, we obtain $c_L \approx 0.28$. It is not unreasonable to assume a variation of c_L with temperature. Numerical simulations of the flux-lattice melting suggest $0.1 \lesssim c_L \lesssim 0.4$ [30], depending on the range of inductions B_m. We realize, however, that the tendency of an increasing c_L with increasing T is opposite to what is predicted by these calculations.

Above $T \approx 85$ K $< T_c$, no magnetic flux could be trapped in the crystal. This observation is confirmed by Hall-probe measurements [37], which indicate an abrupt disappearance of $B_m(T)$ close to but below T_c.

From the temperature dependence of the irreversibility boundary for $Bi_2Sr_2CaCu_2O_8$, we identify two regimes characterized by the dimensionality of the vortex fluctuations. The crossover from the 3D to the 2D regime manifests itself in a distinct upturn of $\log_{10}B_m(T)$ towards lower temperatures, forming a plateaulike feature at $B \approx B_{cr}$. Such a feature should only appear in highly anisotropic compounds which can be considered as a set of weakly interacting superconducting layers, such as $Tl_2Ba_2CaCu_2O_8$ ($\gamma \approx 300$, [38]) and $(Y,Pr)Ba_2Cu_3O_7$ superlattices.

For the above analysis, we assumed the irreversibility boundary to be a melting line, the temperature dependence of which is only determined by $\langle u^2\rangle$. Therefore, we regard our results as a strong support for the concept of melting in describing the irreversibility line in $Bi_2Sr_2CaCu_2O_8$. The observed exponents $n \approx \frac{3}{2}$ of the power law of Eq. (6) near T_c for $YBa_2Cu_3O_7$ and $La_{1.86}Sr_{0.14}CuO_4$ do not contradict the concept of melting. The thermal fluctuations of the vortices are significantly smaller in these compounds because of their lower anisotropy [8]. It has been argued that in such cases, quantum corrections to the total mean-squared displacement $\langle u^2 \rangle$ of the vortices ought to be taken into account [26]. Corresponding calculations give indeed a very good agreement with the experimentally observed temperature dependence of B_m near T_c [20].

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