Pressure Dependence of the Irreversibility Line in $Bi_2Sr_2CaCu_2O_{8+\delta}$: Role of Anisotropy in Flux-Line Formation

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One of the important problems of high-temperature superconductivity is to understand and ultimately to control fluxoid motion. Here we present data on the pressure dependence of the irreversibility line measured up to 2.5 GPa. We observe that the application of pressure changes the interplanar coupling by decreasing the c-axis length, without significantly disturbing the intraplanar superconductivity. Our results directly show the relationship between lattice spacing and the irreversibility line in $Bi_2Sr_2CaCu_2O_{8+\delta}$, and demonstrate the potential for a dramatic reduction in the flux motion.

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The strongly two-dimensional nature of $Bi_2Sr_2CaCu_2O_{8+\delta}$ makes it a particularly apt system in which to study flux dynamics. Theoretically, it has been recognized that the large anisotropy parameter and the temperature dependence of the Josephson coupling between planes should conspire to cause a crossover from vortex lines to pancakes [1–3]. That is, the vortices change their topology from 3D tubes to 2D disks. Experimental evidence indicates such a crossover in studies of the magnetization [4] and muon-spin rotation [5]. Furthermore, the unusual flux dynamics have been shown to lead to an anomalously low irreversibility field, H_{irr} [6], below which resistivity drops in the superconductor [4,7]. The value of H_{irr} forms an irreversibility line in the H-T plane, which is a key feature for understanding flux-line dynamics. Much theoretical effort has been expended to tie this feature to the physical properties of the high-temperature superconductors. More recently, experiments by Fuchs and co-workers [8,9] have clarified the situation by demonstrating that, in $Bi_2Sr_2CaCu_2O_{8+\delta}$, H_{irr} is determined by surface barriers. We capitalize on this experimental fact to demonstrate the role played by interplanar spacing on the formation of flux lines.

Previous investigations of the role of anisotropy have shown shifts of the irreversibility and melting lines in oxygen-reduced $Bi_2Sr_2CaCu_2O_{8+\delta}$ [10–13]. Oxygen annealing simultaneously produces these four physical changes in the sample: (1) the c-axis lattice spacing, (2) T_c, (3) the in-plane penetration depth, λ_{ab}, and (4) the density of pinning sites. A typical annealing study achieves a reduction in the c-axis lattice parameter of roughly 8 pm, a 0.3% change, at the cost of altering T_c by 20% or more [11,14]. Not unrelated is the fact that λ_{ab} at 0 K has been shown to vary with oxygen doping, from 210 to 305 nm [14]. At low temperatures, the situation is further complicated by the influence of bulk pinning. Thus, in a doping study, the effects of interplanar separation, penetration depth, and pinning site density on the flux dynamics are all intermingled. This problem is partially addressed in a study by Tamegai *et al.* [15], which reports shifts in the melting line with the application of pressure. To better understand the irreversible flux motion, it is necessary to deconvolve these phenomena.

In this Letter, we present the results of a study in which we directly investigate the effect of varying the interplanar spacing on the irreversibility line. This is shown to increase the interlayer coupling, but to negligibly change the intraplanar superconductivity. Compressibility studies on $Bi_2Sr_2CaCu_2O_{8+\delta}$ have shown [16] that applying a pressure of 2.5 GPa decreases the c axis by 50 pm (a factor of 3 greater than the change in either the a or the b axis). We find that, at 2.5 GPa, H_{irr} increases by a factor of 10 at high temperatures, T_c is changed by only 4%, and $\lambda_{ab}(T)$ is only marginally altered. As a result, we are able to show clear evidence of a 3D to 2D crossover in the flux dynamics and demonstrate a significant pressure-induced change in the interplanar coupling.

The $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystal used in this study was grown by a self-flux technique using a stoichiometric ratio (Bi:Sr:Ca:Cu = 2.2:1:2) of cations [17,18]. The crystal shape is that of a platelet, with dimensions $200 \times 200 \times 50\ \mu m^3$ and a T_c of 86.3 K. Quasihydrostatic pressure is applied to the sample using a diamond anvil cell with a 4:1 methyl-ethyl alcohol solution as the pressure-transmitting medium. The pressure is applied and measured at room temperature using ruby fluorescence as a standard. Cooling the cell causes an increase in the pressure, due to the thermal contraction of the cell. This effect is calibrated in a separate measurement wherein the temperature-dependent shift in the ruby fluorescence is measured in a cryostat with optical access [19]. Through this procedure, we determine the pressure at low temperatures to within an uncertainty of ± 0.3 GPa.

The irreversible flux motion is detected by measuring the third harmonic of the ac susceptibility with primary and secondary coils wound around the diamond facets. Both the ac and dc magnetic fields are applied parallel to the c axis, which is also parallel to the cylinder axis of the pressure cell. The ac-field amplitude is 0.5 mT, and the excitation frequency is 3.7 kHz. Details of this technique and of the diamond anvil cell are given in Refs. [20] and [19].

The nonlinear response to irreversible flux motion in the superconductor is shown in Fig. 1. The irreversibility line is defined by the locus of points determined by H and the onset temperature T_1 (see Fig. 2). In the past several years, a great deal of progress has been made toward understanding the physical origins of the irreversibility line. Often, this line does not indicate a phase boundary, but is simply a dividing line between reversible and irreversible flux motion, which is limited by extrinsic factors such as geometrical barriers, surface barriers, or pinning. At high temperatures, the irreversibility line has been shown to lie both above and below the melting line, while extending well into the high field regime at low temperatures [4,21]. Furthermore, the onset of irreversibility has been shown to be determined by the barrier energy for flux entry into the superconductor.

The data of Fig. 2 show a crossover in the pressure and temperature dependence of H_{irr} near 50 mT. These results are consistent with the muon-spin-resonance (μSR) data of Aegerter *et al.* [5] who find a 3D to 2D crossover field close to 70 mT. These authors further show that the crossover field is reduced to 30 mT by an increase in λ_{ab} and is independent of the anisotropy. At low temperatures, two-dimensional behavior is expected to occur, and H_{irr} shows a weak pressure dependence. Above the crossover temperature near 60 K, the application of pressure significantly shifts the irreversibility line.

We first focus on the low-temperature regime, where the data are described well by the theoretical model of Burlachkov *et al.* [22]. Here, the essential assumption is that the irreversible behavior is a result of vortex pancakes penetrating surface barriers. For high fields, much larger than the first penetration field ($H \gg H_P \approx 15$ mT) and $T > T_0$ (defined below), the irreversibility field assumes an exponential form

$$H_{\mathrm{irr}} \approx H_{c2}(T_0/2T)\exp(-2T/T_0), \qquad (1)$$

$$T_0 = \frac{\phi_0^2 d}{(4\pi\lambda_{ab})^2 \ln(t/t_0)}, \qquad (2)$$

where H_{c2} is the upper critical field, ϕ_0 is the fluxon, d is the interlayer spacing, and t and t_0 are time scales related to the rate of flux creep over the surface barrier [23]. Here we equate the fractional change in the interlayer spacing with that of the c axis obtained from compressibility data [16]. Then, we are able to determine T_0 by fitting our data to Eq. (1) as shown in Fig. 2. For 0, 1.5, and 2.5 GPa, we obtain for T_0 values of 20.6, 23.5, and 22.9 K, respectively (± 2 K). A constant value of $H_{c2} \approx 180$ T is used here, and we obtain similar values of T_0 over a range of reasonable, constant values for H_{c2} (50 T $< H_{c2} <$ 250 T). The 0 GPa and the 1.5 GPa data are indistinguishable while the irreversibility line at 2.5 GPa is shifted to slightly higher temperatures. Also note that the measured range of T_0 values corresponds to a variation in $\lambda_{ab}(T)$ of only 15 nm. This indicates that the pressure has little effect on the penetration depth. [Here we have taken $\ln(t/t_0)$ to be 30 as in Ref. [22].]

This result is illustrated in Fig. 3 by a plot of λ_{ab} vs c axis from pressure and from doping studies. For the latter studies $\lambda_{ab}(0)$ is determined from magnetization measurements [14,24,25], and for our study from fits to Eq. (2).

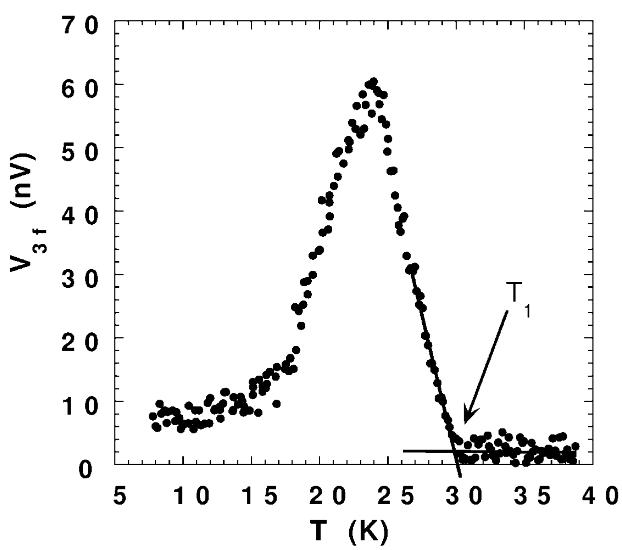

FIG. 1. The third harmonic peak in $Bi_2Sr_2CaCu_2O_{8+\delta}$ when there is no applied pressure and the applied field is 3.0 T. T_1 is defined by the intersection of two linear fits: the first to the background data and the second to the front side of the peak.

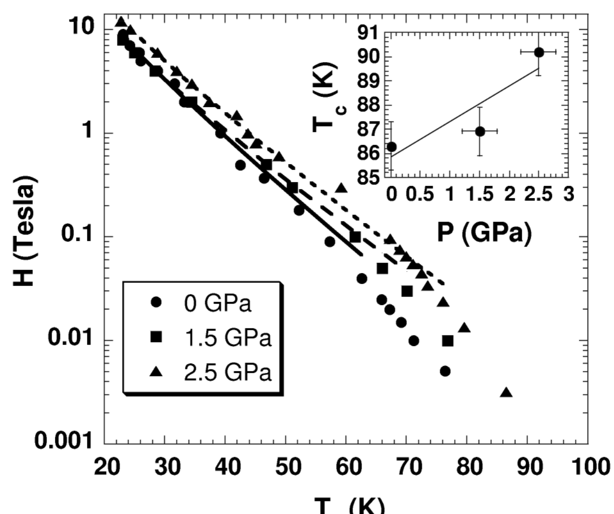

FIG. 2. H_{irr} at various pressures. At high fields the data show an exponential dependence which is expected for vortex pancakes penetrating the surface barrier. The inset shows T_c as a function of pressure. The slope, dT_c/dP is consistent with that observed in other laboratories [32].

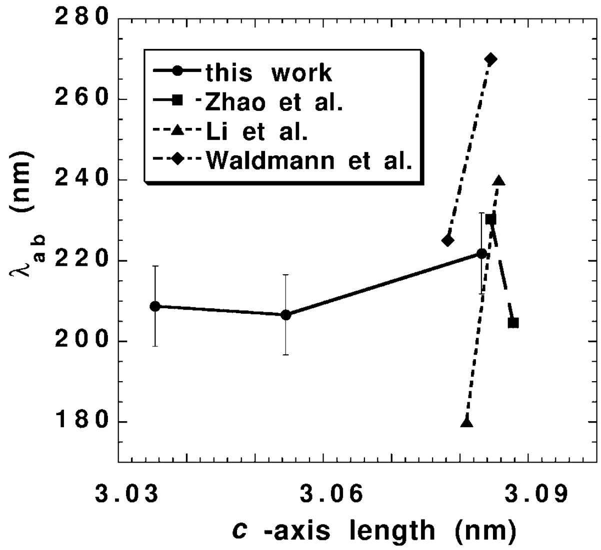

FIG. 3. Comparison of the change in λ_{ab} with c axis for pressure-induced changes (circles) and oxygen-doping-induced changes: squares [14], triangles [24], diamonds [25]. For our data, the c axis is calculated from the pressure and the elastic moduli [16], and, for the other data, from correlations between T_c, oxygen deficiency, and the c-axis spacing [33].

The μSR data of Aegerter *et al.* [5] are not shown, but are consistent with the magnetization data of Li and co-workers [24]. It is clearly shown in Fig. 3 that our experiment probes the effect of changing the interplanar spacing while holding the superconducting properties of the planes nearly constant. In contrast, oxygen-doping experiments probe the effect of modifying the intraplanar-superconducting order parameter, while causing relatively small changes in the interplanar spacing.

Thus far, we have discussed only surface-barrier penetration as the mechanism to explain the irreversibility line. There are other models that we have considered, which are rooted in bulk properties and which predict a power-law dependence for the irreversibility line:

$$H_{\mathrm{irr}} = H_0[1 - (T/T_c)^n]^\alpha. \tag{3}$$

The above result holds for the irreversibility line denoting a flux-lattice-melting transition ($n = 1, \alpha \leq 2$) [10], a Bose-glass transition ($n = 1$, $\alpha = 2$ or 4/3) [26,27], or a bulk-interplanar-decoupling transition of the vortices ($n = -1, \alpha = 1$) [10]. Our data can be represented by these models only for large values of the exponent ($\alpha = 7.4$ for $T < 60$ K and $\alpha = 3.5$ for $T > 70$ K) or for unphysically large values of the scaling fields H_0. This is similar to results obtained by Schilling and co-workers [4]. Thus we conclude that the irreversibility-line data are not indicative of a bulk transition in the sample.

In contrast to the low-temperature data, our high-temperature data show a significant pressure effect. Thus, we are led to conclude that this stiffening of the irreversibility line is due to the onset of 3D coupling between the vortices. This warrants that the data be analyzed in terms of a model based on the penetration of the surface barrier by individual 3D fluxoids.

For this case, the results of Burlachkov *et al.* indicate that the irreversibility line is described by the following expression [22]:

$$\frac{H_{\mathrm{irr}}}{Z^2(T)\ln^3(H_{c2}/H_{\mathrm{irr}})} \approx \frac{\pi}{256\gamma}\,\frac{\phi_0 T_0^2}{d^2}\,\frac{1}{T^2}, \tag{4}$$

where $\gamma = (m_c/m_{ab})^{1/2} = \lambda_c/\lambda_{ab}$ is the effective-mass-anisotropy parameter, and $H_{c2}(T)$ is linear with a slope of -2.7 T/K [28]. $Z(T) = \lambda_{ab}^2(0)/\lambda_{ab}^2(T)$ is the temperature dependence of the penetration depth, taken from the data of Waldmann *et al.* [25]. In Fig. 4 we show the data and fits, and in the inset we linearize the data by plotting the left-hand side of Eq. (4) (H^* in the figure) vs $1/T^2$. At 0 GPa the data show a linear dependence for $10 < H < 40$ mT and $62.6 < T_1 < 71$ K. Not enough data were measured at 1.5 GPa to justify a fit, but the increase in slope is apparent. At 2.5 GPa the slope continues to increase, with the data showing a linear dependence for $24 < H < 96$ mT and $67 < T_1 < 76$ K. As demonstrated by the low-temperature data, the pressure does not significantly alter λ_{ab}. Therefore, the increase in slope is due to a pressure-induced decrease in the effective-mass anisotropy of a factor of 4. The value of the anisotropy is difficult to measure in $Bi_2Sr_2CaCu_2O_{8+\delta}$, because of its two-dimensional electronic properties. Using the fitted values of T_0 from above gives γ values of 530 $\pm$ 100 and 130 $\pm$ 20 for 0 and 2.5 GPa, respectively. At 0 GPa, this is significantly higher than other reports in the literature, except for a value of 370 measured by Schilling and

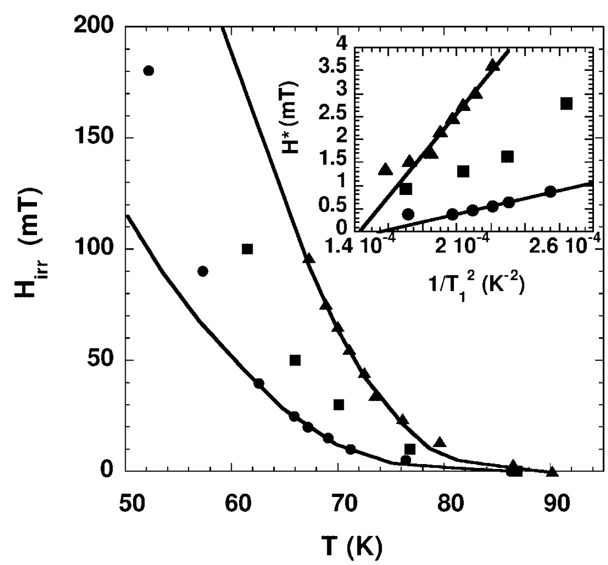

FIG. 4. Fit to the high-temperature data for pressures of 0 GPa (circles), 1.5 GPa (squares), and 2.5 GPa (triangles). The linear dependence seen in the inset is that expected for individual vortex lines penetrating the surface barrier, and the deviation from this fit at high temperatures is observed for applied fields close to H_{c1}.

co-workers [4] in a similar field range. Our result is further supported by the observation of γ increasing rapidly with decreasing field [29] and the lower limit of $\gamma > 150$ from the torque magnetometry measurements of Martínez and co-workers [30].

In a related work, Tamegai *et al.* [15] report a pressure-dependent stiffening of the vortex-lattice melting line up to a pressure of 1 GPa. Their results indicate that the melting field shifts at a rate, $\Delta B_m(P)/B_m(0)$, of 33%/GPa at 65 K. For $B_m \propto 1/\gamma^2$, this corresponds to a 26% decrease in γ at 2.5 GPa, which is smaller than what we obtain using Eq. (4).

Nevertheless, our results clearly show that the interplanar coupling of the vortices changes dramatically with the application of pressure. Such a drastic increase in the interplanar coupling has also been measured by Yurgens *et al.*, who observe a large pressure dependence of the c-axis critical current, I_c, in $Bi_2Sr_2CaCu_2O_{8+\delta}$ [31]. At ~65 K and $H = 0$ mT, the authors report a relative change in I_c, $\Delta I_c(P)/I_c(0)$, of ~133%/GPa for $\Delta P = 0.8$ GPa. Their experiment directly probes the interplanar Josephson effect in $Bi_2Sr_2CaCu_2O_{8+\delta}$, while in our experiment the role of Josephson coupling is manifested through an effective increase in the height of the surface barrier.

In total, the results that we have presented show that even modest changes in the c axis lead to dramatic effects on flux-line formation. We observe that the applied pressure seems to have little influence on the superconducting order parameter (as evidenced by the insensitivity of λ_{ab} and of T_c to pressure). By contrast, the application of pressure decreases the anisotropy and increases the energy needed to bend an individual vortex line. Thus we demonstrate the importance of interplanar spacing on the formation of flux lines.

Our experiment probes the superconducting properties in a very different manner than is done in doping studies. In the pressure experiments (up to our maximum pressure of 2.5 GPa), the intraplanar superconductivity seems to be relatively unchanged, while the coupling between planes is strongly affected. This contrasts to doping experiments where the major effect seems to be to alter the superconducting order parameter, while causing only modest changes in interplanar spacing. Doping does affect the anisotropy, but mainly by changing the magnetic penetration depth.

In a general way, this experiment sheds light on the role of surface barriers to flux penetration in determining the position of the irreversibility line. The consistency of the temperature and pressure dependencies of H_{irr} shows clear evidence that there are two regimes of flux motion. For temperatures below about 60 K, the flux configuration is that of two-dimensional pancake vortices. This crosses over to one of highly anisotropic, three-dimensional flux tubes at higher temperatures. The irreversibility line is then determined by the energy needed to push pancake vortices into the sample at low temperatures or to push line vortices into the sample at temperatures closer to T_c.

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[1] D. R. Nelson and H. S. Seung, Phys. Rev. B **39**, 9153 (1989).
[2] M. P. A. Fisher *et al.*, Phys. Rev. B **40**, 546 (1989).
[3] G. Blatter *et al.*, Rev. Mod. Phys. **66**, 1125 (1994).
[4] A. Schilling *et al.*, Phys. Rev. Lett. **71**, 1899 (1993).
[5] C. M. Aegerter *et al.*, Phys. Rev. B **54**, R15 661 (1996).
[6] D. A. Huse *et al.*, Nature (London) **358**, 553 (1992).
[7] Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988).
[8] D. T. Fuchs *et al.*, Nature (London) **391**, 373 (1998).
[9] D. T. Fuchs *et al.*, Phys. Rev. Lett. **80**, 4971 (1998).
[10] B. Khaykovich *et al.*, Phys. Rev. Lett. **76**, 2555 (1996).
[11] K. Kishio *et al.*, in *Proceedings of the 7th International Workshop on Critical Currents in Superconductors*, edited by H. W. Weber (World Scientific, Singapore, 1994), p. 339.
[12] A. Mumtaz *et al.*, Physica (Amsterdam) **302C**, 331 (1998).
[13] S. Ooi *et al.*, Physica (Amsterdam) **302C**, 339 (1998).
[14] X. Zhao *et al.*, Physica (Amsterdam) **307C**, 265 (1998).
[15] T. Tamegai *et al.*, Physica (Amsterdam) **282-287C**, 2029 (1997).
[16] J. S. Olsen *et al.*, Phys. Scr. **44**, 211 (1991).
[17] C. Kendziora *et al.*, Phys. Rev. B **45**, 13 025 (1992).
[18] C. Kendziora *et al.*, Physica (Amsterdam) **257C**, 74 (1996).
[19] C. C. Kim *et al.*, Rev. Sci. Instrum. **65**, 992 (1994).
[20] M. P. Raphael *et al.*, Rev. Sci. Instrum. **80**, 4971 (1998).
[21] D. Majer *et al.*, Phys. Rev. Lett. **75**, 1166 (1995).
[22] L. Burlachkov *et al.*, Phys. Rev. B **50**, 16 770 (1994).
[23] V. N. Kopylov *et al.*, Physica (Amsterdam) **170C**, 291 (1990).
[24] T. W. Li *et al.*, Physica (Amsterdam) **257C**, 179 (1996).
[25] O. Waldmann *et al.*, Phys. Rev. B **53**, 11 825 (1996).
[26] Y. C. Kim *et al.*, Phys. Rev. B. **52**, 4438 (1995).
[27] Y. Xu and M. Suenaga, Phys. Rev. B. **43**, 5516 (1991).
[28] Qiang Li *et al.*, Phys. Rev. B **48**, 9877 (1993).
[29] S. Kawamata *et al.*, Physica (Amsterdam) **246-247B**, 437 (1998).
[30] J. C. Martínez *et al.*, Phys. Rev. Lett. **69**, 2276 (1992).
[31] A. Yurgens *et al.*, Phys. Rev. Lett. **79**, 5122 (1997).
[32] S. Klotz and J. S. Schilling, Physica (Amsterdam) **209C**, 499 (1993).
[33] X. Sun *et al.*, J. Phys. Condens. Matter **9**, 6391 (1997).