Pressure Dependence of the Irreversibility Line in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$: 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. We present the results of a new technique for measuring the pressure dependence of the transition to superconductivity in a diamond anvil cell. By measuring the third harmonic of the ac susceptibility, we determine the onset of irreversible flux motion. This enables us to study the effects of pressure on flux motion. The application of pressure changes interplanar spacing, and hence the interplanar coupling, without significantly disturbing the intraplanar superconductivity. Thus we are able to separate the effects of coupling from other properties that might affect the flux motion. Our results directly show the relationship between lattice spacing, effective mass anisotropy, and the irreversibility line in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. Our results also demonstrate that an application of 2.5 GPa pressure causes a dramatic increase in interplanar coupling.

The strongly two dimensional nature of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ 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 the temperature dependence of the Josephson coupling to that of the irreversibility line. Experimental evidence indicates such a crossover in studies of Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, and the irreversibility line in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. Our results also demonstrate that an application of 2.5 GPa pressure causes a dramatic increase in interplanar coupling.

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 superconductor. More recently, experiments by Fuchs and coworkers [9-11] have clarified the situation by demonstrating that, in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, $H_{irr}$ 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$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. 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, $\lambda_{ab}$, 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 0.2% change, at the cost of altering $T_c$ by 20% or more [9]. Not unrelated, is the fact that $\lambda_{ab}$ at zero Kelvin has been shown to vary with oxygen doping, from 210 nm to 305 nm [12]. 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. [13], 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. In our study, the application of pressures up to 2.5 GPa decreases the c-axis by 50 pm (a factor of 3 greater than the change in either the a or b-axis). $H_{irr}$ is increased by a factor of 10 at high temperatures; $T_c$ is only changed by 4%; and $\lambda_{ab}(T)$ is only marginally altered. As a result, we are able to show clear evidence of a 3-D to 2-D crossover in the flux dynamics and demonstrate a significant pressure-induced change in the interplanar coupling.

The Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ 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 [14]. The crystal shape is that of a platelet, with dimensions 200 × 200 × 50 µm$^3$ and a $T_c$ of 86.3 K. Quasi-hydrostatic 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 and a calibration is used to 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 references [13] and [14].

The nonlinear response to irreversible flux motion in the superconductor is shown in Figure 1. The irreversible-
The data of Figure 2 show a crossover in the pressure and temperature dependence of $H_{\text{irr}}$, near 50 mT. These results are consistent with the muon-spin-resonance (µSR) data of Aegerter et al. who find a 3-D to 2-D crossover field close to 70 mT. These authors further show that the crossover field is reduced to 30 mT by an increase in $\lambda_{ab}$ and is independent of the anisotropy. At low temperatures, two-dimensional behavior is expected to occur, and $H_{\text{irr}}$ 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 Burchakov et al. 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 $T > T_o$ (defined below), the irreversibility field assumes an exponential form,

$$H_{\text{irr}} \approx H_{c2}(T_o/2T)\exp(-2T/T_o),$$  (1)

$H_{c2}$ is the upper critical field, $\phi_0$ is the fluxon, $d$ is the interlayer spacing, and $t$ and $t_o$ are time scales related to the rate of flux creep over the surface barrier. Here we equate the fractional change in the interlayer spacing with that of the $c$-axis obtained from compressibility data. Then, we are able to determine $T_o$ by fitting our data to Eq. (1) as shown in Figure 2. For 0 GPa, 1.5 GPa, and 2.5 GPa, we obtain for $T_o$ values of 20.6 K, 23.5 K, and 22.9 K, respectively ($\pm 2$ K). A constant value of $H_{c2} \approx 180$T is used here, and we obtain similar values of $T_o$ over a range of reasonable, constant values for $H_{c2}$ ($50T < H_{c2} < 250T$). 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 $T_o$ 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 $\ln(t/t_o)$ to be 30 as in Ref. 2.)

This result is illustrated in Figure 3 by a plot of $\lambda_{ab}$ vs. $c$-axis from pressure and from doping studies. For the latter studies, $\lambda_{ab}(0)$ is determined from magnetization measurements. For our study from fits to Eq. 2. The µSR data of Aegerter et al. are not shown, but are consistent with the magnetization data of Li and coworkers. It is clearly shown in Figure 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.

![Graph showing the change in $\lambda_{ab}$ with $c$-axis length for pressure-induced changes and oxygen-doping-induced changes](image)

**FIG. 3.** Comparison of the change in $\lambda_{ab}$ with $c$-axis for pressure-induced changes [circles] and oxygen-doping-induced changes: squares [diamonds]. For our data, the $c$-axis is calculated from the pressure and the elastic moduli, and for the other data, from correlations between $T_c$, oxygen deficiency, and the $c$-axis spacing.

Thus far, we have only discussed 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:

$$H_{irr} = H_0(1 - (T/T_c)^n)^\alpha.$$  \hspace{1cm} (3)

The above result holds for the irreversibility line denoting a flux-lattice-melting transition (n = 1, $\alpha \leq 2$)\cite{1}, a Bose-glass transition (n = 1, $\alpha = 2$ or 4/3), or a bulk-interplanar-decoupling transition of the vortices (n = -1, $\alpha = 1$)\cite{1}. 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 coworkers\cite{1}. 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. Moreover, the closer these data are to $T_c$, the steeper the temperature dependence. In a strictly 2-D interpretation, this would indicate a decrease in the penetration depth for $T > 60K$ (see Eq. 2): a physical impossibility. Thus, we are led to conclude that this stiffening of the irreversibility line is due to the onset of 3-D coupling between the vortices. Both the change in the temperature dependence and the stronger pressure effect reinforce this interpretation.

![Graph showing fit to high-temperature data for pressures of 0 GPa (circles), 1.5 GPa (squares) and 2.5 GPa (triangles)](image)

**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 $H_{c1}$.

One would then be led to analyze the data in terms of a model based on the penetration of the surface barrier by individual 3-D fluxoids. For this case, the results of Burlachkov et al. indicate that the irreversibility line is described by the following expression\cite{1}:

$$\frac{H_{irr}}{Z^2(T)ln^3(H_{c2}/H_{irr})} = \frac{\pi \phi_0 T_0^2}{256\gamma d^2 T^2} 1$$  \hspace{1cm} (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. $Z(T)$ = $\lambda_{ab}(0)/\lambda_{ab}(T)$ is the temperature dependence of the penetration depth, taken from the data of Waldmann et al.\cite{1}. In Figure 4 we show the data and fits, and in the inset we linearize the data by plotting the left-hand side of Eq. 4 (K in the Figure) vs. 1/T. 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 $\lambda_{ab}$. Therefore, the increase in slope is due to a pressure-induced decrease in the effective-mass anisotropy of a factor of four. The value of the anisotropy is difficult to measure in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, because of its two-dimensional electronic properties. Using the fitted values of $T_0$ from above, gives $\gamma$ values of 530±100 and 130±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...
coworkers in a similar field range. Our result is further supported by the observation of $\gamma$ increasing rapidly with decreasing field, and the lower limit of $\gamma > 150$ from the torque magnetometry measurements of Martínez and coworkers.

In a related work, Tamegai et al. 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 $\gamma$ 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$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. At $\sim 65$K and $H = 0$ mT, the authors report a relative change in $I_c$, $\Delta I_c(P)/I_c(0)$, of $\sim 133$%/GPa for $\Delta P = 0.8$GPa. Their experiment directly probes the interplanar Josephson effect in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, 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 $\lambda_{ab}$ 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 effect 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 dependences of $H_{irr}$ shows clear evidence that there are two regimes of flux motion. For temperatures below about 60K, 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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