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An Explanation of the Irreversibility Behavior in the Highly-Anisotropic High-Temperature Superconductors

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The wide temperature range of the reversible, lossy state of the new high-temperature superconductors in a magnetic field was recognized[1] soon after their discovery. This behavior, which had gone virtually undetected in conventional superconductors, has generated considerable interest, both for a fundamental understanding of the HTS and because it degrades the performance of HTS for finite-field applications. We show that the recently proposed[2] explanation of this behavior for the highly-anisotropic high-temperature superconductors, as a dimensional crossover of the magnetic vortices, is strongly supported by recent experiments on a $Bi_2Sr_2CaCu_2O_x$ single crystal using the high-Q mechanical oscillator technique[3].

Recently, Kim, et al[2] presented resistance measurements in magnetic fields parallel to the *c*-axis for a series of high-temperature superconductors (HTS) and interpreted them in terms of an irreversibility crossover. These data strongly suggested that the flux motion resulted from a thermally-activated crossover from three dimensional (3D) vortex *lines* to 2D *pancake-like* vortices[4], which can move independently in the Cu-O bi- or tri-layers (multilayers). Using a Josephson tunneling model for the *inter*layer vortex coupling, and conventional depinning in the isolated Cu-O multilayers, the characteristic crossover fields, $H^*(t)$, for the more highly-anisotropic HTS, i.e., the $Tl_2Ba_2CaCu_2O_x$, $TlBa_2CaCu_2O_x$, $TlBa_2Ca_2Cu_3O_x$ and $Bi_2Sr_2CaCu_2O_x$ materials, were fit convincingly with parameters which are in substantial agreement with available measurements or reasonable expectations. The systematics of these parameters further supported a Josephson tunneling model, since fitted values of the *c*-axis resistivities, ρ_c, depended approximately exponentially on d_i, the insulator width between Cu-O multilayers, with a reasonable tunneling barrier height of ~ 0.8 eV.

Further evidence on the nature of the vortex state in $Bi_2Sr_2CaCu_2O_x$ was obtained recently by Duran, et al[3] using a high-Q mechanical oscillator technique. They found *two* loss peaks, occurring at temperatures which were solely dependent on the component of the magnetic field along the *c*-axis. They identified the lower-temperature peak with the 3D to 2D transition and the upper-temperature peak with melting or depinning of the 2D pancake vortices. In this communication, the origins of the two loss peaks are only *slightly* reinterpreted and the mechanical oscillator data[3] are reanalyzed within our model to convincingly demonstrate some specific details which were inaccessible to the resistive measurements[2]. The impressive fit, shown below, results in parameters which are in excellent agreement with the previously published resistance measurements[2].

In the model of Ref. 2, there are two relevant energies for the pancake-like vortices. The first is for coupling between adjacent Cu-O multilayers and it is given by the Josephson coupling energy for the phase of the superconducting order parameter[5],

$E_{cj}(H,T)$. The second is for vortex motion within each isolated Cu-O multilayer: this can be thought of in a number of ways, including a 2D-lattice melting transition[6,7] and conventional depinning[8,9]. Kim, et al[2] pointed out that their data fit both of these quite well with reasonably similar parameters: since they cannot be easily distinguished in either experiment, we follow Kim, et al[2] and use depinning for the quantitative analysis.

The resistance data of Ref. 2 was taken in the linear regime of the current-voltage characteristic. Larger currents decrease the measured H^*. In the linear regime, the role of the Lorentz force is only to bias the motion of any free vortices predominantly in one direction, and not to alter their potential energies. Therefore the model of Ref. 2 defined a characteristic crossover temperature from 3D to 2D vortices, as H and/or T increase, by:

$$k_BT = 2E_{cj}(H,T), \qquad (1)$$

where the factor of 2 accounts for the both Cu-O multilayers (above and below). In the 2D, isolated multilayer regime, as H and/or T increase, a characteristic temperature for vortex depinning *within their individual Cu-O multilayer* was defined by:

$$k_BT = E_{cp}(H,T), \qquad (2)$$

where $E_{cp}(H,T)$ is the energy associated with depinning and is given by that fraction of the loss in superconducting condensation energy of a vortex line, which is compensated by a particular pinning site[9]. For the continuous dissipation found in the transport measurements of Kim, et al[2], the pancake vortices must be completely excited out of their potential wells, so the condition is:

$$k_BT = 2E_{cj}(H^*,T)+E_{cp}(H^*,T). \qquad (3)$$

The crossover conditions, represented by the equalities of Eqns. 1-3 are shown in Fig. 1.

Losses in the mechanical oscillator can occur without the transport of vortices over long distances and thus do not require excitation of vortices out of their potential wells. Instead, losses occur whenever *both* conditions 1 and 2 are satisfied individually, in which case, significant pancake-vortex motion is possible *within* its potential well. Although the more stringent condition 3 is necessary for (long-distance) transport dissipation, it will also lead to a loss peak in the mechanical oscillator experiment, since the excursions of the pancake-vortices during the oscillator period can then be over much greater distances.

The result of applying the same fitting procedure as Ref. 2 to the data of Duran, et al[3] is shown in Fig. 2. In order to better compare the mechanical oscillator data with the model, we use a double-logarithmic plot of $H/H_{c2}(0)$ versus 1-t, where $H_{c2}(0)$ is the upper critical field at zero temperature, $t=T/T_{c0}$ and T_{c0} is the transition temperature in zero field. It should be noted that there are no additional parameters to adjust the relative fit of the two peaks: one set of parameters must fit both data. The interpretation of the higher-field data (solid circles) is the same as Ref. 2, i.e., it is H^*. At high temperatures, we interpret the lower-field data (triangles) as a representation of the 3D to 2D crossover, while the lower-temperature behavior is associated with the depinning crossover in the isolated layers. These are separated by a sharp onset at 1-t ~0.45, but the increase of the experimental data of Fig. 2 in going to even lower temperatures is not as steep as expected from the simple model. One possible explanation is inhomogeneities in the pinning force, either within one Cu-O multilayer or between the multitude of stacked Cu-O multilayers making up the single crystal. In the region between the two experimental curves, the pancake vortices can move within their potential well, resulting in dissipation, while crossing the upper curve, i.e., H^*, results in free vortices with greater dissipation. Note also the 1-t dependence near T_{c0}, as anticipated by the theoretical model: this was also found recently in the resistance measurements on epitaxial films of $Tl_2Ba_2CaCu_2O_x$ at lower-fields and is shown in Fig. 3. The parameters that come from fitting the mechanical oscillator data for $Bi_2Sr_2CaCu_2O_x$ and resistance data for $Tl_2Ba_2CaCu_2O_x$ are shown in Table 1, together with the values reported by Kim, et al[2] which were based solely on a resistance criterion and were over a much smaller magnetic field range. The agreement for $Bi_2Sr_2CaCu_2O_x$ implies that the characterizations of the crossovers using the resistive criterion of Ref. 2 and the mechanical oscillator experiment of Ref. 3 are quite similar.

It would be of interest to repeat the mechanical oscillator measurements on other highly-anisotropic HTS for a more inciteful comparison with the model and a determination of important parameters of these materials. Of particular interest is the low-temperature behavior: if it is 2D melting, it is intrinsic like the interlayer Josephson coupling. However, a depinning crossover is not intrinsic, and the extent to which H^* is modified by artificially introducing pinning is an important fundamental and technological issue. It should be recognized, however, that the high quality of the $Bi_2Sr_2CaCu_2O_x$ single crystal in the measurements of Duran, et al[3] was very likely a key to getting such excellent and easily interpretable results.

Finally, for $YBa_2Cu_3O_7$, Kim, et al[2] concluded that the 3D to 2D transition never occurs below $H_{c2}(T)$, based on the much smaller anisotropy (and ρ_c) compared to the other materials studied in Ref. 2. They presumed this was due to the strong interlayer Josephson coupling, probably resulting from the conducting Cu-O chains[10] short circuiting the Josephson tunneling between Cu-O bi-layers. The absence of the 3D to 2D crossover is entirely consistent with mechanical oscillator experiments[11] in $YBa_2Cu_3O_7$ which show only a single loss peak.

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FIGURE CAPTIONS

Fig. 1. These curves represent characteristic fields for the thermally-activated 3D to 2D crossover (solid), flux depinning (dashed) and the combined effect of both (heavy solid line). The temperature dependence of $H_{c2}(T)/H_{c2}(0)=1-t^2$ is also shown (dot-dashed line).

Fig. 2. The mechanical oscillator data of Ref. 3, together with fits to the model of Ref. 2 for a $Bi_2Sr_2CaCu_2O_x$ single crystal. The lines represent calculations of H^* (solid), the 3D to 2D crossover (short-dashes) and depinning (long dashes).

Fig. 3. Measured H^* values, determined from a resistance criterion of 10^{-5} of the normal-state resistance at T_c, for epitaxial $Tl_2Ba_2CaCu_2O_x$ films, together with fits to the model of Ref. 2. The parameters for the fit are shown in Table 1.

Table 1. Parameters for the highly-anisotropic HTS shown in Figs. 2 and 3 with the corresponding samples of Ref. 2. In these, T_c is measured directly while the fits described in the text provide $H_{c2}(0)$, ρ_c and $B_c(0)$, the thermodynamic critical field at zero temperature, the latter assuming the pinning force is given by its maximum value. The Ginzburg-Landau κ, lower critical field, $H_{c1}(0)$, coherence length, $\xi_{ab}(0)$, and penetration depth, $\lambda_{ab}(0)$, are derived from standard formulas.

Sample	T_c (K)	$\mu_0 H_{c2}(0)$ (T)	ρ_c (Ωcm)	$B_c(0)$ (T)	κ (-)	$\mu_0 H_{c1}(0)$ (T)	$\xi_{ab}(0)$ (Å)	$\lambda_{ab}(0)$ (Å)
Bi-2212	82	40	52	0.40	71	0.0169	28	2000
Bi-2212 (Ref. 2)	80	40	34	0.35	81	0.0135	28	2300
Tl-2212	100	67	8	0.47	101	0.0152	22	2200
Tl-2212 (Ref. 2)	100	60	8	0.47	91	0.0164	23	2100

Figure 1

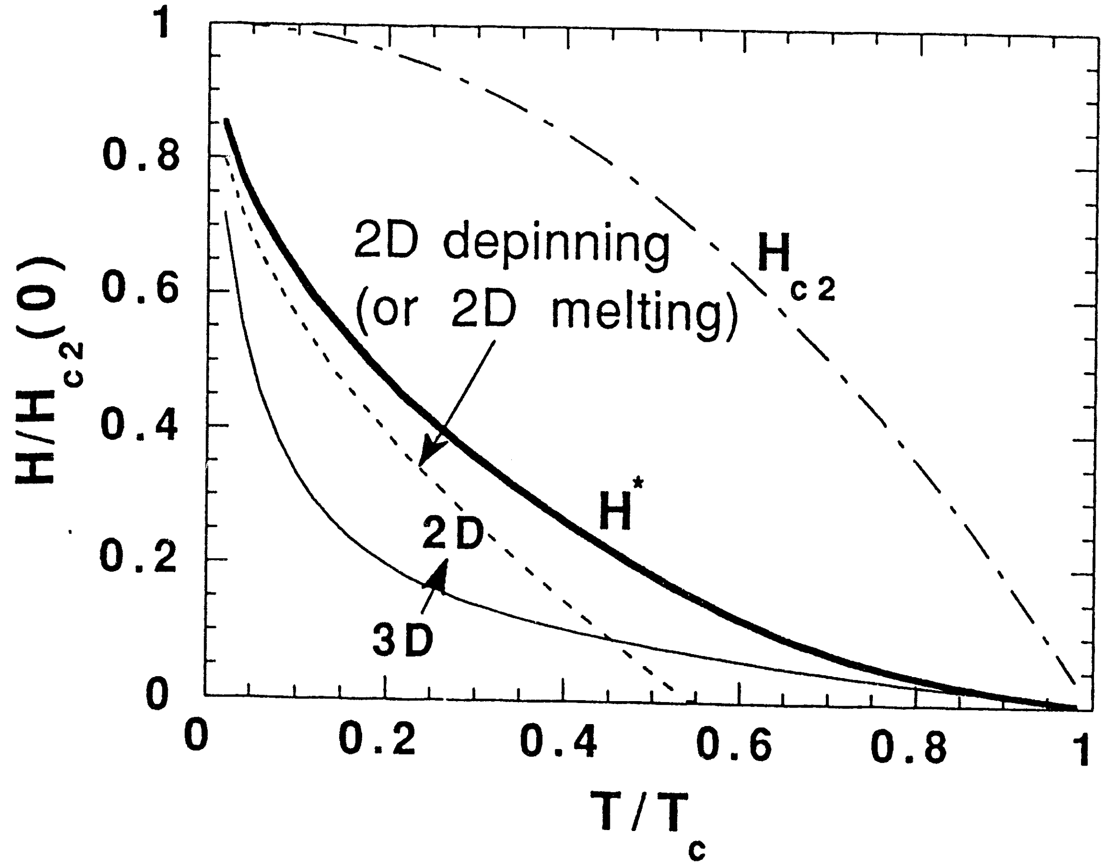

1
0.8
0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
H/H_c2(0)
T/T_c
2D depinning
(or 2D melting)
H_c2
H*
2D
3D

Figure 2

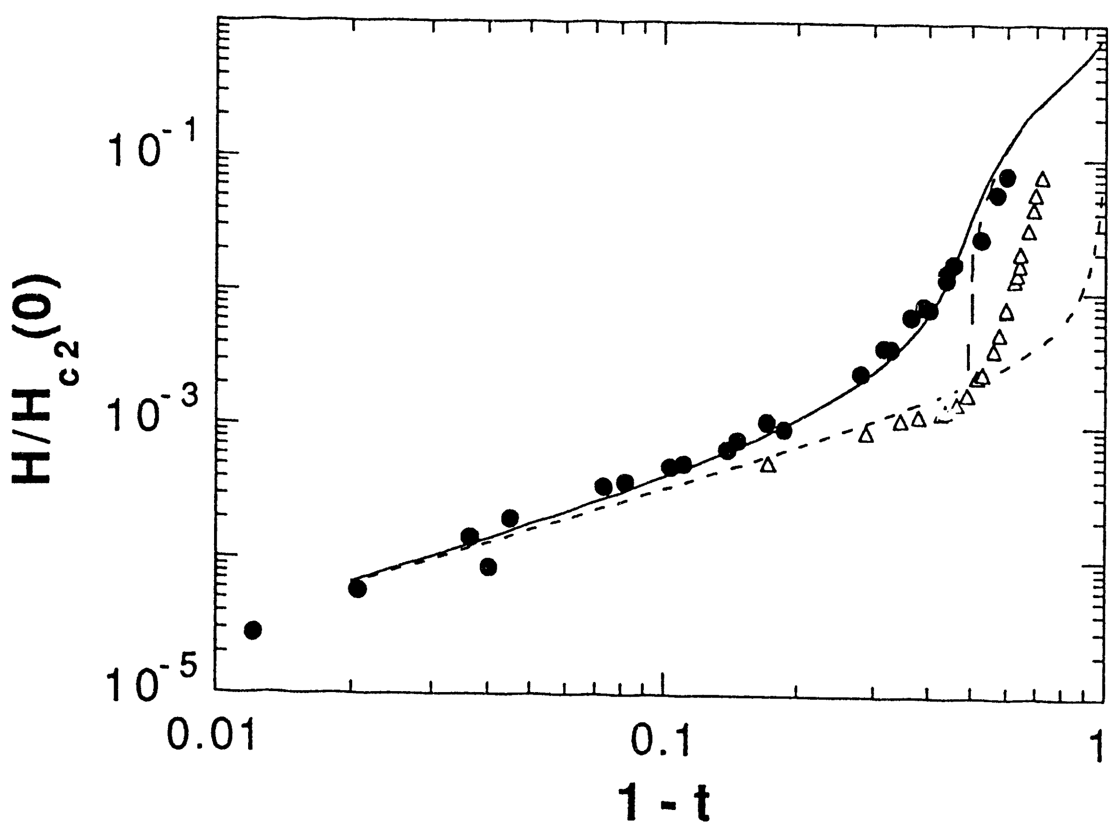
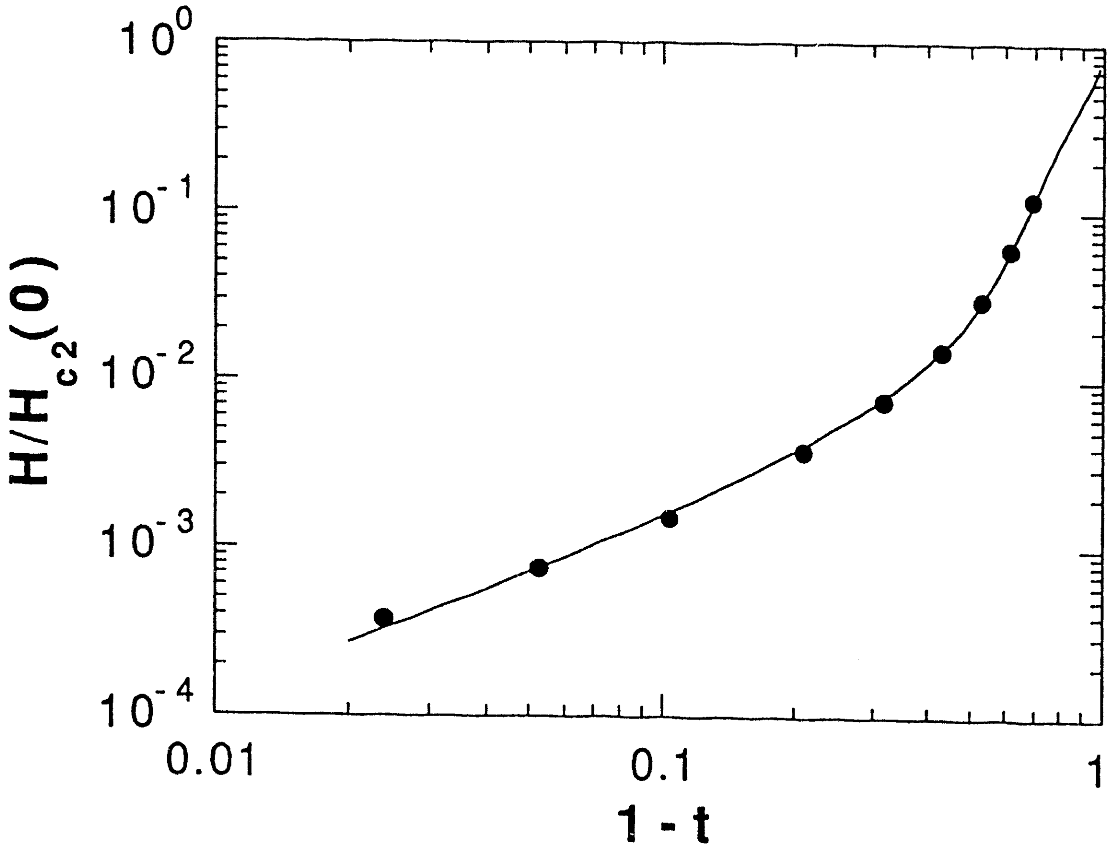


Figure 3



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