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Magnetic relaxation and irreversibility in a superconducting $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ thin film

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The magnetic relaxation in a $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ superconducting thin film has been measured at a range of temperatures (5–70 K) and field strengths (500–5000 Oe). Measurements reveal that the relaxation obeys a logarithmic time dependence in the time interval $2000\ \mathrm{s} < t < 12\,000\ \mathrm{s}$. The relaxation rate is both temperature and field dependent. The average pinning potential U^* calculated from the relationship $U^* = kT/[(-1/M_i)dM/d\ln t]$ is in the range 20–70 meV, which is similar to those of Y-Ba-Cu-O and (Bi,Pb)-Sr-Ca-Cu-O. The anomalous increase of U^* at higher temperature is found to be closely related to the irreversibility line.

I. INTRODUCTION

In recent years many magnetic relaxation measurements have been done on various high-T_c superconductors. Soon after the discovery of high-T_c oxide superconductors, Müller, Takashige, and Bednorz[1] found a large relaxation in the magnetization of the La-Ba-Cu-O superconductor. Following this, extensive studies of magnetic relaxation on single crystals, polycrystals, and thin films of Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O superconductors were carried out.[2–12] In the study of the magnetic properties of the La-Ba-Cu-O oxide superconductor, Müller, Takashige, and Bednorz also observed the presence of an irreversibility line which separates regions of reversible from irreversible magnetic behavior within the Abrikov mixed-phase region. Similar behavior was subsequently observed in many oxide superconductors.[6,13–17] However, the magnetic relaxation and irreversibility of the $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ superconductor, which has the highest transition temperature reported to date,[18] have received relatively less attention.[19,20] In this paper the results of an investigation on the temperature and field dependence of magnetic relaxation, the average pinning potential, and the magnetic irreversibility in a $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ superconducting thin film are presented.

II. EXPERIMENTS

The expitaxial thin film was grown on a $LaAlO_3$ substrate by single-target rf magnetron sputtering with post-annealing conditions similar to those in Ref. 21. The quality of the film was examined by x-ray-diffraction and resistivity measurements. X-ray diffraction revealed that the film consists of mostly the $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ phase, with about 4% of the $Tl_2Ba_2CaCu_2O_x$ phase. The grain sizes of these phases range from 20 to 30 μm. The resistivity measurement yielded a critical temperature T_c of 116 K. The transport critical-current density J_c at zero field was $5\times10^5\ \mathrm{A/cm^2}$ at 100 K, and the size of the film was 4.3 mm×4.1 mm×1 μm. A detailed study of the microstructure and characterization of this film was published elsewhere.[22] The magnetization data were obtained by using a superconducting quantum interference device (SQUID) magnetometer at temperatures below the critical temperature. The magnetic relaxation measurements were taken by first cooling the film under zero field to the desired temperature; then a magnetic field was applied parallel to the c axis of the film, and the magnetization was measured as a function of time. The initial datum point of the magnetization was taken at $t = 170$ s.

III. RESULTS AND DISCUSSION

The magnitude of the magnetization M measured at an applied field $H = 500$ Oe and at temperatures $T = 10$, 15, 20, 30, 40, and 50 K is plotted against the logarithm of the time ($\ln t$) in Fig. 1. The relaxation of the magnetization was linear in $\ln t$ during the observation interval $2000 < t < 12\,000$ s. Some deviation from logarithmic dependence was observed at the short time interval $170 < t < 2000$ s. This transient response might be due to reconfiguration of the inhomogeneous flux-line distribution created within the film.[23] Magnetic relaxation measurements on $YBa_2Cu_3O_7$ powder[24] and a $Bi_2Sr_2CaCu_2O_x$ single crystal[25] also exhibited similar deviations from the linear relationship.

Measurements of the time relaxation of the magnetization have been used to infer an average pinning potential for high-temperature superconductors.[6,7,11,12,24,26,27] The relaxation of the magnetization can be interpreted by the Anderson model[28] of thermally activated flux bundles creeping over an effective pinning potential. If one assumes an effective pinning potential $U_{\mathrm{eff}} = U^* - FVX$, where U^* is the average pinning potential at $F = 0$ and the term FVX is the decrease of the pinning potential due to the Lorentz-force density F acting on the bundle with volume V over a distance X, then one obtains (see Xu *et al.*,[24] and references cited therein) $M(t) = M_i[1-(kT/U^*)\ln(1+t/\tau)]$, where τ is the characteristic relaxation time, which is typically 10^{-6}–10^{-12} s. For $t \gg \tau$ one then obtains $U^* = kT/[(-1/M_i)dM/d\ln t]$, where $dM/d\ln t$ is the relaxation rate, M_i is the initial magnetization at time $t = 170$ s (the time of the first measurement after setting the magnetic field), and

$(-1/M_i)dM/d\ln t$ is the normalized relaxation rate.

In Fig. 2 we plot the relaxation rate $dM/d\ln t$ as a function of temperature for different fields. The $dM/d\ln t$ values are the slopes of the M values versus the $\ln t$ curves shown in Fig. 1. The M values are taken between $\ln t = 7.5$ and 9.5 ($2000 < t < 12\,000$ s) because the relaxation rate becomes constant in this time interval. The curves in Fig. 2 exhibit a similar pattern, namely, that the relaxation rate increases with temperature, reaches a peak value, and then decreases. The temperature at which the peak relaxation rate occurs is the full-penetration temperature[29] at which the field first fully penetrates the whole sample and establishes the critical state.[30] The full-penetration temperature is observed to shift from 15 to 9 K as the field is increased from 500 to 3000 Oe. Shifting of the peak position to lower temperature with increasing applied magnetic field was also reported for other superconductors.[7,29]

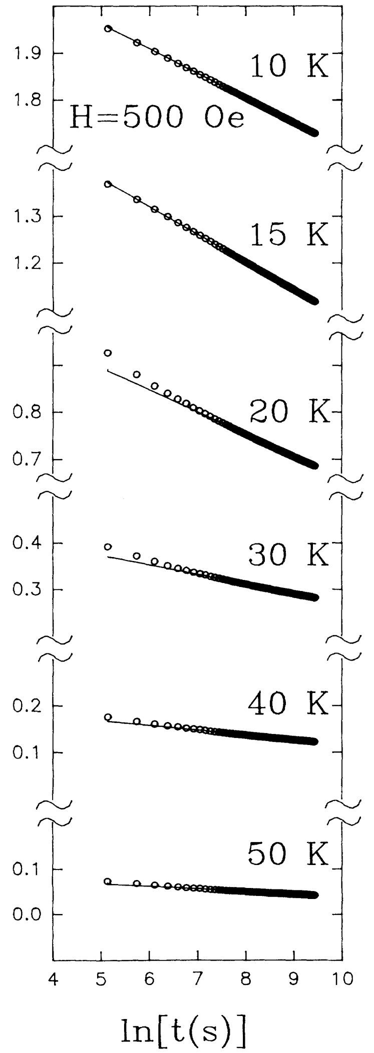

FIG. 1. Magnetization ($-M$) of the $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ thin film vs $\ln[t\,(s)]$ at $H=500$ Oe and $T=10$, 15, 20, 30, 40, and 50 K. The circles are the measured data points, and the solid lines are the linear least-squares fit to the region $7.5 < \ln[t\,(s)] < 9.5$ ($2000 < t < 12\,000$ s).

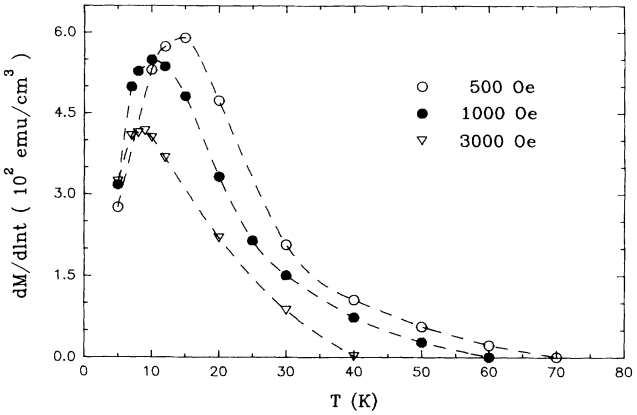

FIG. 2. Temperature dependence of the magnetic relaxation rate $dM/d\ln t$ at different fields ($H=500$, 1000, and 3000 Oe). The dashed lines connect the data points.

In Fig. 3 the initial magnetization M_i is plotted against temperature for applied fields of 500, 1000, and 3000 Oe. It is evident that M_i is sensitive to temperature changes, and M_i decreases rapidly as the temperature increases.

In Fig. 4 the normalized relaxation rate $(-1/M_i)dM/d\ln t$ is plotted against temperature for different applied fields. All the three curves in Fig. 4 exhibit a similar pattern. The normalized relaxation rate increases with temperature, reaches a peak value, and then decreases rapidly. The peak normalized relaxation rate is temperature and field dependent, and the peak's position shifts to lower temperature with increasing applied magnetic field. In addition, the temperatures at which the peak normalized relaxation rates occur (Fig. 4) are higher than the temperatures at which peak relaxation rates occur (Fig. 2).

The average pinning potential U^* is calculated from the relationship $U^* = kT/[(-1/M_i)dM/d\ln t]$ and is plotted against temperature, as shown in Fig. 5. Since the equation $U^* = kT/[(-1/M_i)dM/d\ln t]$, derived with the assumption[31] that the field has fully penetrated the sample and critical state, is established, only those U^* that are at temperatures above the full-penetration

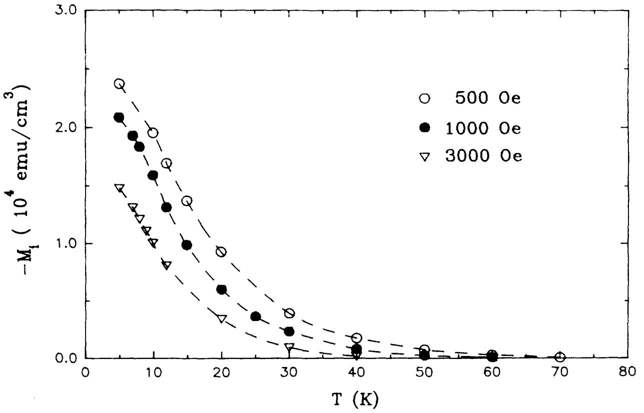

FIG. 3. Temperature dependence of the initial magnetization $-M_i$ at different fields ($H=500$, 1000, and 3000 Oe). The dashed lines connect the data points.

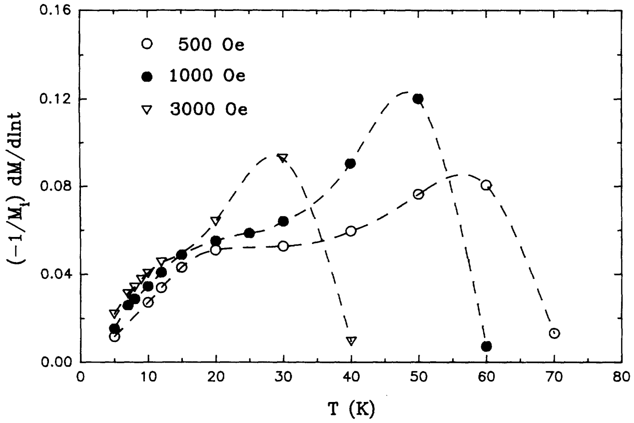

FIG. 4. Temperature dependence of the normalized magnetic relaxation rate $(-1/M_i)dM/d\ln t$ at different fields ($H=500$, 1000, and 3000 Oe). The dashed lines connect the data points.

temperature are plotted in Fig. 5. U^* is observed to be in the range 20–70 meV, which is similar to the value of U^* in Y-Ba-Cu-O (Ref. 3) and (Bi,Pb)-Sr-Ca-Cu-O.[7] In Fig. 5 we also observed a sharp increase of U^* at different temperatures for different applied fields. The anomalous increase of U^* at a specific temperature and field (Fig. 5) is related to the rapid decrease of the normalized relaxation rate at the corresponding temperature and field (Fig. 4).

In addition to the magnetic relaxation measurements, the magnetic irreversibility of the $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ superconducting thin film was also measured. The magnetic irreversibility temperature T^* was determined from the point of merging between the magnetization curve obtained by cooling a sample in the field [field cooled (FC)] and the curve obtained by warming up the sample for which the field has been switched on after it had been cooled in zero field [zero-field cooled (ZFC)]. In Fig. 6 the temperature dependence of FC and ZFC magnetization data taken in a 3000-Oe field is shown, and the irreversibility temperature T^* at which the FC and ZFC curves merged occurs at 45 K. The merging point was determined to be the datum point at which the difference between the FC magnetization (M_{FC}) and the ZFC magnetization (M_{ZFC}) is less than 1 emu/cm^3.

The irreversibility line $T^*(H)$ for the $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ thin film is shown in Fig. 7 on which the irreversibility lines of the $Bi_2Sr_2CaCu_2O_8$ compound[14] and Y-Ba-Cu-O crystals[15] are also shown. The irreversibility line of the $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ thin film is observed to be at the lower part of the field-temperature plane when compared to the irreversibility lines of the $Bi_2Sr_2CaCu_2O_8$ compound and Y-Ba-Cu-O crystals. That indicates that the Y-Ba-Cu-O crystals and $Bi_2Sr_2CaCu_2O_8$ compound can sustain the flux-trapping capability at higher fields and temperatures compared with the $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ thin film.

The magnetic irreversibility observed in various high-T_c superconductors has raised fundamental questions about the nature of the mixed state, where properties such as vortex-lattice behavior and flux pinning are found to be different from conventional type-II superconductors.[1,32–35] The interpretation of the magnetic irreversibility has been a subject of intensive study, with different theoretical models ranging from weakly linked superconducting grains[1] to thermally activated depinning of fluxoids[13,26,36] to vortex-lattice melting[37–39] and vortex-glass freezing.[40] While there is still no conclusive theoretical model which describes the exact nature of the mixed state, the strong temperature- and field-dependent magnetic relaxation and irreversibility observed in this experiment suggest that the vortex behavior and flux pinning may be different in different regions of the mixed state. In Fig. 8 four lines (L_{PM}, L_{PR}, L_{PNR}, and L_{irr}) are drawn on the field-temperature plane to separate three different

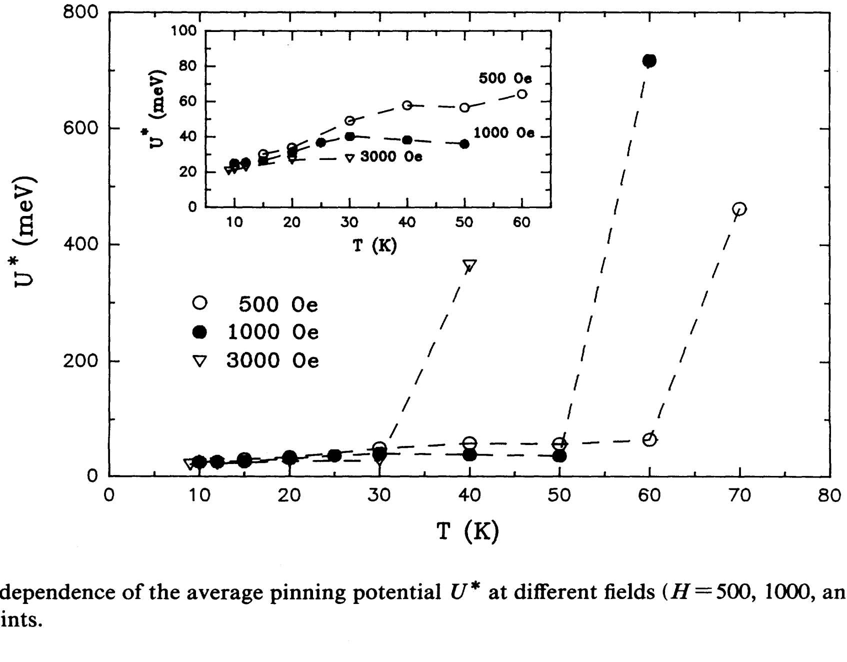

FIG. 5. Temperature dependence of the average pinning potential U^* at different fields ($H=500$, 1000, and 3000 Oe). The dashed lines connect the data points.

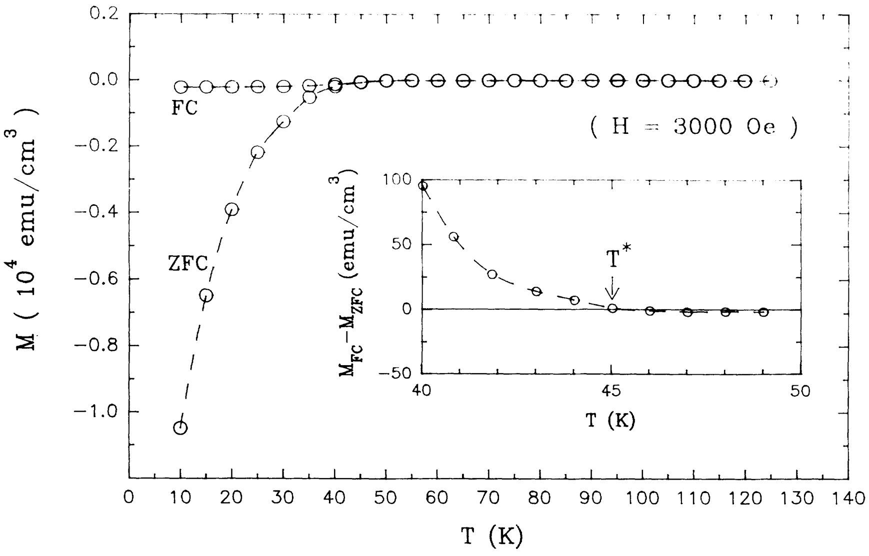

FIG. 6. Temperature dependence of zero-field-cooled (ZFC) and field-cooled (FC) magnetization at $H=3000$ Oe. The irreversibility temperature T^* ($H=3000$ Oe) is determined to be 45 K (see text). The dashed lines connect the data points.

regions [(1), (2), and (3)] in the mixed state of the $Tl_2Ba_2Ca_2Cu_3O_{10\pm x}$ superconductor. The temperature dependence of the relaxation rate and temperature dependence of the normalized relaxation rate, which are related to the vortex behavior and flux pinning, are observed to be different in the three different regions.

In Fig. 8, L_{PM} is the line which locates the fields and corresponding temperatures at which the peaks of magnetization curves occur (Fig. 9). L_{PR} is the line which locates the fields and corresponding temperatures at which the peak relaxation rates occur (Fig. 2). L_{PNR} is the line which locates the fields and corresponding temperatures at which the peak normalized relaxation rates occur (Fig. 4). L_{irr} is the irreversibility line which separates the magnetic reversible region from the magnetic irreversible region (Fig. 7).

The line L_{PR}, which locates the peak relaxation rates, serves as a boundary line between regions (1) and (2). The main difference between regions (1) and (2) is that the relaxation rate in region (1) increases with temperature, while the relaxation rate in region (2) decreases with temperature. In region (1) the magnetic field partially penetrated[29] the sample and established the partially critical state.[41] In region (2) the magnetic field fully penetrated[29] the sample and established the critical state.[30] The temperature dependence of the relaxation rate for the sample in a partially critical state and for the sample in a critical state has been shown[2,29] to be different, which indicates different relaxation behavior in the two regions.

The line L_{PNR}, which locates the peak normalized relaxation rates, serves as a boundary line between regions (2) and (3). In both regions (2) and (3), the critical state has been established. The main difference between regions (2) and (3) is that the normalized relaxation rate in

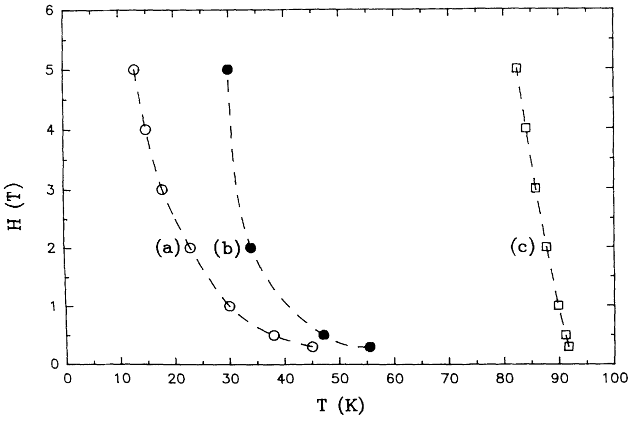

FIG. 7. Irreversibility lines of (a) a 2:2:2:3 phase Tl-Ba-Ca-Cu-O thin film, (b) a 2:2:1:2 phase Bi-Sr-Ca-Cu-O compound (Ref. 14), and (c) Y-Ba-Cu-O crystals (Ref. 15). The dashed lines connect the data points.

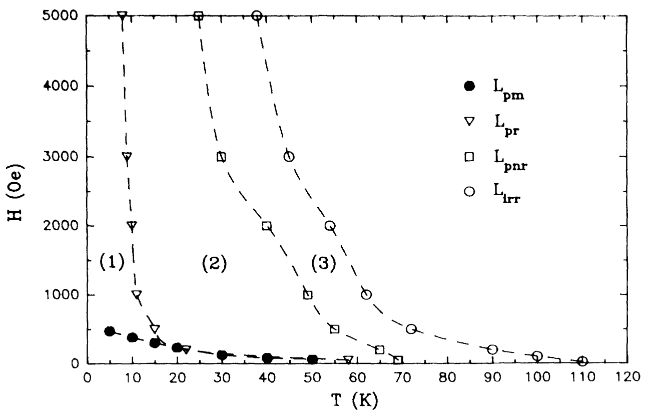

FIG. 8. The lines L_{PM}, L_{PR}, L_{PNR}, and L_{irr} which separate different regions of the mixed state (see text). The dashed lines connect the data points.

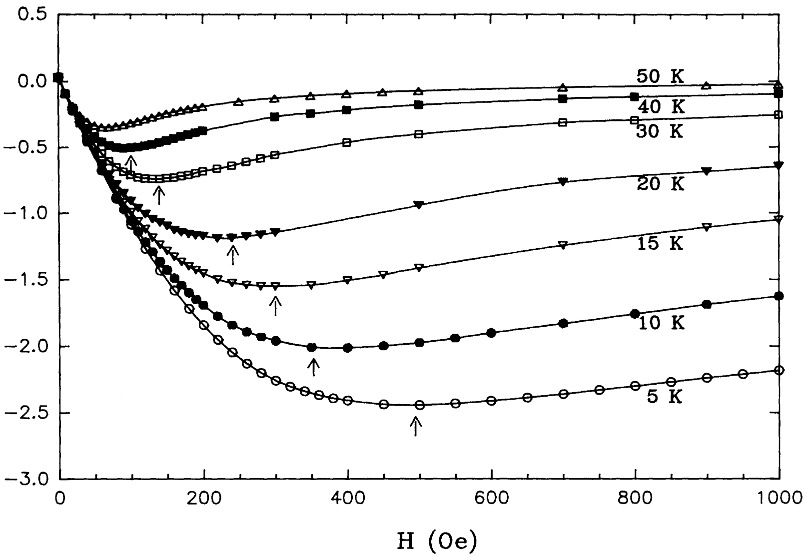

FIG. 9. Field dependence of the magnetization M at different temperatures ($T=5$, 10, 15, 20, 30, 40, and 50 K). The arrows indicate the peaks of the magnetization curves. The dashed lines connect the data points.

region (2) increases with temperature, while the normalized relaxation rate in region (3) decreases with temperature. In region (3), because of the higher temperature and applied field, there is a very small amount of pinned flux to relax. The normalized relaxation rate $[(-1/M_i)dM/d\ln t]$ in this field and temperature region decreases rapidly with the temperature (Fig. 4). Since the average pinning potential is calculated from the relationship $U^*=kT/[(-1/M_i)dM/d\ln t]$, the rapid decrease of the normalized relaxation rate $(-1/M_i)dM/d\ln t$ causes the sharp increase of U^*. The unphysical result that U^* rises as T rises was also reported for other superconductors.[12,24,27] Hagen and Griessen[27] emphasized that the inferred U^* rises with T in high-T_c superconductors and that this manifests itself in the experimental data as a peak in the normalized relaxation rate. They have explained this T dependence by requiring that there be a distribution of U^* in any sample. Xu *et al.*[24] and Maley *et al.*[11] have invoked the idea of Beasley, Labusch, and Webb[42] that the effective pinning potential $U_{\text{eff}}=U^*-FVX$ is actually a nonlinear function of J. Chaddah and Bhagwat[43] have explained the rise of U^* with T by using the critical-state model and assuming that the critical-current density decays exponentially with the field.

While different models have been proposed for the possible reasons that may cause the rise of U^* with T, the similar trend of the lines L_{PNR} and L_{irr} observed (Fig. 8) in this experiment may suggest that the anomalous increase of U^* and the rapid decrease of the normalized relaxation rate are closely related to the irreversibility line. Above the irreversibility line, there is no flux trapping. Near the irreversibility line, the flux trapping is weak, and the weak flux trapping is likely the main reason that there is a reduction in the normalized relaxation rate, which in turn causes the increase of U^*.

IV. SUMMARY

The magnetic relaxation of a $Tl_2Ba_2Ca_2Cu_3O_{10\pm X}$ thin film obeys a logarithmic time dependence in the time interval $2000<t<12\,000$ s. The relaxation rate and normalized relaxation rate are both temperature and field dependent. The average pinning potential U^* is about 20–70 meV, which is similar to those of Y-Ba-Cu-O and (Bi,Pb)-Sr-Ca-Cu-O. The rapid decrease of the normalized relaxation rate and the anomalous increase of U^* are closely related to the irreversibility line.

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