Thermally assisted flux-flow approach to the irreversibility line

Hai-hu Wen and Zhong-xian Zhao
National Laboratory for Superconductivity, Institute of Physics, Academia Sinica, P.O. Box 603, Beijing 100080, China
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By measuring the magnetic torque moment in the field-sweeping process, the temperature and field dependence of the width of the irreversible magnetic moment (ΔM) and the normalized relaxation rate ($Q=d\ \ln j/d\ \ln E$) of a $YBa_2Cu_3O_{7-\delta}$ thin film were obtained. With $\Delta M_{\min}\approx 2.5\times 10^{-5}$ emu as the criterion, the irreversibility lines at different sweeping rates were determined. It was found that at $T_{\rm irr}$ and $B_{\rm irr}$, $E\propto j$, and $B_{\rm irr}^{-1/2}$ is linearly related to $\ln(dB/dt)$, which can only be explained by the thermally assisted flux flow model. Further investigation shows that, at irreversible temperature and field, U_c is much smaller than k_BT, which indicates that the depinning of vortices induced by strong thermal activation is probably the origin of the irreversibility line.

I. INTRODUCTION

Two typical features distinguishing the high-T_c superconductors (HTS's) from the conventional ones are the high transition temperature T_c and the extremely small coherence length ξ(10 Å). Since the small coherence length ξ leads to a small pinning potential U_c (Ref. 1) at a much higher operation temperature in HTS's, U_c/k_BT is much smaller than that of a conventional superconductor. As a result, an irreversibility line (hereafter referred to as IL) which is far away from $B_{c2}(T)$, the upper critical field described by mean-field theory, exists and divides the B-T plane into two major regions: below the IL, owing to the pinning effect, a nonequilibrium distribution of flux lines can be established within the duration of the real experiment, which induces the irreversibility of magnetization in the processes of zero-field cooling (ZFC) and field-cooling (FC);[2] above the IL, however an equilibrium state can be quickly achieved due to strong flux motion and the magnetization becomes reversible. The observation of the IL in HTS was made by Müller, Takashige, and Bednorz[3] on a polycrystalline sample of La-Sr-Cu-O. Because the temperature dependence of the irreversible field $B_{\rm irr}$ as observed was the same as that characterizing the spin glass, the IL was at first referred to as a vortex-glass transition.

For understanding the real origin of the IL, many models have been proposed. Among them are, for example, thermal depinning,[4–6] melting (including conventional thermal fluctuation[7] and quantum melting[8]), and vortex-glass transition,[9] etc. Yeshurun and Malozemoff obtained a similar IL in $YBa_2Cu_3O_{7-\delta}$ and argued that it could be interpreted in terms of conventional flux creep and that the IL is the depinning line.[4] A similar conclusion was drawn by Xu and Suenaga[5] and Matsushita.[6] According to the conventional flux-creep model, it is not necessary to regard the IL as a phase transition, but rather that the experimental critical current density decreases with increasing temperature and finally reaches the minimum detectable current at the irreversibility temperature $T_{\rm irr}$. Therefore, using different criterions for either the current density or the electric field to determine the IL's will give different results. This is in sharp contrast with the melting model[7,8] or the vortex-glass transition model[9] because both of them were supposed to be the thermodynamic processes which predict that the IL only depends on temperature and magnetic field. In other words, with different criterions of current density or electric field to measure the IL's, the results should remain the same.

In this paper we present an intuitive investigation on the IL's determined by measuring the isothermal magnetization. With careful measurements, we obtained the width of the irreversible magnetic moment ΔM and the normalized relaxation rate $Q=d\ \ln j/d\ \ln E$ versus temperature up to $T_{\rm irr}$. It was shown that the IL shifts to lower temperature and field region with lowering the sweeping rate (or electric field), and $E\propto j$ at $T_{\rm irr}$, which can only be interpreted in the thermally assisted flux-flow (TAFF) approach. Further analysis based on the TAFF model shows that at the irreversibility points ($T_{\rm irr}$,$B_{\rm irr}$), U_c becomes much smaller than k_BT, which manifests that thermal depinning is probably the real origin of the irreversibility line.

II. EXPERIMENT

A highly sensitive magnetic torquemeter (10^{-10}–10^{-11} Nm)[10] was used to measure the torque moment (τ) of the sample. The field was applied 45° to the c axis of the film. Therefore the magnetic moment is determined by $M=\tau/(B\sin 45°)$ and the resolution is about 10^{-5} emu. A high-quality $YBa_2Cu_3O_{7-\delta}$ thin film with $T_{c0}=90.8$ K, $\Delta T_c=0.5$ K made with the molecular beam epitaxy technique was used as the sample. It has dimensions of 4 mm×4 mm 1500 Å. X-ray diffraction shows that only (001) peaks are observable and the full width at half height is about 0.3°, which indicates that the film has very good crystallinity.

An Oxford cryogenic system with a superconducting magnet providing a field up to 8 T was used to stabilize the temperature. The temperature controlling is better than ±0.1 K.

As has been discussed extensively in Refs. 11 and 12, using the magnetic sweeping method, the normalized magnetization relaxation rate can be determined as $Q=d\ \ln j/d\ \ln E$, which is almost equivalent to the conventional magnetization relaxation rate determined as magnetization decaying with time $S=-d\ \ln M(t)/d\ \ln t$, where E and j are the electric field and current density, respectively. During the magnetic sweeping process, $E(R)$, the electric field established at the perimeter of the sample, is proportional to the sweeping rate dB/dt. For a very thin superconducting disc, such as our film, the total magnetic moment is mainly determined by the current flowing in the region close to the perimeter, thus even with a nonuniform distribution of current density in the center region, as shown by van der Beek *et al.*,[13] it is still a good estimation that $\Delta M \propto j(R)$, where $j(R)$ is the current density flowing at the perimeter. For example, if the current density is uniform everywhere within the sample, the total magnetic moment is about $j(R)R^3d$, where d and R are the thickness and radius of the film, respectively. It is easy to show that $\frac{7}{8}$ (or 87.5%) of the total magnetic moment is produced by the current flowing in the region $R/2<r<R$. The current flowing in the central part plays a minor role in determining the total magnetic moment. Thus the normalized relaxation rate can also be written as $Q=d\ln j(R)/d\ln E(R) = d\ln\Delta M/d\ln(dB/dt)$, which means that the slope of double logarithmic j-E curve at a certain electric field E_c is equivalent to the normalized magnetization relaxation rate.

III. RESULTS

The width of the irreversible magnetic moment ΔM is plotted as a function of the magnetic field at different temperatures in Fig. 1. It is clear that with the criterion for the magnetic moment, $\Delta M_{\min} \approx 2.5\times10^{-5}$ emu, the irreversible fields can be well determined. In Fig. 2 the IL's determined with $\Delta M_{\min}=2.5\times10^{-5}$ emu and with different sweeping rates were shown. The sweeping rate ranges from 400 to 4 G/s.

So far we have obtained the IL's from the isothermal magnetization measurement. In order to have a comprehensive understanding of the origin of IL, we would like to obtain more information about the E-j characteristics near by T_{irr}. As described in the last section, a good estimation is that $E(R)\propto dB/dt$, $j(R)\propto\Delta M$, hence we can determine the dynamical relaxation rate by $Q=d\ln j(R)/d\ln E(R)=d\ln\Delta M/d\ln(dB/dt)$. In the experiment dB/dt varies from 400 to 4 G/s, which induces a change of $E(R)$ by two orders of magnitude. As we will not investigate the detail of each single E-j curve, what we are interested in is the temperature dependence of the slope $dj(R)/dE(R)$ or $d\ln j(R)/d\ln E(R)$ at the same voltage criterion E_c. In Fig. 3 the temperature dependence of $Q=d\ln j(R)/d\ln E(R)$ at several fields and with $dB/dt=400$ G/s were shown. It is clearly seen that Q increases drastically when the temperature exceeds a threshold, and reaches unity within a few Kelvins. The short thick bars in the upper-right corner of Fig. 3 indicate the positions of the irreversible tempera-

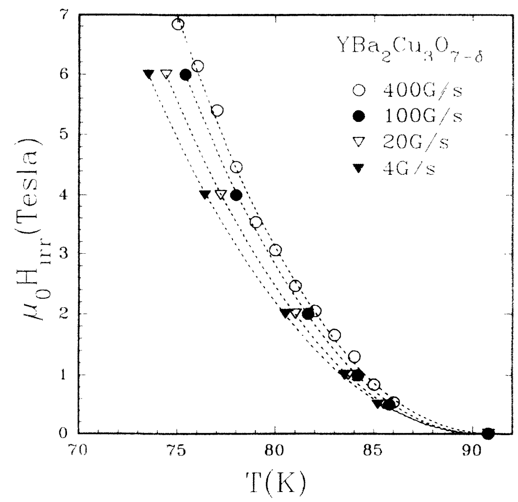

FIG. 2. Irreversibility lines determined with the criterion of $M_{\min}=2.5\times10^{-5}$ emu at a different sweeping rate. The dash lines are guides to the eye.

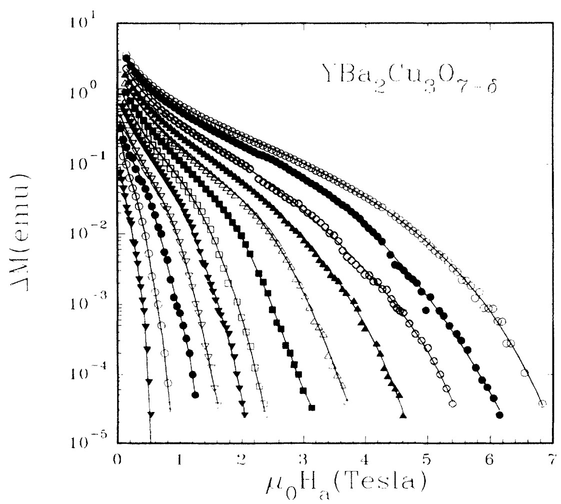

FIG. 1. Field dependence of the width of the irreversible magnetic moment M at temperatures from 75 to 86 K with increments of 1 K. The sweeping rate is 400 G/s which corresponds to $E(R)=10^{-5}$ V/m. The solid lines are guides to the eye.

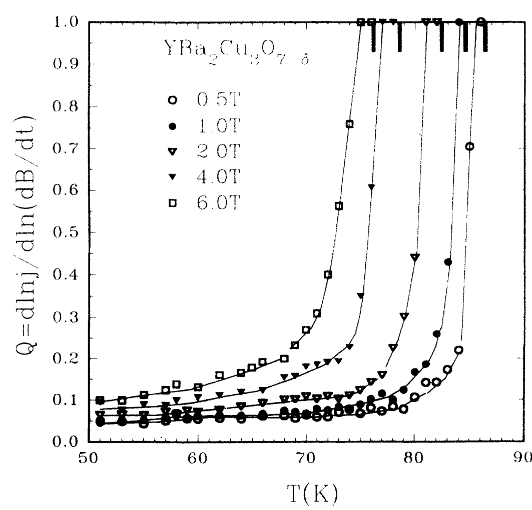

FIG. 3. Correlations between the normalized relaxation rate $Q=d\ln j(R)/d\ln E(R)$ and temperature at several fields. The sweeping rate is 400 G/s. The short thick bars mark the positions of the irreversibility temperatures at fields of 0.5, 1, 2, 4, and 6 T, respectively. The solid lines are guides to the eye.

tures shown in Fig. 2 (the case $dB/dt=400$ G/s). Because $Q=d\ln j(R)/d\ln E(R)$ reflects the slope of the double logarithmic curves of $\ln j(R)-\ln E(R)$, $Q=1$ corresponds to $E(R)\propto j(R)$, which manifests that at irreversible points $T_{\rm irr}$ and $B_{\rm irr}$, $E(R)\propto j(R)$.

IV. DISCUSSION

Up to now we have obtained the IL's at different sweeping rates and the $E(R)$-$j(R)$ characteristics near by $T_{\rm irr}$. Figure 2 clearly shows that the IL shifts to lower temperature and field region with decreasing the sweeping rate, which cannot be explained by either the vortex lattice melting, or the vortex-glass transition models. So we are going to analyze the above results in terms of thermally activated flux motion.

In the presence of a macroscopic current density j, the Lorentz driving force will make the flux bundles (or single vortex) jump over the pinning barrier with the help of thermal activation. By assuming that the jump rate is given by the usual Arrhenius expression and requiring that the flux-motion satisfies a continuity equation, Griessen *et al.*[14] obtained a more general differential equation for the flux density within the sample, which shows

$$\begin{aligned}\partial B/\partial t &= -\partial E(r)/\partial r\\ &= v_0\exp(-U_c/k_BT)\\ &\quad\times\frac{\partial}{\partial r}[B\sinh(-\Delta W/k_BT)\\ &\qquad -(w\mu_0 j/2)\cosh(-\Delta W/k_BT)]\ ,\end{aligned} \tag{1}$$

where v_0 is the maximum velocity for the flux motion; ΔW is the work done by the driving force to make the volume V_c move from one pinning center to next one; U_c is the pinning potential; w is the hopping distance, which is equal to the average distance between two neighboring pinning centers. Because U_c is the energy required to depin the volume V_c, therefore it can be expressed as

$$U_c=j_cBV_cr_p\ , \tag{2}$$

where r_p is the pinning range, for isolated vortex-core or point pinning defects, $r_p\approx\xi$. The work done by the driving force ΔW is

$$\Delta W=F_1V_cw=jBV_cw=U_c(j/j_c)(w/r_p)\ . \tag{3}$$

For large current density, $\Delta W/k_BT\gg1$, vortices move mainly towards the Lorentz force direction, i.e., the reverse hopping is negligible, which leads to a nonlinear E-j relation. With extremely small current density j, however, $\Delta W/k_BT\ll1$, the reverse hopping becomes important, Eq. (1) reduces to

$$\partial E(r)/\partial r=v_0\exp(-U_c/k_BT)\frac{\partial}{\partial r}(B\Delta W/k_BT+w\mu_0 j/2)\ . \tag{4}$$

By integrating both sides of Eq. (4) from $r=0$ to $r=R$, and with $j(0)=0$, we have

$$E(R)=v_0B\exp(-U_c/k_BT)[j(R)w/j_cr_p]\times[U_c/k_BT+\mu_0j_cr_p/(2B)]\ . \tag{5}$$

Now we can make an estimation for the value of $\mu_0j_c/r_p/(2B)$ in the right-hand side of above equation. With $\mu_0=4\pi\times10^{-7}$ A/m, $r_p\approx\xi\approx10$ Å, $j_c=10^{10}$ A/m^2, $B=1$ T, $\mu_0j_cr_p/(2B)\approx10^{-5}$, which should be much smaller than U_c/k_BT. Thus the above equation can be extended to the TAFF expression

$$E(R)=v_0B\exp(-U_c/k_BT)[j(R)U_cw/j_ck_BTr_p]\ . \tag{6}$$

Normally the current density j for determining the irreversibility line is as small as the resolution of the measurement instrument, for example in the measurement of ZFC–FC with a superconducting quantum interference device, $\Delta M_{\rm min}=10^{-6}$ emu, for a sample with dimensions of 1 mm^3, $j_{\rm min}\approx10$ A/m^2. Thus it seems quite relevant to interpret the IL's with the TAFF approach. The first veracity of the TAFF explanation comes from Fig. 3 in which the data shows that $Q=d\ln j/d\ln E=1$ at $T_{\rm irr}$, which is predicted by the TAFF approach as well [as shown by Eq. (6)]. Now we present other evidence to show that our IL's can really be interpreted with the TAFF approach. If we take a fixed criterion for the electric field E, and with increasing temperature, from Eq. (6) we know that the current density j drops almost exponentially with U_c/k_BT. Up to a certain temperature, j drops below the resolution ($j_{\rm min}$) of the instrument, we define this temperature as the irreversible one $T_{\rm irr}$, thus an expression for the IL can be obtained as

$$U_c(T,B_{\rm irr})=k_BT\ln\left[\frac{2v_0B_{\rm irr}U_cj_{\rm min}w}{R(dB/dt)k_BTj_cr_p}\right]\ , \tag{7}$$

where $B_{\rm irr}$ is the irreversibility field at temperature T. The same result was obtained by Kes *et al.*[15] while they started with looking for the maximum position of the out-off phase permeability μ''. As U_c is related to T through $H_c\propto(1-t^2)$, $\xi\propto(1-t^2)^{-1/2}$, $\lambda\propto(1-t^4)^{-1/2}$, to B through $a_0\propto B^{-1/2}$, thus we can assume that $U_c\propto(1-t)^\alpha/B^\beta$, where α and β can be positive or negative values. Inserting the above description for U_c into Eq. (7) and noting $E\propto dB/dt$, we found that at a fixed temperature, since the influence due to the minor change of $B_{\rm irr}$ in the logarithmic term can be neglected, so $B_{\rm irr}^{-\beta}$ should be linearly related to $\ln(dB/dt)$. In Fig. 4 we present curves of $1/B^\beta$ versus $\ln(dB/dt)$ at several temperatures with $\beta=0.5$, where the symbols correspond to experiment data, solid lines are predictions of TAFF model. It is clear that the fitting between experimental data and the TAFF approach is remarkably good. The above conclusion also rules out the possibility of interpreting the IL's with the flux-flow model. Although the flux-flow model[16] predicts $E\propto j$ as well, but as we know, based on this model, $\rho_{\rm flux-flow}=\rho_n[H/H_{c2}(T)]$, at a fixed temperature and current density, ρ_n and H_{c2} are constant, we arrive at $H_{\rm irr}\propto E\propto dB/dt$, which means that $H_{\rm irr}$ would increase two orders of magnitude with dB/dt varying from 4 to 400 G/s. This is certainly inconsistent with the experiment. In Fig. 2 we can see that at a certain temperature, the shift of the irreversible field $B_{\rm irr}$ is small, e.g., $\delta B_{\rm irr}/B_{\rm irr}\le30\%$ with the changing of the sweeping rate by two orders of magnitude. Therefore we

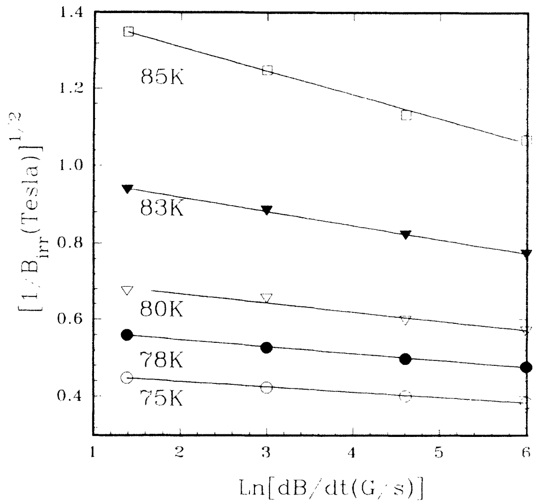

FIG. 4. Plots of $(B_{irr})^{-1/2}$ vs $\ln(dB/dt)$ at different temperatures. The symbols are experimental data, the solid lines are the fittings to the TAFF model. It is clear that the TAFF approach interprets the data very well.

can safely conclude that the linearity between E and j at irreversibility points is due to TAFF rather than flux flow.

So far we have shown that the IL's obtained in the experiment can be explained very well with the TAFF approach. Next we are going to have a discussion on the possible origin of the IL. According to the TAFF model, the experimental critical current density j at a certain electric-field criterion E_c is

$$j=j_c\frac{E_c}{v_0B}\frac{k_BT}{U_c}\frac{r_p}{w}\exp\left[\frac{U_c}{k_BT}\right] . \tag{8}$$

At a fixed field, U_c/k_BT will drop with increasing temperature, so the current density j will be exponentially influenced by U_c/k_BT. At irreversibility temperature, j drops below the minimum current $j_{\min}$. In this sense the irreversibility points are critical conditions when U_c/k_BT is smaller than a certain value, which means that the irreversibility line probably originates from the depinning induced by strong thermal activation. Here we can make a rough estimation for U_c/k_BT at irreversibility points. Near by the IL, $\rho_{\text{flux-flow}}\approx\rho_{\text{TAFF}}$, so $v_0B_{irr}/j_c\approx E_c/j_{\min}$, for $YBa_2Cu_3O_{7-\delta}$, $r_p\approx\xi\approx 10$ Å, $w\approx a_0\approx 100$ Å, thus at irreversible temperature T_{irr}, from Eq. (7) we have

$$U_c(T_{irr},B)\approx 0.1k_BT . \tag{9}$$

The above concluding equation suggests that the pinning effect near by T_{irr} is actually very weak. Because of the strong thermal activation effect at T_{irr}, even in the presence of the weak pinning effect, the vortices move rapidly, which eliminates the irreversibility of magnetization during isothermal sweeping up and down process or in the ZFC–FC process. This strongly manifests that the IL is not a phase transition but a symbol to show qualitatively that the thermal activation is stronger than the pinning effect. A similar conclusion was drawn by Yeshurun and Malozemoff[4] (YM), Xu and Suenaga,[5] Matsushita,[6] and many other authors. What we want to note is that the treatment done in YM's paper[4] took only the forward creep (that along the Lorentz force direction) into account, which is, however, impossible to obtain the linear relation between E and j near T_{irr}. In addition, Xu and Suenaga clearly show that at $T\ll T_{irr}$, the temporal decay of ΔM can be explained very well by the conventional flux-creep model in combination with collective pinning, or by the vortex-glass model, which means that at that temperature the forward creep is the dominant one. But at $T\approx T_{irr}$, the one-direction creep seems difficult to account for in the data, which may indicate that the reverse hopping was already quite important, and which should be incorporated into the flux-creep expression.

In conclusion, by using the magnetic sweeping method, we measured the irreversibility lines and the temperature and field dependence of the dynamic relaxation rate$Q=d\ln j/d\ln E$. It was found that the IL shifts to a lower temperature and field region with decreasing sweeping rate, which cannot be explained by either the vortex-lattice melting or the vortex-glass transition model. Further investigation shows that the data can be well interpreted with the thermally activated flux-creep model in the small current region, the TAFF approach. As a result of this treatment, at irreversibility points (T_{irr},B_{irr}), U_c was found to be much smaller than k_BT, which means that depinning induced by strong thermal activation effect is probably the origin of irreversibility line.

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