Temperature and field dependence of magnetic relaxation in a $Bi_2Sr_2CaCu_2O_x$ single crystal

Donglu Shi, Ming Xu,* A. Umezawa,† and Ronald F. Fox*
Materials Science Division, Argonne National Laboratory, Argonne, Illinois 60439
(Received 19 January 1990; revised manuscript received 26 March 1990)

We measured the magnetic relaxation in a $Bi_2Sr_2CaCu_2O_x$ single crystal at a wide range of temperatures (6–25 K) and field strengths (100–4000 G). We found that the relaxation rate ($dM/d\ln t$) is highly temperature and field dependent. By expanding Kim's model, we developed an expression for $dM/d\ln t$ as a function of field that we used to interpret the rise and fall of the magnetic relaxation in both the $H<H^*$ and $H>H^*$ regions.

INTRODUCTION

Strong magnetic relaxation has been observed in all high-T_c superconductors.[1–5] This phenomenon raises fundamental questions about the nature of the mixed state at high fields ($H>H_{c1}$), where properties such as magnetic irreversibility, vortex lattice behavior, flux pinning, and critical current density are found to be essentially different from those of conventional superconductors.

Muller *et al.*[1] attributed the large magnetic relaxation to the glassy characteristics of weakly lined superconducting grains in the samples. Later, however, it was found that single crystals of high-T_c superconductors exhibit similar magnetic relaxation.[2,3]

Based on both magnetic and transport measurements, a flux-creep model was then proposed to explain the large magnetic relaxation.[2,6,7] These studies indicated that the magnetization decays logarithmically in a wide range of temperature and field strength. The studies also reported that the motion of the flux lines is thermally activated. The activation energies of high-T_c superconductors were estimated to be about 100 times lower than those of conventional superconductors. More important, an irreversibility line was found below the $H_{c2}(T)$ boundary in the H-T phase diagram, which shows that high-T_c superconductors have a distinctly different mixed state from that of conventional superconductors.

In contrast with the flux-creep model, Fisher proposed the so-called vortex-glass superconductivity model and demonstrated that an equilibrium phase boundary exists in the H-T plane.[8] Crossing this boundary, the flux lines transform into a new state: vortex-glass, in which a true superconducting state is present. Koch *et al.* later reported experimental results in epitaxial $YBa_2Cu_3O_{7-x}$ thin films. Their data support the vortex-glass model and indicate a phase transition from vortex liquid to vortex glass.[9]

In this paper we present magnetic relaxation data for a $Bi_2Sr_2CaCu_2O_x$ single crystal. We develop an expression for the magnetic relaxation rate $dM/d\ln t$ and interpret the rise and fall of the magnetic relaxation in different range of applied field. We discuss the relationships between the relaxation rates and the temperature and the applied field.

EXPERIMENTAL PROCEDURE

A single crystal was grown with the flux method.[10] The quality of the crystal was examined by x-ray diffraction, resistivity, and magnetization measurements. The x-ray-diffraction results showed a single $Bi_2Sr_2CaCu_2O_x$ phase. A sharp superconducting transition at 86 K was observed in both the resistivity and magnetization experiments. The magnetization data were taken by using commercial SQUID magnetometer over a wide range of temperatures (6–25 K) and applied fields (100–4000 G). The sample was first cooled in zero magnetic field to a desired temperature T below the transition temperature T_c. A magnetic field H was then applied and the magnetization M of the sample was measured as a function of time t. The initial data point of the magnetization was taken at $t=180$ s. The direction of the applied field was normal to the a-b plane of the single crystal.

RESULTS

Figure 1 shows magnetization versus time data plots at different field for a constant temperature of 8 K. As can be seen in the figure, the magnetization exhibits small relaxation rates at low fields (0–1000 G), which gradually increase with increasing field and reach a maximum near 1500 G. The relaxation rate then decreases with increasing field thereafter. Figure 1 shows that considerable magnetic relaxation is still present at the highest field (5000 G).

In Fig. 2 we plot the relaxation rate ($dM/d\ln t$) as a function of field for different temperatures indicated. It should be noted that the $dM/d\ln t$ values are the slope of the M versus $\ln t$ curves shown in Fig. 1, which are taken between $\ln t=7$ and $\ln t=9$, since the relaxation rate becomes constant at a given field in this time interval. Again, we note, the relaxation rate increases with the increasing field at low-field regions. Figure 2 shows a peak shift of the $dM/d\ln t$ values at different temperatures.

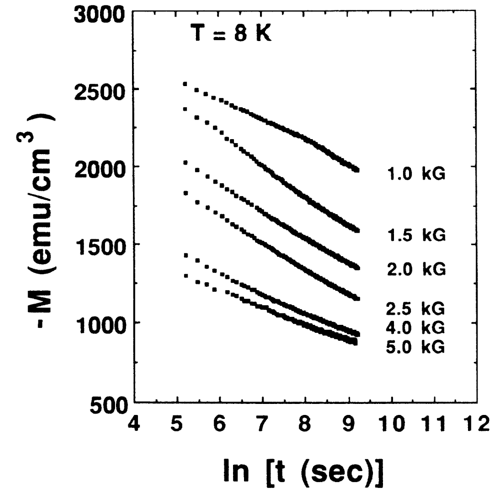

FIG. 1. Magnetization vs time at a given temperature $T=8$ K for a $Bi_2Sr_2CaCu_2O_x$ single crystal at the various field indicated. The field, parallel to c, is applied after cooling the sample in zero field.

Although some $dM/d\ln t$ peaks are not seen in the figure because of the limited data points, we can distinguish a clear peak shifting associated with the temperature change. Figure 2(a) shows the relaxation versus applied field data at 6, 8, and 10 K. The relaxation rate at 8 K initially increases with the increasing field in the low-field region. It reaches a maximum value near 1500 G and then gradually decreases. The field, H_p, at which the $dM/d\ln t$ experiences the peak also shifts towards the low fields with the increasing temperature. As shown in Fig. 2(a), the $dM/d\ln t$ peak takes place at near 1000 G as the temperature is increased to 10 K. However, the H_p value at 6 K cannot be estimated well in this experiment because of the limited data points. As indicated in Fig. 2(b), the $dM/d\ln t$ peak may have shifted to much lower field regions (below 500 G) when the temperature increases to above 15 K. The absolute values of $dM/d\ln t$ at different fields are also significantly suppressed by increasing the temperature. As shown in Fig. 2(b), the $dM/d\ln t$ value at 1000 G drops from 150 emu/cm^3 to zero as the temperature increases from 8 to 25 K.

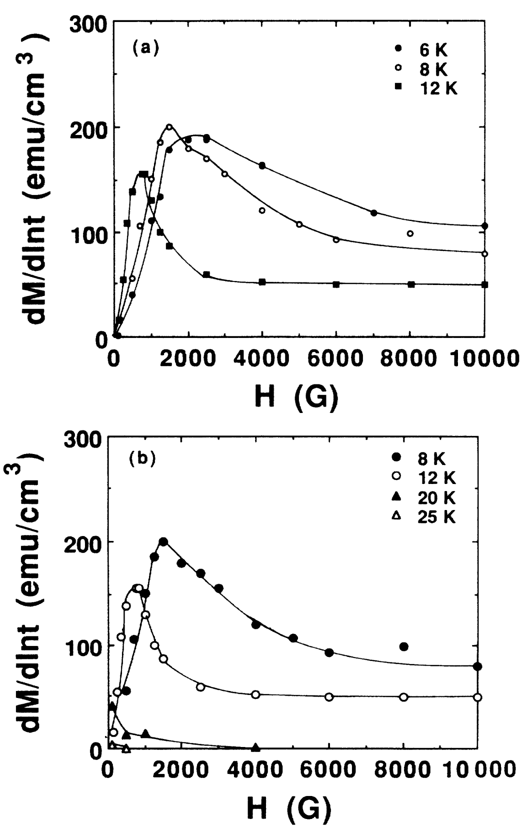

FIG. 2. Magnetic relaxation rate $dM/d\ln t$ vs field at various temperatures. The solid lines are a guide for the eye.

DISCUSSION

Yeshurun *et al.*[2,3,11] explain the magnetic relaxation based on Anderson's classic flux-creep model.[12] The model assumes certain pinning mechanisms caused by inhomogeneities in the materials. An Abrikosov vortex sitting in a potential pinning well with a height of U_0 may be activated an hop out of the well as a result of thermal excitation. Such motion of the flux lines results in magnetic relaxation and reduction of the critical current density, J_c. Yeshurun *et al.* extended Bean's critical state model and qualitatively described the magnetic relaxation in $YBa_2Cu_3O_{7-x}$ and $Bi_2Sr_2CaCu_2O_x$ single crystals.

According to Bean's model,[13] the local critical current $J_c(T,H_i)$ is assumed to be a constant, $J_c(T)$, independent of the local field H_i. This model was later modified by Kim[14] can be written as

$$J_c(T,H_i)=\frac{J_c(T)}{1+H_i/H_0(T)}\ , \tag{1}$$

where H_0 is a material parameter with magnetic field dimension which can be determined experimentally. In the studies by Yeshurun *et al.*,[3,11] the H_0 value is assumed to be comparable to H_{c1} and is much lower than H_i. They extended Eq. (1) and obtained

$$J_c(T,H_i)=J_c(T)(H_0/H_i)^n\ . \tag{2}$$

For $n=1$, Eq. (2) can be derived from the Kim model [Eq. (1)] with condition $H_i \gg H_0$. For $n=0$, Eq. (2) becomes the expression of Bean model. Using this assumption, Yeshurun *et al.* derived an expression for the magnetic relaxation in $YBa_2Cu_3O_{7-x}$ single crystals.

However, the condition $H_i \gg H_0$ is not always satisfied as we indicate later. Moreover, Watson suggested that H_0 can be much greater than H_i for conventional superconductors.[15] With these considerations, we expand Kim's model Eq. (1) for $H_i \ll H_0$ and obtain

$$J_c(T,H_i)=J_c(T)(1-H_i/H_0)\ . \tag{3}$$

In a critical state we have

$$-dH_i/dx=4\pi J_c(H_i)/c\ , \tag{4}$$

where c is the speed of light (we use Gaussian units throughout the paper). If we consider a slab of thickness D with the field parallel to the plane of the slab and assume H_{c1} negligible, we can develop an expression for the local field, H_i,

$$H_i(x)=H_0-(H_0-H)\exp(x/x_0) , \quad (5)$$

where $x_0=cH_0/4\pi J_c(T)$ and H is the applied magnetic field. The average magnetic induction is given by

$$\langle B\rangle=\frac{2}{D}\int_0^{D/2}H_i(x)dx . \quad (6)$$

Substituting Eq. (5) into Eq. (6) and considering appropriate boundary conditions, we obtain

$$\langle B\rangle=-H_0\frac{2x_0}{D}\ln\left[1-\frac{H}{H_0}\right]-\frac{2x_0}{D}H, \quad H\le H^* , \quad (7a)$$

$$\langle B\rangle=H_0+\frac{2x_0}{D}\left[\exp\left[\frac{D}{2x_0}\right]-1\right](H-H_0) , \quad H\ge H^* , \quad (7b)$$

where $H^*=H_0[1-\exp(-D/2x_0)]$, which is the field required for the flux to first completely penetrate the sample. According to Campbell and Evetts[16]

$$J_c(T)=J_{c0}[1-(kT/U_0)\ln(t/t_0)] , \quad (8)$$

where J_{c0} is the critical current density when the thermal disturbance is not present, $1/t_0$ is the attempt frequency for the flux lines to jump over the pinning well, and U_0 is the activation energy for the motion of the flux lines. Substituting Eq. (8) into Eq. (7) and knowing that the magnetization $4\pi M$ is given by $\langle B\rangle-H$, we take the derivative of the magnetization with respect to time to the first-order approximation in kT/U_0. We obtain[17]

$$4\pi\frac{dM}{d\ln t}=\begin{cases}\alpha(H^2/H_0)(kT/U_0), & H\le H^* , \quad (9a)\\ \beta(-H+H_0)(kT/U_0), & H\ge H^* , \quad (9b)\end{cases}$$

where $\alpha=x_0/D$ and

$$\beta=(2x_0/D)\{1+[(D/2x_0)-1]\exp(D/2x_0)\} .$$

It should be pointed out that the induction $\langle B\rangle$, $d\langle B\rangle/dH$, and $dM/d\ln t$ [Eq. (9)] are all continuous at $H=H^*$. However, we noticed that d^2M/dH^2, $d^2M/(d\ln t)^2$, and $d^2M/dHd\ln t$ are discontinuous at $H=H^*$. From Eq. (9a) we can see that in the low-field region with $H<H^*$, $dM/d\ln t$ increases with H^2. By fitting the experimental data of $dM/d\ln t$ taken at 8 K with Eq. (9a), we find the results are quite reasonable [see the solid line (a) in Fig. 3]. As indicated in Eq. (9b), $dM/d\ln t$ should decrease linearly with the applied field. This is confirmed by fitting $dM/d\ln t$ data in the higher-field region ($H>H^*$) [see the solid line (b) in Fig. 3]. We have obtained the parameters J_c, H_0, and U_0 through fitting the experimental data to Eq. (9), which are 10^5 A/cm^2, 9000 G, and 5 meV, respectively. These values quite reasonably agree with the previously reported results in the Bi-Sr-Ca-Cu-O system.[18]

Based on the Bean model $J_c(T,H_i)=J_c(T)$, we can also develop an expression for $dM/d\ln t$ with the same approach indicated earlier, which can be written as

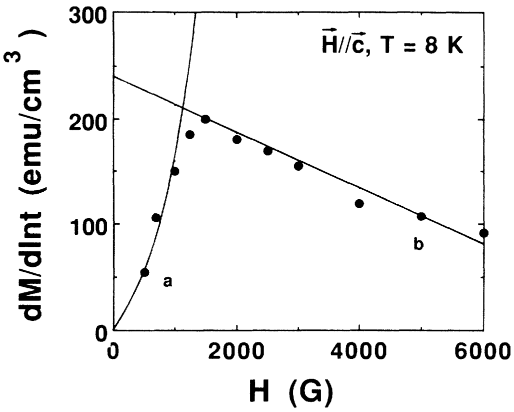

FIG. 3. $dM/d\ln t$ vs field at 8 K for a $Bi_2Sr_2CaCu_2O_x$ single crystal. The solid lines are the fit to Eq. (9a) (line a) and Eq. (9b) (line b).

$$4\pi\frac{dM}{d\ln t}=\begin{cases}\frac{H^2}{2h^*}\frac{kT}{U_0}, & H\le h^* , \quad (10a)\\ \frac{h^*}{2}\frac{kT}{U_0}, & h\ge h^* , \quad (10b)\end{cases}$$

where h^* is the field for the flux to first penetrate the sample and $h^*=2\pi DJ_c(T)/c$. It should be noted that although the physical meanings of H^* and h^* are identical, they have different expressions due to employment of different critical state models.[19] For $H<h^*$, the same field of $dM/d\ln t$ ($\sim H^2$) is obtained indicating that the Bean model is applicable in the low-field region. However, $dM/d\ln t$ becomes independent of field in the region $H>h^*$, which disagrees with our experimental data. This results from the fact that the Bean model assumes a constant critical current density which is also independent of magnetic field. Again, we checked the continuity of Eq. (10) and found that the induction $\langle B\rangle$, $d\langle B\rangle/dH$, and $dM/d\ln t$ [Eq. (9)] are all continuous while the second-order derivatives of magnetization such as d^2M/dH^2, $d^2M/(d\ln t)^2$, and $d^2M/dHd\ln t$ are not continuous at $H=H^*$.

As we indicated before, Yeshurun *et al.* developed an expression for $dM/d\ln t$ based on the extended Bean model

$$J_c(T,H_i)=J_c(H_0/H_i)^n$$

[Eq. (2)], which well described magnetic relaxation behavior in the $YBa_2Cu_3O_{7-x}$ with $n=1$. By fitting the experimental data with Eq. (9), we have estimated the H_0 value to be 9000 G. This value is much greater than the H_{c1} value in $Bi_2Sr_2CaCu_2O_x$. Thus, the assumption of Yeshurun *et al.* is that $H_i \gg H_0$ may not be appropriate for the $Bi_2Sr_2CaCu_2O_x$ system. This conclusion implies that Eq. (3) provides a better physical foundation for developing the field dependence of $dM/d\ln t$ for $Bi_2Sr_2CaCu_2O_x$.

Furthermore, by taking $n=0$ in Eq. (2) the model developed by Yeshurun *et al.* gives an H^2 dependence of $dM/d\ln t$ in a $Bi_2Sr_2CaCu_2O_x$ single crystal in the $H<H^*$ region. However, their model is incapable of describing the magnetic relaxation in the $H>H^*$ region ($n=0$ results in a constant $dM/d\ln t$ in the $H>H^*$ region). Also, since $n=0$ implies the original Bean model, it thus allows a quite different expression for $dM/d\ln t$ to be developed as we indicated in Eq. (10). In contrast, our model [Eq. (9)], based on the condition $H_i \ll H_0$, is able to fit both the low- and high-field magnetic relaxation well.

From Eq. (9) and Fig. 3 we can assume that the H^* value should be roughly the field at which $dM/d\ln t$ experiences a peak H_p. Therefore, H_p is directly related to the temperature dependence of H^*. As we indicated earlier,

$$H^*=H_0[1-\exp(-D/2x_0)] \ .$$

The term $[1-\exp(-D/2x_0)]$ $\{=[1-\exp(-2\pi DJ_c/cH_0)]\}$ contains H_0 and J_c which are both decreasing functions of the temperature. In the low-temperature range (~ 10 K), where J_c is large, the condition $D/2x_0 \ll 1$ is well satisfied and the full penetration field can be written as $H^*=2\pi DJ_c(T)/c$ (see Ref. 19). From this relation, H^* is directly related to the temperature dependence of the critical current density J_c. As temperature increases, J_c is reduced, and thus H^* shifts to lower field. However, it is difficult to predict the specific temperature dependence of H^* based on the present experimental data.

CONCLUSIONS

We measured the magnetic relaxation in a $Bi_2Sr_2CaCu_2O_x$ single crystal at various temperatures and applied fields. We observed that the relaxation rate rises and falls with field and that the field (H_p) at which the maximum $dM/d\ln t$ takes place is highly dependent on temperature. By expanding Kim's model we developed an expression for the field dependence of $dM/d\ln t$. Our model agrees excellently with the experimental data and gives some new physical interpretations for the rise and fall of the magnetic relaxation.

ACKNOWLEDGMENTS

We are very grateful to G. W. Crabtree for many stimulating discussions during this research. This work was supported by the U.S. Department of Energy, Basic Energy Sciences-Materials Sciences, under Contract No. W-31-109-ENG-38. One of us (A.U.) was supported by the Killam Memorial Fund, the University of Alberta, Canada.

---

*Also at School of Physics, Georgia Institute of Technology, Atlanta, Georgia 30332.

†Also at Department of Physics, The University of Alberta, Edmonton, Alberta, Canada T6G 2J1.

[1] K. A. Muller, M. Takashige, and J. G. Bednorz, Phys. Rev. Lett. **58**, 1143 (1987).

[2] Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988).

[3] Y. Yeshurun, A. P. Malozemoff, T. K. Worthington, R. M. Yandrofski, L. Krusin-Elbaum, F. H. Holtzberg, T. R. Dinger, and G. V. Chandrashekhar, Cryogenics **29**, 258 (1989).

[4] T. T. M. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, Appl. Phys. Lett. **54**, 763 (1989); T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, and J. V. Waszczak, Phys. Rev. Lett. **61**, 1662 (1988).

[5] J. P. Rice, D. M. Ginsberg, M. W. Rabin, K. G. Vandervoort, G. W. Crabtree, and H. Claus, Phys. Rev. B **41**, 6532 (1990).

[6] M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).

[7] C. W. Hagen and R. Griessen, Phys. Rev. Lett. **62**, 2857 (1989).

[8] M. P. A. Fisher, Phys. Rev. Lett. **62**, 1415 (1989).

[9] R. H. Koch, V. Foglietti, W. J. Gallagher, G. Koren, A. Gupta, and M. P. A. Fisher, Phys. Rev. Lett. **63**, 1511 (1989).

[10] Donglu Shi, Ming Tang, Y. C. Chang, P. Z. Jiang, K. Vandevoot, B. Malecki, and D. J. Lam, Appl. Phys. Lett. **54**, 2358 (1989).

[11] Y. Yeshurun, A. P. Malozemoff, F. H. Holtzberg, and T. R. Dinger, Phys. Rev. B **38**, 11 828 (1988).

[12] P. W. Anderson, Phys. Rev. Lett. **9**, 309 (1962); M. R. Beasley, R. Labusch, and W. W. Webb, Phys. Rev. **181**, 682 (1969).

[13] C. P. Bean, Phys. Rev. Lett. **8**, 250 (1962); Rev. Mod. Phys. **36**, 31 (1964).

[14] Y. B. Kim, C. F. Hempstead, and A. R. Strnad, Phys. Rev. Lett. **9**, 306 (1962); Phys. Rev. **129**, 528 (1963).

[15] J. H. P. Watson, J. Appl. Phys. **39**, 3406 (1968).

[16] A. M. Cambell and J. E. Evetts, Adv. Phys. **21**, 199 (1972).

[17] It should be noted that the original form of Eq. (9a) is

$$4\pi\frac{dM}{d\ln t}=H_0\frac{2x_0}{D}\left[-\ln\left[1-\frac{H}{H_0}\right]-\frac{H}{H_0}\right]\frac{kT}{U_0}, \quad H\le H^* \ . \tag{9a'}$$

As we assume $H/H_0 \ll 1$, the term $\ln(1-H/H_0)$ can be expanded to be $-H/H_0-(H/H_0)^2/2$. Thus, Eq. (9a′) is simplified and can be written as Eq. (9a).

[18] Y. Yeshurun, A. P. Malozemoff, T. K. Worthington, R. M. Yandrofski, L. Krusin-Elbaum, F. H. Holtzberg, T. R. Dinger, and G. V. Chandrashekhar, Cryogenics **29**, 258 (1989).

[19] We show $H^*=h^*$ as the condition $H_0 \gg 2\pi J_c(T)D/c$ is satisfied. As we indicated in the paper, $H^*=H_0[1-\exp(-D/2x_0)]$. The condition $H_0 \gg 2\pi J_c(T)D/c$ is equivalent to $D/2x_0 \ll 1$ where $x_0=cH_0/4\pi J_c(T)$. The term $\exp(-D/2x_0)$ can be expanded to be $(1-D/2x_0)$ as we take the first-order approximation in $D/2x_0$ if $D/2x_0 \ll 1$. Thus, H^* can be written as $H^*=H_0D/2x_0=2\pi J_c(T)D/c=h^*$.