Time-dependence of the magnetization in $Ba_2Sr_2CaCu_2O_x$ single crystal under zero field cooled condition

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ABSTRACT

We have measured the time-dependence of the magnetization in $Ba_2Sr_2CaCu_2O_x$ single crystal under the zero field cooled condition with various magnetic fields ranging from 100 Oe to 1500 Oe along c axis at different temperatures ranging from 15K to 35K. The magnetic moment decays logarithmically with time. The decay curves have been fitted with a nonlinear logarithmic function based on the Anderson-Kim thermally activated flux creep model. We have obtained the relation between the fitting parameters and the parameters provided by the Anderson-Kim model. It is believed that our experimental results agree with the predictions made by the theoretical model.

Keywords: magnetic moment decay, vortex dynamics, magnetic flux creep, flux pinning, flux fluid-glass transition.

1. INTRODUCTION

The phenomena of magnetic moment decay in high T_c superconductors has been intensively studied both experimentally and theoretically. It is obvious that these studies have both scientific significance and technological impact on the electronic industries. As we know that the magnetic field generates the microscopic current loops called vortices when the field is greater than the lower critical Josephson field applied to the high T_c superconductor[1] and the motion of these vortices will cause energy dissipation[2]. Although resistance due to the vortex motion in the conventional type II superconductors can be exceedingly small as is evidenced by the existence of persistent magnets with very long decay times, this prediction implies that in the presence of a penetrating magnetic field, type II superconductors are not truly superconducting[3].

The nature of the mixed state including magnetic irreversibility, vortex-lattice behavior, flux pinning, and transport properties has stimulated many groups of scientist in the studies of the mechanism of the high T_c superconductivity[4].

To interpret the magnetic moment decay in the superconductors, we employed the Anderson-Kim flux-creep model[5] which is believed to be responsible for the energy dissipation of conventional type II superconductors. It is assumed in the model that an Abrikosov flux line or flux bundle can be thermally activated and jump over the pinning barriers.[6]

Vortices (also called fluxons) can, in some instances, be treated as particles with interactions among them. If the interaction is weak and/or the temperature is high, they may be considered depinning of uncorrelated single vortex.[2] M. Inni *et al.*[7] have found that this model agreed will with the experimental results. However, in general, the interactions among them could result in a correlated motion, such as flux melting, flux freezing, or vortex glass and even vortex lattice phase transitions. Fischer *et al.* introduced the collective flux creep model[8] considering that 'flux-line bundle" is correlated over a finite volume which in the conventional theory is identified with the volume $V_c = \zeta L_c$ which is activated during a jump, where ζ is the Ginzburg-Landau coherence length and L_c is the activated length.[8]

T.K Worthington *et al.* observed a vortex-glass phase by examining the shape of the E-J (or R-J) curves at different temperatures.[3] The difference between the flux-creep model and the vortex-glass is the fact that the flux-creep model predicts that there should be an Ohmic resistance at all nonzero temperatures due to the thermal activation of the flux lines out of the pinning well, but the vortex-glass model predicts that $\lim(E/J) = 0$. which implies that the creep model fails to interpret it.

NMR spectra with the field along the c axis also suggests the existence of the vortex-glass phase.[9] Lensink *et al.*[10] proposed that the magnetic relaxation at low temperature is due to a nonthermal process, for example, flux vortex tunneling.[11] However, according to Wright *et al.*[12], Pastra *et al.*, using single crystal sample, found that a thermally activated flux creep model describes the experimental results quite well when the pinning energy $U_0 \gg k_BT$ and when U_0 becomes comparable to the thermal energies, the flux flow model agrees with their data better. Other models,[12] such as Ambegaokar and Halperins' (AH) are based on the assumption that the energy dissipation is caused by thermal fluctuation of the phases of the order parameters across a highly damped, current driven Josephson junction. The techniques to study the vortex state of superconductors including the magnetization decay and mechanical-oscillator are most widely used by many groups of scientist.[13]

Most of the studies of flux motion inside the superconductor are concentrated on the magnetization decay in the zero field cooled condition. Fewer works[14] are working on field cooled condition. In this paper we investigated the time dependence of the isothermal magnetization under zero field cooled condition. We analyzed the data and discuss the mechanism responsible for the time-dependence of the isothermal magnetization based upon the thermal activation theory.

2. EXPERIMENT

The single crystal of $Bi_2Sr_2CaCu_2O_x$ provided by Xu, was grown by using the so-called flux method.[15,16] It was about 2x2x1 mm^3. The X-ray diffraction shows that the crystal is of high quality and single phase. We first measured the magnetization versus temperature on a commercial superconducting quantum interference device (SQUID) under zero field cooled (ZFC) conditions and the magnetic field applied was 100 Oe along c axis. The transition temperature was found to be about 85K. The magnetization versus time was also carried out on the SQUID. The applied field was 100 Oe along c axis also. The field was turned off and the sample was warmed up to a temperature of 130K well above the superconducting phase transition temperature (86K) and then the SQUID was cooled down to the desired temperature. and the magnetic field was then turned on. Keeping the temperature constant, we measure the magnetization every four minutes up to more than 16 hours. The first data point was taken at the time about 1960 seconds after the field was turned on.

3. RESULTS

Fig. 1 shows the magnetization of the $Bi_2Sr_2CaCu_2O_x$ single crystal from the temperature 160K to 10K with a magnetic field of 100 Oe along c axis under both zero and field cooled conditions.[17]

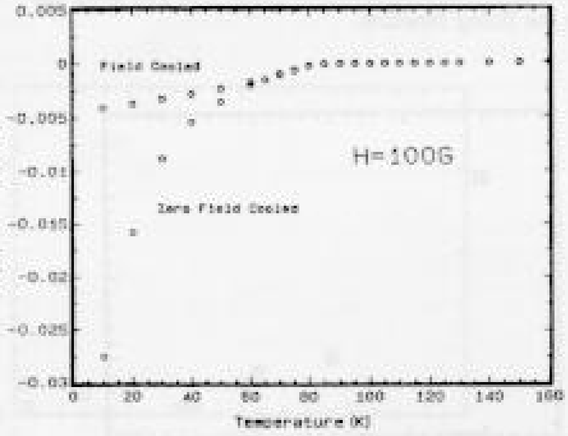

Figure 1. The magnetization of the $Bi_2Sr_2CaCu_2O_x$ single crystal from the temperature 160K to 10K with the magnetic field along the c axis.

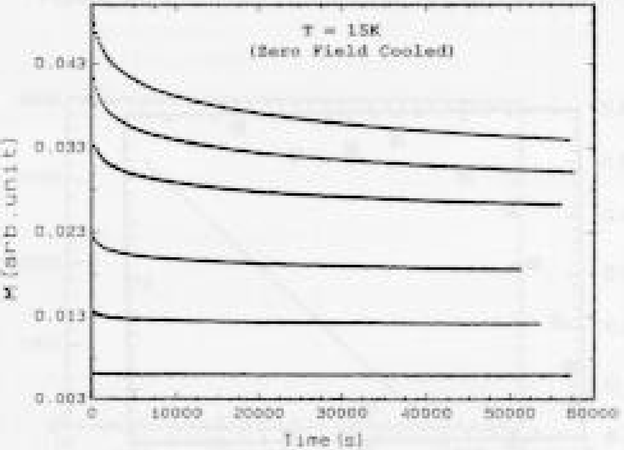

Figure 2. The magnetic moment decay with various magnetic fields under field cooled condition at temperature 15K.

In Fig. 2 we show the isothermal magnetic moment decay at different magnetic fields from 100 Oe to 1500 Oe along c axis at temperature 15K under zero field cooled condition. The isothermal magnetization decreases with time (the magnetic moment decays) for all fields applied. Fig. 3 shows the isothermal magnetic moment decay at different temperatures with a magnetic field of 100 Oe along c axis under zero field cooled condition. Fig.4 shows the isothermal magnetic moment decay at different temperatures with a magnetic field of 1000 Oe along c axis under zero field cooled condition. The solid lines in Fig. 4 are the plot of the fitting functions for the time dependence of the magnetization

$$M(t) = M_0 + b\ \ln\left(\frac{t}{t_0}\right) + d\left[\ln\left(\frac{t}{t_0}\right)\right]^2 \qquad (1)$$

where M_0, b, d, t_0 are constants. Fig. 5 and 6 show the initial magnetization, i.e. the fitted parameter M_0 in Eq. (1). Fig. 7 and 8 show the parameter b versus the magnetic field and temperature, respectively. Fig. 9 and 10 show the parameter d vs. magnetic field and temperature, respectively. Fig. 11 and 12 show the parameter t_0 vs. magnetic field and temperature, respectively.

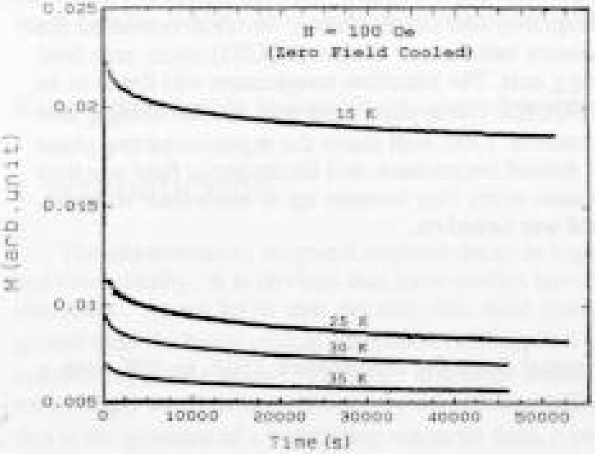

Figure 3. The magnetic moment decay at various temperatures with magnetic field 100 Oe.

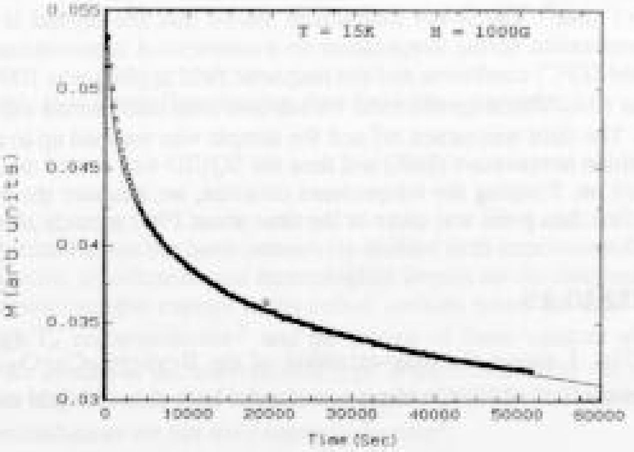

Figure 4. The magnetic moment decay at temperature 15K with magnetic field 1000 Oe. The solid line is the fitting function.

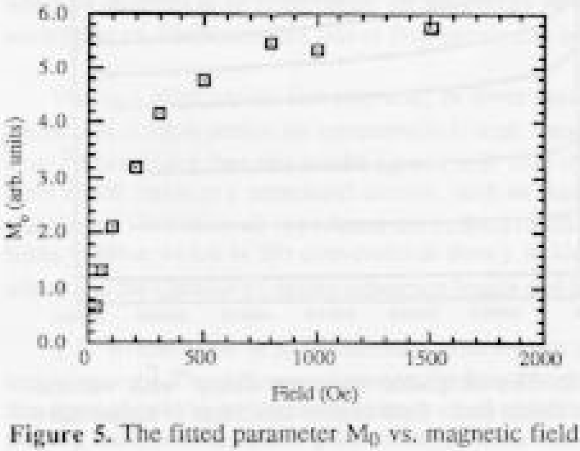

Figure 5. The fitted parameter M_0 vs. magnetic field.

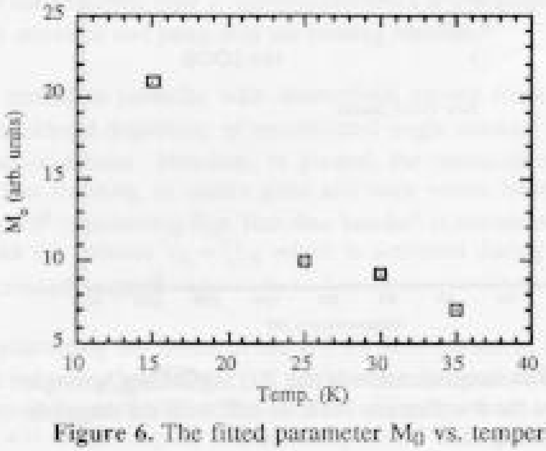

Figure 6. The fitted parameter M_0 vs. temperature.

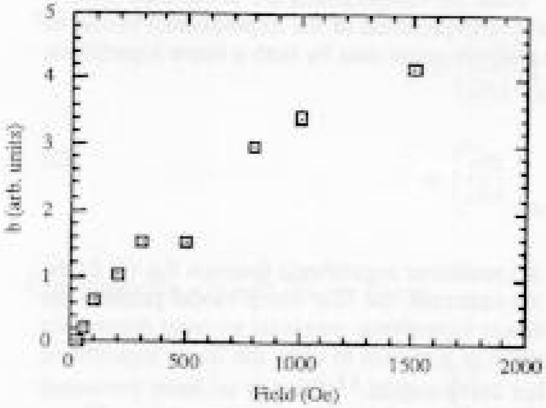

Figure 7. The fitted parameter *b* vs. field.

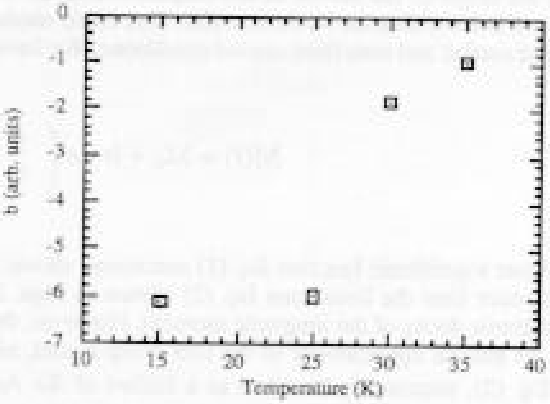

Figure 8. The fitted parameter *b* vs. temperature.

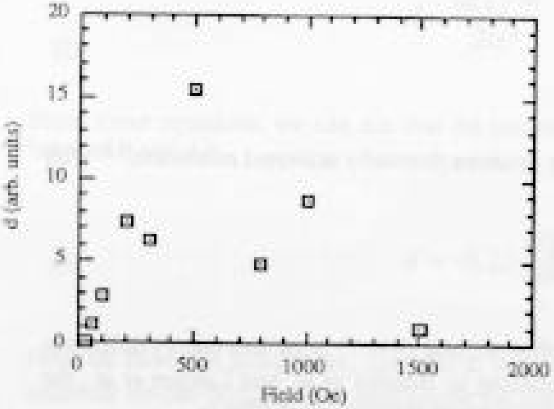

Figure 9. The fitted parameter *d* vs. magnetic field

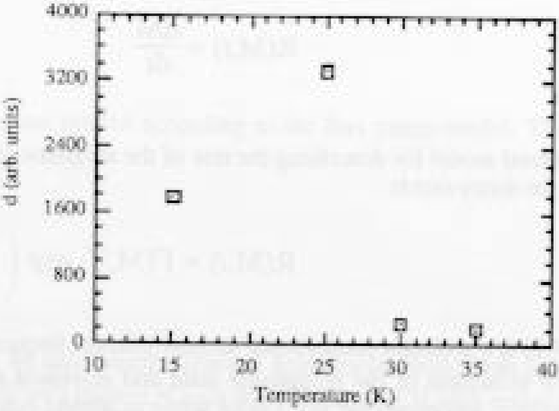

Figure 10. The fitted parameter *d* vs. temperature.

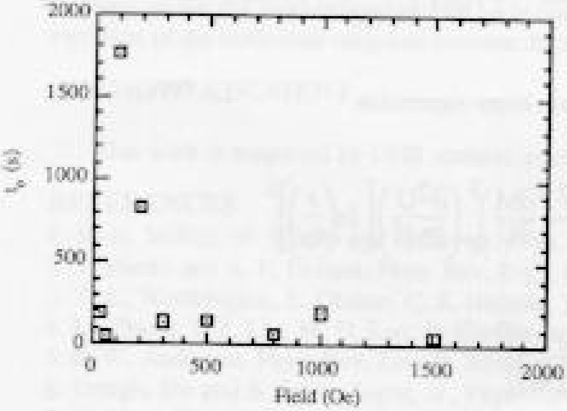

Figure 11. The fitted parameter t_0 vs. magnetic field

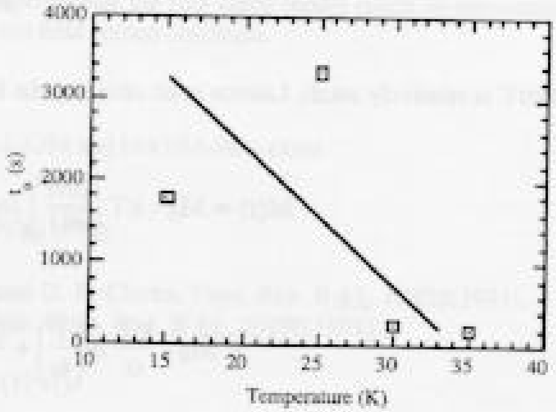

Figure 12. The fitted parameter t_0 vs. temperature.

4. DISCUSSION

We have done the isothermal magnetization measurements under both zero field and field cooled conditions, and we have found that the shape of the curves of the magnetization vs. time are similar, when the temperatures are lower than 35K.[17] Therefore, we believe that the Anderson-Kim flux creep model could be a valid interpretation of the experimental results of both the field cooled and zero field cooled conditions. We have tried to fit the magnetization data by both a linear logarithmic function

$$M(t) = M_0 + b\ ln\left(\frac{t}{t_0}\right) \tag{2}$$

and a nonlinear logarithmic function Eq. (1) mentioned above. We found that the nonlinear logarithmic function Eq. (1) fit the data much better than the linear one Eq. (2) shown in Figs. 2, 3 and 4. As we expected, the flux creep model predicts the linear logarithmic decay of the magnetic moment. However, the observed nonlinear logarithmic magnetic moment decay does not affect the general applicability of the flux creep model, nor should the failure of a system to obey the linear logarithmic function, Eq. (2), necessarily be taken as a failure of the Anderson-Kim flux creep model.[11] Ding *et al.* have presented independent evidence showing the vortex-glass phase or the collective creep mechanism in the high T_c superconductors.[18]

By definition, the rate of the isothermal magnetic moment decay is

$$R(M,t) = \frac{dM}{dt} \tag{3}$$

The general model for describing the rate of the magnetic moment decay assumes thermally activated relaxation.[11] With this model the decay rate is

$$R(M,t) = \Gamma(M,T)\ exp\left(-\frac{U(M,T)}{kT}\right), \tag{4}$$

where $\Gamma(M,T)$ is a prefactor proportional to some attempt frequency and length scale, and $U(M,T)$ is the free energy difference between the minimum of the metastable state and activated states.[11] According to Beasley *et al.* and Lairson *et al.*, the pinning potential was expanded in a Taylor series to second order about the initial magnetization M_0 at time t_0

$$U(M) \equiv U(M_0) + \left(\frac{\partial U}{\partial M}\right)_{M=M_0}(M - M_0) + \frac{1}{2}\left(\frac{\partial U}{\partial M}\right)_{M=M_0}(M - M_0)^2 \tag{5}$$

Assuming that Γ is relatively small, Lairson *et al.* obtained the following approximate expression

$$M(t) = M_0 - kT\left(\frac{\partial M}{\partial U}\right)_0 ln\left(\frac{t}{t_0}\right) + \frac{(kT)^2}{2}\left(\frac{\partial M}{\partial U}\right)_0^3\left(\frac{\partial^2 U}{\partial M^2}\right)\left[ln\left(\frac{t}{t_0}\right)\right]^2$$

$$= M_0 - \frac{kT}{\alpha} ln\left(\frac{t}{t_0}\right) + \frac{(kT)^2}{2}\frac{\beta}{\alpha^3}\left[ln\left(\frac{t}{t_0}\right)\right]^2 \tag{6}$$

where

$$\alpha = \left(\frac{\partial U}{\partial M}\right)_{M=M_0}$$

and

$$\beta = \left(\frac{\partial^2 U}{\partial M^2}\right)_{M=M_0}$$

$$= \left(\frac{\partial \alpha}{\partial M}\right)_{M=M_0}$$

Combining Eq. (1) with (6), we found

$$b = \frac{kT}{\alpha} \tag{7}$$

and

$$d = \frac{(kT)^2\beta}{2\alpha^3} \tag{8}$$

From these equations, we can see that the parameters b and d are related according to the flux creep model. The relation between b and d is

$$d = -0.25\,\frac{dH}{dM}\,\frac{d(b^2)}{dH} \tag{9}$$

Now we have two independent methods to determine d, first, we can directly obtain d from curve fitting with Eq. (1), and secondly we can calculate d by multiplying the derivative of (b^2) with respect H with the derivative of H with respect to M.

According to the formulae we developed here, the parameter t_0 is inversely proportional to the frequency ν_0, the attempt frequency of flux hopping. Obviously, ν_0 should be a function of temperature in such aspect that it increases with increasing temperature. Indeed, our results agree with the prediction shown in Fig. 12. However, at this moment we do not have any explanation for the field-dependence of t_0. In conclusion, we believe that the flux creep model could be responsible for the evolution of the isothermal magnetic moment decay under the zero field cooled condition.

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