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Magnetic Moment Decay in $Bi_2Sr_2CaCu_2O_8$ Single Crystal

J. T. Wang, S. Tsai, and W. Williams
Department of Physics, Lincoln University
C L. Lin, and T. Mihalisin
Department of Physics, Temple University
M. Xu
Department of Physics, Iowa State University
T. P. Chen
Department of Physics, Villanova University

INTRODUCTION

The phenomena of magnetic moment decay in the high T_c superconductors has been intensively studied both experimentally and theoretically. It is obvious that these studies have both the scientific significance and the technological impact to 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 the energy dissipation.[2] Although the 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 have stimulated many group of scienfists in the studies of the machnism of the high T_C superconductivities.[4]

To interpret the magnetic moment decay in the superconductors, we employ the Anderson-Kim flux-creep model[5] which is believed to be responsible for the 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 or 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 vortices.[2] M. Inni et al.[7] have found that this model agreed well with the experimental results. However, in general, the interactions among them could result in a correlateral motion, such as flux melting, flux frozen, or vortex glassy 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 ρ-J) curves at different temperature.[3] The difference between the flux-creep model and the vortex-glass model is the fact that flux-creep model predicts that there should be an Ohmicresistance at all nonzeros temperatures due to the thermal activation of the flux lines out of 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.'s[12], Pastra et. al., using single crystal, have found that a thermally activated flux creep model describes the experiment results quite well when the pinning energy $U_0 >> k_B T$ and when U_0 become comparable to thermal energies, the flux flow model is better off for their data. Other model,[12] such as Ambegaokar and Halperins' (AH) are based on the assumption that the energy dissipation is caused by the 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 namy groups of scientists.[13]

Most of the studies of flux motion inside the superconductor are concentrated on the magnetization decay in the zero field cooled condition. A fewer work[14]is on field cooled condition. In this paper we investigated the time dependence of the isothermal magnetization in the field cooled condition. We found that when the temperature is lower then 35K the isothermal magnetization decreases with time for every temperature at which the isothermal magnetization measurements werecarried out. On contrast, when the temperature is higher then 35K, the isothermal magnetization increases at some temperatures but decreases at the others in the period (15-20 hours) in which we carried out the measurements. We discuss the mechanism of the discovered time-dependence of the isothermal magnetization based upon the thermal activation theory.

EXPERIMENT

The single crystal of $Bi_2Sr_2CaCu_2O_x$, provided by Xu, was grown by using a so-called flux method.[15,16] Unfortunately, the crystal is not well parallelepipeds. It was about $2x2x1mm^3$. The sample quality was determined by X-ray defraction. It shows that the crystal is in high quality and in a single phase. We first measure the magnetization versus temperature on commercial superconducting quantum interference device (SQUID) under field cooled (FC) condition and the magnetic field is 100 Oe along c axis. The transition temperature is found to be about 86K and the irreversible temperature for the crystal is about 65K. The magnetization versus time is also carried out on the SQUID. The applied field is 100 Oe along c axis also. The field was turned on when the temperature was 130K well above the transition temperature(86K) and then the SQUID was cooled down quickly (within about 30 minutes) to the desired temperature. Keeping 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.

RESULTS

In Fig.1 we show the magnetization of the $Bi_2Sr_2CaCu_2O_8$ singlecrystal from the temperature 160K to 10K with the magnetic field of100 Oe along c axis under both zero and field cooled conditions.[17] In Fig.2 we show the isothermal changes of the magnetization as a function of time at different magnetic field from 100 Oe to 1500 Oe along c axis at temperture 15K on zero field cooled condition. The isothermal magnetization decrease with time (magnetic moment decays) for all fields applied. Fig.3 shows the isothermal decays of the magnetization at different temperatures with magnetic field of 100 Oe along c axis on zero field cooled condition. Fig.4 shows the isothermal decays of the magnetization at different tempoeratures with magnetic field of 1000 Oe along c axsis on zero field condition. The solid lines in Fig.2, Fig.3 and Fig.4 are the plot of the fitting functions

$$M(t)=M_0+b\ln(t/t_0)+d[\ln(t/t_0)]^2 \quad \text{..........}(1)$$

Fig.5, and Fig.6 show the initial magnetization, i.e. the fitting parameter M_0 in the function M(t) vs magnetic field and temperature respectively. Fig.7, and Fig.8 show the parameter b vs magnetic field. and temperature respectively. Fig.9,and Fig.10 show the parameter d vs magnetic field.and temperature respectively. Fig.11, and Fig.12 show the parameter t_0 vs magnetic field and temperature respectively.

DISCUSSION

We have done the isothermal magnetization measurements for 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. Therefore, we believe that the flux creep model could be valid for interpretation of the experiment results of both field cooled condition and zero field cooled condition. We have tried to fit the magnetization data by both linear logarithmic function

$$M(t)= M_0 + b\ln(t/t_0) \qquad \text{.......................................}(2)$$

and a nonlinear logarithmic function mentioned above. And we have found that the nonlinear logarithmic one fit the data much better than the linear one shown in Fig.2, Fig.3, and Fig.4. As we have known that the flux creep model predicts the linear logarithmic decay of the magnetic moment.

However, the found nonlinear logarithmic magnetic moment decay do not affect the general applicability of the flux creep model, nor should the failure of a system to obey the linear logarithmic function, the Eq.(2), necessarily be taken as a failure of the Anderson flux creep model.[11]

By definition the rate of the isothermal magnetic moment decay is

$$R(M,T)=-dM/dt \quad \dotfill \tag{3}$$

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

$$R(M,T)= \Gamma(M,T)\exp[-U(M,T)/kT] \quad \dotfill \tag{4}$$

where $\Gamma(M,T)$ is a prefactor proportional to some attempt frequency and length scale, while $U(M,T)$ 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 to the second order of Taylor series about the initial magnetization M_0 at time t_0:

$$U(M)\approx U(M_0)+(\partial U/\partial M)_0(M-M_0)+(1/2)(\partial^2 U/\partial M^2)(M-M_0) \quad \dotfill \tag{5}$$

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

$$M(t)=M_0-kT(\partial M/\partial U)_0\ \ln(t/t_0)\ +[(kT)^2/2](\partial M/\partial U)^3(\partial^2U/\partial M^2)\ln^2(t/t_0)$$

$$=M_0-[kT/\alpha]\ln(t/t_0)+\ [(kT)^2/2]\ [\beta/\alpha^3]\ln^2(t/t_0)\ \ \ldots\ldots\ldots\ldots(6)$$

Where

$$\alpha=(\partial U/\partial M)_0$$

and

$$\beta=(\partial^2U/\partial M^2)_0=(\partial\alpha/\partial M)_0$$

Comparing Eq.(1) with Eq.(6), we found that

$$b=-kT/\alpha\ \ \ldots\ldots\ldots\ldots(7)$$

and

$$d=(kT)^2\beta/(2\alpha^3)\ \ \ldots\ldots\ldots\ldots(8)$$

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

$$d=-0.25(dH/dM)d(b^2)/dH\ \ \ldots\ldots\ldots\ldots(9)$$

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 multifying the derivative of (b^2) with respect to H with the derivative of H with respect to M. This is shown in Fig.13. Comparing these curves, we found that the two curves are similar, but are not exact the same.

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. Then t_0, on contrast, decreases with increasing temperature. Indeed Fig.12 shows this prediction. However, at this moment we do not have the explanation for the relation between t_0 and field. In conclusion, we believe that the flux creep model could be responsible for the evolution of the isothermal magnetization in zero field cooled condition.

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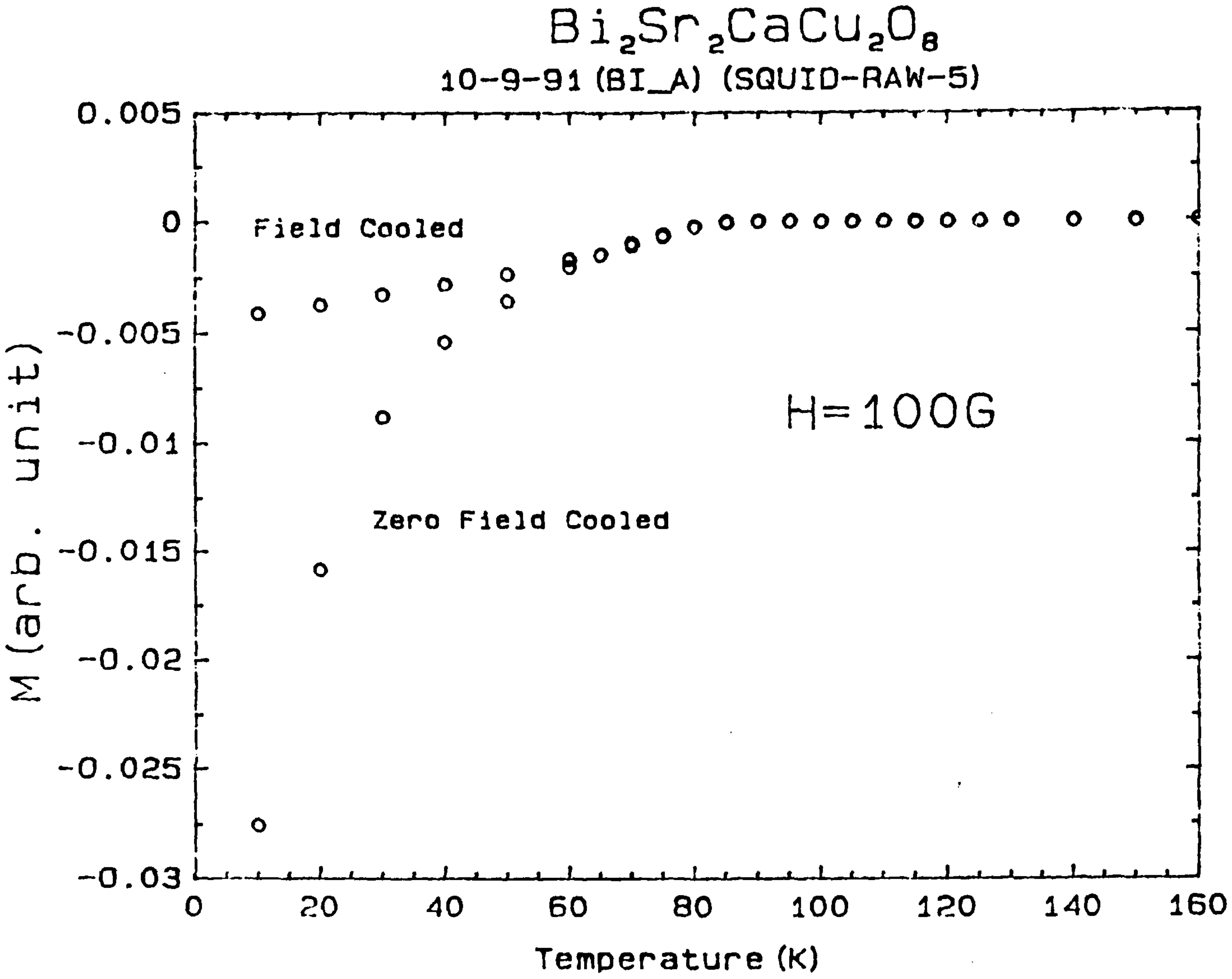

$Bi_2Sr_2CaCu_2O_8$
10-9-91 (BI_A) (SQUID-RAW-5)
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
-0.03
M (arb. unit)
Field Cooled
Zero Field Cooled
H=100G
0
20
40
60
80
100
120
140
160
Temperature (K)

Fig. 1

Fig. 2

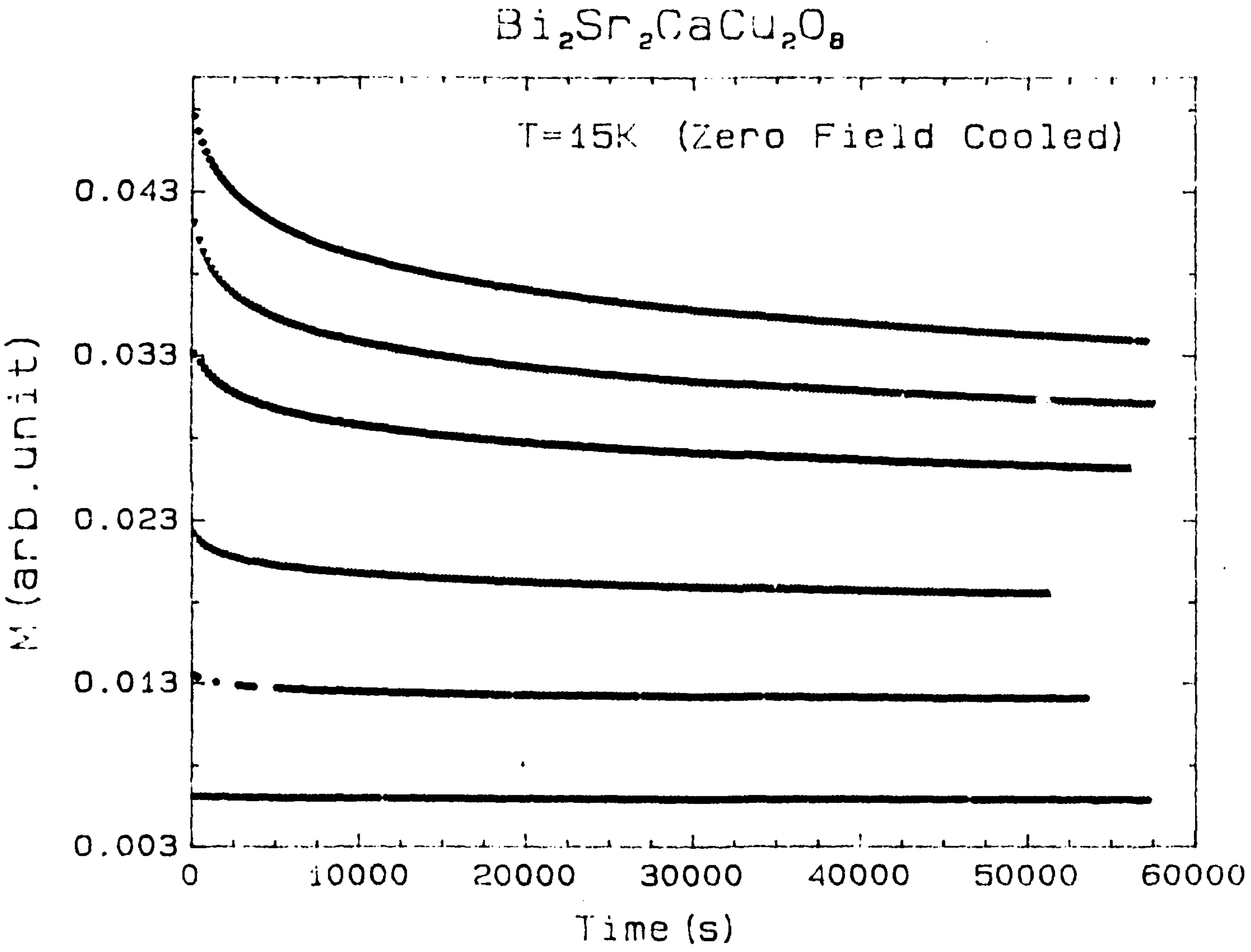

$Bi_2Sr_2CaCu_2O_8$
T=15K (Zero Field Cooled)
M (arb.unit)
0.043
0.033
0.023
0.013
0.003
0
10000
20000
30000
40000
50000
60000
Time (s)

Fig. 3

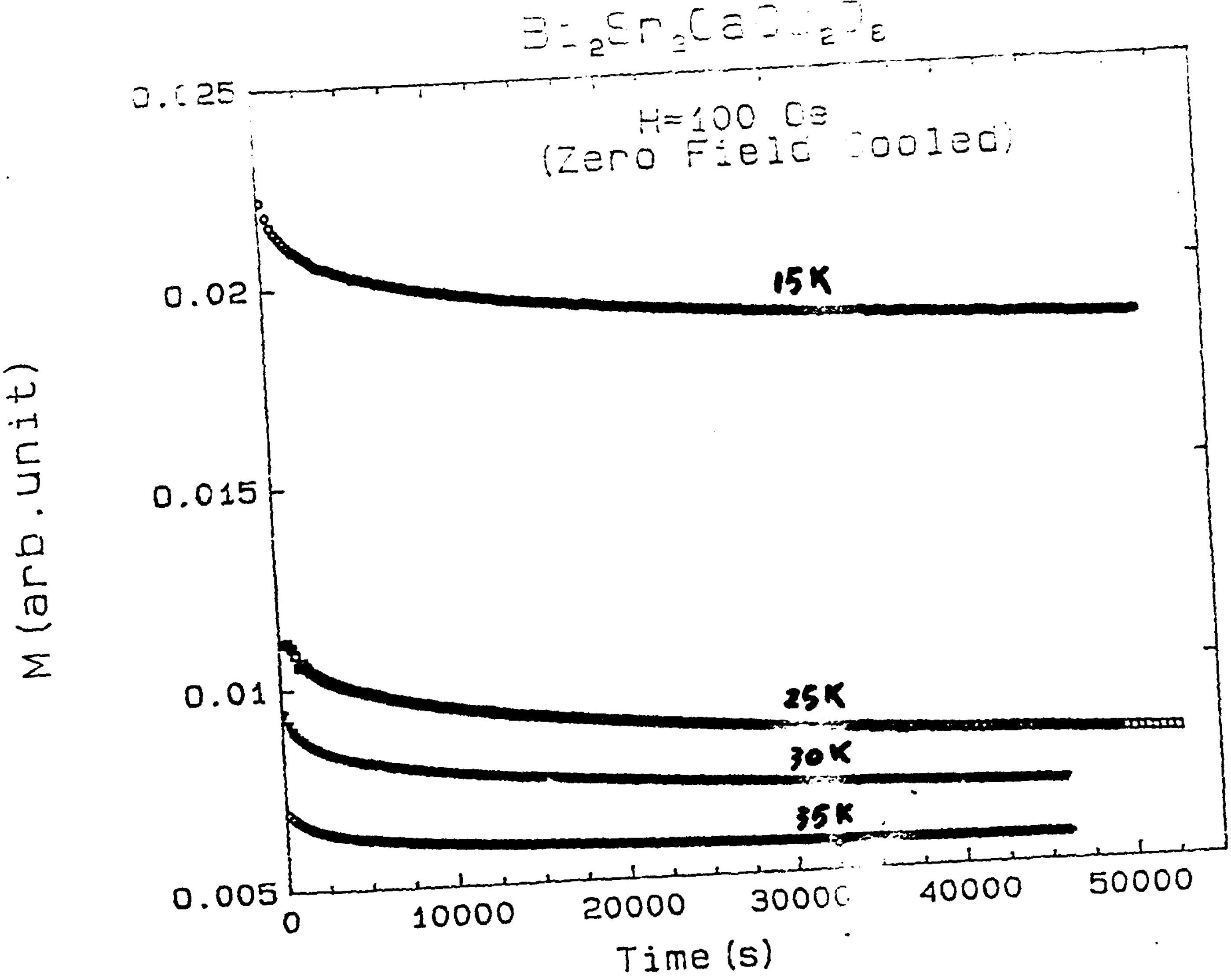
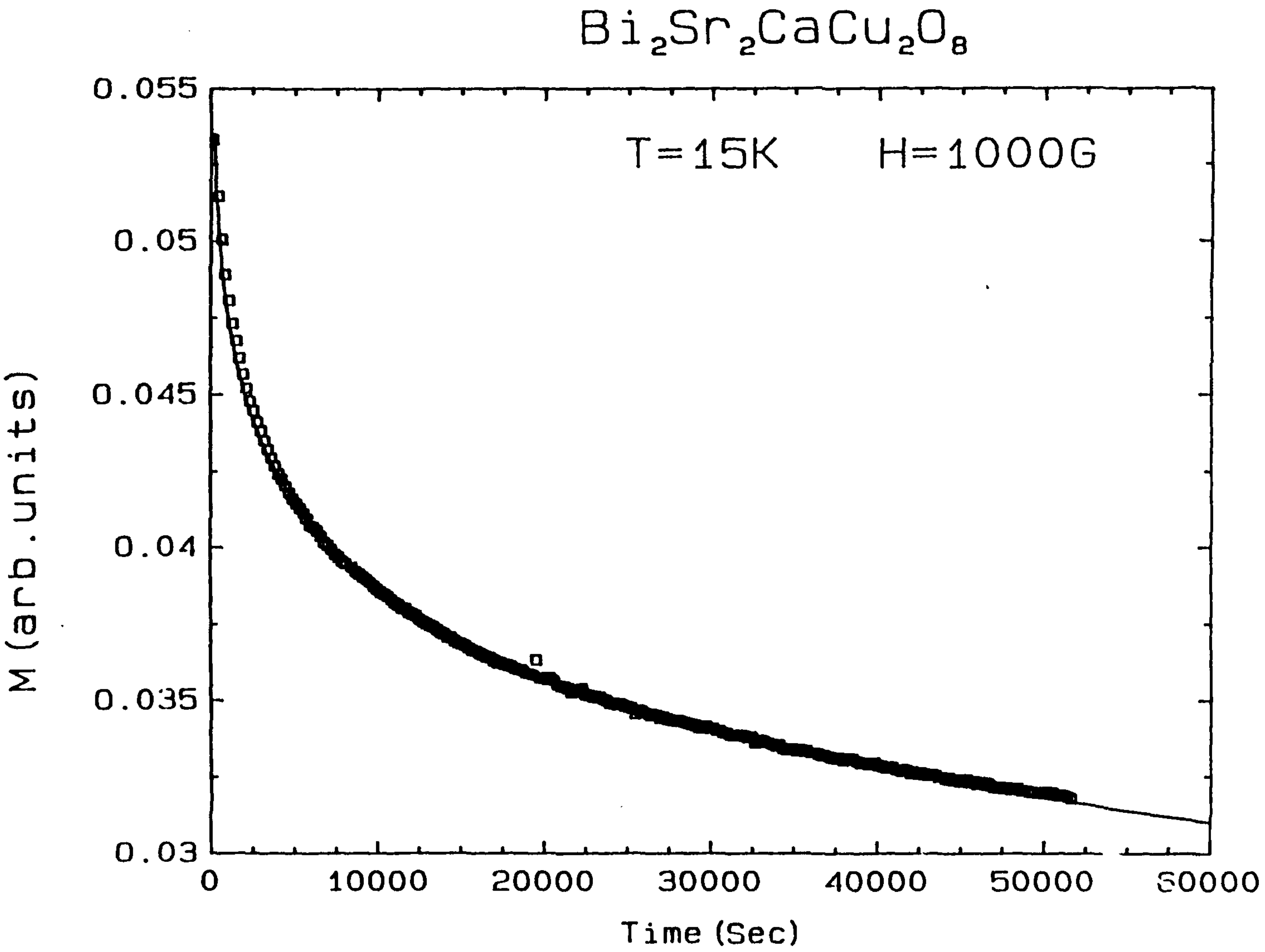

$Bi_2Sr_2CaCu_2O_8$
H=100 Oe
(Zero Field Cooled)
15K
25K
30K
35K
0.025
0.02
0.015
0.01
0.005
M (arb.unit)
0
10000
20000
30000
40000
50000
Time (s)

Fig. 4


$Bi_2Sr_2CaCu_2O_8$
T=15K
H=1000G
M (arb.units)
0.055
0.05
0.045
0.04
0.035
0.03
0
10000
20000
30000
40000
50000
60000
Time (Sec)

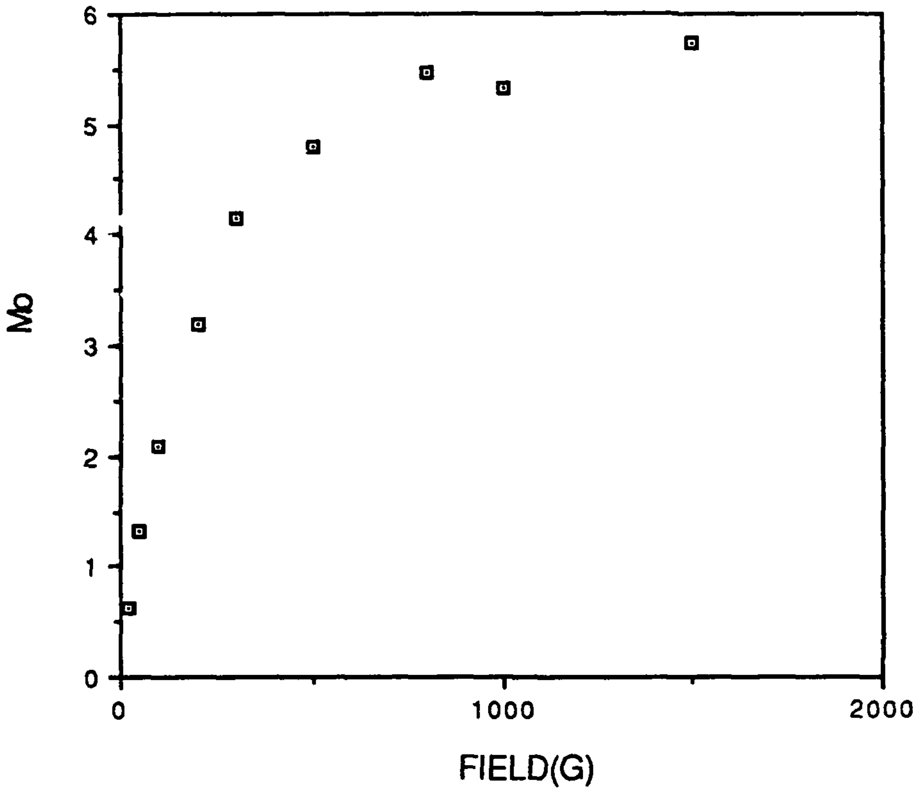
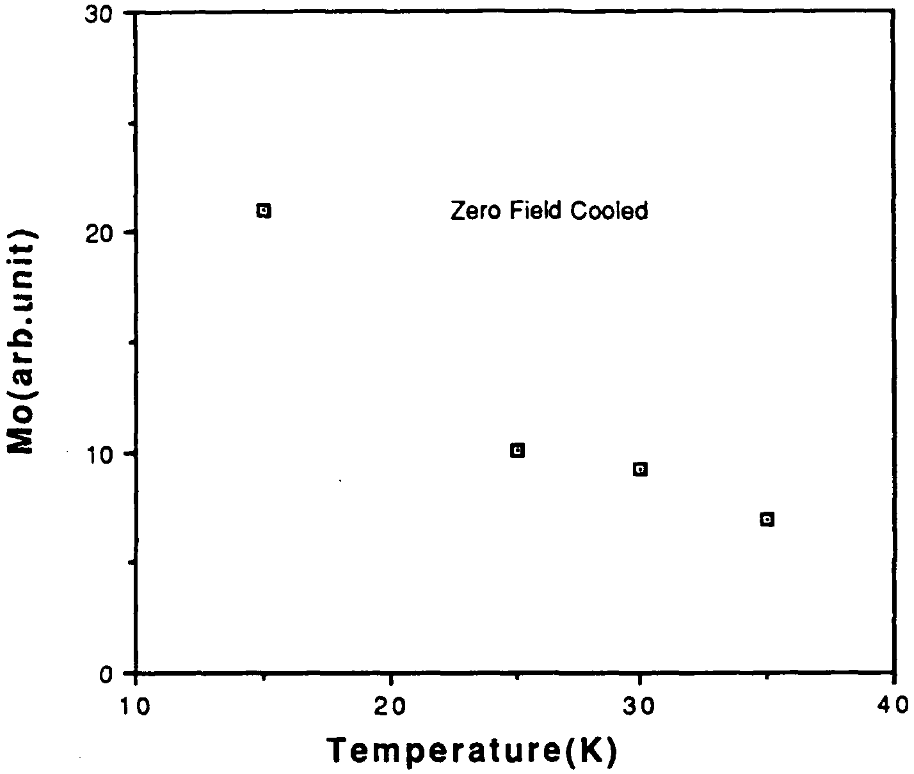


Fig. 5

Fig. 6



30
20
10
0
10
20
30
40
Mo(arb.unit)
Temperature(K)
Zero Field Cooled

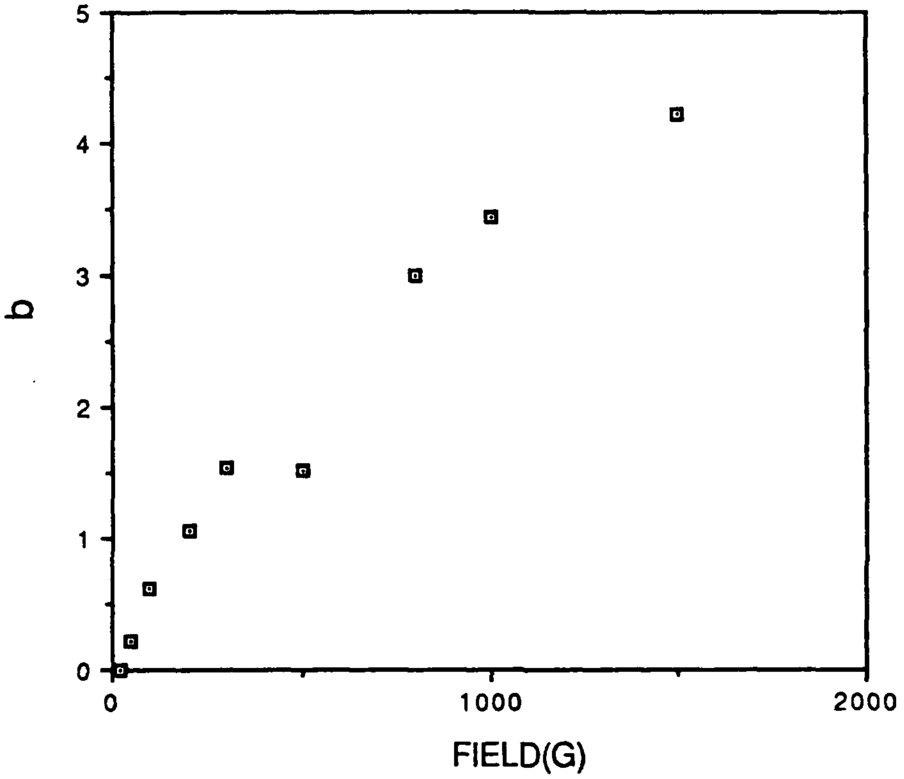
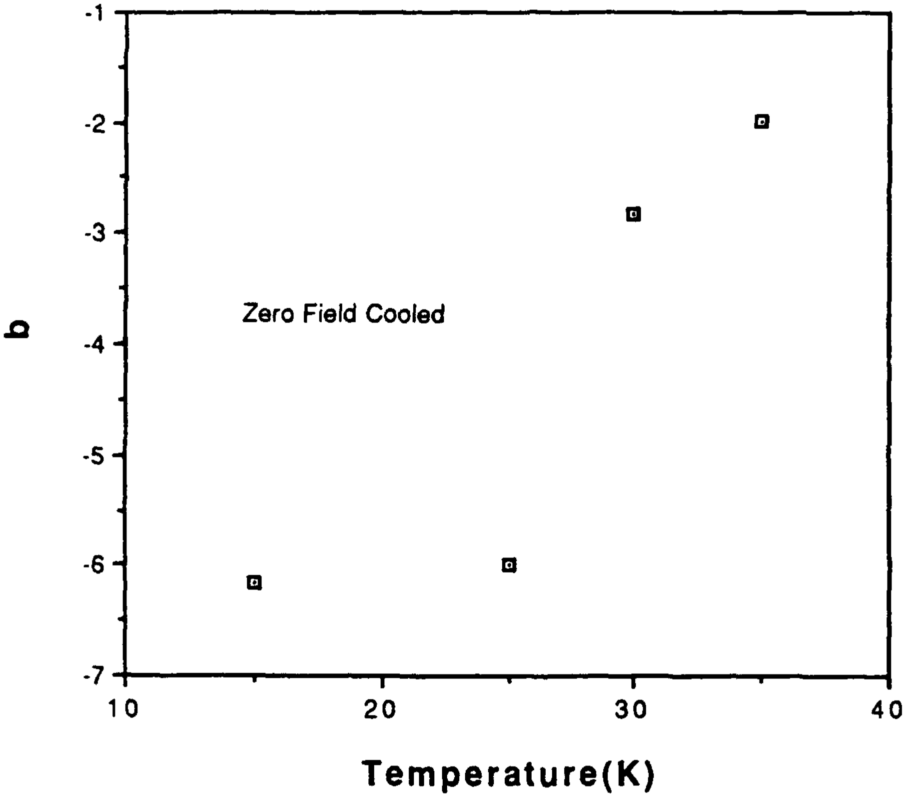


Fig. 7

Fig. 8



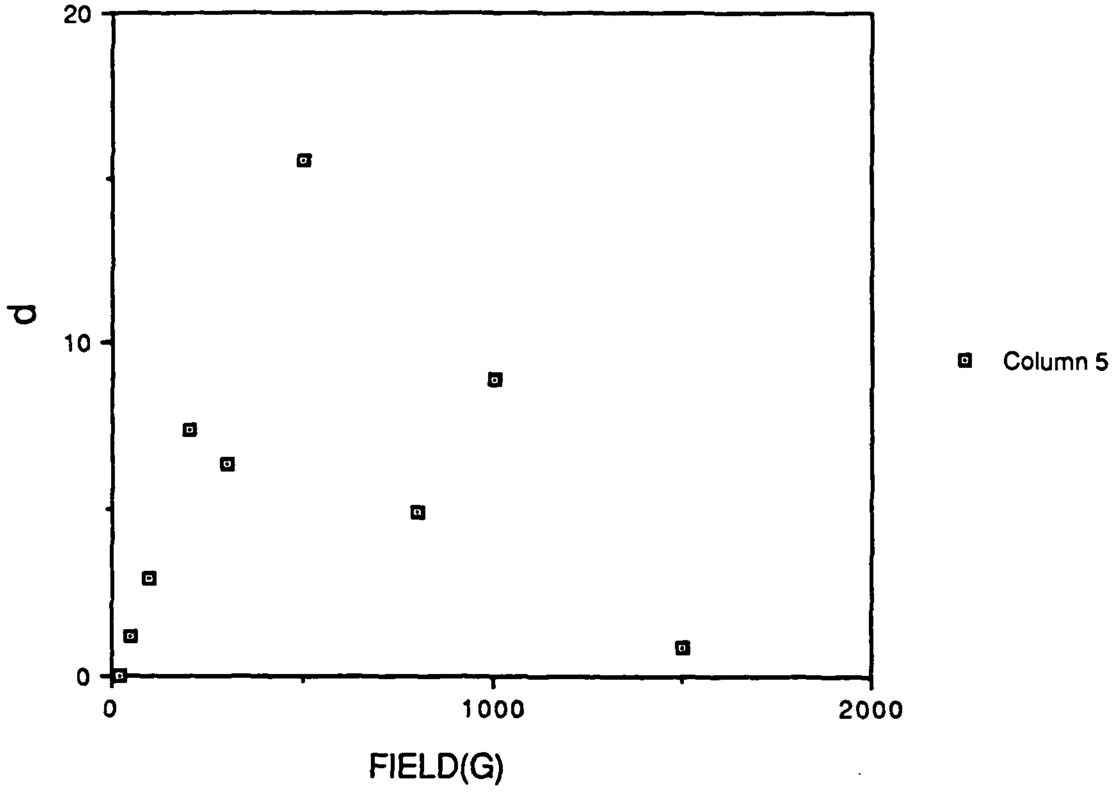
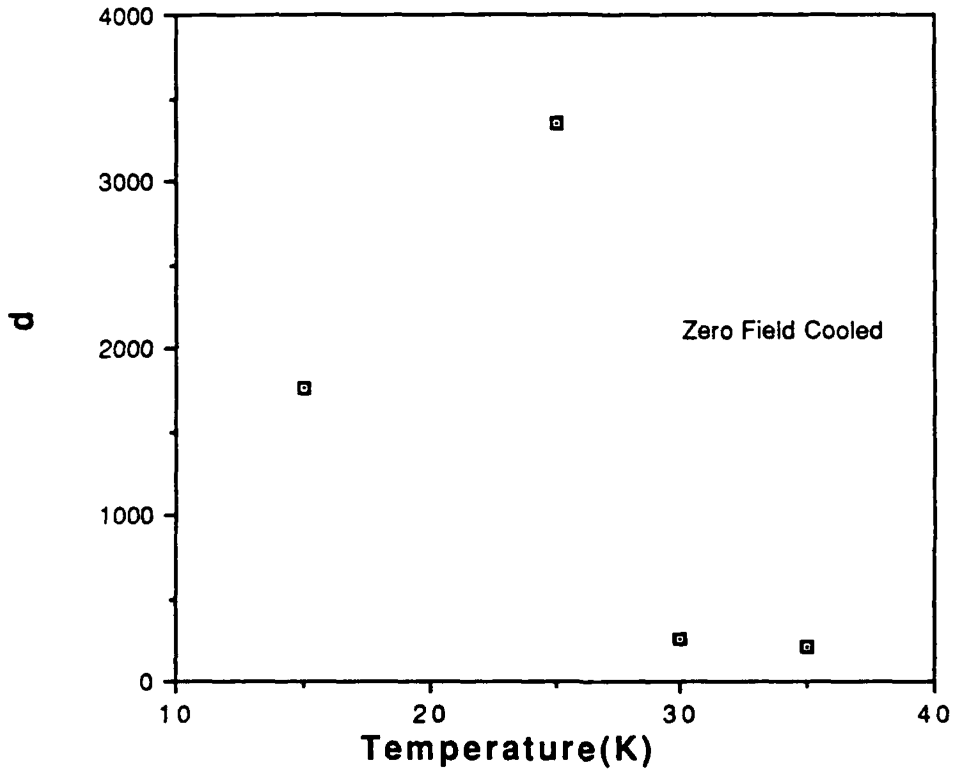


Fig. 9

Fig. 10


4000
3000
2000
1000
0
d
Zero Field Cooled
10
20
30
40
Temperature(K)

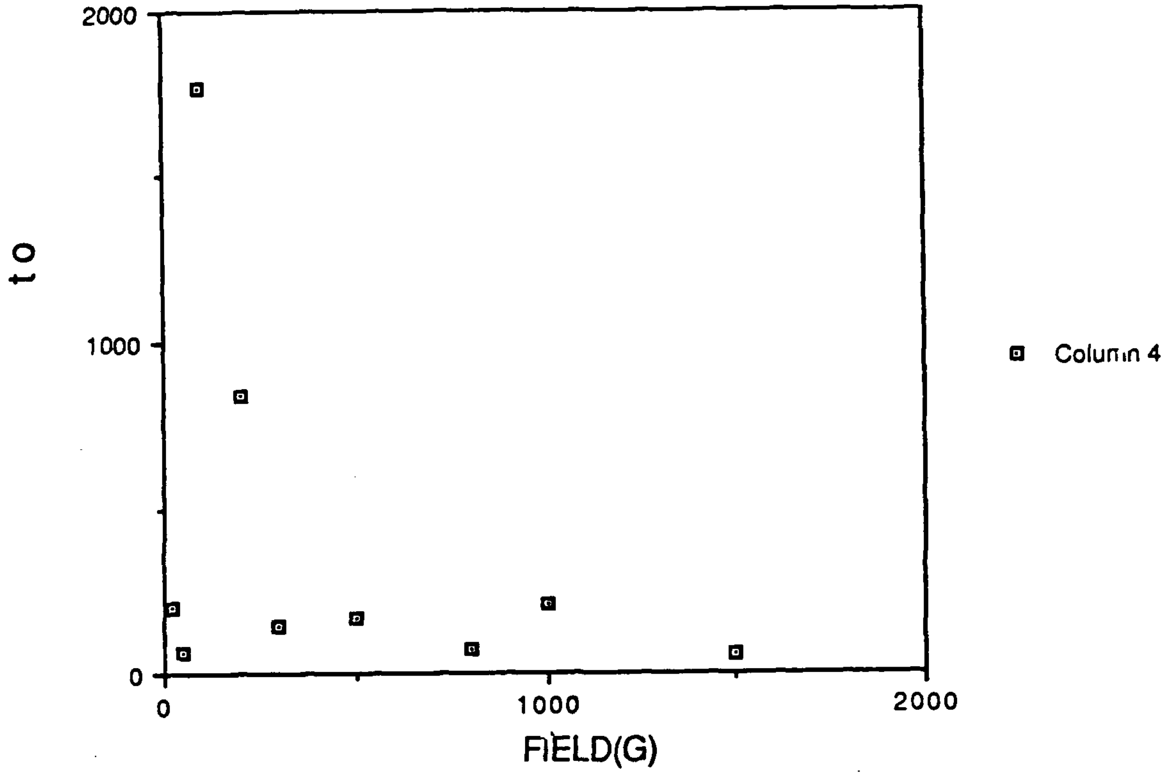


Fig. 11

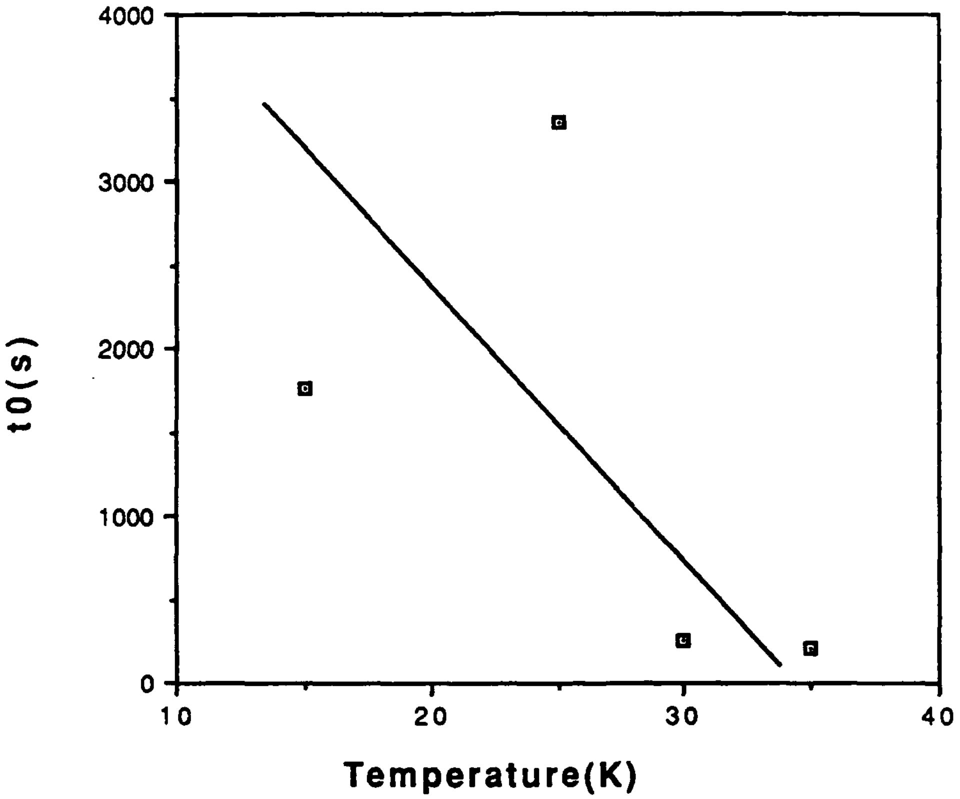


Fig. 12