

Magnetic Hysteresis Loops and Fast Relaxation of Vortex Lattice in YBaCuO Single Crystal

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Abstract — The magnetic moment values \mathcal{M} at conventional magnetic moment relaxation at constant magnetic field and in magnetic hysteresis loop experiment are directly related and are the same if $\mu_0(d\mathcal{M}/dt)_{CR} = \chi_0(dB_e/dt)_{MHL}$. Dependencies of $\mathcal{M}(dB_e/dt)$ measured by vibrating sample magnetometer on YBa₂Cu₃O_{7- δ} single crystals at temperatures ranging from 2.5K to 54K are analyzed. Activation energy $U_e = -kT[\ln(dB_e/dt) - C]$ vs. \mathcal{M} is plotted with parameter C being adjusted to form a smooth curve. In this way the critical sweep rate $(dB_e/dt)_C = \exp(C)$ corresponding to the critical state $U_e(\mathcal{M}_C) = 0$ is determined. A detailed analysis shows that $\ln(dB_e/dt)_C$ increases approximately linearly with temperature. This dependence can be removed by scaling the activation energy by a temperature dependent factor. At temperatures below 5K departure from the thermally activated relaxation occurs, the origin of which can be the quantum tunnelling effect.

I. INTRODUCTION

Magnetic moment induced in a superconductor by a change of external magnetic field undergoes after a field stop significant degradation with time. In conventional superconducting materials this decay is slow (logarithmic) and reaches only a few per cent in several days. In high temperature superconductors (HTS) magnetic moment decreases much more rapidly which presents also a serious problem for technical applications. This difference is not only due to a significant increase of critical temperature in HTS but, first of all, due to the difference in pinning barrier U_e . In conventional superconductors $U_e \ll kT_C$ and, consequently, magnetic moment is close to the critical value. Flux motion is then well described by Anderson and Kim's theory of thermally activated flux creep [1] in which effective activation energy is a linear function of magnetic moment and relaxation is logarithmic in time.

Low pinning barrier in HTS causes a rapid drop of magnetic moment (and related persistent current). In Bi-based materials the irreversibility line lies well below T_C even at zero field. In this range the flux totally relaxes off in a few minutes after a field stop [2]. The relaxation is in this case strongly non-logarithmic. In Y-, La- BaCuO and similar materials flux creep is appreciable but non-zero irreversible magnetic moment persists at low fields for a long time even at temperatures close to T_C . Relaxation in these materials, especially at shorter time window and lower

temperatures, has often been interpreted in terms of Anderson and Kim's model.

Increasing efforts in investigation of relaxation phenomena and improved experimental techniques (long periods of observation time [3] or special techniques oriented towards short time region [4]-[6]) have made it obvious that effective pinning energy in HTS is in general a non-linear function of magnetic moment and relaxation is non-logarithmic. This conclusion emerges from practically all recent theories of superconducting state (collective pinning, vortex glass, self-organised critical state, etc.). Assuming only the thermally activated character of the relaxation process, Maley et al. [7], [8] have investigated the effective activation energy in dependence on magnetic moment (i.e. also current), temperature, and field. The non-linear relation between the effective pinning barrier and current follows naturally from this concept.

Equivalence between the relaxation processes in conventional magnetic moment relaxation at constant magnetic field and in magnetic hysteresis loop (MHL) experiment [5], [6] enables us to examine data of both experiments in the same way and considerably extend the inspected ranges of magnetic moment \mathcal{M} and corresponding magnetic decay rate $d\mathcal{M}/dt$.

In this paper we apply the Maley's approach to MHL data and demonstrate full compatibility of MHL experiment with conventional relaxation. Specific features of MHL data can be here appreciated: (i) magnetic moments detected on hysteresis loops are, as a rule, higher than those obtained from corresponding conventional relaxation, i.e. MHL data correspond to the very early fast stage of the conventional relaxation, (ii) the sweep rate and also the corresponding decay rate is the same at all temperatures and fields, independent of the magnetic moment value. We construct the Maley's curve, i.e. the plot of effective activation energy vs. magnetic moment, from only the MHL data and analyse it in a wide temperature range.

II. MODEL

All our samples are c-oriented flat single crystal platelets. This form will be here approximated by a flat disk of radius r and thickness d placed in external field parallel to the symmetry axis. In this paper \mathcal{M} means an irreversible magnetic moment determined as a half difference between magnetic moments measured on MHLs with increasing and decreasing field. According to Bean's model magnetic moment and current density are related as $\mathcal{M} = -\Omega j$, where

Ω is geometrical factor equal to $\Omega = \pi r^3/d^3$ for the cylindrical symmetry.

The process of relaxation is assumed to be thermally activated. In this case vortex motion is described by a flux-creep equation [6], [9], [10].

$$-\mu_0 \frac{d\mathcal{M}}{dt} = \chi_0 \frac{dB_e}{dt} - (\Delta v_0 B_e) \exp\left(-\frac{U_e(\mathcal{M})}{kT}\right), \quad (1)$$

where U_e is the effective activation energy, dependent on the temperature T and the magnetic field B_e . Δ is a geometrical factor. The differential susceptibility χ_0 and Δ are expressed for our samples by [5], [10]

$$\chi_0 = \frac{\pi^2 r^3}{3L}; \quad \Delta = \frac{2\chi_0}{r}, \quad (2)$$

where μ_0 is permeability of vacuum and $\mu_0 r L$ is the self-inductance of the disk [12], $L = [\ln(8r/d) - 0.5]$.

Vortices move at velocity v given by Arrhenius law, $v = v_0 \exp[-U_e(\mathcal{M})/kT]$ for thermally activated motion, where v_0 is the critical velocity corresponding to the state determined by $U_e(\mathcal{M}_c) = 0$. Equation (1) applies both to the conventional relaxation ($dB_e/dt=0$) and the MHL experiments ($d\mathcal{M}/dt=0$). Decay rate $d\mathcal{M}/dt$ in relaxation and sweep rate dB_e/dt in MHL corresponding to the same value of \mathcal{M} are related as [7], [11]

$$\mu_0 \left[\frac{d\mathcal{M}}{dt} \right]_{CR} = \chi_0 \left[\frac{dB_e}{dt} \right]_{MHL} \quad (3)$$

Eq. (3) enables us to convert the results of both types of experiment into the same representation (either \mathcal{M} vs. $\ln(t)$, either \mathcal{M} vs. $\ln(dB_e/dt)$). In terms of sweep rate the equation (1) can be rewritten as

$$\frac{dB_e}{dt} = \frac{\Delta v_0 B_e}{\chi_0} \exp\left(-\frac{U_e(\mathcal{M})}{kT}\right), \quad (4)$$

where the factor $(dB_e/dt)_c = (\Delta v_0 B_e)/\chi_0$ represents the sweep rate just necessary to induce in the superconductor the critical state determined by $U_e(\mathcal{M}_c) = 0$. (4) can be converted into the explicit form for the pinning energy as a function of magnetic moment $\mathcal{M} = -\Omega j$ as

$$U_e(\mathcal{M}) = -kT \left[\ln\left(\frac{dB_e}{dt}\right) - \ln\left(\frac{dB_e}{dt}\right)_c \right]. \quad (5)$$

The plot of $U_e(\mathcal{M})$ vs. \mathcal{M} is the Maley's curve [8], [9] constructed from the MHL data.

III. EXPERIMENTAL DETAILS

The measurements were performed with a vibrating sample magnetometer PAR 155 equipped with a cryostat working between 2.5K and 300K placed in the electromagnet ranging to $\pm 2T$. In this paper we present data obtained on $YBa_2Cu_3O_{7.8}$ single crystal grown by pseudo-flux method in the form of a thin plate of area 2.12 mm^2 and thickness $20 \mu\text{m}$. All measurements were conducted with field applied parallel to c-axis (perpendicular to sample plane) at temperatures ranging from 2.5K to 54K. Magnetic hysteresis loops were recorded with sweep rates ranging from 90 to 0.076 mT/s.

MHL data represents pairs of values $(\mathcal{M}, dB_e/dt)$ established for different sweep rates at different temperatures. \mathcal{M} was evaluated at $B_e = 1T$. Reversible component was small and negligible.

The differential susceptibility χ_0 was measured as a quasistatic ac susceptibility at a given field B_e after careful demagnetization of the sample by additional bias ac field with decreasing amplitude. Then field component ramping with rate 0.03 mT/s was applied in the limits $B_e \pm 0.03 \text{ mT}$. Magnetic response is reversible in these limits. χ_0 determined in this way is equal to 1.3 mm^3 independent of temperature in the whole analysed temperature range. We observed only a slight dependence on magnetic field. It is, moreover, equal within the experimental error to the initial susceptibility measured on the virginal MHL after zero field cooling and to the slope of reverse leg of MHL [12].

IV. RESULTS AND DISCUSSION

Effective activation energy calculated from MHL data for the single crystal is presented as a function of magnetic moment in Fig. 1.

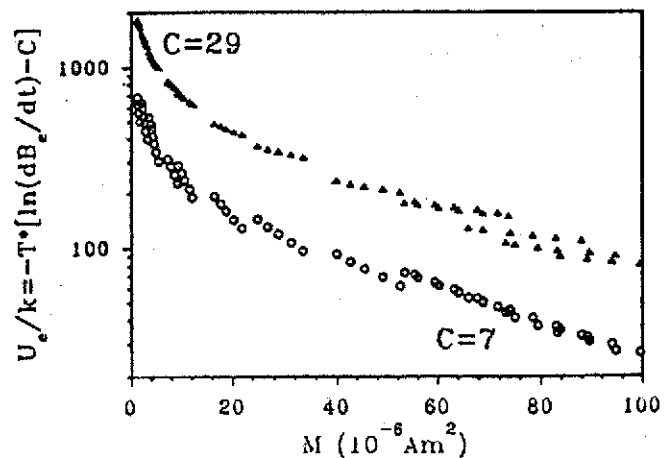


Fig. 1. Effective activation energy of $YBaCuO$ single crystal as a function of magnetic moment \mathcal{M} measured at temperatures between 2.5K and 53K on magnetic hysteresis curves run with sweep rates ranging from 0.074 mT/s to 90 mT/s. Values of C correspond to dB_e/dt given in T/s, U_e/k is in [K].

We see from (5) that a good fit requires temperature dependent adjustable parameter $C = \ln(dB_e/dt)_c$. Values of C needed to line up data at high and low temperatures are quite different. This difference implicates a change of several orders in $(dB_e/dt)_c$ which can hardly be explained within any present theoretical model of relaxation. Much more realistic seems to be scaling of the activation energy by a temperature dependent factor (Fig.2.) as proposed by Henry et al. [8]. This approach, taking into account an increase of vortex thermal energy with increasing temperature, results not only in the very good fit of experimental data with one value of C but also reflects the natural divergence of activation energy at T_c (or, more precisely at the "irreversibility" temperature.)

The lower part of Fig.2 presents a quite impressive fact that Henry's approach gives for our YBaCuO single crystal a straight line in a log-log plot throughout the temperature range 4.8K to 53K. Only the data for temperatures beneath 4.8K depart. It implies the following: Effective activation energy U_e of our single crystal has in a wide temperature range a general form $U_e/(1-T/T_c)^{1.5} \propto M^\alpha$ where $\alpha = -0.91$. It revokes the functional dependence resulting from the collective creep theory, $U_e = U_c/\mu ((M/M_c)^{-\mu}-1)$, which just at low temperatures should depart from approximate dependence $M^{-\mu}$. The argument against this conclusion is the $M(T)$ dependence shown in Fig.3. The low-temperature limit in this case gives $M(dB_e/dt) = M_c[1 - \ln((dB_e/dt)/(dB_e/dt)_c)]$ the zero-temperature extrapolation of which is M_c irrespective of sweep rate value. Fig.3 shows that the

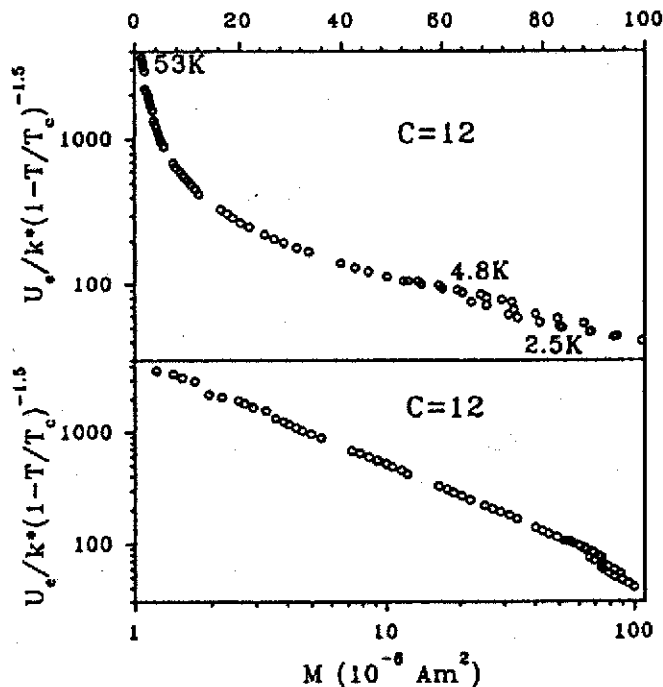


Fig 2. The same as in Fig.1. but the effective activation energy scaled by factor $(1-T/T_c)^{-1.5}$. Linear scale of magnetic moment at the top, logarithmic scale at bottom. Again, C values correspond to dB_e/dt given in [T/s] and values on Y-axes are in [K]

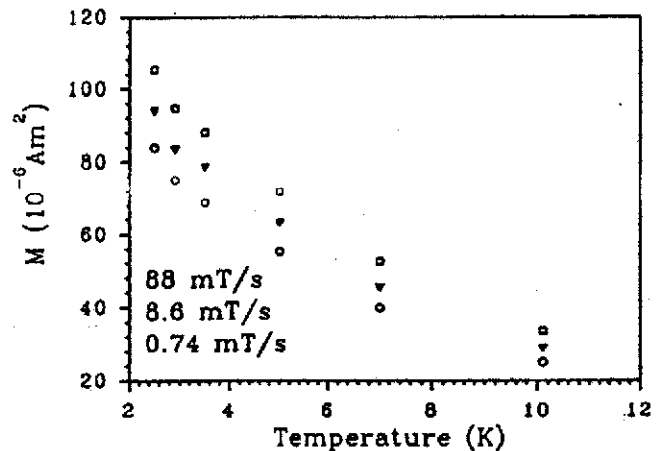


Fig.3. Magnetic moment from Fig.1. versus temperature in the low temperature range for different sweep rates.

opposite is true. The departure of low-temperature data in Fig. 2 is probably due to the contribution of an additional relaxation mechanism in this temperature range, which might be the quantum tunnelling of vortices.

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