Diffusion of magnetic flux into $Bi_2Sr_2CaCu_2O_y$ single crystals

N. V. Zavaritskiĭ and V. N. Zavaritskiĭ

P. L. Kapitsa Institute of Physical Problems, Russian Academy of Sciences, 117973, Moscow, Russia; Institute of General Physics, Russian Academy of Sciences, 117942, Moscow, Russia

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The relaxation of the nonequilibrium magnetization $\delta M(t)$ caused by a small change $\delta H = 0.02$–4 Oe $\ll H_0$ in the external magnetic field $H_0 = 0.7$–10 kOe $\gg H_{c1}$ has been measured. The results reveal temperature intervals in which the initial part of the $\delta M(t)$ curve is governed by a diffusion of magnetic flux into the sample: $\delta M \propto \exp(-bt)$. The model of a thermally activated flux flow (TAFF) is used along with the curves of $b(T) \propto \rho(T)$ for the field range studied to determine the heights of the barriers to the motion of vortices: $U(H) \simeq 525$–325 K.

Research on the relaxation of a nonequilibrium magnetization in single crystals of the high-T_c superconductors has revealed obvious deviations from a logarithmic law (a logarithmic time dependence) in several cases.[1,2] One possible explanation for these observations is based on a model of a diffusive penetration into the sample of the magnetic field, whose change produced the nonequilibrium magnetization.[3]

When the density of vortex filaments in a type-II superconductor is sufficiently high, the overlap of the magnetic fields of the individual vortices substantially weakens the modulation (due to the vortex cores) of the magnetic induction over the sample. The vortex lattice can be represented as a continuum in this case, and the fields **E**, **B**, and **J** can be replaced by their semimacroscopic averages (averages over several lattice constants of the vortex lattice). In this approximation, the properties of the superconductor can be described by a system of nonlinear partial differential equations. In the case of a slight spatial variation, $B(\mathbf{r},t) \sim \mathbf{B}_0$, and under the assumption that $\rho_\perp$ and $\rho_\parallel$ are linear (i.e., independent of the current), the expression for $B(\mathbf{r},t)$ can be linearized, and we obtain

$$\partial B/\partial t = D\nabla^2 B, \tag{1}$$

where $D = \rho_\perp(B_0,T)/\mu_0$ is the diffusion coefficient describing the diffusion of magnetic flux into the sample. As a result, the flux through a thin-plate sample in a perpendicular field[4] has a time evolution (in a first approximation)

$$\propto \exp(-t/\tau_0), \qquad \tau_0 \simeq cwd/\pi^2 D = \mu_0 cwd/\pi^2 \rho_\perp, \tag{2}$$

where d is the thickness of the plate, w is its width ($d \ll w$), and the numerical factor is $c \simeq 1$.

For the high-T_c superconductors, with large values $\kappa \simeq 200$, the field range in which this approach is valid extends to relatively weak fields $H \gg 2H_{c1}$.

The model of a diffusive penetration of flux into a superconductor has been used previously[5] in measurements of the susceptibility of single crystals of high-T_c superconductors in an alternating magnetic field. In the present letter we are concerned with flux diffusion in a quasisteady external field. The diffusion coefficient was found as a function of the temperature and the external field, $D(T,H)$, for $Bi_2Sr_2CaCu_2O_y$ single crystals over the field range $H = 0.7$–10 KOe. It was thus possible to examine the temperature dependence of the resistivity to 10^{-9} $\mu\Omega\cdot$cm and to determine the characteristics of the thermally activated flux flow (TAFF).

The $Bi_2Sr_2CaCu_2O_y$ test crystals, with $T_c \simeq 95$ K, were platelets ~ 1 mm^2 in area with a thickness $d \simeq [(6\text{–}23) \pm 2]$ μm. In the experiments we measured $\delta M(t)$, the time evolution of the nonequilibrium increment in the magnetic moment of the sample due to a small change in the external field H_0 ($\delta H \ll H_0$).

A static magnetic field $H_0 = 0.7$–10 kOe, directed perpendicular to the basal plane of the sample, was generated by a superconducting solenoid under short-circuiting conditions. A weak auxiliary magnetic field $\delta H \sim (0.2\text{–}4)$ Oe, directed parallel to the main field H_0, was produced by a separate coil. The change in magnetic moment, $\delta M(t)$, was detected by a SQUID magnetometer; the test sample was placed in one of the flux-transformer loops of this magnetometer. The detection circuit of the transformer was balanced in such a way that the imposition of the field δH at $T > T_c$ did not give rise to a signal. The time constant of the measurement apparatus was no longer than 0.2 s. The main field H_0 was applied at the beginning of the experiment. The measurements were begun after a time long enough (on the order of several hours) that the transient effects due to the application of the main field were at a neglibible level. The time dependence $\delta M(t)$ was measured over a time interval of 100–1000 s after δH was applied (or turned off); the results were stored in computer memory. The temperature of the sample, in a vacuum container, was measured by a resistance thermometer; it could be varied from 1 K up to the T_c of the sample.

In the standard formulation of a SQUID-magnetometer experiment,[6] one measures the amplitude of the change in the output signal V which arises as the sample is pulled through the loops of the gradiometer coil of the flux transformer. Here we have $\delta V \sim [M(t_1) + M(t_2)]$, where t_1 and t_2 are the times at which the sample is in the corresponding loops. In the case of relaxation experiments, the effect is to impose a lower limit on the measurement time interval ($t \sim 10$–100 s). In the experiments which we are describing here, we measured the change in the SQUID output signal $\delta V(t)$, which is proportional to the *change* in the magnetic moment of the sample, $\delta M(t)$. The fixed position of the sample made it possible to expand the time range by more than an order of magnitude and to eliminate the parasitic effects caused by motion in the nonuniform field. The total magnitude (and temperature dependence) of the magnetic moment in the unperturbed field H_0 was measured by heating the sample from the measurement temperature to $T > T_c$. The total nonequilibrium increment δM was estimated from the measurements of $\delta M(t)$ for two directions of δH.

It was found that the nonequilibrium increment in the magnetic moment, δM, of a crystal in a field $H_0 = 1$ kOe varies in proportion to the absolute value of δH and is described by a single functional dependence $\delta M(t)$ as long as the condition $\delta H \leqslant 1$ Oe holds. The application and removal of the trial field result in changes δM which are identical in absolute value (see the inset in Fig. 1). This result is evidence that there is no surface barrier opposing the entrance of vortices into the sample (or opposing the escape of vortices from the sample) over the H_0 range studied. At larger values of δH, the absolute value of δM, when the field is turned off, is usually slightly smaller than that when the field is turned on. This difference apparently indicates a change in the dynamics of the response of this system from a thermally assisted flux flow (TAFF, $j \ll j_c$) to a flux creep. This suggestion is supported by an observed change in the nature of the relaxation as the field is raised to $\delta H \simeq 100$ Oe, in which case we have $\delta M(t) \sim \ln(t)$ over essentially the entire measurement range. The results which we are discussing in this letter were obtained under conditions corresponding to $\delta M \sim \delta H$.

In Ref. 6, a logarithmic relaxation was observed over essentially the entire measurement range. The results of the present study, in contrast, reveal an exponential relaxation of the nonequilibrium magnetization (in time):

$$\delta M \propto a \exp(-bt) \tag{3}$$

(see the inset in Fig. 1). This behavior was observed over a temperature interval ~ (5–

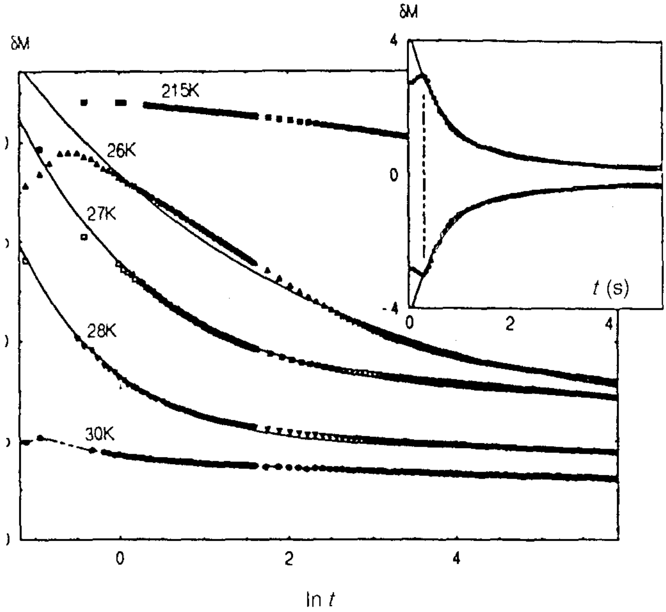

FIG. 1. Relaxation of the nonequilibrium magnetic moment $\delta M(t)$ (in arbitrary units), caused in a $Bi_2Sr_2CaCu_2O_y$ single crystal by a small change $\delta H < 1$ Oe in the external magnetic field $H_0 = 1$ kOe. Shown in the inset are the initial parts of the $\delta M(t)$ curves upon the application and removal of δH. The curves were approximated by the law $\delta M(t) = a \exp(-bt) + c$ (the solid lines) at $t > t_{\text{app}}$; the apparatus time t_{app} is shown by the vertical dot-dashed line. The parameter c in this approximation law reflects the presence of the measured change $\delta M(t)$ in the course of the experiment, from the complete value of the nonequilibrium increment to the magnetization. The parameter values for the curves in the inset are $a = \pm 0.39$ and $b \simeq 1.4$. In the main part of the figure, the values of b for $T = 30, 28, 27$, and 26 K are $\simeq 2.1$, 1.0, 0.5, and 0.3, respectively.

10) K wide for all the fields H_0 studied. Outside this interval, and after a long time ($t \gg 1/b$), the relaxation curves approach the logarithmic curve $\delta M \sim \ln t$, as is clear from Fig. 1. The value of b depends on the temperature. The solid lines in Fig. 1 show the results of a fit of relation (3) to the typical experimental curves of $\delta M(t)$ for $H_0 = 1$ kOe. Working from these curves, we were able to reliably determine the value of b in the interval $\sim 3 \geqslant b \geqslant 0.05$. The upper limit on this interval is set by the time constant of the measurement apparatus; the lower limit is set by the finite measurement time and by the appearance of significant deviations (like those which can be seen on the curve for $T = 26$ K in Fig. 1) of the experimental $\delta M(t)$ curves from relation (3). This relation is evidently valid only in a first approximation.

It seems natural to link the exponential nature of the dependence $\delta M(t)$ with a diffusion of magnetic flux into the sample [cf. (2) and (3)]. In this case the quantity b is determined by the resistivity $\rho_\perp$ of the sample, which is given in a zeroth approximation by[4]

$$\rho \simeq bwd/\pi^2. \tag{4}$$

To compare the results on the different samples, we used values of this parameter referred to a thickness $d = 7$ μm: $b^* = bd/(7\ \mu\text{m})$. [A normalization in terms of the values of w would be overly precise in this case, since the thicknesses of the test samples differed by a factor of several units, while the dimensions in the (**ab**) plane differed by less than 20%.] Also using (4), we find an estimate of the resistivity: $\rho \simeq 10^{-8} b^*$, where ρ is in $\mu\Omega \cdot$cm, and b^* is in s^{-1}.

The agreement of the values calculated for ρ for the three crystals with different thicknesses (Fig. 2), selected at random from one lot, would seem to support the validity of relation (4). However, the corresponding estimate for a fourth sample differs by an order of magnitude. The reason for this discrepancy has not been finally resolved.

Under TAFF conditions, the resistivity of a superconductor has a temperature dependence[7]

$$\rho_\perp = \rho_0 \exp(-U/T), \tag{5}$$

where U (in kelvins) is a characteristic dimension of the potential relief for the motion of vortices. The $\rho(T)$ dependence found from the experimental data under the assumption that (4) is valid does not contradict expression (5) anywhere in the range of magnetic fields studied (Fig. 2). Values of U found from the experimental curves with the help of (4) and (5) are shown in the inset in Fig. 2. The variation in U with the magnetic field (the inset in Fig. 2) can be approximated satisfactorily by the power law $U = 480H^{-\alpha}$ (the solid line) with $\alpha = 0.16$, with H in kiloersteds. In fields $H \leqslant 10$ kOe, this dependence is apparently typical of highly anisotropic (quasi-2D) superconductors.[8] The values which we found agree satisfactorily with the results of Ref. 5, but they are lower by a factor of nearly 2 than those reported in Ref. 9. A distinguishing feature of Ref. 9 was that the measurements were carried out at higher temperatures, and the resistances were much higher. As a result, measurements may have been made outside the TAFF region. Our data furthermore do not support the assertion in Ref. 9

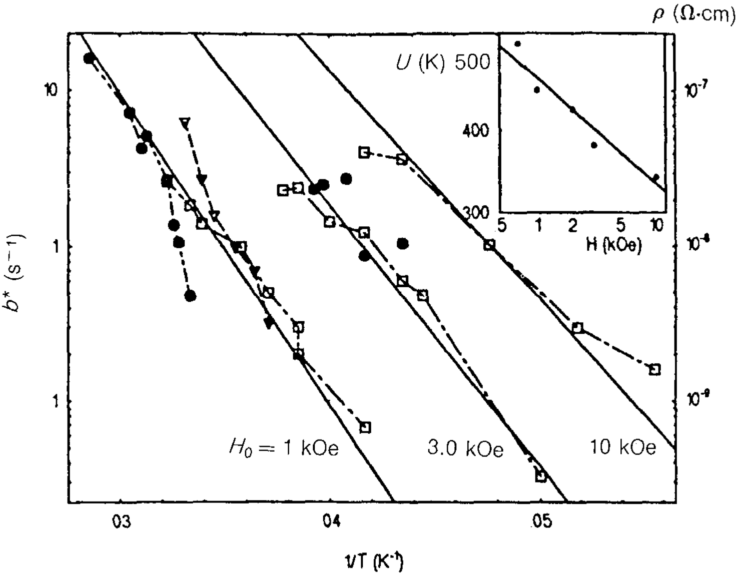

FIG. 2. Comparison of the reduced values $b^* = bd/(7\ \mu\text{m})$ and the resistivities $\rho \simeq 10^{-8} b^*$ (ρ is in $\mu\Omega\cdot$cm, and b^* is in s^{-1}) calculated from (4) for fields $H_0 = 1.0$, 3.0 and 10.0 kOe. □—Sample 1, $d = 5$–$8\ \mu$m; ▽—sample 2, $d \simeq 22 \pm 2\ \mu$m; ●—sample 3, $d = 20 \pm 1\ \mu$m. The solid lines are an approximation by the law $\rho(T) = 0.1 \exp(-U/T)$ (ρ is in units of $\mu\Omega\cdot$cm). The inset shows values of the effective barrier height U for various fields H, along with the approximation $U = 480H^{-0.16}$.

that the preexponential factor in (5) is substantially greater (by three orders of magnitude) than the resistance of the sample in the normal phase (at $T \gg T_c$). For all the fields which we studied, this preexponential factor is $\sim 10^{-1}\ \mu\Omega\cdot$cm, much lower than the resistivity of the sample in its normal state. The accuracy with which ρ_0 is determined from the approximation of the $\rho(T)$ dependence by (5) is not good, since a 10% change in U leads to a change of an order of magnitude in ρ.

Flux diffusion is manifested experimentally only if the nonequilibrium magnetization caused by the small change $\delta H \ll H_0$ in the external field is itself small in comparison with the scale value of $M(H_0)$, i.e., only if the surface current which is excited satisfies $j \ll j_c$, where j_c is the critical current density. At larger values of δH, relation (1) is no longer valid. At $j \simeq j_c$ the change in the nonequilibrium magnetization is governed by a thermally activated vortex creep, and the relaxation of the moment is logarithmic. These are the conditions which have prevailed in most of the studies which have been carried out on magnetization relaxation in high-T_c superconductors.

A qualitative change in the dynamics[6,10] of the vortex system has recently been seen in flux-creep experiments on Bi-2212 single crystals at $T_j \simeq T_c/5$. In the experiments which we have reported here, we were unable to determine how the nature of the diffusion changes at $T = T_j$.

[1] P. Svendlindh, C. Rossel, K. Niskanen *et al.*, Phys. C **176**, 336 (1991).
[2] C. J. van der Beek, P. H. Kes, M. P. Maley *et al.*, Phys. C **185–189**, 2507 (1991).
[3] L. D. Landau and E. M. Lifshitz, *Electrodynamics of Continuous Media*, Pergamon, Oxford, 1984.
[4] E. H. Brandt, Z. Phys. B **80**, 167 (1990).
[5] C. J. van der Beek and P. H. Kes, Phys. Rev. B **43**, 13032 (1991).
[6] V. N. Zavaritskiĭ and N. V. Zavaritskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. **54**, 25 (1991) [JETP Lett. **54**, 22 (1991)].
[7] E. H. Brandt, J. Mod. Phys. B **2**, 751 (1991).
[8] J. W. Hsu, B. Batlogg *et al.*, Appl. Phys. Lett. **57**, 1061 (1990).
[9] T. T. M. Palstra, B. Batlogg *et al.*, Phys. Rev. B **41**, 6621 (1990).
[10] H. Safar, P. L. Gammel *et al.*, Phys. Rev. Lett. **68**, 2672 (1992).

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