Early magnetization relaxation and effect of magnetic field on flux creep in $Bi_2Sr_2Ca_1Cu_2O_x$ single crystals

V. V. Moshchalkov, A. A. Zhukov, V. D. Kuznetsov,[1)] V. V. Metlushko,[1)] and L. I. Leonyuk

M. V. Lomonosov Moscow State University;[1)] D. I. Mendeleev Moscow Chemical Engineering Institute

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A magnetization relaxation has been observed in $Bi_2Sr_2Ca_1Cu_2O_x$ single crystals in the initial time interval. This relaxation is tentatively attributed to a viscous flow of Abrikosov vortices at currents above the critical current. This relaxation gives way to a logarithmic relaxation upon the transition to thermally activated flux creep. The field dependence of the logarithmic relaxation rate has been studied in detail at various temperatures for the first time.

One aspect of the behavior of the high-T_c superconductors in the superconducting state ($T < T_c$) in a magnetic field is a logarithmic relaxation of the magnetization,[1–4] which is assoicated with a thermally activated flux creep. In research on this effect, a logarithmic law has been observed beginning at a certain finite time t_0 ($t_0 \sim 200$ s) after the magnetic field is applied. So far there has been no study of the dynamics of the vortex structure during the initial time interval, $t < t_0$. Our purpose in the present study was thus to learn about the magnetization relaxation processes in

$Bi_2(Sr,Ca)_3Cu_2O_x$ single crystals. At a fixed configuration of the sample, this magnetization is proportional to the magnetic moment P_m of the sample at $t < t_0$. At the same time, we solved the problem of determining the effect of a magnetic field on the relaxation rate of $P_m(t)$ at times $t > t_0$ for various orientations of the magnetic field. Data on the effect of the temperature on the relaxation rate $dP_m(t)/d\ln t)$ can be found in several studies.[1–4] There has been no detailed study of the field dependence $dP_m(t,B)/d\ln t) = f(B)$.

We measured the magnetic moment in the field interval $B = 0$–300 mT in the ZFC regime on a SQUID magnetometer[5] with a sensitivity $\sim 10^{-10}$ A/m^2. The apparatus makes it possible to operate over the temperature range 1.8–300 K.

Figure 1 shows a typical complete relaxation curve $P_m(t)$. We can distinguish two quite different regions on the $P_m(t)$ curve: a first region $(t < t_0)$ with a rapid relaxation of $P_m(t)$, and a second $(t > t_0)$ with a slow logarithmic relaxation. We found that at $t < t_0$ the behavior of $P_m(t)$ is approximately exponential (see the upper inset in Fig. 1); in the limit $t \to 0$ the magnetic moment is determined exclusively by the external magnetic field provided there is total diamagnetic screening (the shape of the sample has been taken into account). At $t > t_0$ we observe a logarithmic relaxation of the moment $P_m(t)$, as illustrated by the straight lines in the lower inset in Fig. 1 [$\ln(t) > 2$ where t is in minutes]. The nonlogarithmic relaxation of $P_m(t)$, which is observed during the initial time interval, may be (in our opinion) a consequence of a viscous flow of Abrikosov vortices at currents J above the critical current J_c. A situation with $J > J_c$ can arise at sufficiently high temperatures T and fields B. This as-

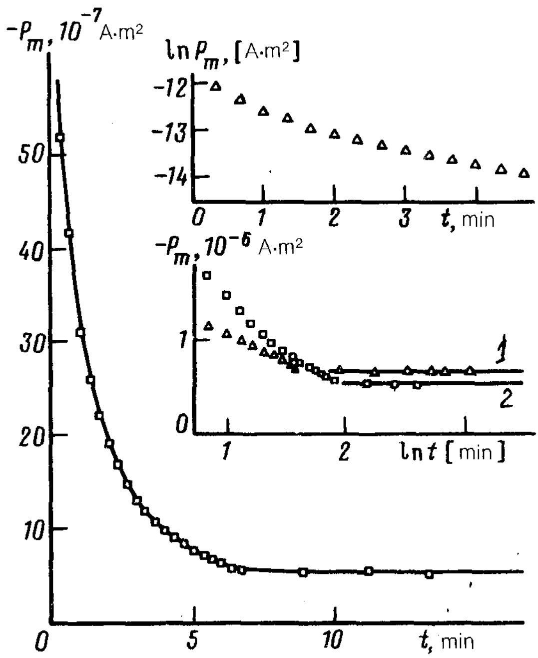

FIG. 1. Time evolution of the magnetic moment of the $Bi_2Sr_2Ca_1Cu_2O_x$ single crystal (ZFC, $T = 77 \pm 0.1$ K, $B = 8.92$ mT, $\mathbf{B} \| \mathbf{c}$). Inset 1 shows the time evolution of the logarithm of the magnetic moment of a $Bi_2Sr_2Ca_1Cu_2O_x$ single crystal at $T = 77$ K with $\mathbf{B} \| \mathbf{c}$ and $B = 8.92$ mT. Inset 2 shows the magnetic moment of a $Bi_2Sr_2Ca_1Cu_2O_x$ single crystal versus the logarithm of the time at $T = 77$ K with $\mathbf{B} \| \mathbf{c}$. 1—$B = 4.23$ mT; 2—$B = 8.92$ mT.

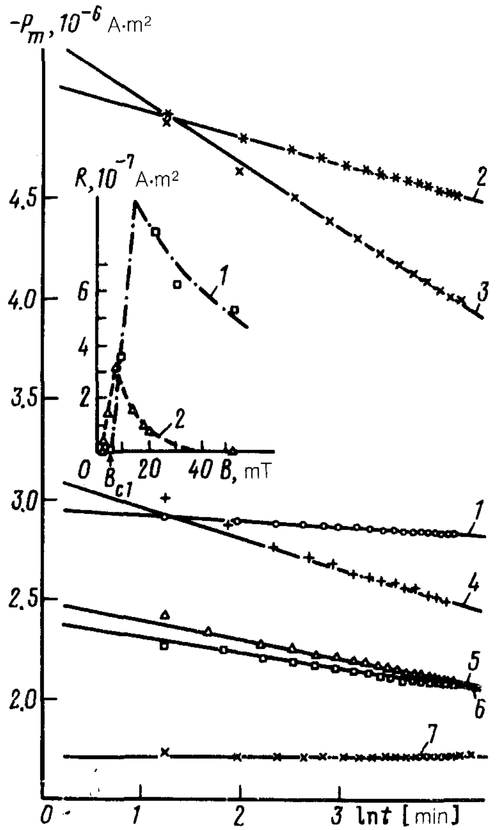

FIG. 2. Magnetic moment of a $Bi_2Sr_2Ca_1Cu_2O_x$ single crystal versus the logarithm of the time (the time is expressed in minutes) for $\mathbf{B}\|\mathbf{c}$ and $T = 50$ K). 1—$B = 2.45$ mT; 2—$B = 4.51$ mT; 3—$B = 7.83$ mT; 4—$B = 13.84$ mT; 5—$B = 18.28$ mT; 6—$B = 20.22$ mT; 7—$B = 52$ mT. The inset shows the relaxation rate R of a $Bi_2Sr_2 Ca_1Cu_2O_x$ single crystal versus the magnetic field B for the case $\mathbf{B}\|\mathbf{c}$. 1—$T = 30$ K; 2—$T = 50$ K.

sumption is supported by our measurements of $P_m(t)$ at lower values of T and B (Fig. 2), for which the time dependence $P_m(t)$ becomes logarithmic at a substantially earlier time (curves 1 and 2 in Fig. 2).

Figure 2 shows the field dependence of the logarithmic relaxation of the moment at a fixed temperature T_0. The field dependence $R(B) = dP_m(B,T_0)/d(\ln t)$ is like the temperature dependence of the rate,[1-4] $R(T) = dP_m(B_0, T)/d(\ln t)$ in that it has a sharp maximum. This maximum shifts down the field scale with increasing T_0. The nonmonotonic behavior $R(T,B)$ is a consequence of a multiplication of a monotonically increasing function (kT) and a monotonically decreasing function $[J_c(T,B)]$, which determine the temperature dependence and field dependence of the relaxation rate[4]:

$$R = (aJ_c/3)(kT/U_0),$$

where J_c is the critical current density, and U_0 is the average activation energy of the vortices. The sharp maximum on the $R(B,T)$ curves can be attributed to the appearance of a topological transition in the distribution of screening currents and thus in the distribution of Abrikosov vortices. The point of the transition, which corresponds to a penetration of the screening currents to the center of the sample, can be calculated for a square plate from the relation[4]

$$B_a - B_{c1} = \frac{6\sqrt{2}\mu_0 M_t}{\pi L^3} \ln(2L/D),$$

where B_a and B_{c1} are the applied field and the first critical field, respectively, M_t is the magnetic moment at the transition point, L is the transverse dimension of the plate, D is its thickness, and the field is directed perpendicular to the plane of the plate. Using the magnetization curves for the corresponding temperatures, we find the values $B_a = 16$ mT and $B_a = 6$ mT for the transition point at $T = 30$ K and $T = 50$ K, respectively. It can be seen from Fig. 2 that these values agree well with the positions of the maxima on the $R(B,T_0)$ curves. An extrapolation of $R(B,T_0)$ to $R = 0$ yields the first critical field B_{c1} (demagnetization is ignored here)[2]: B_{c1} ($T_0 = 30$ K) $= 5.5$ mT, B_{c1} (50 K) $= 1.5$ mT. These values agree well with the values found for B_{c1} from the beginning of the deviation of $P_m(B,T_0)$ from linearity.

To the best of our knowledge, the literature on high-T_c superconductors does not yet have any data on the relaxation of $P_m(t)$ in $Bi_2Sr_2Ca_1Cu_2O_x$ single crystals for the orientation **B**⊥**c**. We accordingly carried out a special study of the dependence $P_m(t)$ for the case **B**⊥**c** also (Fig. 3). Since the first critical field is anomalously low even at $T = 4.2$ K in this orientation, we observe significant fluctuations in the regular distribution of Abrikosov vortices. Only at sufficinetly high fields, $B \gtrsim 52$ mT, does the $P_m(t)$ dependence become smoother (Fig. 3), and at $t > t_0$ and for **B**⊥**c** we also observe a logarithmic relaxation.

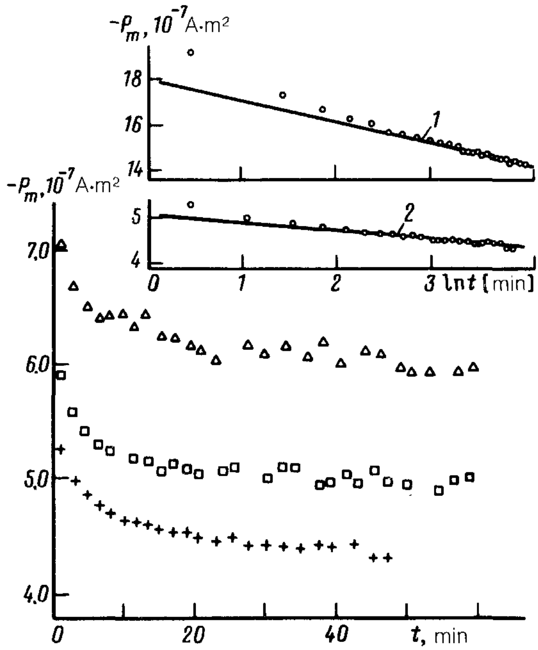

FIG. 3. Time evolution of the magnetic moment of a $Bi_2Sr_2Ca_1Cu_2O_x$ single crystal for **B**⊥**c** and $T = 50$ K. □—$B = 4.63$ mT; △—$B = 10.72$ mT; +—$B = 52$ mT. The inset shows the magnetic moment of a $Bi_2Sr_2Ca_1Cu_2O_x$ single crystal versus ln t for **B**⊥**c** and $B = 52$ mT. 1—$T = 30$ K; 2—$T = 50$ K.

Let us summarize. First, this study has included the first study of the nature of the relaxation of $P_m(t)$ in the initial time interval, in which a rapid relaxation, approximately exponential, is observed. For a superconducting ring a "pure" exponential dependence $P_m(t)$ is found in the approximation of the viscous flow of vortices:

$$L\frac{dJ}{dt}=-R_{fl}(J-J_c)$$

where L is the inductance of the ring, and R_{fl} is the resistance due to the viscous flow of the vortices.

Second, a sharp maximum has been observed on the field dependence of the relaxation rate, $R(B,T_0)$; i.e., the field B affects $R(B,T_0)$, just as the temperature affects $R(B_0,T)$ (Refs. 3 and 4).

Third, in the orientation **B**⊥**c** we have also established that at $t>t_0$ a logarithmic relaxation of $P_m(t)$ begins, if the measurements are carried out in sufficiently strong magnetic fields.

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