Dynamics of the vortex structure in $Bi_2Sr_2CaCu_2O_y$ single crystals

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A qualitative change has been observed in the dynamics of the vortex structure in $Bi_2Sr_2CaCu_2O_8$ single crystals at $T_j \simeq 17 \pm 1$ K. This change is seen as an abrupt order-of-magnitude change in the normalized rate of the logarithmic flux creep, as a sharp change in the temperature dependence of the remanent magnetization $M_R(T)$, and as a change in the dependence of the barrier height U on the density of the nondecaying current. It is found that $U_0 \rightarrow$ const in the limit $T \rightarrow T_c$.

The critical state of the high-T_c superconductors has a weakly pinned vortex structure. As a result, long-term relaxation processes develop to a great extent,[1-3] the critical current is low, the resistance of the samples is of a thermal-activation nature[4] near T_c, etc. These effects are determined by the relative height U_0/T of the potential barrier for flux creep. The height of this barrier in the high-T_c superconductors ($U/T \leqslant 10$) is smaller by more than an order of magnitude than in conventional type-II superconductors. This problem has been the subject of a significant number of experimental[1-4] and theoretical[5-7] studies. The Bi and Tl representatives of the high-T_c family are favorites for experimental study, since they have no twin boundaries (pinning at twin boundaries can complicate the problem seriously). The experimental data presently available, even on $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) single crystals, are afflicted with obvious discrepancies. In particular, the height of the potential barrier for vortex motion estimated from resistance measurements[4] and mechanical measurements[8] at $T \geqslant T_c/2$ is $U_0 > 1000$ K, while low-temperature studies of the magnetization relaxation yield the much lower values[1-3] $U_0 \simeq 80$–150 K. This discrepancy is particularly surprising, since it is at low temperatures that substantial critical current densities are observed. Moreover, an experimental test is required for the results of Refs. 9 and 10, which predict a linear decay $U_0 \propto (T_c - T)$ near T_c. Our purpose in the present study was to learn about the dynamics of the vortex structure in the case $H \| c$ in Bi-2212 single crystals over the wide temperature range from 4.2 K up to $(T_c - T) < 1$ K.

The single crystals with the nominal stoichiometry $Bi_2Sr_2CaCu_2O_8$, which were studied in the present experiments, were grown by the procedure of Ref. 11. They had a transition temperature $T_c \simeq 95$ K and a transition width $\Delta T \simeq 0.5$–1.5 K, as determined from magnetization measurements in weak fields $\leqslant 0.1$ Oe. A study was made of the characteristics of the remanent magnetization M_R in a Bi-2212 single crystal which had been cooled beforehand in a zero field to a point below T_c (zero-field cooling: ZFC) after being put through an extreme (or partial) hysteresis loop. A study was also made of the remanent magnetization M_{TR} in a sample which was cooled in an external field (field cooling: FC). This study was made after the external field was turned off. The time taken to measure the relaxation of the remanent magnetization was 1–15 h, depending on the relative magnitude of the effect. The sample temperature was regulated within $\simeq 50$ mK and within $\simeq 5$ mK at low temperatures and near T_c, respectively, in the course of the experiments. The measurements in the range 4–80 K were carried out with the help of a computer-controlled Yurgens SQUID magnetometer. The high-T_c SQUID magnetometer described elsewhere[12,13] was used for precise measurements near T_c.

According to Bean's model,[14] the value found for the remanent magnetization M_R in an extreme hysteresis loop is proportional to the critical current density j_c in the sample. We found that this dependence is anomalous in nature (Fig. 1) in the Bi-2212 single crystals and can be approximated by

$$M_R(T) \propto \exp(-T/T_0) \qquad (1)$$

with $T_0 \simeq 2$–3 K at 4 K$\leqslant T \leqslant$17 K and $T_0 \simeq 17$–18 K at higher temperatures. A similar behavior has been observed previously[15] in ceramic Bi-2223. The relaxation of the magnetization of these single crystals can be approximated well over the entire tem-

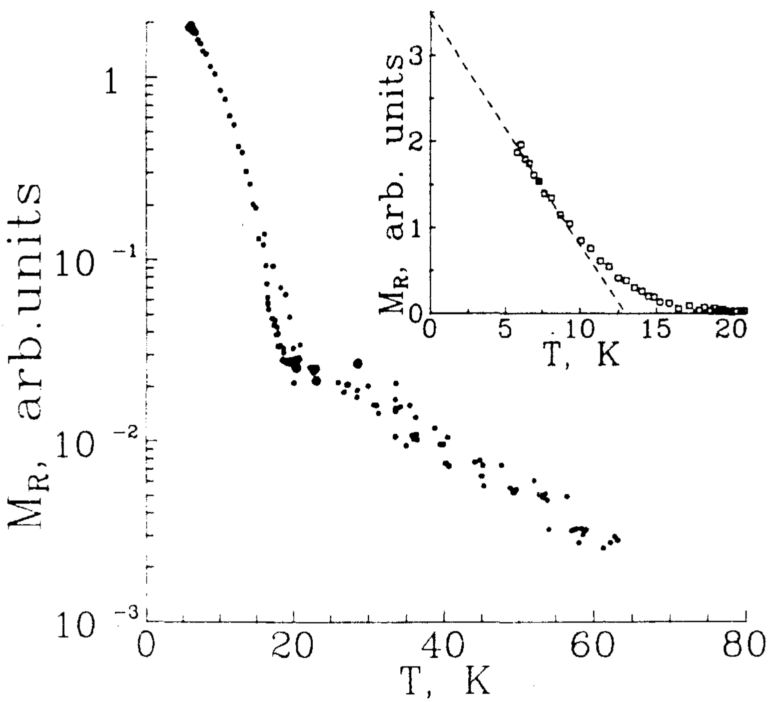

FIG. 1. Typical temperature dependence of the remanent magnetization M_R (T) of a Bi-2212 single crystal. The inset shows an approximation of $M_R(T)$ by (2).

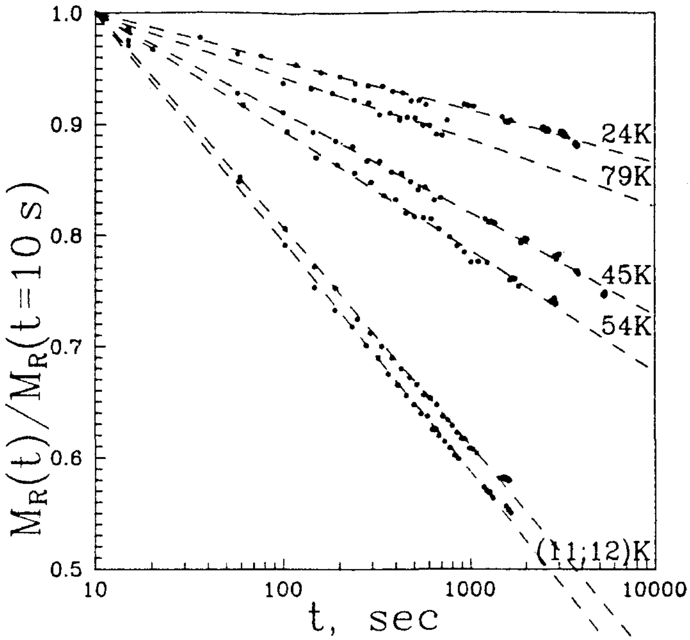

FIG. 2. Typical characteristics of the isothermal relaxation of the normalized magnetization for Bi-2212. Dashed lines—Approximation by $M_R(t)/M_R(t_0) = 1 - S\ln t$.

perature range (except $T \simeq 15$–18 K) by the expression $M = M_0(1 - S\ln t)$ (Fig. 2), which is customarily interpreted in the model of a thermally activated flux creep.[16] According to those ideas, the relaxation of the magnetization $M(t)$ is determined by a characteristic barrier height U_0 for the creep of a vortex structure and is also characterized by a dimensionless relaxation rate $S = T/U_0 = -(1/M_0)\partial M(t)/\partial \ln t$. The sharp decrease in the current with increasing temperature which we observed at $T \ll T_c$ may have stemmed from a creep-induced decrease in the current over the typical duration of the $M_R(T)$ measurements ($t_1 \simeq 1$ min). Working from the model of Ref. 16, and assuming $j_c = \text{const}$, we find

$$j/j_c = 1 - (T/U_0)\ln(t_1/\tau_c); \tag{2}$$

i.e., we would expect a linear decrease in the "magnetic" critical current with the temperature. The low-temperature part of the $M_R(T)$ curves can be approximated by (2), as is illustrated by the inset in Fig. 1. A rigorous analysis[17] shows that the $M_R(T)$ curves reflect primarily the temperature dependence of the logarithmic creep rate, $S(T)$. Figure 3 shows values found for S for seven test crystals over the entire temperature range, by approximating the relaxation dependence of the extreme remanent moment by the law $M_R(t) \propto \ln t$. Comparison of the data on the nature of the temperature dependence of the critical current density (Fig. 1) and the normalized relaxation rate S (Fig. 3) indicates a change in the dynamics of the vortex structure at

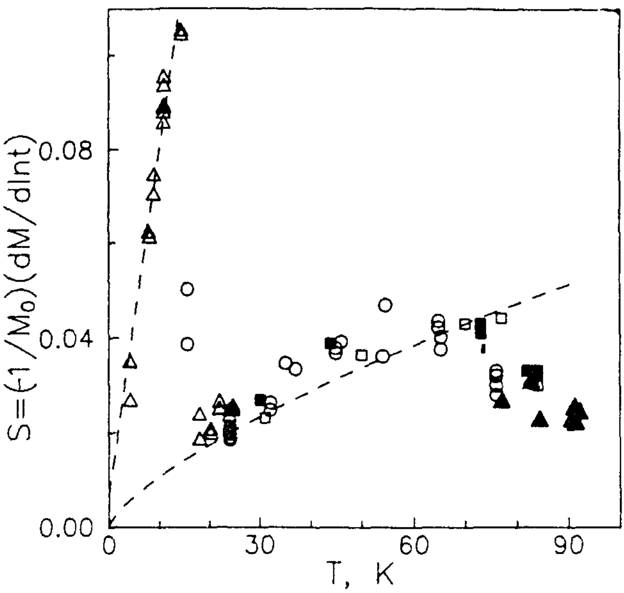

FIG. 3. Normalized relaxation rate of the remanent magnetization for seven test crystals, found through an extrapolation of the experimental relaxation curves with the help of the law $M_R(t) \simeq M_0(1 - S\ln t)$. Dashed lines—Approximation of the experimental temperature dependence $S(T)$ by expression (3) with $\alpha \sim 1$ and $\alpha \simeq 1.5$.

$T = T_j \simeq 17$ K. This change is seen as an abrupt change in the barrier height $U_0 = T/S$, which leads to a weakening of the temperature dependence of the critical current. Under the assumption that there are two types of pinning centers, which differ in depth and concentration, we would conclude that the decrease in the critical current with increasing temperature at $T < T_j$ stems from a thermally activated liberation of vortices from shallow pinning centers, which are responsible for the current at low temperatures. As the temperature is raised, the effectiveness of the pinning by the centers falls off with decreasing value of the ratio U_0/T, from $\simeq 50$ at 4 K to $\simeq 5$ at T_j. Above this temperature, the shallow centers are no longer capable of pinning a vortex, and the pinning is determined exclusively by deep centers. The result is a change in the dependence $j_c(T) \propto M_R(T)$ at $T > T_j$.

For a detailed explanation of this effect, we can invoke the model of Ref. 16, as modified in Ref. 17 for the case of pinning centers of two types: one type with high barriers $U_m = U_1$ and one type with low barriers $U_m = U_2$. According to Ref. 17, the magnetization relaxation rate is given by

$$S = -\partial \ln M / \partial \ln t = \alpha^{-1}(T/U_m)^{1/\alpha}[\ln(t/\tau_0)]^{1/\alpha - 1}, \quad (3)$$

where α is the exponent in the functional dependence of the barrier height on the current density, $U \sim (j/j_c)^{\alpha}$. At low temperatures, $T \ll U_2/\ln(t/\tau_0)$, and at low currents, $j \ll j_c$, expression (3) is valid for $U_m = U_2$. At $T > U_2/\ln(t/\tau_0)$, the shallow pinning centers drop out of the picture, but we can still use (3), replacing U_m by U_1.

In contradiction of earlier experimental data, the model of Ref. 17 predicts a sharp jump in S at the temperature

$$T_j = U_2/\ln(t/\tau_0). \tag{4}$$

To the best of our knowledge, this has been the first observation of a jump on the temperature dependence $S(T)$ (Fig. 3).

According to (3), the temperature dependence $S(T)$ is sensitive to the theoretical parameter α, which in turn depends on the nature of the creep and the dimensionality of the problem.[6,7] Different values of α for the cases of the creep of isolated vortices and for a collective creep of bunches of vortices were predicted in Ref. 6 for the 3D case, under the assumption that the characteristic jump length is short in comparison with the average distance between vortices. The value of α also depends on the relative size of the bunch in comparison with the London penetration depth. An approximation of the experimental $S(T)$ behavior by expression (3) yields an estimate $\alpha \sim 1$ at $T \leqslant T_j$. At high temperatures $T > T_j$, the accuracy of the approximation is poorer, so we can offer no more than a lower estimate $\alpha \simeq 1.5$ (the approximations found with these values of α are shown by the dashed lines in Fig. 3).

To refine the absolute values of α, we studied the isothermal relaxation of the remanent moment from the state of the vortex system corresponding to the original value M_R, but after relaxation for an arbitrarily long time. This method is based on utilizing the difference between the states of the vortex structure reached when different methods are used to create the remanent magnetization: M_R and M_{TR}. In the former case, a critical state is set up in the sample before the field is removed. Although the absolute value of M_R can be anywhere from zero up to the maximum value (which corresponds to the removal of the field after a well-developed critical state has been reached), the relaxation rate S is determined in a first approximation by the same critical current, regardless of how close the hysteresis loop is to the extreme loop. In preparing a "thermoremanent" state M_{TR} we cooled the sample and put it into a superconducting state in a static external field (H_{FC}). This field created and sustained an ordered vortex structure in the sample. The density of this structure was determined by the field strength. In this case the state of the system of vortices before the field was turned off differs only in density from the state created in an extreme hysteresis loop at the given temperature.

While the curves of $M_R(T)$—curves of the remanent magnetization found by putting the sample through a partial hysteresis loop—can be described by a common functional dependence, the curves of $M_{TR}(T)$ are determined by the relative value of H_{FC}. The $M_{TR}(T)$ curve found after cooling the sample in a strong field $H_{FC} > H_{c1}$ agrees with the $M_R(T)$ curve found by putting the sample through an extreme hysteresis loop. At lower densities of the original vortex structure, the changes in $M_{TR}(T)$ are similar to those on the $M_R(T)$ curves found after a prolonged isothermal relaxation.

Regardless of the particular method used to reach the original state (M_R and/or M_{TR}), the magnetization relaxation can be described well by a logarithmic law. We find a strong dependence of the rate S found from the curves of the isothermal relaxation of $M_{TR} \simeq j$. This strong dependence can be approximated by

$$S_{TR} \sim (M_{TR}/M_{TR}^{max})^{\alpha}. \qquad (5)$$

The exponent here is $\alpha = 1.0 \pm 0.1$ at $T \cong 14$ K and reaches $\alpha = 1.8 \pm 0.2$ and 2.8 ± 0.2 at $T \simeq 78$ and $\simeq 30$ K, respectively. The quantity S_R—the relaxation rate of M_R—remains constant, in the zeroth approximation, as the absolute value of M_R is varied by more than an order of magnitude (the dashed line in Fig. 4). There is a satisfactory agreement between the estimates of α found by the two independent methods.

In determining S from (2) we used as M_0 the value M_R ($t_0 = 10$ s). When we take the difference between t_0 and τ_0 into account, we find the following relationship between the measured relaxation rate S and the actual relaxation rate S_G:

$$S_G \simeq S/[1 + S\ln(t_0/\tau_0)]. \qquad (6)$$

It follows from (6) that the customary approach[1-3] of identifying the first measured point with M_0 may lead to not only an overestimate of the absolute value of S but also a distortion of its temperature dependence. Estimates[18] yield $\tau_0 \sim 10^{-2}$–10^{-12} s, but there are also indications[19] that this parameter may have a much larger value. A comparison of the coefficients of a linear extrapolation of $j(T)$ (see the inset

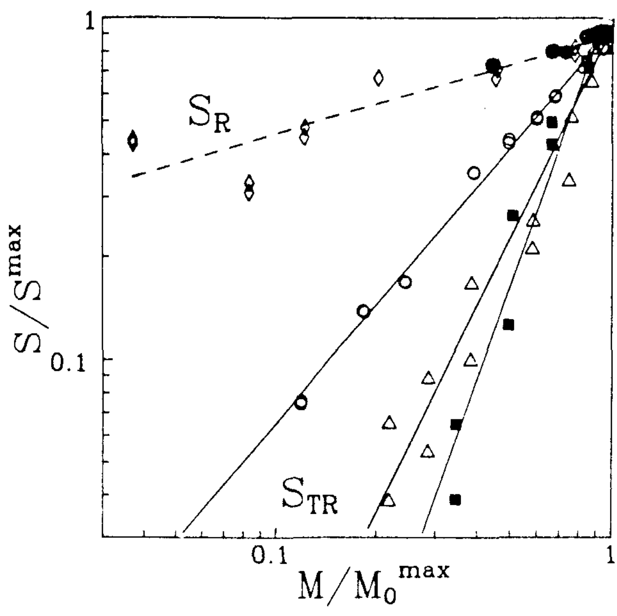

FIG. 4. Normalized relaxation rate S versus the reduced magnetization. ○, □, △—Normalized rates S_{TR} for the isothermal relaxation of M_{TR} at $T \simeq 11$, 30, and 78 K, respectively; ●, ◇—S_R as determined from the M_R relaxation at $T \simeq 11$ K and 30 K, respectively. Also shown here are approximations of the experimental data by the expression $S \propto (M_{TR}^{max}/M_{TR})^{-\alpha}$. Solid lines) Approximations of S_{TR} with $\alpha = 1.05$, 2.8, and 2 for $T \simeq 14$, 30, and 78 K, respectively; dashed line) a much weaker $S_R(M_R)$ dependence ($\alpha \simeq 0.2$).

in Fig. 1) and the result of a substitution into (2) of the experimental data on $S(T)$ [modified in accordance with (6)] yields the estimate $\tau_0 \sim 1$–7 s at $T < T_j$. Since $\tau_0 \sim t_0$, correction (6) is negligible in comparison with the scatter in the experimental points, and it can be ignored (at least at low temperatures). Our experimental results yield an independent estimate of τ_0, from (4); this estimate supports the value given above.

It follows from the results above that the entire body of experimental data can be described satisfactorily in a model of a thermally activated flux creep[16] and in the theory of a collective creep.[6,17] On the other hand, we cannot rule out several other models, which lead to similar results.

a) Under the assumption that a Bi-2212 crystal consists of thin superconducting layers separated by nonsuperconducting interlayers, one might suggest that the increase in H_{c1} and in the critical current with decreasing temperature below T_j stems from the onset of a superconductivity in these layers as a result of a proximity effect [this model was used, in particular, in Ref. 20 to explain the increase in H_{c1} in 1-2-3 (YBCO) at low temperatures]. The temperature T_j thus separates regions in which the vortices have different structures. At $T > T_j$, on the other hand, a vortex consists of a system of "pancakes" (with a core $\sim \xi$ in size), connected by pieces of core-free Josephson vortices in the normal layers. At $T < T_j$, the vortex structure is close to the standard picture of a vortex tube. According to this interpretation, the abrupt increase in $U_0 = T/S$ at $T = T_j$ stems from a change in the vortex structure and from the circumstance that the pancake-shaped vortices are pinned primarily by kinks on the votex lines, which are characterized by incomparably larger values of U_0 (Ref. 22).

b) On the face of it, we cannot rule out the possibility of a melting of the vortex lattice and a transition to a glassy state at $T = T_j$, which would lead to a sharp incrase in U_0.

We have established experimentally that the relaxation of the remanent magnetization in Bi-2212 crystals is described by a logarithmic law $M_0[1 - (T/U)\ln t]$ over the entire temperature range from 4.2 K up to the transition temperature, $(T_c - T) \simeq 1$ K. We have established that the effective barrier height for flux creep is a power-law function of the current density, $U \sim U_0(j_c/j)^{\alpha}$. It has been established experimentally for the first time that we have $U \to \text{const}$ as $T \to T_c$. We have observed a jump on the $S(T)$ curve, as predicted in Ref. 17. The deviations of the initial region ($t < 1000$ s) of the magnetization relaxation curve from a logarithmic law are observed in only a narrow vicinity (≈ 32 K wide) of T_j, but the curves can be approximated logarithmically over longer times. These results indicate that the temperature T_j plays a special role in the dynamics of the vortex structure in Bi-2212 crystals: It separates regions differing in the temperature dependence of the critical current density and differing in the mechanism for the pinning of vortices and/or a structure of vortices. These differences are seen as differences in the values of U_0 and in the values of U_0 and in the values of the exponent α. The slight increase in the effective barrier height as the temperature is raised to T_c may stem from the approximate nature of the very simple model which has been used. [A more rigorous analysis[19] predicts a linear increase in the quantity $T/S2 \sim U + T\ln(t/\tau_0)$ with the temperature.]

Although it is not possible to make a clear choice among the various models, in the absence of detailed theoretical calculations on the dynamics of vortices during relaxation of the remanent relaxation, the most plausible explanations, in our opinion, are those of Refs. 16 and 17 and that in Subsection (a) above. An interference among them is also quite likely.

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