Magnetic relaxation in $Tl_2Ba_2CaCu_2O_y$ single crystals

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A qualitative change in the dynamics of the vortex structure in Tl-2212 single crystals is manifested at $T_j \simeq 23 \pm 1$ K. It is seen on the temperature dependence of the remanent magnetization, $M_R(T)$. It is also seen as an abrupt change, of nearly an order of magnitude, in the normalized logarithmic flux-creep rate S. The latter change is evidence of an increase in the effective height U_0 of the barriers which determine the motion of the vortices. This increase is from ~ 19 meV at $T \leqslant T_j$ to $U_0 \sim 140$ meV at $T_j < T \leqslant 60$ K. No abrupt change in the relaxation rate is observed in $Y_1Ba_2Cu_2O_7$. The $S(T)$ curves for Tl-2212, Bi-2212, and 123-YBCO single crystals are qualitatively similar at $T_j < T$. They go through a maximum at 60–70 K.

The "giant" flux creep exhibited by the high-T_c superconductors continues to hold interest, because of applications and also because of the new physics which underlies this phenomenon. The magnitude of the effect is determined by the relative height (U_0/T) of the potential barrier for flux creep. In the high-T_c superconductors $(U_0/T \leqslant 10)$, this height is an order of magnitude lower than in conventional type-II superconductors. This problem has been the subject of a fair number of experimental[1-4] and theoretical[5-7] studies. However, the experimental data available have been clearly contradictory. In particular, the height of the potential barrier for vortex motion for $Bi_2Sr_2CaCu_2O_8$ (Bi-2212) single crystals has been estimated to be $U_0 > 100$ meV on the basis of resistive[4] and mechanical[8] measurements, while much lower values, $U_0 \simeq 8$–20 MeV, have been found in low-temperature studies of magnetization relaxation.[1-3] We offered an experimental explanation of this discrepancy in Ref. 9. We found a qualitative change in the dynamics of the vortex structure of $Bi_2Sr_2Ca_1Cu_2O_8$ single crystals at $T_j \simeq 17 \pm 1$ K. This change was seen as an abrupt, order-of-magnitude change in the normalized logarithmic flux-creep rate $S = T/U_0 = -(1/M_0)\partial M(t)/\partial \ln t$, a sharp change in the nature of the temperature dependence of the remanent magnetization, $M_R(T)$, and a change in the behavior of the barrier height U_0 as a function of the undamped-current density. According to those results, the pinning of the vortex structure in Bi-2212 at $T \leqslant T_j$ and $T > T_j$ is characterized by barrier heights $U_0 \simeq 11 \pm 1$ meV and 100 ± 10 meV, respectively. It appeared worthwhile to carry out similar studies for other members of the family of high-T_c superconductors. In the present letter we are reporting a study of the dynamics of the vortex structure in the field orientation $H \| c$ in Tl-2212 and 123-YBCO single crystals, over the wide temperature range from 4.2 K up to $T - T_c < 2$ K.

The single crystals with the nominal stoichiometry $Tl_2Ba_2CaCu_2O_y$ (Tl-2212) studied in the present experiments had $T_c \simeq 107$ K and a transition width $\Delta T_c \simeq 2.5$–4.5 K. This width was found from magnetization measurements in weak fields, $\leqslant 0.1$ Oe. The $Y_1Ba_2Cu_3O_7$ (YBCO) single crystal had $T_c \simeq 92$ K and $\Delta T_c \simeq 0.4$ K. We studied the characteristics of the remanent magnetization M_R which arose in the Tl-2212 or YBCO single crystal after it had first been cooled in a zero field (ZFC) below T_c, and after a limiting (or partial) hysteresis loop was traced out (in a field perpendicular to the *ab* plane of the sample). The time taken to measure the relaxation of the remanent magnetization was 1–5 h, varying with the relative magnitude of the effect. The sample temperature was regulated within $\simeq 30$ mK during an experiment. The measurements were carried out on a computer-controlled rf SQUID magnetometer.

The remanent magnetization M_R found in the limiting hysteresis loop is proportional to the critical current density j_c in the sample, according to Bean's model.[10] As was shown in Refs. 11 and 12, if the temperature dependence $M_R(T)$ is determined by flux creep, then at sufficiently low temperatures, at which we can set $j_c = \text{const}$, we have

$$M_R(T)/M_R(0) \sim j(T)/j_c = 1 - (T/U_0)\ln(t_1/\tau_0). \qquad (1)$$

In other words, the magnetization M_R should decrease linearly with increasing temperature. It has been found that the $M_R(T)$ curve for Tl-2212 single crystals (as for Bi-2212 single crystals[9]) can be approximated by expression (1) at low temperatures, as demonstrated by dotted line in Fig. 1. This result is evidence in favor of the very simple model[11] of a thermally activated flux creep, which was used in analyzing these results. A more rigorous analysis[12] shows that the $M_R(T)$ curves primarily reflect the temperature dependence of the logarithmic creep rate $S(T)$. A comparison of the $M_R(T)$ curves shown for Bi-2212, Tl-2212, and YBCO in Fig. 1 supports the immediate assertion that in a zeroth approximation the relaxation processes in the first two of these materials are determined by a similar distribution of potential barriers. The data on the YBCO single crystal, in contrast, cannot be described by simple models based on barriers with one or a few characteristic heights. It becomes necessary to appeal to more-refined models. The curves of $M_R(T)$ for the YBCO single crystal can be approximated over nearly the entire temperature range by

$$M_R(T) \propto \exp(-T/T_0) \qquad (2)$$

with $T_0 \simeq 20$ K (this approximation is also shown in Fig. 1, by a dashed line). The curves of $M_R(T)$ for Tl-2212 can also be approximated in this way in the temperature interval $50 < T < 100$ K.

Over the entire temperature range (except $T \simeq 20$–23 K in the case of Tl-2212), the magnetization relaxation of these single crystals can be approximated well by a law $M = M_0(1 - S\ln t)$ (Fig. 2), which is customarily interpreted on the basis of a model

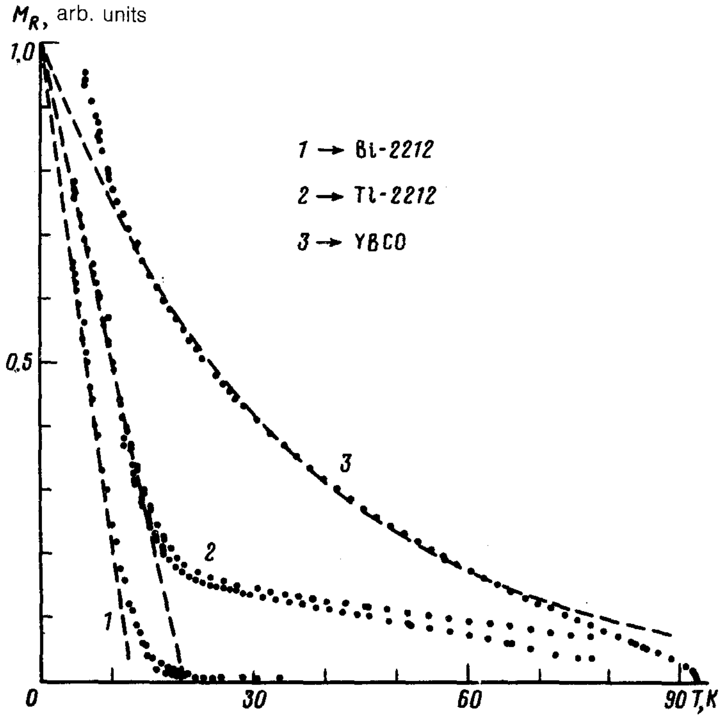

FIG. 1. Typical temperature dependence of the remanent magnetization, $M_R(t)$ of Tl-2212, Bi-2212, and YBCO single crystals (2, 1, and 3). The dashed lines are approximations of curves 1, 2, and 3 by expressions (1) and (2), respectively.

of a thermally activated flux creep.[11] According to this picture, the magnetization relaxation $M(T)$ is determined by some characteristic barrier height U_0 for the creep of the vortex structure and also by a dimensionless relaxation rate $-(1/M_0)\partial M(t)/\partial \ln t$. Figures 3 and 4 show values of the rate S determined for these Tl-2212 and YBCO crystals, respectively, through an approximation of the relaxation curves of the remanent moment by a law $M_R(t) \sim \ln t$. Comparison of the data on the nature of the temperature dependence of the critical current (Fig. 1) and the normalized relaxation rate S (Fig. 3) indicates a change in the dynamics of the vortex structure of Tl-2212 with $T = T_j \simeq 23$ K. This change can be interpreted as an abrupt change at $T = T_j$ in the barrier height $U_0 = T/S$ which determines the creep dynamics of the vortex structure. The change is from $U_0 \simeq 19$ meV to $U_0 \geqslant 130$ meV. The temperature dependence of the critical current is accordingly weakened. 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 magnitude at low tem-

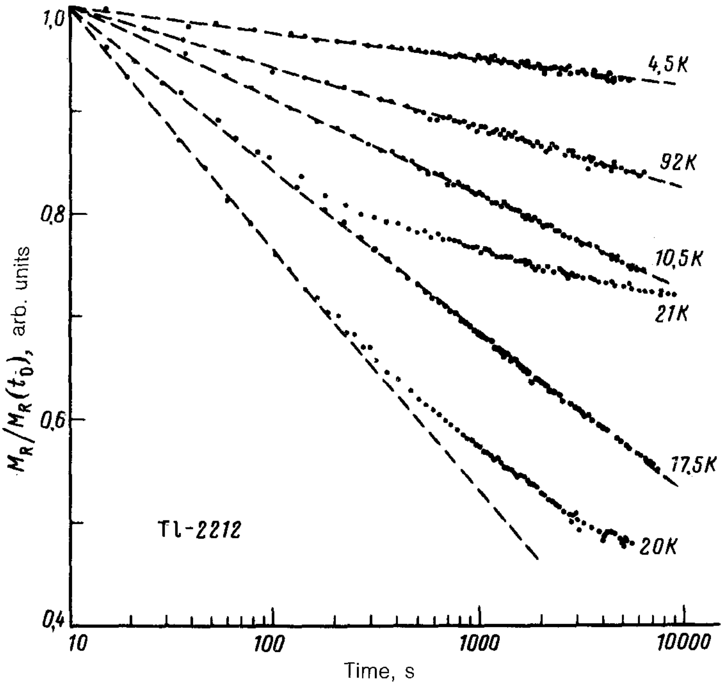

FIG. 2. Typical characteristics of the isothermal relaxation of the normalized magnetization for Tl-2212. The dashed lines are approximations by $M_R(t)/M_R(t_0) = 1 - S\ln t$. The curves for $T \simeq 20$ and 21 K demonstrate the typical behavior of the relaxation processes near T_j.

peratures. As the temperature is raised, the efficiency of the pinning by these centers falls off with decreasing 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 able to pin a vortex, and the pinning is determined exclusively by the deep centers. It is for this reason that there is a change in the $j_c(T) \propto M_R(T)$ dependence at $T > T_j$.

To find a detailed description of this phenomenon, we can use the model of Ref. 11, as modified in Ref. 12 to apply to the case of two types of pinning centers, with high barriers $U_m = U_1$ and low barriers $U_m = U_2$. The magnetization relaxation rate is described by the following expression according to Ref. 12:

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

Here α is the exponent in the 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 low currents $j \ll j_c$, expression (3) is valid at $U_m = U_2$. At $T > U_2/\ln(t/\tau_0)$, the shallow pinning centers drop out of the picture, and we can use expression (3) again, but replacing U_m by U_1. The abrupt jump in $S(T)$ at $T = T_j \simeq 17$ K found in the Tl-2212 single crystals (and also, in

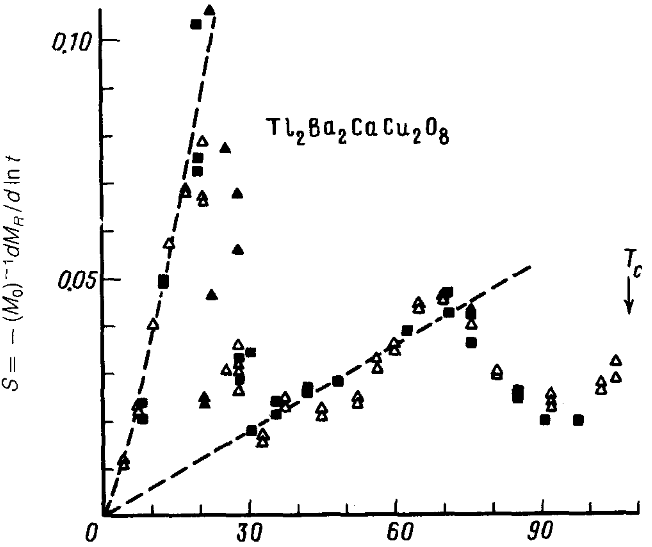

FIG. 3. Normalized relaxation rate of the remanent magnetization of Tl-2212 crystals, found through an extrapolation of the experimental relaxation curves by means of the law $M_R(t) \simeq M_0[1 - S\ln(t/\tau_0)]$. Open symbols—measured in a field making an angle ~15° with the c axis of the crystal; dashed lines—approximation of the results by $S = T/U_0$ for $U_0 \simeq 19$ meV and $U_0 \simeq 140$ meV, respectively.

previous experiments,[9] in Bi-2212) can be identified with the jump in the normalized relaxation rate which is predicted to occur at

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

by the model of Ref. 12.

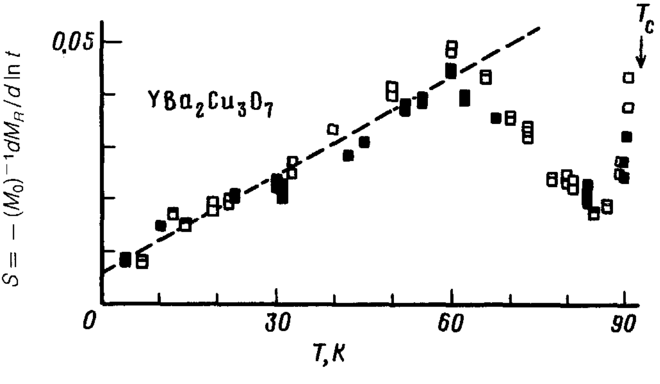

FIG. 4. Normalized relaxation rates of the remanent magnetization of an YBCO crystal found through an extrapolation of the experimental relaxation curves by $M_R(t) \simeq M_0[1 - S\ln(t/\tau_0)]$.

The magnetization relaxation of the Tl-2212 single crystal near T_j can be approximated by two logarithmic laws (the curves for 20 K and 21 K in Fig. 2), which differ in the value of S (these results are shown by the filled triangles in Fig. 3). In this regard, there is a distinction from Bi-2212, whose magnetization relaxation in the corresponding temperature interval is approximated by

$$M(t) \sim \exp[-(t/\tau)^{\beta}] \quad \text{or} \quad M(t) \sim (t/\tau_0)^{\beta}.$$

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] For example, Geshkenbein *et al.*[6] predict different values of α in the case of a creep of isolated vortices and in the case of a collective creep of flux bundles in the 3D case, under the assumption that the characteristic hopping length is small in comparison with the average distance between vortices. The value of α also depends on the relative size of a bundle in comparison with the London depth. A fit of expression (3) to the low-temperature parts of the experimental $S(T)$ curves (Figs. 3 and 4) yields $\alpha \simeq 1.2$ at $T \leqslant T_j$ for Tl-2212 and $\alpha \simeq 2$ for YBCO (for Bi-2212, the value $\alpha \simeq 1$ has been found previously at $T \leqslant T_j$). The complex shape of the $S(T)$ curves, particularly in the case of YBCO (these curves are amenable to a linear approximation with a nonzero value of S at $T = 0$, as shown by the dashed line in Fig. 4) may also have a different explanation, e.g., a so-called quantum flux creep.[13] On the basis of the experimental data available, and at the present state of the theory, it is not possible to make a final choice of model.

From the $S(T)$ curve in Fig. 4, we find an estimate $U_0 \simeq 0.11$ eV of the height of the barrier which determines the magnetization relaxation in a $Y_1Ba_2Cu_3O_7$ single crystal at 20 $K \leqslant T \leqslant 60$ K. This figure is considerably higher than the value (~ 0.02 eV) given in Ref. 1. The difference is probably due to the known acceleration of the relaxation with increasing field and the nonlinearity of the $S(T)$ curve as $T \to 0$ (Fig. 4). In Tl-2212, where we have also found a strong dependence of the relaxation rate on the external field, the barrier height found at $T \leqslant T_j$ ($U_0 \simeq 22$ meV) agrees well with the estimate $U_0 \sim 30$ meV found in Ref. 14 at 10 K. The scale size ($U_0 \simeq 0.14$ eV) of the potential relief, which determines the relaxation of the vortex structure in Tl-2212 at $T > T_j$, agrees qualitatively with corresponding estimates found from resistance measurements.[15] This study of the magnetic relaxation in Tl-2212 single crystals (like the previous study of Bi-2212), thus makes it possible to resolve the contradiction between estimates of the effective height of the potential barriers for the creep of the vortex structure found by different methods.[14,15]

It follows from the results above that the entire set of experimental data found for Tl-2212 and Bi-2212 is described satisfactorily by the model of a thermally activated flux creep[11] and the theory of collective creep.[6,12] This conclusion does not, of course, rule out the possibility that the results could also be interpreted on the basis of other models.[9] The sharp change observed in U_0 may reflect a change in the nature of the creep in these materials. Under the assumption that the scale size of a flux bundle[12] decreases with decreasing temperature, we would naturally associate the low barrier energies with the creep of isolated vortices, which would give way to a collective creep at T_j. The movement of a flux bundle in the case of a fixed weak potential barrier obviously requires the surmounting of a high potential barrier. This conclusion agrees qualitatively with the experimental data. The decrease in the relaxation rate at high temperatures according to Ref. 11 corresponds to an increase in U_0. A qualitative explanation of this effect can be found on the basis of the theory of Refs. 6 and 12, by taking account of the temperature-dependent contributions of the individual (shallow) pinning centers (because of a change in the bundle sizes) and the elastic deformation of the vortex lattice (due to an interaction between different bundles).[16]

The qualitative similarities in the $S(T)$ curves found for the Bi-2212, Tl-2212, and YBCO single crystals at $T > 30$ K—in particular, the maximum in the relaxation rate at $T \simeq 60$–70 K and the monotonic decrease in this rate with a further increase in temperature—seem to imply similarities in the dynamics of the vortex systems in these materials at moderately high temperatures. On the other hand, there are differences in the characteristics of these materials at low temperatures and again in the immediate vicinity of T_c. In the highly anisotropic compounds Tl-2212 and Bi-2212 the creep of the vortex structure at $T \leqslant T_j$ is determined by low barriers, with $U_0 \sim 11$–19 meV, while the nature of the $S(T)$ curves at low temperatures in the YBCO crystals is evidence that the conclusions of the simple theory of Ref. 11 do not apply to this case. While the relaxation rate S of Bi-2212 falls off monotonically as the temperature is increased from $T > 60$ K all the way up to the transition temperature,[9] the Tl-2212 and YBCO crystals (Figs. 3 and 4) exhibit evidence of an increase in the rate S in the immediate vicinity of T_c. This result can be interpreted in the model of Ref. 11 as a corresponding decrease in $U_0 \sim T_c - T$, which has been predicted in several theoretical papers.[17,18]

It is highly likely that the qualitative differences in the behavior of the logarithmic creep rate of the vortex structure as a function of the temperature in the compounds Tl-2212, Bi-2212, and $Y_1Ba_2Cu_3O_7$ are results of the much greater anisotropy of the compounds of the first two families and the circumstance that their crystal lattices are not distorted by twinning (in contrast with YBCO).

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