Time relaxation of the magnetization in a single-domain $TmBa_2Cu_3O_{7-\delta}$ single crystal

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The time relaxation of the residual magnetization RM(t) in a single-domain single crystal of $TmBa_2Cu_3O_{7-\delta}$ is studied. The relaxation rate $r = d\,\mathrm{RM}(t)/d(\ln t)$ has a sharp maximum at T_{max} ($H = 2.8$ kOe) ≈ 15 K. Although the quantity $r(T)$ is strongly anisotropic, its anisotropy is suppressed almost completely when it is normalized to the initial magnetization.

Studies of the magnetic properties of high-temperature superconductors have shown that at $T < T_c$ the magnetization of these superconductors varies logarithmically with time.[1-6] The granular structure of superconducting ceramics and the presence of twinning planes in the single crystals of high-T_c superconductors which have been studied make it appreciably more difficult, however, to interpret the data on the magnetization relaxation. In view of this circumstance, the study of nonequilibrium magnetic properties of high-T_c superconductors in single-crystal samples, in which the twinning planes are virtually absent, would be of interest.

In our experiment we have measured the time relaxation of the residual magnetic moment (RM) of a single-domain single crystal of $TmBa_2Cu_3O_{7-\delta}$ with a transition temperature $T_c = 83$ K. The term "single domain" is used here in the following context: A visual observation of the single crystal in question under a microscope in a reflected polarized light showed that $\sim 75\%$ of its area constitutes a single domain. To measure RM(T), the sample was first cooled in an external field $H_0 > H_{c1}$ to the required temperature, the field was then applied at the time $t = 0$, and the residual

moment was measured. The measurements were carried out for two orientations, $\mathbf{H}_0 \| \mathbf{c}$ and $\mathbf{H}_0 \perp \mathbf{c}$.

The plots of RM vs $\ln t$ are shown in Fig. 1. From the slopes of the linear segments of the $\mathrm{Rm}(\ln t)$ curves we can determine the relaxation rate of the magnetic moment, $R = d(\mathrm{RM})/d \ln t$, and the normalized velocity $r = d(\mathrm{RM}/\mathrm{RM}_0)/d \ln t$, where RM_0 for all the temperatures is given by $\mathrm{RM}(t = 1 \text{ min})$.

The temperature dependences of $R(T)$ for the two values of the field, $H_0 = 2.8$ kOe and 1.3 kOe, are shown in Fig. 2. We see that the relaxation rate is strongly anisotropic. In the $\mathbf{H}_0 \| \mathbf{c}$ orientation the sample can be regarded as a cylinder of radius $a \approx 0.5$ mm, and the relaxation rate R can be determined from the equation[1]

$$R = (aJ_c/3c)(kT/U_0), \tag{1}$$

where J_c is the critical current density, and U_0 is the mean activation energy of the vortices. In the other orientation we can use the equation for a plate of thickness $d \approx 0.1$ mm, with the field directed parallel to its plane[1]:

$$R = (dJ_c/4c)(kT/U_0). \tag{2}$$

It is clear that the anisotropy of the relaxation rate stems primarily from the

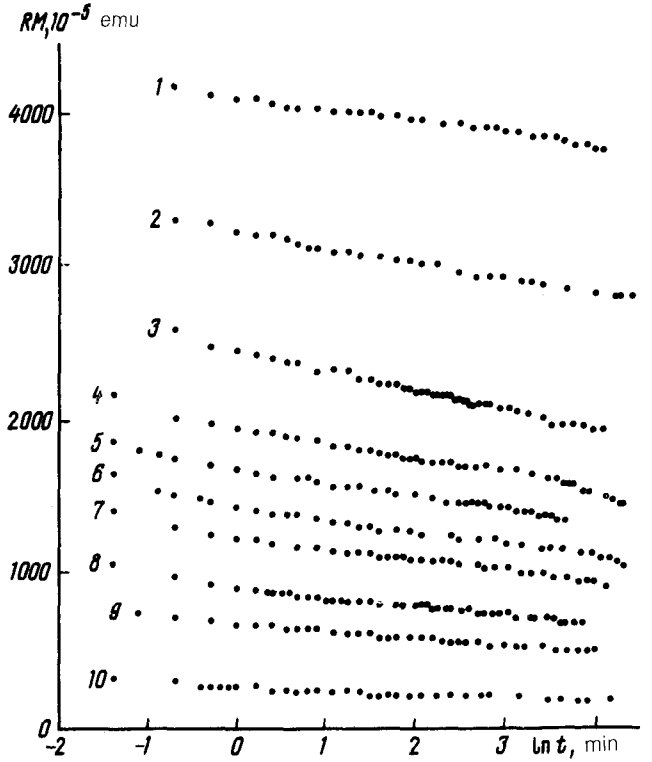

FIG. 1. Time evolution of the residual magnetization (RM) of a $TmBa_2Cu_3O_{7-\delta}$ single crystal, measured after cooling the sample in a magnetic field $H_0 = 2.8$ kOe to various temperatures: 6.5 K (1), 10 K (2), 15 K (3), 18 K (4), 20 K (5), 25 K (6), 30 K (7), 35 K (8), 40 K (9), and 50 K (10) in a field $\mathbf{H}_0 \| \mathbf{c}$.

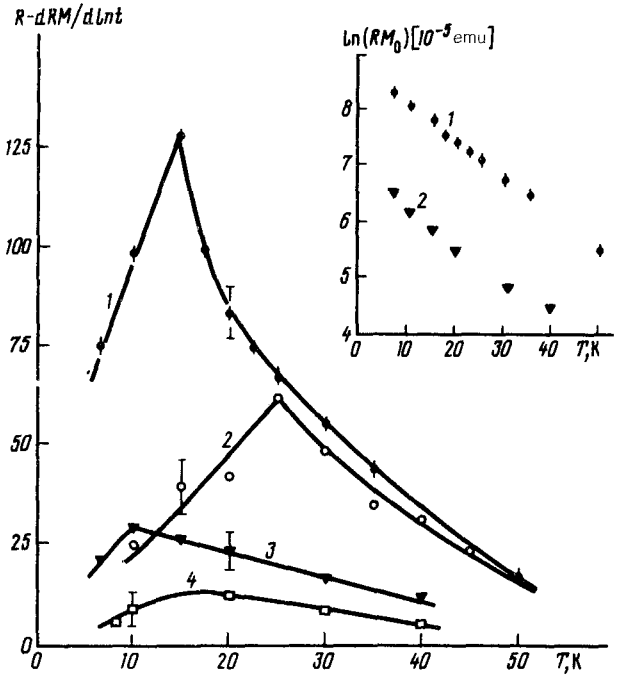

FIG. 2. Temperature dependence of the relaxation rate $R(T)$ of a $TmBa_2Cu_3O_{7-\delta}$ single crystal, measured for various values and various orientations of the external magnetic field **H**: 1—2.8 kOe$\|$**c**; 2—1.3 kOe$\|$**c**; 3—2.8 kOe$\perp$**c**; 4—1.3 kOe$\perp$**c** (RM is given in units of 10^{-5} emu; t is given in min). Inset—Temperature dependence of the initial magnetization, $RM_0 = RM$ ($t = 1$ min) in the coordinates $\ln(RM_0) = f(T)$ for various orientations of the field $H = 2.8$ kOe: 1—**H**$\|$**c**; 2—**H**$\perp$**c**.

anisotropy of the critical current density. In the $\mathbf{H}_0\|\mathbf{c}$ orientation the critical current is greater than in the $\mathbf{H}_0\perp\mathbf{c}$ orientation.

As was shown by Bean,[7] in a field much higher than $\mathbf{H}_{c1}$ the residual magnetic moment is determined by J_c

$$RM_0 \sim \begin{cases} J_c a, & \mathbf{H}\|\mathbf{c} \\ J_c d, & \mathbf{H}\perp\mathbf{c} \end{cases} . \tag{3}$$

In our case the external field is $H_0 \geqslant 1$ kOe. This means that the internal field $H_{int} = H_0/(1-n)$ in each case will be higher than H_{c1} (Ref. 8) if the demagnetizing factor is taken into account ($n_\| \approx 0.8$, $n_\perp \approx 0.1$), and we can use the equations given above. Consequently, the normalized relaxation rate $r = R/RM_0 \sim kT/U_0$ does not explicitly depend on J_c, although it depends explicitly on the parameter U_0, which may be anisotropic. Figure 3 is a plot of $r(T)$ for two orientations $\mathbf{H}_0\|\mathbf{c}$ and $\mathbf{H}_0\perp\mathbf{c}$ and for the magnetic fields $H_0 = 2.8$ kOe and 1.3 kOe. Note that the anisotropy of the normalized relaxation is virtually absent. As one of the possible causes of the suppression of anisotropy one might cite the peculiarity in the behavior of the Abrikosov vortices in strongly anisotropic type II superconductors.[9,10] In the case of 1–2–3 high-T_c superconductors, even a small divergence of the **H** vector from the **c** axis may lead to a pileup of the vortices in the *ab* plane.[9,10] From the viewpoint, a small anisotropy of the normalized relaxation rate may account for the fact that virtually the same vortex configuration is analyzed for $\mathbf{H}\|\mathbf{c}$ and $\mathbf{H}\perp\mathbf{c}$.

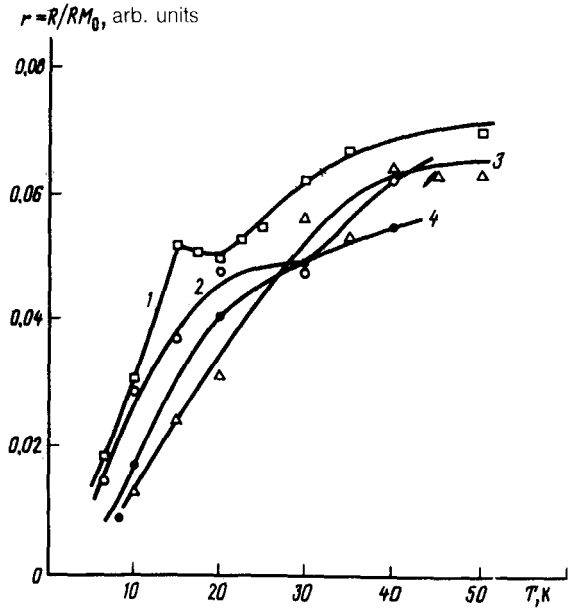

FIG. 3. Temperature dependence of the normalized relaxation rate, $r(T) = R(T)/\mathrm{RM}_0(T)$, of a $TmBa_2Cu_3O_{7-\delta}$ single crystal, measured in various external magnetic fields **H**, with two orientations: 1—2.8 kOe$\|$**c**; 2—1.3 kOe$\|$**c**; 3—2.8 kOe$\perp$**c**; 4—1.3 kOe$\perp$**c**.

The maximum on the $R(T)$ curve was previously found to exist in the Y–Ba–Cu–O (Ref. 2) and Er–Ba–Cu–O (Ref. 3) polycrystals and the Y–Ba–Cu–O film.[4] This observation is in qualitative agreement with the results obtained using a $YBa_2Cu_3O_7$ single crystal[1] and can be explained completely in terms of the theory of flux creep. If, on the other hand, a sufficiently smooth peak was observed in Ref. 1, then our curves cannot be described by such a smooth curve because of a highly pronounced structural feature near $T_{\max}$. We recall that a smooth maximum occurs as a result of multiplying the function kT, which increases linearly with temperature, and the function $J_c(T)$ in Eq. (1), which decreases with temperature.

The temperature of the maximum depends essentially on the field H_0: If $T_{\max} \approx 15$ K in a 2.8-kOe field, the temperature of the maximum will increase to 25 K as the field is lowered to 1.3 kOe. The effect involving an increase in $T_{\max}$ as the external magnetic field H_0 is lowered was also observed in Ref. 2 in Y–Ba–Cu–O polycrystals: $T_{\max}$ (300 Oe) ≈ 50 K, while $T_{\max}$ (10 Oe) ≈ 70 K.

The sharp peak on the temperature dependence of the relaxation rate can be explained, in our view, on the basis of the flux-creep model in the following manner. At high temperatures the critical current $J_c(T)$ flows in the bulk of the sample, while at low temperatures it flows only in the thin surface layer.[2] In other words, there is a certain temperature T^* at which a distinctive topological transition occurs. This transition corresponds to the vanishing of the critical current $J_c(T^*)$ at the center of the sample. The slope change on the curve for the relaxation rate at $T = T^*$ should then correspond to the presence of a structural feature on the temperature dependence $\ln(\mathrm{RM}_0) = f(T)$. Our experimental data (see the inset in Fig. 2) show, however, that

the slope change at $T = T_{max}$ is much less pronounced than that on the $r(T)$ curve. This model also explains the agreement between the relaxation rates at $T > T_{max}$: At $H = 1.3$ kOe and 2.8 kOe the quantity r is determined by J_c in Eq. (1) which is proportional to the magnetization near the saturation point, where M (and hence J_c) does not depend on the external field.

The sharp maximum on the $R(T)$ curve and the decrease in the relaxation rate R with increasing temperature have, in our view, yet another explanation which is based on the assumption that a state of the superconducting-glass type exists in the 1–2–3 single crystals.[2,5,6,11] At low temperatures the relaxation rate is linear with respect to the temperature and is given by Eq. (1), as before. An increase in the temperature due to a possible nonuniform oxygen distribution in the sample causes the sample to undergo a transition to the superconducting-glass state, in which the relaxation rate naturally falls off with temperature[2,6,11] and the peak on the $R(T)$ curve shifts up the temperature scale as the external magnetic field decreases (see Fig. 2). The sharp peak on the $R(T)$ curve may be the analog of an abrupt slope change on the temperature dependence of the magnetic susceptibility of classical spin glasses.

Our data can be qualitatively explained by the flux-creep model and the superconducting-glass model. Further research and quantitative calculations must be carried out before a choice between these two models can be made.

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