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Magnetic relaxation and critical current in an YBaCuO crystal

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We have measured the temperature dependence of magnetic relaxation and critical current in an YBaCuO single crystal. Unusually strong time-logarithmic magnetic relaxation is observed. The relaxation rate increases initially with temperature, peaks at $\simeq 25$ K and slows down at higher temperatures. The results, interpreted with a thermally activated flux model, yield a low-temperature pinning energy $U_0 \simeq 0.02$ eV. This low pinning energy results in an unusually rapid decrease of the critical current as temperature is increased.

Many studies[1] of the new high-temperature T_c ceramic superconductors have reported metastability of the zero-field-cooled (zfc) susceptibility and of the remanent magnetization. In most of these studies the decay of the magnetization is found to be linear with the logarithm of the time. Recently we reported[2] on the first extensive study of magnetic relaxation in an YBaCuO crystal. We observed strong, anisotropic magnetic relaxation of the field-cooled and the zero-field-cooled relaxations along the principal axes of the crystals. The interpretation of the results is based on classic models of thermal activated flux creep processes,[3–6] and takes into account the unusually strong ("giant") relaxation and the low pinning energy which characterize the YBaCuO system. This model offers a natural explanation for a variety of phenomena observed in high-T_c materials: The irreversibility line,[2] the field dependence of the Meissner fraction,[7] the frequency dependence of the ac susceptibility,[8] and the size of the remanent magnetization.[9] (For a recent review of this topic see Ref. 10).

In the present article we show new relaxation data for another crystal.[11] In addition we present critical current data for the same new crystal. We focus here on relaxation of the zfc magnetization for H parallel to the orthorhombic c axis. In most of the temperature regime the relaxation is linear with the logarithm of time. In Ref. 2 we used standard formulas for the temperature dependence of the relaxation rate. Here we extend our analysis to include low-temperature field corrections. The temperature dependence of the relaxation data confirms our previous conclusion[2] of the unusual low pinning energy in these materials. This low pinning energy leads to a natural explanation for the observed strong drop of the critical current as temperature is increased.

Figure 1 exhibits typical time dependencies of several magnetic isotherms, after applying a field $H = 0.6$ kOe parallel to c. The measured magnetic values M are normalized to $|M_0|$, the first measured data point. (This point is taken at $t_0 = 200$ s after field application.) This figure demonstrates that flux is slowly penetrating the sample even at the lowest temperature and that the normalized flux penetration rate increases monotonically with temperature. Note the relative size of the effect, e.g., at 70 K we observe $\simeq 30\%$ change in M during the first hour.

Figure 2 summarizes the 0.6-kOe zfc decays by displaying the absolute relaxation rate $dM/d\ln t$ as a function of temperature. Qualitatively, the rise and fall of the relaxation rates resemble the behavior reported previously[2] though the maximum in this crystal is found at somewhat lower temperature. The low-temperature field dependence of $dM/d\ln t$ for the same crystal is presented in Ref. 12.

Figure 3 displays the critical current J_c for zero field, extracted from hysteresis loops at various temperatures and based on the Bean model of the critical state.[6] In this model simple relations can be derived between the measured critical current and the magnetic remanence M_r at zero field obtained in a hysteresis loop. For a cylinder of radius R, one has

$$J_c = 30 M_r / R. \tag{1}$$

[In Eq. (1) and throughout this paper we use practical units, i.e., Oe, cm, and A/cm^2.]

To interpret the experimental results we use a classical flux creep model.[3–6] This model considers a type II superconductor with a conventional Abrikosov vortex or flux line lattice. Inhomogeneities in the material cause pinning of these vortices in potential valleys of height U_0. Such pinning prevents motion of vortices in the presence of current thus controlling the critical current density J_c. However, thermal activation of flux lines over the potential barrier induces magnetic relaxation and reduction of critical current. The reduction of the measured critical current is given by[5]

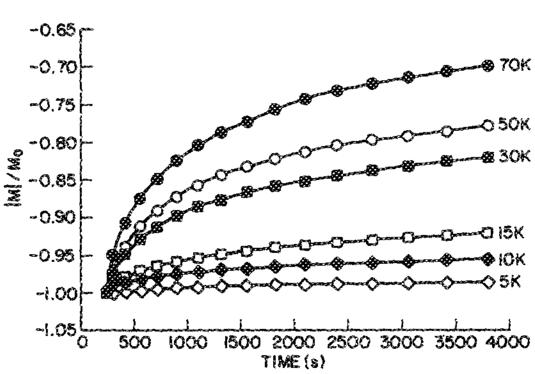

FIG. 1. Decay of the normalized magnetization as a function of time for an YBaCuO crystal. The field $H = 0.6$ kOe, parallel to c, is applied after cooling the sample in zero field.

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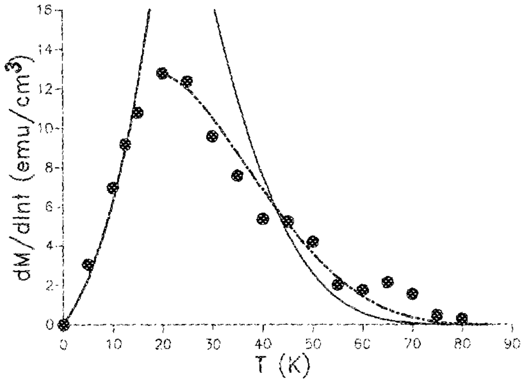

FIG. 2. Relaxtion rate of the zero-field-cooled magnetization as a function of temperature for field parallel to the orthorhombic c axis of an YBaCuO crystal. Solid lines are fits to Eqs. (2) with $m = 6$; broken line is a fit with $m = 4$. See text.

$$J_c = J_{c0}\,[1 - (kT/U_0)\ln(t/t_0)], \tag{2}$$

where J_{c0} is the critical current in the absence of thermal fluctuations, $1/t_0$ is a characteristic attempt frequency of order 10^9 Hz (Ref. 8), and t is a characteristic time window of the experiments, estimated to be 10^3–10^4 s in a typical magnetic hysteresis measurement.

The magnetization relaxation of a cylinder of radius R is derived by substituting Eq. (2) into the original Bean's equations[6] which assume J_c independent of H. We find to lowest order in kT/U_0 and ignoring H_{c1}:

$$\frac{d(4\pi M)}{d\ln t} = \left(\frac{H^2}{H^*}\right)\left(\frac{1-2H}{3H^*}\right)\left(\frac{kT}{U_0}\right), \quad H \ll H^*, \tag{3a}$$

$$\frac{d(4\pi M)}{d\ln t} = \left(\frac{H^*}{3}\right)\left(\frac{kT}{U_0}\right), \quad H \gg H^*, \tag{3b}$$

where $H^* = 4\pi J_{c0}R/10$ is the field for which flux first penetrates entirely through the sample.[8] [In Ref. 12, Eqs. (3a) and (3b) are generalized to include the onset of irreversibility at H_{c1} and the field dependence of J_c. Taking this more realistic approach, we find that $dM/d\ln t$ increases as H^3, faster than the present prediction. This affects our conclusions only slightly; see the discussion below.] Note that H^* decreases with temperature due to the implicit dropoff of J_{c0} to zero at the critical temperature.

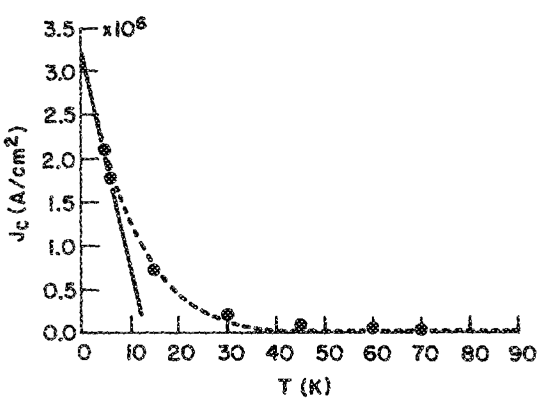

FIG. 3. Critical current densities at zero field deduced from magnetic remanence and the Bean model, as a function of temperature for an YBaCuO single crystal. Solid line is a fit to Eq. (3) in the low-temperature regime. The broken line which describes $J_c = 3.3\times 10^6\ (1-t)^8$ serves here as a guide to the eye.

Equations (3a) and (3b) describe the qualitative trends of Fig. 2 very well. At low temperature with $H \ll H^*$, the relaxation rate increases initially linearly with T as predicted by Eq. (2a). However, as T increases, the term $(1 - 2H/3H^*)$ becomes more significant and $dM/d\ln t$ rises more moderately towards a maximum at a temperature T_{max}. As temperature increases further $H = H^*$ and the temperature dependence of $dM/d\ln t$ crosses over to the behavior predicted by Eq. (2b), namely that the drop in J_{c0} (or, equivalently, in H^*) dominates the fall of $dM/d\ln t$. (U_0 also drops with temperature but usually more weakly.[2])

For a more quantitative analysis of the data we apparently need some knowledge of the critical current densities for this crystal. In conventional superconductors the critical current is usually described by $J_c = J_c(0)(1-t)^n$ where $J_c(0)$ is the critical current at zero temperature, t is the reduced temperature, and n ranges from 1 to 2.5. This is apparently not the case for our crystal (Fig. 3) for which J_c drops very rapidly as temperature is increased, consistent with previous reports.[13] The strong reduction of the measured current densities suggests that the thermal activation term in Eq. (2) is bigger than usual. In conventional superconductors $U_0 = 1$–2 eV; so kT_c/U_0 is of order 10^{-3} and the reduction term in Eq. (2) is a negligible 2%. Clearly, for the high-T_c sample this term is quite important. In part, this is due to higher temperatures. However, an important factor in the magnitude of the reduction term is U_0. To get an initial estimate of U_0 we take the measured J_c at the lowest temperature (5 K) as a good approximation for J_{c0} and substitute in Eq. (3a) $R = 0.024$ cm (half the platelet dimension) and $H = 8500$ Oe (the low-temperature value for the field, corrected for demagnetization). This yields $U_0 \simeq 0.02$ eV which is an order of magnitude smaller than our earlier estimates[2] using Eq. (3b) instead of the more appropriate Eq. (3a). Thus, for YBaCuO $(kT_c/U_0)\ln(t/t_0)$ is of order unity already at $T \simeq 10$ K. In other words, the effect of thermal activated processes is so big that Eq. (2) may serve as a good approximation only at the low-temperature limit. In this limit we may take the initial linear slope of $J_c(T)$ (solid line in Fig. 3) and with the help of Eq. (2) we find $J_{c0}(0) = 3.3\times 10^6$ A/cm^2 and $U_0 = 0.03$ eV in agreement with the value derived from the relaxation data. We are not able, however, to deduce reliable $J_{c0}(T)$ data for Eq. (2). Instead, we suggest a phenomenological model[2]: $J_{c0}/U_0 \propto (1-t)^m$. Substituting this expression into Eq. (3a) yields a maximum at $T_{max} \simeq 25$ K for $m = 6$. (The maximum is pushed to higher temperatures if we choose a $1 - t^2$ dependence for J_{c0}.) Taking $R = 0.024$ cm and $H = 8500$ Oe as above, gives the solid line in the low-temperature part of Fig. 2 with $U_0 \simeq 0.022$ eV at zero temperature. The same parameters, substituted in Eq. (3b), give the solid line in the high-temperature regime of Fig. 2. The predicted maximum rate is larger by a factor $\simeq 1.7$ than the observed one. A better description of the high-temperature regime is obtained for $m = 4$ and $U_0 \simeq 0.07$ eV (see the broken line in Fig. 2). Note however that the derivation of Eq. (3b) was based on the assumption that $kT/U_0 \ll 1$—an assumption which is apparently invalid for high-T_c materials at high temperatures. Corrections to Eq. (3b), based on the predicted crossover[14] in the behavior of J_c, will be considered elsewhere. For the purpose of this paper we take the low-temperature data as the basis for our determination of U_0. As mentioned above, a more realistic model should consider the field dependence of J_c and the onset of irreversibility at H_{c1}. These corrections yield a cubic rise of $dM/d \ln t$ with field[12] but do not alter the value of U_0 by more than a factor of 2. Considering the simplicity of the present approach the fit in Fig. 2 seems satisfactory.

While a different reported temperature dependence of J_c may reflect different pinning mechanisms and different values of U_0, the values appear to remain within an order of magnitude of the small value we report here. This result can be understood[2,15] as a direct consequence of the small coherence length in the new high-T_c materials. Anderson and Kim[3] have suggested that U_0 should scale as $H_c^2\xi^3/8\pi$, where H_c is the thermodynamic critical field and ξ is the superconducting coherence length. For conventional type II materials this usually comes out to several eV, in agreement with earlier measurements[4,5] of U_0. The value $U_0 \simeq 0.02$ eV for YBaCuO is also consistent with this formula, taking $\xi^3 = \xi_{ab}^2 \xi_c$ and considering the range of parameters quoted in literature.[16]

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