Flux Creep in the Critical State of a High-Temperature Superconductor

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We have measured the field and temperature dependences of the logarithmic flux-creep relaxation in an oriented-grain sample of Y-Ba-Cu-O in the critical state. The data indicate that the effective activation energy U_0 increases continuously with increasing T between 6 and 30 K, and that $U_0(T)$ tends to increase rather than decrease with increasing applied field. These results are compared to predictions of the thermally activated flux-creep model.

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One of the remarkable features of the high-T_c superconductors is the fast relaxation of the magnetization.[1] After it was shown that relaxation occurred in single crystals[2] as well as in ceramic samples these effects have generally been ascribed to thermally activated flux motion as observed in conventional superconductors.[3,4] The well-established explanation of this behavior is in terms of flux-gradient-driven movements of bundles of flux lines over pinning barriers.[5] For activation energies U_0 strong compared to kT this model leads to logarithmic decays as observed experimentally. In the critical state[4] at temperature T and under field B the relaxation rate $S=dM/d\ln t$ is expected to be proportional to J_cT/U_0, where J_c is the critical current. J_c itself should be proportional to U_0/BVX, where VX is the product of the activation volume V by the pinning length X. For a given sample geometry, such as a sphere or a plate, the sample magnetization is proportional to J_c.[6]

Related to the decay is the onset of reversible behavior in field at temperatures below T_c. This is an important effect as the superconductor can only support nondissipative currents when the pinning is effective. The form of the irreversible-to-reversible crossover was discussed by Yeshurun and Malozemoff[2] who postulated that the activation energy is proportional to $1/B$. The results for the flux-flow-regime resistivity appear to be convincingly explained in this way.[7]

Relaxation data have been reported on ceramic, thin-film, and single-crystal samples[2,8,9] and have been analyzed by Hagen and Griessen[10] in terms of a parallel decay model where different regions of the sample have different effective pinning strengths. Using this model, a distribution of activation energies is obtained from the experimental decay rates.

We have measured the relaxation as a function of field and temperature in a grain-aligned sample of Y-Ba-Cu-O. We find that the form of the temperature dependence of the relaxation rate S in the critical state[6] is quite different from results obtained in low-field experiments. If the relaxation is parametrized using the standard flux-creep model, for our range of temperatures (6 to 30 K) U_0 increases regularly with T and tends to *increase* rather than decrease with increasing applied field. We discuss these results using the thermally activated flux-creep model.

The sample consisted of Y-Ba-Cu-O monocrystalline grains of dimension of about 50 μm which had been aligned in epoxy under a field of 8 T. The rocking curve indicated alignment of the c axes to within about 1°. The parent material had a sharp transition near 91 K and magnetic data on the sample itself were in agreement with this. This form of sample has the advantage of a field orientation which is well defined with respect to the crystal axes and suffers less from complications associated with incomplete flux penetration than would a large single crystal.[11] All measurements reported here were performed on a commercial SQUID magnetometer (Quantum Design) with the sample c axis parallel to the field direction. Over the rather restricted time range we have used (1.5 decades) the results can always be parametrized by a logarithmic decay.

The aim of the experiment was to obtain data on the sample in the critical state, as in the classic experiments of Beasley, Labusch, and Webb[4] on relaxation in a conventional superconductor. First, however, we carried out measurements in a similar manner to those reported by Tuominen, Goldman, and Mecartney;[8] the sample was cooled in 500 G from 100 K to a temperature T where the field was reduced to zero and the magnetization decay observed. The results for $S(T)$ closely resemble those of Refs. 2 and 8, with S increasing proportionally to T at low T to reach a peak just above 20 K (Fig. 1).

For stronger applied fields, possible technical problems arise because of the decay of the field from the superconducting coil itself. As is well known, after the current in a coil is initially installed the field at constant current decays logarithmically, because of flux creep in the windings. Direct measurements with a Hall probe show that the field creep is of the order of 10 G in the first hour after a large change in the nominal field. Even if this decay is weak, the magnetic response of the superconducting sample to a small reduction in field can be strong. In

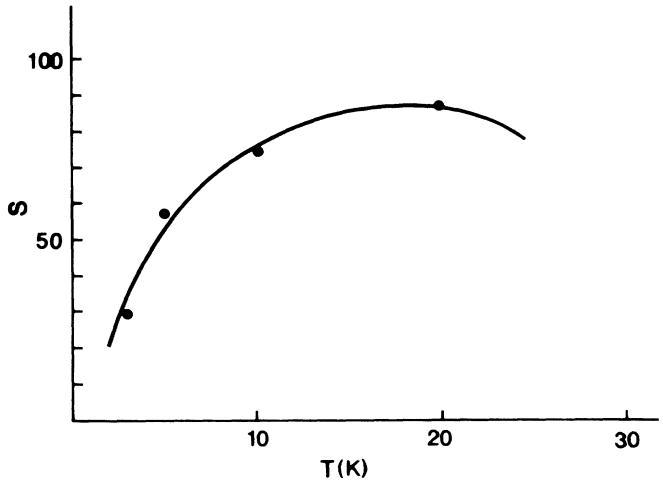

FIG. 1. The logarithmic decay rate $S = dM/d\ln t$ as a function of temperature T after the sample is field cooled in 500 G and the field is reduced to zero. S is taken 10 min after the field is turned off. The units of S are arbitrary but are the same in Figs. 1 and 2.

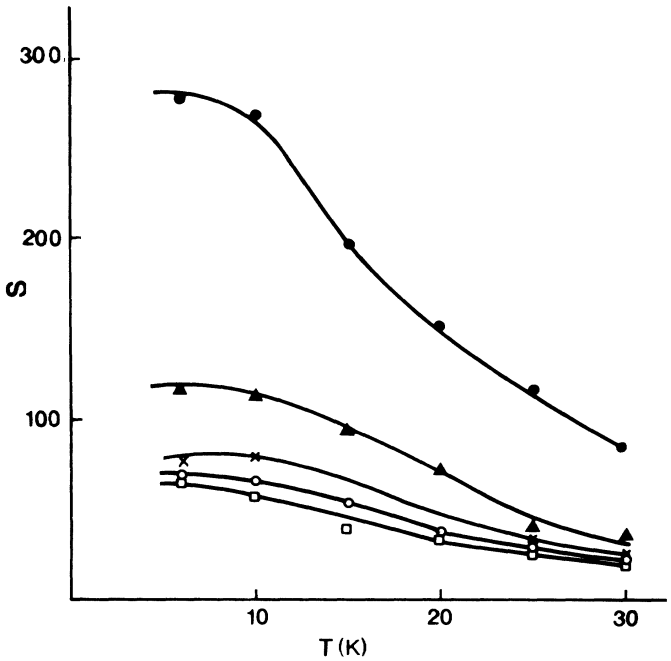

FIG. 2. The logarithmic decay rate S for the sample prepared in the critical state as described in the text. Taking the curves from top to bottom, the field applied during the measurement is 0, 1, 2, 3, and 4 T.

addition, any drop in the applied field tends to take the sample out of the critical state and so dramatically affect its intrinsic relaxation.[4] Thus the decay in an applied field which automatically follows any imposed field change in a superconducting coil can be a serious source of experimental artifacts in relaxation measurements.

In order to avoid this source of error as far as possible we have used step changes in temperature. The sample was cooled to 4.5 K in zero field and the field was then set at the desired value. After a 2-h wait to stabilize the field, the temperature was raised (without overshoot) by steps to 6 K, 10 K, etc., the magnetization decay being observed for about 40 min at each step. This procedure should assure us that the sample is in the true critical state in a quasiconstant field at each measurement. For the zero-field points the same procedure was followed after the field was initially raised to 2 T and reduced to zero again followed by a wait, all at 4.5 K.

Another potential source of error in these experiments is the field inhomogeneity during the sample travel at each measuring point. This effect was minimized by using short travel lengths. Subsequent torque-relaxation experiments which are not subject to these systematic errors gave data consistent with the results reported here.

The results for $S(T)$ in the critical state for different values of the applied field are shown in Fig. 2. The curves are all of the same form and are strikingly different from that of Fig. 1. For the range of temperature down to 6 K, S continues to increase as T drops. If there is an initial low-temperature regime where S drops linearly towards zero, it must be restricted to the domain below 6 K. In Ref. 8, Tuominen, Goldman, and Mecartney report in passing that the maximum of $S(T)$ for their sample was reduced to 5 K for cooling in 5000 G, and strong effects of the applied field on S have been reported.[11,12] Stollman *et al.*[13] show $S(T)$ for a thin film which depends on the magnetic history in a similar way to our data.

The same results normalized by the magnetization value taken 10 min after the temperature is stabilized are given in Fig. 3. This relative decay rate shows a very broad plateau in temperature with indications of a drop at the high and low ends of the range we have used. The relative decay rate drops slowly with increasing applied field. As M is proportional to J_c in the critical-state model, the data in Fig. 3 can be taken to represent S/J_c.

The difference between the curves of Figs. 1 and 2 shows that the decay rates observed after a small field is applied or removed (data such as those on which the analysis of Ref. 10 was based) are not representative of the relaxation in the critical state. We suspect that the drop in S below 20 K in Fig. 1 occurs because the sample gets further from the critical state as the temperature is lowered. For a complete picture of the critical-state behavior it will be important to have low-temperature data, to which we have no access in the present setup. These may show S tending to a nonzero value at zero temperature. Lensink *et al.*[14] have suggested the possibility of nonthermally activated relaxation. If we use the relations $S \propto J_c T/U_0$ and $J_c \propto U_0/BVX$ from the critical-state flux-creep model,[4] the experimental data indicate that for our range of temperature and field (Fig. 4) (a) U_0 grows with increasing T and is not strongly dependent on applied field (except that in zero field U_0 is significantly smaller) and (b) VX increases strongly with

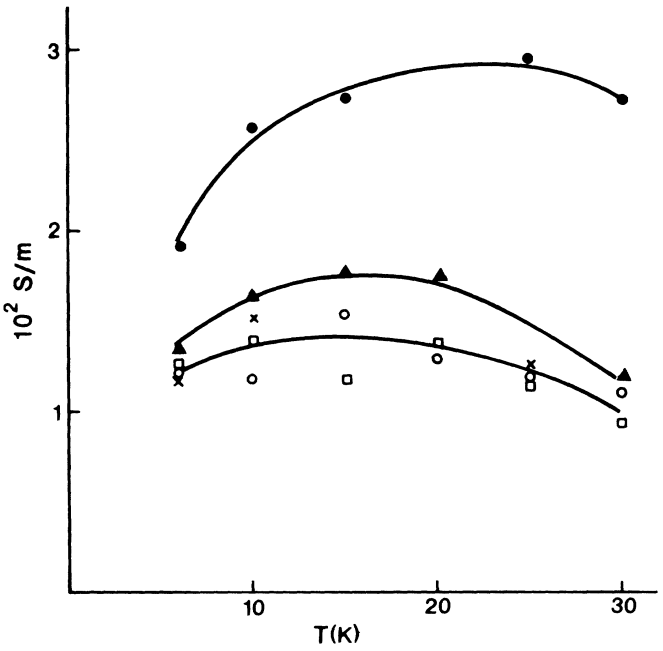

FIG. 3. The normalized decay rate S/M, where S is taken from Fig. 2 and M is the magnetization measured 10 min after the temperature is stabilized. The top curve is for zero applied field, the middle is for $H=1$ T, and the bottom represents $H=2$, 3, and 4 T within the scatter.

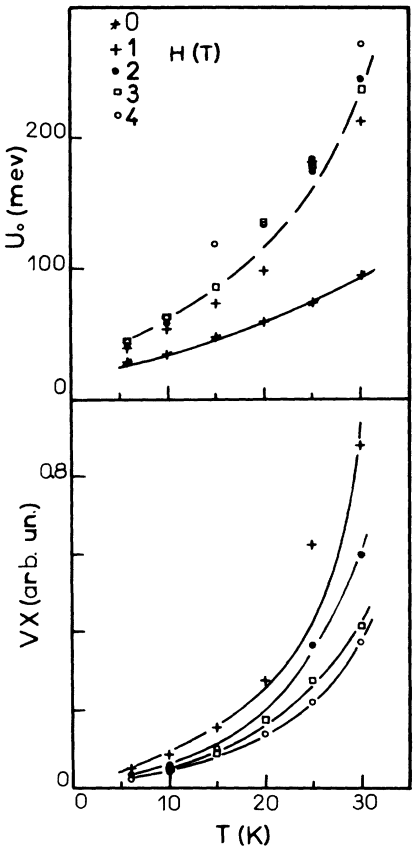

FIG. 4. Temperature dependence of the parameters U_0 and VX derived from the experimental data at different fields. In the top part of the figure the lower curve is for zero applied field and the dashed curve represents fields from 1 to 4 T within the scatter. In the lower part the curves are for fields of 1 to 4 T from top to bottom. The symbols are the same in both parts of the figure.

increasing T, and decreases with increasing field.

The temperature variation of U_0 is similar to that from data taken on a thin film after cycling to high fields,[13] so it appears to be the magnetic state rather than the type of sample that is important in determining the form of $U_0(T)$.

We suggest that it may be possible to interpret these results within the critical-state model without invoking inhomogeneity in the sample. Beasley, Labusch, and Webb[4] give a discussion of the nonlinear relation between the effective barrier height U_0 and the flux gradient, taking as an example a pinning potential $U(\mathbf{r})$ which varies sinusoidally with position in the sample. They use the notation U_p for the activation barrier in absence of flux gradient and X_p as the pinning length. They point out that "the parameters U_0 and VX are not trivially related to the height U_p and width X_p of the actual energy barrier." For their choice of potential $U(\mathbf{r})$, the apparent values of the barrier U_0 and the pinning length X deduced from measurements at finite time t would both vary as $[1-J_c(t)/J_c(0)]^{1/2}$, where $J_c(t)$ is the effective critical current observed at measuring time t and $J_c(0)$ is the critical current in the absence of creep. Suppose we have a fixed experimental time range for measurements at different temperatures. The higher the measuring temperature T the more creep that will already have taken place before measuring time t; $J_c(t)/J_c(0)$ will be close to 1 at low T and will be lower at higher T, so the apparent barrier height U_0 will increase from low values at low T towards U_p when T is high (see Fig. 1 of Ref. 4). This effect should be much more visible in high-temperature superconductors than in conventional superconductors because the creep is greater. The detailed relation between $U_0(T)$ and J_c will depend on the form assumed for $U(\mathbf{r})$ but the qualitative behavior should be general; the observed value of U_0 should only tend to the intrinsic activation potential value U_p at high temperatures, where the effective J_c will be strongly reduced by creep. Other predictions can be made—for instance, S should decrease gradually with time in a given run—but we will not discuss these further here.

The field dependence of U_0 and J_c will only indirectly reflect variations with field of U_p and VX_p. However, from Fig. 4 the trend indicates an increase rather than a decrease in U_0 with increasing field even at the highest temperatures, which leads to the unexpected conclusion that it is unlikely that U_p decreases strongly with increasing applied field as was proposed in Ref. 2.

In summary, we observe logarithmic flux-creep rates for a Y-Ba-Cu-O sample in the critical-state regime to increase progressively as T is lowered down to at least 6 K, and that the apparent barrier height U_0 and pinning length X decrease strongly with decreasing T. We suggest that behavior of this type can be understood with a homogeneous flux-creep model, and arises because the effective activation energy will generally be a nonlinear function of the flux gradient.[4] Because of creep, the parameters J_c and U_0 deduced from experimental data are not trivially related to the intrinsic barrier height and pinning length. We do not find evidence indicating that the intrinsic activation potential U_p decreases strongly with increasing applied field.

After this paper was submitted for publication we learned that similar data had been reported by Xu, Suenaga, Moodenbaugh, and Welch.[15]

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