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Transient moment relaxation in high-temperature superconductors

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The decays of the persistent supercurrent have been derived for several characteristic I-V relationships with few sample-dependent parameters. The results are compared with recent short-time flux-creep data in a short "transient" time window (10^{-4}–10^{2} s). The results favor the I-V characteristics $V \propto \exp[-(I_0/I)^{\mu}]$, as predicted by the collective-pinning and vortex-glass models. However, the μ so obtained is greater than 1, in contrast with that predicted. This may imply a different type of vortex elemental excitation observed in our low-field conditions.

More than 20 years ago, Anderson and Kim[1] pointed out that a persistent supercurrent density I would decay in a manner solely determined by the I-V characteristics of a superconductive sample after a transient period, where V is the voltage drop. Specifically, exponential I-V characteristics lead to a logarithmic decay of I. Later, Beasley *et al.*[2] experimentally demonstrated that this conclusion is true in a time window of 10^2-10^5 s. However, the situation was less certain for a shorter time window. Based on a simplified model calculation as well as a numerical simulation, Hagen and Griessen[3] proposed an interpolated formula for the Anderson-Kim model:

$$M(t)=M(0)\left[1-\frac{kT}{U}\ln\left[1+\frac{t}{t_0}\right]\right],$$

where $M(t)$ is the time-dependent magnetization, U is the effective pinning potential, T is temperature, and t_0 is interpreted as an intrinsic oscillation period of the flux bundles estimated to be $\sim 10^{-10}$ s. Malozemoff and Fisher[4] extended this interpolation to the vortex-glass model and adopted a similar interpretation of t_0. In such models, the short-time decay would be uniquely determined by intrinsic parameters. On the other hand, Sun *et al.*,[5] Griessen,[6] and Feigel'man *et al.*[7] showed that the t_0 could be a sample-dependent macroscopic parameter. Such ambiguity might not make much difference if data in the earlier time window are experimentally inaccessible as is the case with conventional magnetometers like vibrating sample magnetometers and superconductivity quantum interference devices. However, recent technical developments in our group[8] make the high-quality relaxation data available at as early as 10^{-4} s. By deriving analytically the interpolation formulas based on various models and comparing them with our short-time relaxation data, we have shown that the collective-pinning and vortex-glass models describe the flux relaxation of $YBa_2Cu_3O_{7-\delta}$ better than others.

The decay of the persistent current in a superconductor is due to the joule heating $\mathbf{E}\cdot\mathbf{J}$, where $\mathbf{E}$ is the electric field strength and $\mathbf{J}$ is the persistent current density. According to the Bean model, $\mathbf{J}$ should be proportional to the magnetization M of the sample. It is easy to prove (see, for example, Ref. 5) that $\mathbf{E}\sim d\mathbf{J}/dt$. For simplicity, consider an infinitely long, thin-walled superconducting cylinder with uniform current density $\mathbf{J}(t)$. It turns out that $\mathbf{E}=-(4\pi s/c^2 l)(d\mathbf{J};dt)$, where s is the cross section of the cylinder and l is the cross sectional circumference. Assume the I-V (or rather $\mathbf{J}$-$\mathbf{E}$) characteristics $E=f(J)$, where $f(J)$ is some function of J, are known, then from

$$E=f(J)=-\frac{4\pi s}{c^2 l}\frac{dJ}{dt}, \tag{1}$$

one should, in principle, be able to integrate and obtain the time dependence of $J(t)$. As an example, consider the Anderson-Kim model where exponential E-J characteristics $E=a\exp(bJ)$ are suggested. a and b may be treated as constants. By integrating Eq. (1), one obtains

$$\begin{aligned} J(t)&=-\left[\frac{1}{b}\right]\ln\left[e^{-bJ_0}+\left[\frac{c^2abl}{4\pi s}\right]t\right]\\ &=J_0\left[1-\left[\frac{1}{b}\right]\ln\left[1+\frac{t}{t_1}\right]\right], \end{aligned}\tag{2}$$

where

$$J_0=J(t=0),$$

$$t_1=\frac{4\pi s}{c^2abl}e^{-bJ_0}\gg t_0\sim 10^{-10}\text{ s}.$$

The above discussion shows that (1) the decay of the persistent current in a superconductor can be uniquely determined provided the J-E characteristics and initial conditions are given, and more important, (2) the parameter t_1 depends exponentially on J_0, the current density at the very beginning, and thus depends on the history of the experimental conditions. This point can be better explained if we consider the following two cases. For simplicity, we shall consider the J-E characteristics of the Anderson-Kim model $E=a\exp(bJ)$; however, the argument is valid with any J-E characteristics of the general form $E=f(J)$. We shall assume that the relaxation measurement is carried out immediately after a quick linear increase of the external magnetic field with a sweep rate of $dB/dt=\varepsilon$. In the first case, consider ε to be small. Immediately after the magnetic field ramp, the induced electric field along the current path is easily found to be $E = s\varepsilon/cl$. E will induce a persistent current density J_1. If at this moment (at this current density), the relation of J and E already obeys the suggested J-E form $E = a\exp(bJ)$, then one would take $J_0 = J_1$ in Eq. (2) and the decay of J would closely depend on the field ramping rate. In the second case, consider ε to be large enough such that right after the field ramp, J_1 is already in the flux flow region. As a result, the induced current will at first decay exponentially (as any induced current in a normal metal would decay) until a crossover current J_0 is reached. Only after J_0 has been reached does the persistent current decay according to Eq. (2). In this case, the parameter t_1 will be independent of the field ramping speed, although it will still be sample-size dependent. As a result, one has to be careful in comparing the measured data with theoretical predictions. Fortunately, the J-E characteristics inferred from the decay data should be independent of experimental conditions and thus would still be an intrinsic property.

For a solid superconductivity cylinder the situation is more complicated. In this case, the cylinder can be regarded as a superposition of many concentrated cylindrical tubes which decay interactively. However, the numerical simulation of Ref. 3 suggests there is a quasistable field and current distribution. After a transition period, all current would decay in the same way as a thin wall cylinder. In other words, the field $B(r,t)$ can be written as $B_1(r)B_2(t)$ and for a cylinder, $B_1(r)$ would be a solution of the corresponding differential equation. The transient period t_1 of a solid cylinder can thus be assumed to be on the order of that for a cylinder of similar size. As a result, the t_1 in the interpolation formula would still be a macroscopic parameter depending on sample size, and on the field switch speed, if the switching is too slow.

Similarly, for power-law J-E characteristics $E = aJ^n$, the supercurrent in a thin-wall cylinder will decay as

$$J(t) = J_0 \left[1 + \frac{t}{t_1}\right]^{-1/(n+1)} , \tag{3}$$

where $t_1 = (4\pi s)(J_0^{n-1})/[a(n-1)c^2 l]$. For J-E characteristics $E = J^{\mu+1}\exp[-(J_0/J)^{\mu}]$, similar to that predicted by the collective pinning and vortex-glass models[9]

$$J(t) = \frac{J_0}{\{\ln[(t+t_2)/t_1]\}^{1/\mu}} , \tag{4}$$

where $t_1 = (4\pi s/c^2 l)(1/\mu J_0 \mu)$ and $t_2 = t_1 \exp[(J_0/J_1)^{\mu}]$, where J_0 is the current at $t=0$. With the macroscopic parameters $t_1, t_2 \gg t_0$, the interpolation formula is different from that in Ref. 4. For the J-E characteristics $V \propto \exp[-(J_0/J)^{\mu}]$ predicated by the collective-pinning models, the decay law might be slightly different. However, the slow-changing pre-exponential factor $J^{\mu+1}$, used here to facilitate integration, is unlikely to affect our conclusion qualitatively.

To explore the decay in the short-time window, a special pulsed magnetometer was developed, the details of which will be published elsewhere.[8] Essentially it consists of a pulsed magnetic field coil, a Hall probe, and several HP digital voltmeters. Fed with a current pulse (~ 500 A, up to 10 ms width), the pulsed coil produces a pulsed field ~ 1 T with switching-off time of $\leq 10^{-4}$ s. A Hall probe (EHA-921 F.W. Bell Inc.) was used to measure the field trapped by the sample. The superconductor sample was glued onto the surface of the probe and mechanically fixed in the center of the field coil. The Hall probe signal and the current pulse were simultaneously measured by two HP-3458A voltmeters. The background thermal emf signal corresponds to a few gauss and drifts only a few percent in a period of a few hours. The induced transient pick-up background signal was measured during a dummy run without a sample. The resulting background signal shows a monotonic, fast switching-off of the pulse field. After 1 ms, the small transient background is already less then 10 G. In contrast, the typical sample signal is more than ten times larger than that. To exclude the possibility of self-heating, the field pulse has been increased up to four times the penetration field H^*. Between $2H^*$ and $4H^*$ the signal remains the same, suggesting that the self-heating effect is negligible. An EG&G 155 vibrating sample magnetometer (VSM) has also been used to check the relaxation of a melt-textured $YBa_2Cu_3O_{7-\delta}$ sample between 10^2 and 10^4 s. The relative moment decay measured by the VSM is consistent with the data obtained by the pulse magnetometer for the same sample within an experimental resolution of 1%. We should further point out that the data so obtained are also consistent with that determined by the pulse-inductance method.[8] Using the pulse magnetometer described above, we are able to measure the relaxation of the trapped field beginning at 3×10^{-4} s with a relative accuracy of $\sim 1\%$.

The samples used for the present investigation were high-quality melt-textured $YBa_2Cu_3O_{7-\delta}$ which had been demonstrated to be essentially weak-link free.[8,10] Typical sample dimensions were $\sim 1\times 1\times 0.5$ mm^3. Measurements were made with the c axis parallel to the pulse field. A typical result is shown in Fig. 1 with the sample in a remanent state at 77 K. We found the data to be described well with a relative deviation of a few percent by

$$M(t) = M(0)\frac{1}{\ln[(t+t_2)/t_1]^{1/\mu}} , \tag{5}$$

where $\mu = 1.8$. The parameters are obtained from a least-squares program setting μ, t_1, t_2, $M(0)$ as free-fitting parameters. Similar decay behavior was observed at other temperatures as displayed in Fig. 2.

The uncertainty of the data fitting is related to the strong correlation between various parameters, especially t_1, t_2, and μ. Both larger t_1 and μ would make the calculated $M(t)$ vs $\ln t$ curve "bend over." Taking the 78-K data as an example, one can choose t_1 to be any value between 10^{-2} and 10^{-7} s, let t_2 and μ be free-fitting parameters and get comparable fitting errors ($\sim$ few percent). Considering the uncertainty of the real J-E characteristics and the experimental resolutions, the fitting error of t_1 is rather large ($\geq 10^2$). However, as an order of mag-

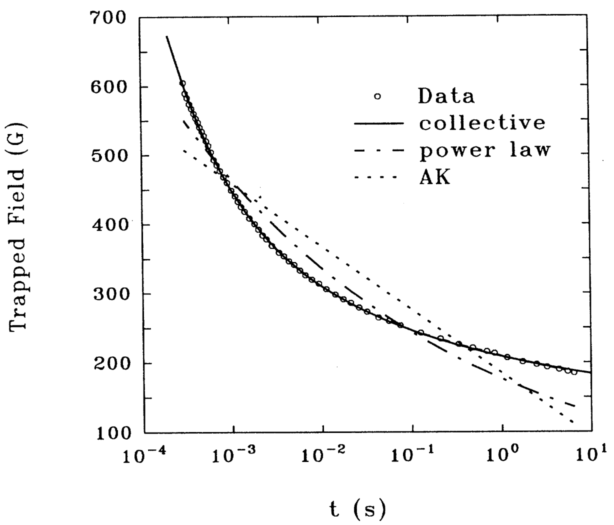

FIG. 1. The decay of the trapped field of a melt-textured Y-based 1:2:3 sample at 77 K and in the remanent state. Circles are experimental data. The various lines are fits to the different models indicated.

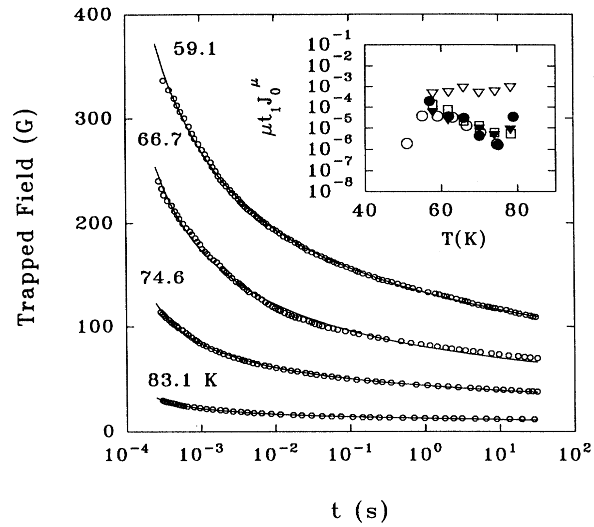

FIG. 2. The decay of the trapped field of a melt-textured Y-based 1:2:3 sample at various temperatures in the remanent state. Solid lines are fits to the collective-pinning model. Inset: The fitting parameter $\mu t_1 I_0^\mu$ vs temperature at field: (○)$H=0$ kG, (●)$H=1$ kG, (▽)$H=2$ kG, (▼)$H=3$ kG, (□)$H=4$ kG.

nitude estimate the fit $\mu t_1 J_0^\mu$ vs T is plotted in the inset of Fig. 2 for several external fields. Although t_1 and J_0^μ both change quickly (μJ^μ change 10^6 from 50 to 80 K) with T, $\mu t_1 J_0^\mu$ are roughly within a factor of 10^2-10^3 for various T and H considering the uncertainty involved. This result might not be in contrast with the formulas derived above.

In spite of the difficulty concerning μ, our data clearly support the collective-pinning and vortex-glass model over the Anderson-Kim model[1,2] and the power-law decay model.[11] Neither the Anderson-Kim model nor the power-law decay model can be fitted satisfactorily, as shown in Fig. 1. That is largely due to the significant "bending over" in $M(t)$ vs $\ln t$ detected.

Such bending is closely related to a large negative curvature in the corresponding $\log(J)$-$\log(E)$ plot.[8] The negative curvature, as pointed out earlier by Koch *et al.*,[12] is a trademark for the proposed vortex-glass model. Our results, therefore, appear to support strongly the collective-pinning and vortex-glass models.

The parameter μ is also relatively insensitive to the fitting procedures. At 78 K, varying t_1 from 10^{-7} to 10^{-1} s, the corresponding μ changes between 1.5 and 5 which, overall, is in conflict with the theoretical prediction $\mu<1$[4,9] and it is in conflict with our high-field relaxation results.[13] According to Fisher *et al.*[14] the value of μ is determined by the elemental vortex excitation mode and $\mu<1$ corresponds to single vortex loop excitation. Our data suggest that at a very low field the vortex-glass excitation mode may have changed. Considering the proposed vortex-lattice melting near H_{c1},[14] our data might suggest some interesting phenomena near H_{c1}.

In summary, we have derived the relaxation behaviors of J for several I-V characteristics associated with various models of flux dynamics. Comparison of these behaviors with the short-time decay data supports the collective-pinning and vortex-glass model. This suggests that the vortex interaction plays a very important role even in a very low field. Our data further imply that the elemental vortex excitation in a low field is different from that in a high field.

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