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Precision measurement of magnetic relaxation in $YBa_2Cu_3O_7$: Power-law versus logarithmic decay

D. A. Brawner and N. P. Ong
Joseph Henry Laboratories of Physics, Princeton University, Princeton, New Jersey 08544

Z. Z. Wang
Lab 2M/Centre National de la Recherche Scientifique, 196 avenue Henri Ravéra, 92220 Bagneux, France
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Using a sensitive, micrometer-sized, scanning Hall probe, we have made precision measurements of the relaxation of the remanent magnetization in single crystal $YBa_2Cu_3O_7$. The technique allows us to determine how the relaxation rate varies over the face of the crystal. At all temperatures from 4.2 to 74 K, the relaxation is observed to follow a *power-law* dependence $B \sim (1+t/\tau)^{-1/\sigma}$, instead of logarithmic behavior. We discuss the origin of τ, and compare the relaxation behavior with recent calculations of vortex diffusion.

One of the most intensively studied properties of the vortex state in the high-temperature superconductors is the relaxation of the magnetization $M(t)$ at fixed temperature T. Because magnetic relaxation involves the diffusion of vortices, the relaxation rate presents a way to estimate the barrier height U impeding motion of vortices.[1-3] Early relaxation measurements on high-temperature superconductors[1,4-6] were compared with an expression derived from the model of Anderson and Kim expression,[2,3] viz.

$$M(t)=M(0)[1-S\ln(t/t_0)]\ , \tag{1}$$

where S equals T/U. However, recent experiments in $YBa_2Cu_3O_{7-\delta}$ reveal that, at low temperatures, $M(t)$ displays positive curvature when plotted against log t (Refs. 7–11). To account for the curvature, "interpolation" formulas of the form

$$M(t)=M(0)/[1+(\mu kT/U)\ln(t/t_0)]^{1/\mu} \tag{2}$$

have been used and related to various models[12] (the exponent $\mu \leq 1$, and t_0 is a microscopic attempt time). Although Eq. (2) provides an improved fit,[7,9,11] a troublesome aspect is that the derived parameters μ, U, and t_0 attain values or display nonmonotonic temperature dependences unexpected from the underlying theory. [S is also found to be nonmonotonic in T if Eq. (1) is adopted.] We note that Eqs. (1) and (2) are based on qualitative arguments, and usually justified by appealing to measurements. Recently, Vinokur, Feigel'man, and Geshkenbein[13] (VFG) solved a one-dimensional model and obtained a power-law relaxation, viz. $B(x,t) \sim (1+t/\tau)^{-1/\sigma}$, instead of logarithmic dependence. In light of these uncertainties, we have reexamined the experimental situation in $YBa_2Cu_3O_7$.

Relaxation experiments using conventional magnetometers are usually restricted to times longer than several 10's of seconds because of instrumental integration times. This precludes comparison of the above equations with measurements at early times. A notable exception is Gao and co-workers[10,11] who use a Hall probe to measure the decay of the magnetization after a 10-ms field pulse is applied. In contrast to the large-area Hall probe used by Gao and co-workers, we have developed a scanning Hall sensor[14] with an active area (2×4 μm^2) that can resolve changes in flux density over micrometer-scale distances. The sensor can be scanned over the a-b face of a crystal at a constant height of ~ 15 μm to record the z component of the local induction $B_z(x,t)$. With a dc probe current of 300 μA, the field resolution is 3×10^{-5} T in a constant background field of 7 T. The results reported here are from a "twinned 90-K" $YBa_2Cu_3O_{7-\delta}$ crystal (of size $\approx 280\times500\times60$ μm^3), with sharp resistive transition at $T_c \approx 91$ K. Less complete, but similar results were obtained in two other crystals. The scan direction (x axis) is parallel to the short side of the a-b face, through the crystal center (inset, Fig. 1). After the sample is zero-field cooled to the operating temperature, the field is increased to 6 T (this is 3 times the field for complete flux penetration at 4.2 K). The maximum remanent magnetization is produced when the field is subsequently ramped to zero (at a constant rate 1.5×10^{-2} T/s). We define the relaxation of $B_z(\mathbf{x},t)$, as recorded by the Hall sensor, to start ($t=0$) when H reaches zero (this assumption is discussed below).

First, we describe how the relaxation rate varies with position over the a-b face at a fixed temperature (4.2 K). With the Hall probe fixed at the center of the crystal, we record the relaxation of the remanence for approximately 1000 s. In Fig. 1 (lower panel) the Hall probe readings at 2 and 400 s are shown as open and solid squares, respectively. The sample is then warmed by ~ 50 K to erase the remanence and the experiment is repeated with the probe in a new position. In addition to these fixed-probe measurements, we display a continuous scan taken roughly 500 s after H is turned off (solid line). The results show that relaxation occurs at all points across the sample, instead of just at the center. Significantly, the *fractional* decrease $\Delta B/B(x,0)$ for a fixed elapsed time, i.e., the relaxation rate, is roughly uniform in a large region of

size 200 μm around the center of the crystal. (As discussed later, analysis of the data shows that the relaxation rate actually has a weak variation, as shown in the upper panel.)

The approximate uniformity of $\Delta B/B(x,0)$ implies[15] that the diffusion coefficient D for vortex creep must increase with J. In the model of VFG,[13] the barrier strength is given by $U(J)=U_0\ln(J_c/J)$, and the diffusion coefficient by $D\sim|J|^{\sigma}$, with $\sigma=U_0/T$. The scaling solution then yields for the normalized remanent induction $b=B(x,t)/B(0,0)$ the form

$$b(x,t)=\phi(x)(1+t/\tau)^{-1/\sigma}\ , \tag{3}$$

where $\phi(x)$ describes the overall shape of the remanence profile. Equation (3) predicts that the quantity $b(x,t)/\phi(x)$ decays with a universal time dependence, which agrees with the observed unformity in $\Delta B/B(x,0)$ described above.

The time dependence in Eq. (3) is not logarithmic, although it is almost linear in log$t$ within the window $\tau\ll t\ll t_{\log}$, where $t_{\log}=\tau\exp(0.2\sigma)$. Figure 2 shows our measurement of $B(0,t)$ at 4.2 K in a semilog plot over 4 decades in time ($1\text{s}<t<2.3\times10^4$ s). Instead of straight-line behavior, deviations are apparent at both short and long times. The data fit very well to the time dependence in Eq. (3) with $\sigma=35.8$ and $\tau=3.9$ s (the upper panel shows that deviations are less than 10 G). Similar data at 15.8 K are also shown. We remark that if S is determined as a fit to Eq. (1) of the data within the window $[\tau,t_{\log}]$, it approaches $1/\sigma$ when $\sigma\gg1$ (we will refer to both S and $1/\sigma$ as the relaxation rate). One can see that, at elevated temperatures, S so determined is a poor approximation because the window shrinks rapidly and moves to shorter time scales. At 40 K, for example, where $\sigma\approx14.5$, $\tau<0.01$ s, and $t_{\log}\sim0.2$ s, curvature is quite apparent in a semilog plot (Fig. 3). Thus, forcing data taken at times longer than $t_{\log}$ to fit Eq. (1) severely underestimates the relaxation rate, especially above 40 K. This may explain why S, determined using Eq. (1), tends to *decrease* above 40 K in earlier work. We have also fitted the 4.2 K data in Fig. 2 with the interpolation formula [Eq. (2)]. For times longer than 10^2 s, the fit to Eq. (2) is comparable to that obtained with Eq. (3). In order to match the data at short times, however, we had to shift the origin of t by changing the denominator in Eq. (2) to $[1+(\mu kT/U)\ln\{(t+t_1)/t_0\}]^{1/\mu}$ (see broken line in Fig. 2). Because there is broad latitude in selecting such a large number of parameters (4) for "optimal" fit, we have not succeeded in determining unambiguously how they change with temperature. We should mention that Xue *et al.* have found that a different form of the interpola-

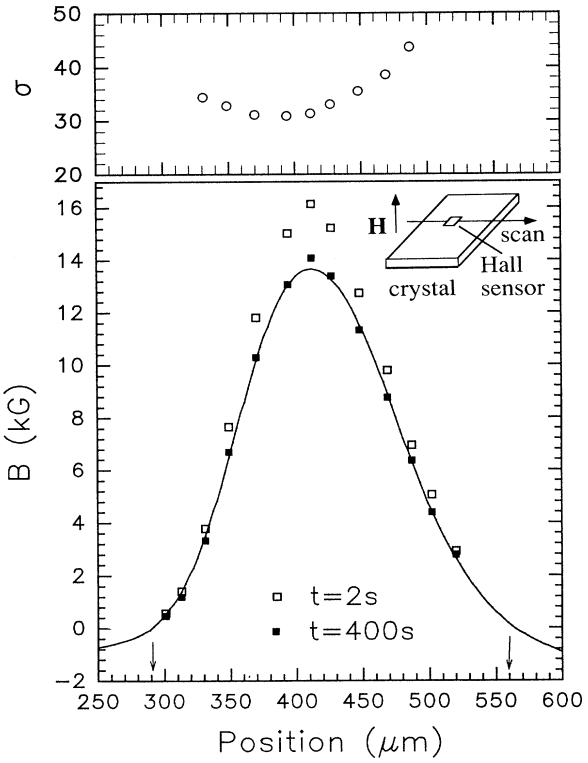

FIG. 1. Lower panel: Local induction $B(\mathbf{x},t)$ measured at different points $\mathbf{x}$ on the a-b face of a crystal of $YBa_2Cu_3O_{7-\delta}$. $B(\mathbf{x},t)$ is measured by a micrometer-sized Hall sensor either fixed or scanned at a height 15 μm above the crystal face (inset). Open (solid) squares indicate data taken 2 s (400 s) after the external field reaches zero ($\mathbf{H}\|\mathbf{c}$). The solid line is a continuous scan taken at $\sim$500 s. Arrows indicate the edges of the sample. Upper panel: σ obtained by fitting each relaxation curve to Eq. (3).

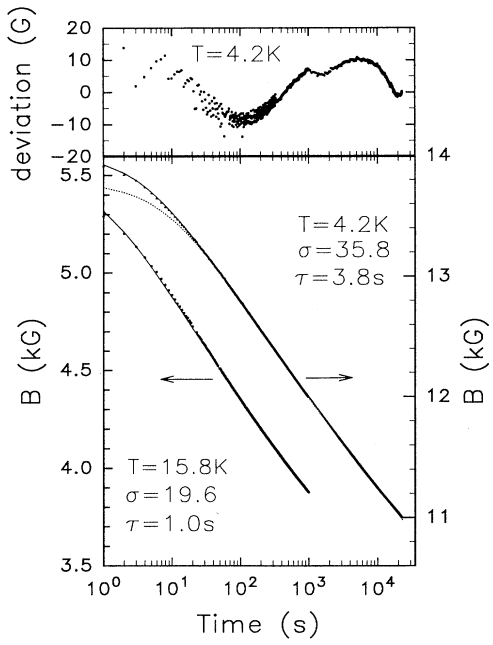

FIG. 2. Lower panel: Time dependence of the relaxation of $B(0,t)$ at the maximum of the remanent peak at 4.2 and 15.8 K. The critical-state profile is prepared by imposing a field of 5 T ($\|\mathbf{c}$) and then reducing it to zero at a rate -0.015 T/s. The fit to $B(0,0)(1+t/\tau)^{-1/\sigma}$ [Eq. (3)] is shown as a solid line. Deviations from the fit at 4.2 K to Eq. (3). Upper panel: The fit to the interpolation formula equation (2) is shown as a broken line (with $\mu=0.25$, $kT/U=9.26\times10^{-3}$, $t_0=5.3\times10^{-11}$ s, and $t_1=8.7$ s).

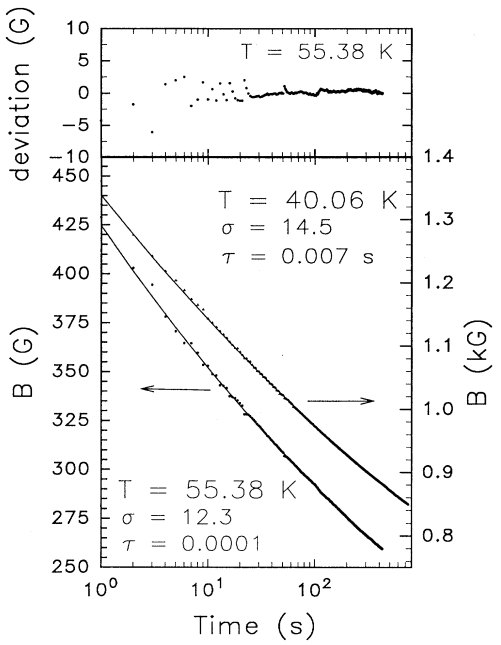

FIG. 3. Lower panel: Relaxation of $B(0,t)$ at 40.06 and 55.38 K fitted to $B(0,0)(1+t/\tau)^{-1/\sigma}$ [Eq. (3)]. Upper panel: Deviations at 55.38 K. Curvature in the semilog plot is apparent at all times scales.

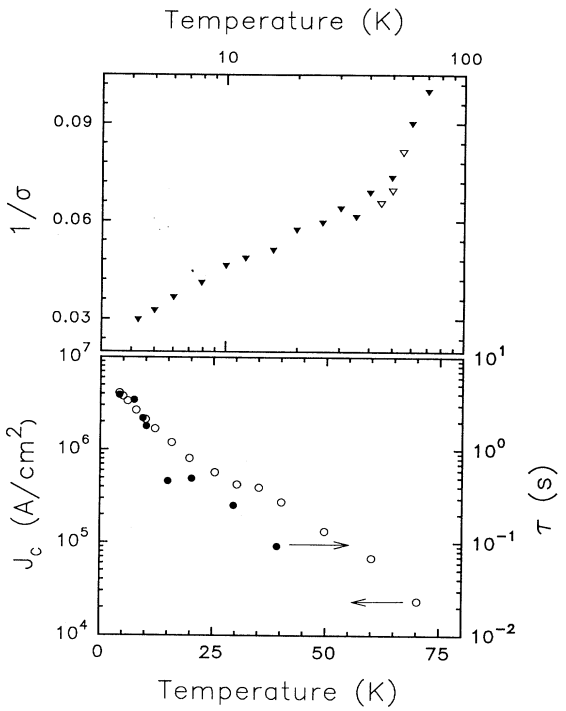

FIG. 4. Upper panel: Temperature dependence of the exponent $1/\sigma$ (solid circles) obtained by fitting the relaxation data to Eq. (3). (Open symbols represent data taken 2 weeks earlier than the closed symbols.) Below 50 K, the exponent $1/\sigma$ decreases roughly as $\log T$ [$1/\sigma \approx 0.018 \ln(T/1\text{ K})$]. Lower panel: Temperature dependence of J_c and τ. Below 30 K, J_c may be fitted to $J_{c0}\exp(-T/8.9\text{ K})$, with $J_{c0}=6.5\times10^6$ A/cm^2, while τ fits wells to $\tau_0\exp(-T/8)$, with $\tau_0=7$ s.

tion formula $M\sim\{\ln[(t+t_2)/t_1]\}^{-1/\mu}$ fits their pulsed data better than a power law. However, they get a value for $\mu=1.8$ that is larger than 1.

The shift of the time origin associated with t_1 has been discussed by several groups.[5,6] Gurevich *et al.*[6] argue that the log$t$ in Eq. (1) should be changed to $\ln(1+t/\tau)$ because of the transient electric field induced by ramping the magnetic field. In their analysis, τ is proportional to $J_c(dH/dt)$, where J_c is the critical-state current density. By varying the ramp rate (at the fixed temperature 20 K), they confirm that τ is inversely proportional to dH/dt. In our experiments, we have observed a similar dependence of τ on the ramp rate at 4.2 K. In addition, we have examined the correlation between τ and J_c. Since we can measure directly the remanence profile at each temperature (Fig. 1, lower panel), we can determine the slope dB/dx and identify it with J_c. Our values for J_c are displayed in Fig. 4 (lower panel), together with the values of τ derived from fitting the relaxation to Eq. (3). At temperatures below 25 K, where τ can be determined most accurately, we find that τ scales as J_c. These two findings confirm that τ is to be identified with the transient electric field, as discussed by Gurevich *et al.* Thus, there is actually only one parameter (σ) that is intrinsic in Eq. (3). We turn next to its temperature dependence.

With the sensor fixed at the center of the *a-b* face, we have determined σ by fitting the relaxation data at each temperature to the power-law equation. At all temperatures, we find that Eq. (3) provides an accurate description of the relaxation. Instead of nonmonotonic variation, we find that $1/\sigma$ increases *monotonically* with temperature (from 0.03 at 4.2 K to 0.1 at 70 K, upper panel of Fig. 4). Thus, our results contradict many earlier reports[4,5,16] that the relaxation rate displays either a broad maximum or a plateau above 50 K. We now compare the temperature dependence of $1/\sigma$ with the VFG model. In the latter, $1/\sigma=T/U_0$ is expected to decrease linearly with T (U_0 is assumed temperature independent). However, our measurements show that the decrease in $1/\sigma$ is much slower. Below 50 K, the temperature dependence of $1/\sigma$ may be approximated by $A\ln(T/T_0)$, with $A=0.018$ and $T_0\approx1.0$ K. (The data do not fit a simple power law.) It would be interesting to see if the logarithmic behavior can be generated in VFG's approach by adopting different assumptions on $U(J)$. Below 1 K, we expect that corrections to the log$T$ dependence will appear, signaling a crossover to a regime in which quantum tunneling effects become observable.

In addition to relaxation of the trapped magnetization in zero field, we have also studied how the magnetization relaxes after H is ramped up and then fixed at a finite value H_0. In such "in-field" experiments, however, a slow drift in the background field H_0 precludes high-precision measurements for times longer than 500 s. Below 20 K, where sufficient accuracy is attainable, the in-field relaxation data produce values of σ and τ in close agreement with the remanence experiments.

Most experiments on magnetic relaxation involve mea-

surements of the relaxation rate *averaged* over the volume of the crystal. Fits to such measurements make sense only if the relaxation rate is uniform. The point-by-point resolution afforded by our Hall probe reveals that this assumption needs to be checked carefully, especially at low temperatures. In Fig. 1 (upper panel), we find that σ is nominally uniform over a significant fraction of the sample around the center, and this uniformity justifies our focus on the relaxation of the remanence peak at the center of the *a-b* face. However, as we move the probe closer to the sample edge, the local value of σ changes dramatically. These changes are closely related to an interesting asymmetry in the remanence profile induced by the field *direction,* which becomes prominent below 30 K (Ref. 17). The existence of these large local fluctuations in σ near the sample edges makes the "average" magnetization (which combines relaxation near the edges with that in the center) a rather ill-defined quantity to study at low temperatures.

In summary, we have studied magnetic relaxation in $YBa_2Cu_3O_{7-\delta}$ with a Hall sensor technique that resolves flux-density changes over micrometer-scale distances. We find that relaxation of the remanent field is well fitted to a power law in t [Eq. (3)]. The exponent $1/\sigma$ increases *monotonically* with temperature. Previous analyses based on Eqs. (1) or (2) (or variants) obtain a nonmonotonic temperature dependence of the relaxation rate. The present work raises the question whether this nonmonotonic variation is intrinsic or stems from excessive number of fitting parameters. In our opinion, the closeness of the fit, using Eq. (3), together with the monotonic temperature dependence of the single intrinsic parameter σ, argues in favor of power-law behavior in magnetic relaxation.

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