Low Temperature Action in $YBa_2Cu_3O_{7-\delta}$

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(Received 1 September 1994)

We have performed a high-resolution study of the temperature dependence of vortex dynamics for $5 \times 10^{-4} < T/T_c < 10^{-2}$ in untwinned single crystals of the high-T_c superconductor, $YBa_2Cu_3O_{7-\delta}$. Through the introduction of a "bithermal" magnetization relaxation technique, we have uncovered a previously unresolved, linear temperature contribution to the semiclassical action for vortex tunneling. Finally, we have compared the weak and strong pinning regimes through heavy ion irradiation of a series of crystals.

PACS numbers: 74.60.Ge, 74.50.+r, 74.72.–h

Even at the very lowest temperatures, it is possible to measure significant relaxation of the magnetization in type II superconductors. In high-T_c superconductors [1–6], where flux flow is formidable, as well as in more traditional superconducting alloys [7,8], a sizable magnetization relaxation rate appears to extrapolate to a finite value at zero temperature. Furthermore, within the 10% scatter typical of these measurements, the relaxation rate is found to be essentially temperature independent. Taken together, these results imply that quantum processes need to be included in any low-temperature description of vortex motion.

We report here the first high-resolution study of temperature dependence in vortex dynamics at very low temperatures. By applying a modified magnetization relaxation technique to untwinned single crystals of $YBa_2Cu_3O_{7-\delta}$ at millikelvin temperatures, we reveal a linear temperature dependence in the Euclidean action for tunneling of vortices.

Theoretical discussions of vortex tunneling [9–13] rely on the instanton approximation. The vortex is envisioned as a semiclassical entity, and its tunneling rate is taken to be proportional to $\exp(-S_E/\hbar)$, where S_E is the action of the classical (extremal) trajectory. Assuming a Bean-like state with near spatially constant bulk shielding currents, the time t derivative of the magnetization M is given by

$$\frac{dM(t)}{dt} = A \exp[-S_E(M(t), T)/\hbar], \tag{1}$$

providing a connection between theory and experiment. Hence, a sufficiently sensitive determination of flux flow characteristics in the quantum limit permits experimental characterization of the semiclassical action, a fundamental, but usually inaccessible, theoretical quantity.

As magnetization relaxation at low T typically shows little deviation from $\ln(t)$ behavior, Eq. (1) can be expanded about some time t_1 giving

$$\frac{dM(t)}{dt} = A \exp[-S_E(M(t_1), T)/\hbar] \times \exp\left(\frac{\partial S_E(M(t), T)}{\partial M}\bigg|_{t=t_1} \frac{\{M(t) - M(t_1)\}}{\hbar} \right). \tag{2}$$

If the magnetization experiment is performed isothermally, then integration of Eq. (2) provides $dM/d[\ln(t)] = -\hbar/(\partial S_E/\partial M)$. If S_E has only a weak power-law dependence on M, then $S_E \sim \hbar M(t=0)/[dM/d(\ln(t))] \sim 10^2\hbar$. Hence, isothermal relaxation measurements with a characteristic scatter of 10% can only bound $|\partial S_E/\partial T| < 10\hbar/\mathrm{K}$ [subject again to the above assumption about $S_E(M)$]. As shown in Fig. 1 for a variety of high-T_c superconductors, the normalized magnetization relaxation rate deviates little below $T = 1$ K from its finite zero-temperature intercept. It is difficult to ascertain whether

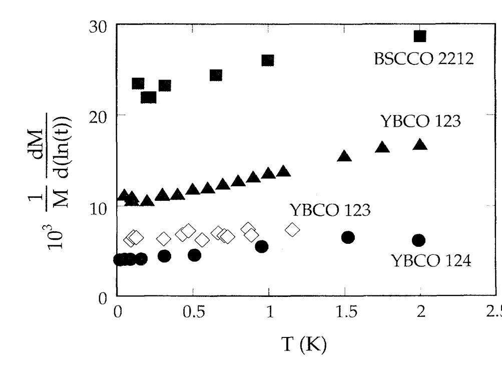

FIG. 1. Normalized magnetization relaxation rate in the low-temperature limit for a number of high-T_c superconductors. Squares (Ref. [5], $H = 5$ kOe, single crystal); triangles (Our work, $H = 20$ kOe, untwinned single crystal); diamonds (Ref. [3], $H = 2$ kOe, single crystal); circles (Ref. [1], $H = 0$, granular bulk).

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or not the relaxation rate truly is temperature independent in the $T \rightarrow 0$ limit.

We now present an analysis of the relaxation rate's response to a single rapid change of the sample temperature during a magnetization relaxation measurement. We show that this "bithermal" relaxation measurement permits a direct and far more sensitive determination of the temperature dependence of the semiclassical action. We illustrate schematically in Fig. 2 the behavior of Eq. (2) for two temperatures, with the hypotheses of a nonzero temperature dependence of $S_E(M,T)$ and a temperature-independent prefactor A. The prefactor A depends mainly on the quantum attempt frequency and, therefore, should have little temperature dependence in the quantum regime. Consider a typical experiment starting at temperature T_i just after magnet ramping has been completed. The system then evolves with time toward equilibrium, as shown. After a time t_w has elapsed, the sample temperature is rapidly changed to T_f. The continuing time evolution of the magnetization is then determined by the middle curve in Fig. 2. Clearly, dM/dt will show a discontinuity at the change in temperature. Quantitatively,

$$\frac{dM/dt\,\big|_{t=t_w,T=T_f}}{dM/dt\,\big|_{t=t_w,T=T_i}} = \exp\{S_E(M(t_w),T_i) - S_E(M(t_w),T_f)\}. \quad (3)$$

The magnitude of the discontinuity in dM/dt will be measurably dependent on t_w only if $\partial S_E/\partial M$ is sufficiently different at the initial and final temperatures; this can be seen by the increasing vertical displacement between the curves in Fig. 2 as the absolute value of magnetization decreases.

The bismuth Hall-probe gaussmeter used in this experiment was photolithographically prepared on a 0.3 mm thick sapphire substrate. The contact pads consisted of 100 nm of Au on top of 10 nm of Cr. The thermally evaporated 500 nm thick bismuth films were granular with a grain size of 0.5 μm and a Hall coefficient approximately 10% of the bulk Bi value. A thin layer of Apiezon N grease separated the 2 μm $\times$ 2 μm active region of the gaussmeter from a large a-b face of the $YBa_2Cu_3O_{7-\delta}$ crystal, placed at least 0.3 mm away from any edge. Details of gaussmeter calibration have been discussed elsewhere [4]. The Hall probe and sample were top loaded into a helium dilution refrigerator and measured by an ac lock-in technique at 16 Hz with a 3 sec time constant and an rms current limited to 0.1 μA to avoid heating. Under typical experimental conditions at $H = 30$ kOe, the device resolution was 2 Oe.

We report complete results on a $1.05 \times 0.50 \times 0.05$ mm^3 $YBa_2Cu_3O_{7-\delta}$ single crystal grown by a conventional flux method in a gold crucible and detwinned by applying uniaxial stress at elevated temperature [14]. Relaxation measurements were prepared by ramping the superconducting solenoid from zero field to the target field at 10 Oe/sec, with H parallel to the crystallographic c axis. The magnet was quickly switched to persistent mode after initial current stabilization, and the resulting magnetization relaxation measured to times as long as 5×10^4 sec.

We plot in Figs. 3(a) and 3(b) isothermal relaxation at $H = 30$ kOe for $T = 0.3$ and 0.1 K. The relaxation rates are $dM/d[\ln(t)] = 44.2 \pm 0.8$ and 43.9 ± 0.6 Oe, respectively. By contrast, we obtain curve 3(c) by applying the bithermal relaxation technique with $T_i = 0.3$ K, $T_f = 0.1$ K, and $t_w = 4 \times 10^3$ sec. The data have a clear kink at t_w, and they are fitted with a single free parameter, $\Delta S_E = S_E(M(t_w),T_f) - S_E(M(t_w),T_i)$ via integration of Eq. (2) with $t_1 = t_w$. We obtain $\Delta S_E = (0.97 \pm 0.25)\hbar$.

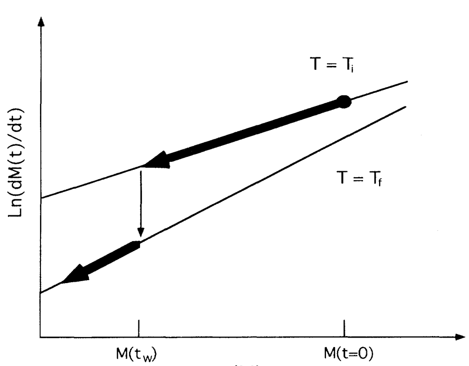

FIG. 2. Schematic of bithermal magnetization M relaxation, changing temperature from T_i to T_f at time t_w. See text for details.

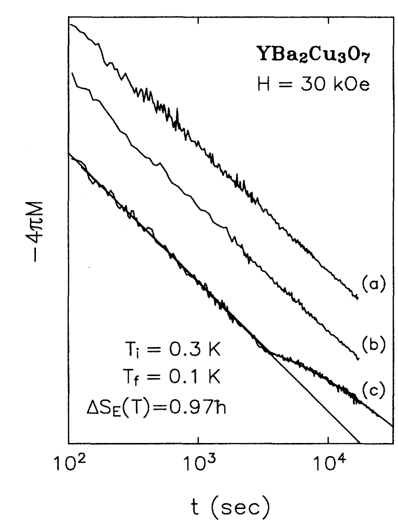

FIG. 3. Magnetization M vs logarithm of time t after ramping to magnetic field $H = 30$ kOe for (a) temperature $T = 0.3$ K, (b) $T = 0.1$ K, and (c) isothermal relaxation at $T = 0.3$ K until 4×10^3 sec, followed by cooling to $T = 0.1$ K and subsequent isothermal relaxation. The curves have been offset for clarity.

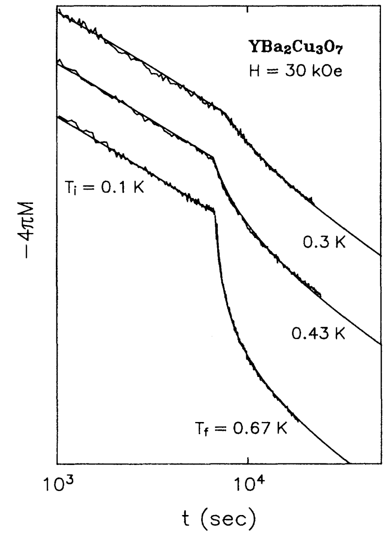

FIG. 4. Bithermal relaxation with heating from initial temperature $T_i = 0.1$ K to three different final temperatures T_f. Solid lines are best fits obtained by the integration of Eq. (2) with one free parameter.

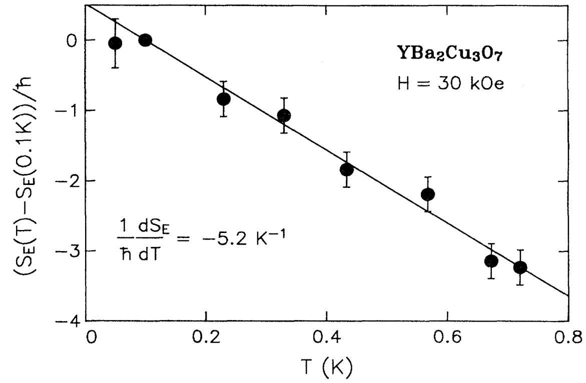

FIG. 5. Temperature T dependence of the Euclidean action S_E determined by the bithermal relaxation method. Line is a linear least squares fit.

We show in Fig. 4 bithermal relaxation data with $T_i = 0.1$ K, but with three different values of T_f. In all three cases, kinks are observed at t_w, and the data are again fitted well by integration of Eq. (2). Note that the sign change in ΔS_E reflects the self-consistency of the data in Figs. 3 and 4; the former were obtained by cooling at t_w and the latter by heating at t_w. These results provide conclusive evidence for a significant, measurable temperature dependence in $S_E(M,T)$ for $YBa_2Cu_3O_{7-\delta}$ well below $T = 1$ K. The existence of such a temperature dependence in the semiclassical action is the central result of this Letter.

We performed bithermal relaxation measurements for a variety of initial and final temperatures at $H = 30$ kOe. We plot in Fig. 5 the fitted temperature dependence of S_E for $0.05 \leq T \leq 0.75$ K. At lower temperatures inductive heating of the refrigerator and sample becomes important, while significant temperature dependence in the magnetization relaxation rate becomes apparent for $T \geq 0.8$ K (see Fig. 1). The errors are dominated by the error in defining t_w because of the finite time necessary to execute the temperature step and uncertainties in $dM/d[\ln(t)]$ (and thus in dS_E/dM) at $T = T_f$. The linear least squares fit has a slope $dS_E/dt = (-5.2 \pm 0.2)\hbar/\mathrm{K}$.

Theoretical studies of the quantum behavior of vortices agree that vortex tunneling is expected to be strongly dependent on dissipation and pinning. Ao and Thouless [12] have included the role of the vortex velocity dependent part of the Magnus force in a recent treatment of vortex tunneling, and *in the limit of low dissipation and weak pinning* predict a linear decrease in $S_E(T)$ with increasing temperature. Their finding is in qualitative agreement with the data shown in Fig. 5 and, together, support arguments that high-T_c superconductors are in the "superclean" limit at low temperatures [11]. Quantitative comparison of experiment of theory, however, is inhibited by the difficulty in defining an appropriate "vortex mass."

The contribution to the tunneling rate from the presence of the Magnus force is expected to decrease as the effects of dissipation and pinning grow [12]. Although it is unclear how to estimate if our samples are sufficiently clean for the theory to apply, we can move to the strongly pinned limit by introducing columnar defects along the c axis through heavy ion irradiation [15]. For this test, we used thin (12 to 20 μm), untwinned as-grown $YBa_2Cu_3O_{7-\delta}$ single crystals. Before the introduction of columnar defects, these samples exhibited a $\Delta S_E(T)$ identical (within error bars) to that of the thicker $YBa_2Cu_3O_{7-\delta}$ single crystal discussed above. After irradiation, a different story emerged. We found no kink at t_w in the bithermal relaxation and, hence, no measurable temperature dependence in the semiclassical action for samples with columnar defect densities B_φ of either 10 or 20 kOe (defined relative to an equivalent vortex density at internal magnetic field B), subject to the constraint that $B/B_\varphi < 1$. When $B \gg B_\varphi$, so that each vortex was no longer pinned by a column, then we moved back to the clean (point defect pinning) limit and recovered the temperature dependence in S_E.

In conclusion, we have developed a modified magnetization relaxation technique which reveals definitively a temperature dependence in the semiclassical action associated with the tunneling of vortices in untwinned single-crystal $YBa_2Cu_3O_{7-\delta}$ at millikelvin temperatures. We find a linear decrease in S_E with increasing temperature on the scale of $5\hbar/\mathrm{K}$ which has not been reported in previous magnetization relaxation experiments on type II superconductors in the $T \to 0$ limit. The introduction of strong pinning through columnar defects suppresses the temperature dependence of the action. Hence, high-T_c superconductors can be used for unique explorations of the interplay of vortex tunneling, pinning, and dissipation because of this sensitivity of the temperature dependence of the action to defect morphology.

The work at the University of Chicago and at Argonne National Laboratory was supported by the National Science Foundation (Grant No. DMR91-20000) through the Science and Technology Center for Superconductivity. G. W. C. acknowledges support from the U.S. Department of Energy, Basic Energy Sciences-Materials Science under Contract No. W-31-109-ENG-38.

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