Self-Heating versus Quantum Creep in Bulk Superconductors

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(Received 23 April 1993)

We have performed simultaneous measurements of magnetic relaxation and the accompanying power dissipation in a number of BiSrCaCuO crystals at temperatures between 0.5 and 4.2 K. The nonvanishing relaxation rate in bulk superconductors at low temperatures, recently discussed as evidence of a quantum tunneling of vortices, is argued to be governed by self-heating of the superconductor by moving vortices.

PACS numbers: 74.60.Ge, 74.25.Bt

The search for macroscopic quantum phenomena has recently been focused on the low-temperature movement of vortices in superconductors. It has been found by a number of groups that the rate by which superconductors relax from their metastable critical state does not vanish when temperature is lowered towards zero, as should be expected for a temperature activated mechanism [1] of vortex movement. Instead, the relaxation rate saturates at a nonzero value below temperatures of the order of 1 K. This phenomenon has been observed in different families of type-II superconductors, including the high-temperature [2–4], heavy-fermion [5], and Chevrel-phase compounds [6]. A number of different explanations have been proposed [6–8], but the idea of quantum tunneling of vortices has turned out to be the favorable one.

An important qualitative limitation of the quantum tunneling in macroscopic systems lies in the relative importance and nature of the coupling to the environment. In macroscopic systems the coupling can be so strong that the motion is highly damped. It has been shown by Caldeira and Leggett [9] that the quantum description, nevertheless, can be extended to macroscopic systems, although the quantum tunneling rate is suppressed by friction to the environment. A theory of vortex tunneling in bulk superconductors in the limit of strong dissipation and for moderate magnetic fields has been developed by Blatter, Geshkenbein, and Vinokur [10,11]. For the oxide superconductors the theory predicts a typical relaxation rate, $(1/M_0)dM/d\ln t$, of the order of 1%. This compares favorably with the experimental findings. The second prediction of the theory, concerning the field dependence of the tunneling rate, is, however, contradicted by the experiments. Instead of the expected suppression of the quantum tunneling with increasing magnetic field, the relaxation rate is found to rise [4].

In all previous discussions the interaction with the environment has been regarded through its effect on the tunneling probability under strictly isothermal conditions. The effect of the moving vortices *on* their environment has been traditionally neglected. However, the relaxation from the metastable state involves a release of magnetic energy, stored within the superconductor. For a bulk sample the dissipated energy causes a local heating, which is not negligible at low temperatures. It is the purpose of this Letter to demonstrate that the effective temperature of the vortex environment in bulk superconductors does not scale down with the experimentally measured temperature of the sample's surface, but saturates at a certain level. Vortex movement at low temperatures is, therefore, determined by an effective local temperature and is, practically, independent of the temperature of the bath.

To clarify the role of the energy dissipation on the low-temperature vortex movement, we have performed simultaneous *in situ* measurements of the magnetic relaxation and the accompanying power dissipation for a number of BiSrCaCuO crystals at temperatures between 0.5 and 4.2 K.

When a hard type-II superconductor relaxes from its metastable critical state, the power P, dissipated by moving vortices, can be estimated as

$$P=\alpha H\frac{dM}{dt}=\int_V J\frac{dB}{dt}dv\,, \tag{1}$$

where H is an applied magnetic field, M the magnetization, α a coefficient depending on the field penetration in the sample, J the local screening current, B the averaged local magnetic induction, and an integration is over the volume in which the screening currents flow. The total power P dissipated in our samples has been measured by monitoring the temperature of the sample surface under quasiadiabatic conditions. The experimental setup is the following. The sample is mounted on a sapphire plate, the latter one equipped with a RuO thermometer and a heater. The vacuum in the cell is about 10^{-6}–10^{-7} torr. A thin manganin wire provides a limited thermal link to the frame. The temperature of the frame is controlled and stabilized within 1 mK. A Hall probe which is thermally coupled to the frame has been installed within 0.1 mm above the sample's surface. The field above the sample surface is measured with an accuracy of ± 0.1 G. The magnetization in this case is linearly proportional to the difference between the field near the surface, measured by the Hall probe, and the applied field, determined by the current flowing through a calibrated superconducting magnet. Since only the relative variation of the mag-

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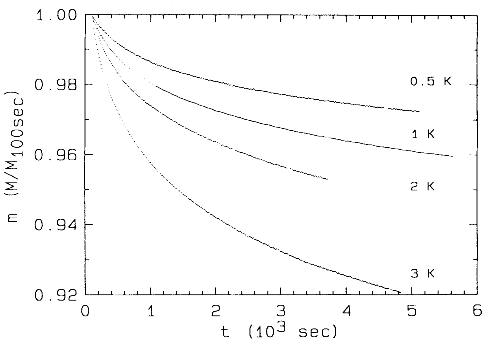

FIG. 1. The time variation of the normalized magnetization of a single-crystalline BiSrCaCuO sample measured in a magnetic field of 1 T at several temperatures.

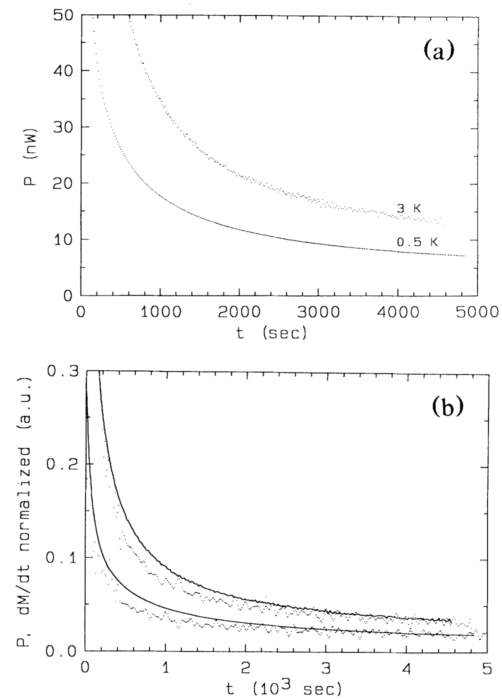

FIG. 2. (a) The time variation of the power dissipated by moving vortices during the relaxation at fields of 1 T at 3 K and at 0.5 K. (b) The time variation of the normalized dissipated power P (solid curves) and the magnetization variation rate dM/dt (points) at fields of 1 T at 3 K (upper pair) and at 0.5 K (lower pair) The curves are normalized at 100 sec after the start of the relaxation. dM/dt is calculated from $M(t)$ data displayed in Fig. 1. The quasioscillations in dM/dt are the artifact of the averaging procedure.

netization is relevant for our discussion, we shall assume the proportionality coefficient to be 1 and shall define the experimentally measured signal as the magnetization of the sample.

In thermodynamic equilibrium, the temperature of the sample T, the dissipated power P, the specific heat of the system C, and K, the thermal conductance to the bath kept at temperature T_0, are connected by

$$C\frac{dT}{dt}=P-K(T-T_0)\,. \qquad (2)$$

The specific heat C and the thermal conduction to the frame, K, of the system have been measured *in situ* by passing a known current pulse through the heater. The dissipated power P is determined by Eq. (2).

In large crystals with dimensions of the order of 1 mm, the critical state (i.e., the field has penetrated in the whole volume of the sample) can be achieved at low temperatures by applying magnetic fields of several tesla. However, for fields above 1.5 T, the magnetic state has been found to become unstable and large flux jumps have been observed [12]. We, therefore, have limited the field range up to 1 T, which implies that the samples are not in the critical state.

The time variation of the normalized magnetization measured in a magnetic field of 1 T at several temperatures is shown in Fig. 1. Since the samples are not in their critical state, the formal definition $(1/M_0)dM/d\ln t$ can be misleading. Moreover, the magnetization does not follow strictly a logarithmic time variation. A qualitative comparison (see Fig. 1) shows that the relaxation rate keeps decreasing down to 0.5 K. However, the normalized relaxation rate (although roughly defined) remains of the order of 1% at 0.5 K and cannot be extrapolated to zero for T approaching zero. This confirms the previously reported results [2–4].

The power dissipated by moving vortices during the relaxation is shown in Fig. 2(a). At 3 K, the dissipated power is higher than at 0.5 K, which is consistent with a higher relaxation rate at 3 K. The self-consistency between the power dissipation P and the rate of the magnetization variation dM/dt is further demonstrated in Fig. 2(b), where we plot both P and dM/dt normalized shortly after the start of the relaxation at 0.5 and 3 K.

The most important result of this experiment is that at temperatures as low as 0.5 K, the power dissipated after thousands of seconds remains on the level of 10 nW. For the sample with linear dimensions of $3\times2\times0.1$ mm, this gives about 1.5 nW/mm^3. When the superconducting sample is in its critical state, the dissipation per unit of volume is expected to be even higher. The dissipated power, being proportional to dM/dt, gradually decreases with time. However, this reduction rate dP/dt is very slow after a few thousand seconds and is of the order of 0.1 pW/mm^3sec at 0.5 K after 5000 sec of the relaxation.

The normalized magnetization variation as a function of time measured at 0.5 K under fields of 0.5 and 1 T is plotted in Fig. 3(a). The relaxation rate is evidently higher for higher magnetic field. This result confirms the previously reported data [4] and contradicts the predictions of the quantum collective creep theory [10]. However, it is consistent with the power dissipated by moving

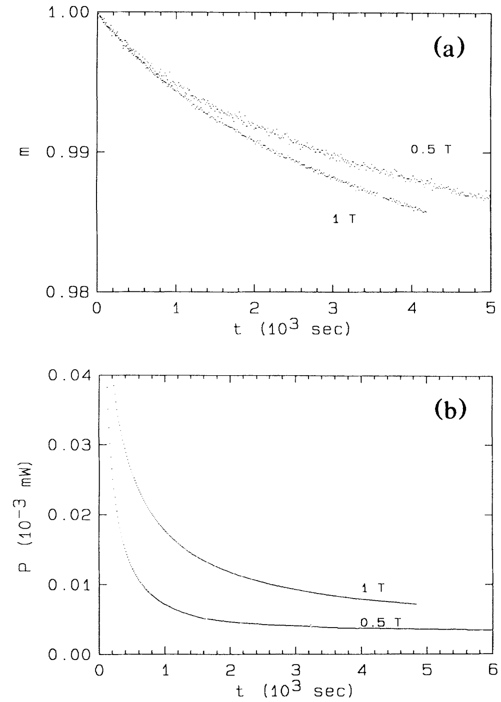

FIG. 3. (a) The normalized magnetization variation as a function of time measured at 0.5 K under fields of 0.5 and 1 T. (b) The power dissipated by moving vortices during the relaxation at 0.5 K under fields of 0.5 and 1 T.

vortices during the relaxation process as shown in Fig. 3(b). The power dissipated in a field of 1 T is about 2 times higher than that in 0.5 T. Following the simple Bean model [13] consideration, the magnetic field penetrates twice deeper inside the sample in 1 T than in 0.5 T. The volume, in which the dissipation takes place, and, therefore, the total dissipated power is approximately doubled.

The concept of quantum creep assumes the existence of a nonzero relaxation rate at zero temperature. The quantum process should dominate the vortex movement up to the temperature at which the temperature activated mechanism will exceed it. Let us assume that the quantum regime is reached at the temperature T^* and that the relaxation rate is constant for all temperatures below it. Assuming that the critical current, and, therefore, the effective screening current is constant in this temperature range, we expect a temperature-independent power dissipation as well. To simplify the picture, let us assume that all this power is released in the center of a sample. In the state of thermodynamic equilibrium, the temperature in the center of the sample is given by

$$T_i = T_s + P/kl\,, \qquad (3)$$

where T_i is an internal temperature within the sample; T_s is a temperature of the sample's surface, measured during the experiment; k is the material thermal conductivity; and l is the distance from the heating source to the surface.

Taking, for example, a phonon dominated low-temperature thermal conductivity, $k = \alpha T^3$, with $\alpha = 2500$ μW/K^{4}cm [14], $P = 1.5$ nW (measured after 5×10^3 sec of the relaxation), and $l = 0.5$ mm, we calculate for the intrabulk temperature T_i values of 1.000012, 0.112, and 12.01 K for $T_s = 1$, 0.1, and 0.01 K, respectively. This qualitative estimate is, evidently, exaggerated, but it illustrates well our claim. Namely, with the intrinsic internal heating source an effective local temperature within the bulk of the superconductor does not scale down with the sample's surface temperature, but rather saturates at a certain nonzero level.

The heating power P follows the magnetization variation rate dM/dt and, therefore, is expected to vanish after an infinitely long time. The internal temperature of the superconductor is expected to attain its surface temperature when the heating is over. It has been mentioned above that after 5000 sec the rate of the heating reduction dP/dt is about -0.1 pW/mm^{3}sec at 0.5 K in the field of 1 T. This corresponds to the internal cooling with the rate dT/dt of about -10^{-5} K/sec. Therefore, the steady state temperature gradient within the bulk superconductor does not disappear and is practically constant (after a few thousand seconds) at the time scales of the real experiments.

Microscopically, the movement of vortices is not steady. Instead, they move by short quick hops. We can assume that during its move, the velocity of the vortex is determined by the magnetic diffusion coefficient of the material. In type-II superconductors, including the high-temperature superconductors, the magnetic diffusion coefficient is much larger than the thermal diffusion coefficient. Therefore, the vortices move in effectively adiabatic conditions. With the specific heat vanishing at low temperatures, this effect can give a significant local overheating of the vortex surrounding and stimulate depinning of the neighboring vortices. The best illustration of this process is the onset of a magnetic instability or flux jump. In this phenomenon, the heat adiabatically released by a moving vortex triggers a correlated simultaneous depinning of its neighbors, in this way enhancing the dissipated power. Under favorite conditions a macroscopic self-accelerating avalanche reaction can start. This instability can also remain local in which case a limited magnetization or temperature jump is traced. Temperature and magnetization jumps which are associated with macroscopic thermomagnetic instabilities are indeed observed in thicker ($2\times2\times0.5$ mm) crystals during the relaxation process under an applied field of several tesla (Fig. 4).

To conclude, we have studied the effect of moving vortices on their environment. The energy released during the relaxation process is converted into heat, which can-

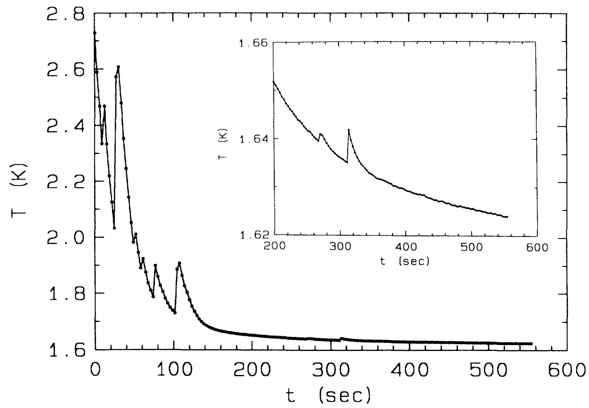

FIG. 4. Temperature jumps associated with macroscopic magnetic instabilities in $2\times2\times0.5$ mm BiSrCaCuO sample during the relaxation under an applied field of 3.5 T. The bath temperature is 1.6 K.

not be neglected at low temperatures. The effective local temperature within the bulk of a superconductor does not scale down with the sample's surface temperature, but rather saturates at a certain nonzero level. This explains a nonvanishing relaxation rate for any bulk type-II superconductor at low temperatures. The self-heating by moving vortices is an essential obstacle for the observation of the macroscopic quantum creep in bulk superconductors.

We are indebted to V. Duijn, N T. Hien, A. Menovsky, K. Bakker, and Z. Koziol for samples and help. This work has been supported by the Dutch Stichting FOM within the scope of the National Program in High Temperature Superconductivity.

[1] M. R. Beasley, R. Labusch, and W. W. Webb, Phys. Rev. **181**, 682 (1969).

[2] A. C. Mota, A. Pollini, P. Visani, K. A. Muller, and J. G. Bednorz, Phys. Rev. B **36**, 4011 (1987).

[3] R. Griessen, J. G. Lensink, and H. G. Schnack, Physica (Amsterdam) **185-189C**, 337 (1991).

[4] L. Fruchter, A. P. Malozemoff, I. A. Campbell, J. Sanchez, J. Konczykowski, R. Griessen, and F. Holtzberg, Phys. Rev. B **43**, 8709 (1991).

[5] A. C. Mota, A. Pollini, P. Visani, G. Juri, and J. J. M. Franse, in *Proceedings of the International Conference on Transport Properties of Superconductors*, edited by R. Nicolsky (World Scientific, Singapore, 1990), p. 37.

[6] A. V. Mitin, Zh. Eksp. Teor. Fiz. **93**, 590 (1987) [Sov. Phys. JETP **66**, 335 (1987)].

[7] J. Z. Sun, C. B. Eom, B. Lairson, J. C. Bravman, and T. H. Geballe, Phys. Rev. B **43**, 3002 (1991).

[8] E. Simanek, Phys. Rev. B **39**, 11 384 (1989).

[9] A. O. Caldeira and A. J. Leggett, Phys. Rev. Lett. **46**, 211 (1981).

[10] G. Blatter, V. B. Geshkenbein, and V. M. Vinokur, Phys. Rev. Lett. **66**, 3297 (1991).

[11] G. Blatter and V. Geshkenbein, Phys. Rev. B **47**, 2725 (1993).

[12] A. Gerber, J. N. Li, Z. Tarnawski, J. J. M. Franse, and A. A. Menovsky, Phys. Rev. B **47**, 6047 (1993).

[13] C. P. Bean, Phys. Rev. Lett. **8**, 250 (1962).

[14] G. Sparn, M. Baenitz, S. Horn, F. Steglich, W. Assmus, T. Wolf, A. Kapitulnik, and Z. X. Zhao, Physica (Amsterdam) **162-164C**, 508 (1989).