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High-Temperature Superconductors: SOC in a Driven System***

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Transport Resistive Broadening by Avalanche Flux Motion in High-Temperature Superconductors: SOC in a Driven System

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Abstract

Characteristics of self-organized criticality (SOC) are investigated for a driven system in high- T_c superconductors. By applying a bias current to a single crystal of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$, we are able to drive the vortex state to criticality. We establish a magnetic field profile for a type-II superconductor by considering both the magnetic force (caused by the Bean critical current) and the Lorentz force (associated with the bias current). The resistive broadening is interpreted in the framework of SOC. We show that the R vs. T curve is divided into regions of flux flow, thermally activated flux avalanche and thermally activated flux creep.

The transport resistive broadening under a magnetic field in high- T_c superconductors has been studied extensively since it provides important information about dynamical behavior of the flux motion [1-7]. Several models, such as flux creep [3,4], Josephson-junction tunneling [5], superconducting fluctuation [6], and flux melting [7], have been proposed to explain this phenomenon. Although these models treat flux motion with different physical origins, they usually apply only in a small j regime, which can not give an entire dynamical picture of flux motion, particularly near the critical state. Further, no temporal correlation is considered in these models.

To deal with realistic flux motion in a wide range of driving forces, new dynamical theories are needed. In our previous work [8-10], we have proposed that the vortex state is a typical spatially and temporally extended system and can well be described in the framework of self-organized criticality (SOC) [11-13]. An SOC system lacks intrinsic scales in both space and time. Specifically, in the vortex state, the hopping distance and time considered in the flux-creep model are replaced by the avalanche size and time in SOC, with both variables obeying power laws. This is a fundamentally different view of studying flux motion. We have demonstrated in a series of magnetic relaxation experiments that avalanche flux motion dominates at a large j and that individual creep sets in as j is considerably reduced [9]; a dynamical crossover occurs between the avalanche and flux-creep behavior. Other theoretical investigations of vortex dynamics have also exploited the concept of SOC [14]. For example, Oscar Pla and Franco Nori [14] have made numerical simulations and observed that the displacement of a flux line with a small increase of the Lorentz force has an SOC power-law distribution.

Although there have been extensive studies on flux motion in magnetization measurements, the SOC characteristics have not been investigated in the transport experiments. The situation in a transport measurement is more complicated as a result of bias current present in the sample. The field profile in the sample is not well established when a bias current is applied. In this paper, we use the concept of SOC to explain the transport resistive broadening in high- T_c superconductors. The novel feature here is that, unlike the case of magnetization measurements in which the system naturally evolves to the critical state, the vortex state in our transport measurements is driven to criticality by an externally supplied current. For the first time, we establish the field profile in a single crystal sample by considering both the Lorentz force associated with the bias sample current and the magnetic force caused by the Bean critical current [15]. We show experimentally that the dynamics of the vortex state in a driven system is an SOC system with flux motion governed by spatially and temporally correlated avalanches.

Transport measurements were made by using a standard four-point technique in a gas-flow helium cryostat equipped with a 13-T superconducting magnet. The $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ single crystal with the dimensions 3 mm X 0.5 mm X 0.1 mm was prepared by the flux method [16]. The zero-field-cooled magnetization vs. temperature data shows a sharp superconducting transition at 86 K. The single crystal had a smooth surface on which four copper leads were attached with silver paint. The transport current was perpendicular to the applied field and directed in the a-b plane of the crystal. The measuring dc current density was 50 A/cm². The curves of resistivity vs. temperature were obtained by sweeping the temperature at a fixed magnetic field.

We illustrate in Fig. 1 the field profile from the R vs. T experiment for a small bias current. As the superconductor is brought into the vortex state, three forces must be considered: the pinning force, F_p , which arises from the interaction between the flux lines and the defects; the Lorentz force, F_L , which is directly related to the bias current; and the magnetic force, F_g [17], which is proportional to the field gradient dB/dx (Bean critical current). In an inductive measurement, F_L is zero; therefore the driving force comes solely from F_g . The situation is complicated, however, when there is a bias current in the driven system. In the R vs. T transport measurement, the Lorentz force keeps constant and the pinning force increases with decreasing temperature. As shown in Fig. 1, the flux line is uniform slightly below T_c (Fig. 1a). As the temperature is lowered, the increased F_p will balance F_L , and criticality is reached (Fig. 1b). At moderately low temperatures where $F_p > F_L$ (Fig. 1c), a triangular field profile is established as a result of more pronounced F_g ; in this situation, the flux avalanches are beginning to slow down. As the temperature further decreases (Fig. 1d), the pinning force becomes stronger and the dynamic process enters the flux-creep regime, in which the shape of the profile gradually becomes an isosceles-like triangle. We shall describe flux motion at the stage from Fig. 1a to 1b with SOC. The flux motion behavior at the stage indicated by Fig. 1d has been investigated previously by the flux creep model [4].

According to SOC theory, the avalanche size, s , scales with the reduced temperature [12], which can be written as

$$s = s_c(1 - T/T_c)^{-n}, \quad (1)$$

where the s_c is the characteristic size, T_c is the critical temperature, and n is the critical exponent. Near the critical temperature, the flux jump rate can be written as [18]

$$\omega = \omega_0 \exp(-U/kT), \quad (2)$$

where ω_0 is the attempt frequency and U is the activation energy, which has a scaling form [4]

$$U = U_0 (1-T/T_c)^m, \quad (3)$$

where U_0 is the characteristic energy and m is the critical exponent. The voltage, V , measured in the transport experiment, is induced by flux motion and can be written as

$$V = n\phi_0 v d = B v d, \quad (4)$$

where n is the density of the vortex lines, ϕ_0 is the magnetic flux quantum, v is velocity of the flux motion, d is the separation of the contacts, and $B (=n\phi_0)$ is the surface magnetic field. Near the critical state, flux motion is dominated by the avalanches. The velocity of the flux motion is determined by the avalanche size and the thermal hopping rate. Using Eqs. (1), (2) and (3), we can express the velocity as

$$v = s\omega = s_c \omega_0 (1-T/T_c)^{-n} \exp(-U_0(1-T/T_c)^m/kT), \quad (5)$$

Substituting Eq. (4) with Eq. (5), the resistivity for a small bias current can be written as

$$\begin{aligned}
 \rho &= E/j = (V/d)/j \\
 &= Bs_c \omega_0 (1-T/T_c)^{-n} \exp(-U_0(1-T/T_c)^m/kT)/j \\
 &= \rho_0 (1-T/T_c)^{-n} \exp(-U_0(1-T/T_c)^m/kT), \tag{6}
 \end{aligned}$$

where ρ_0 ($= Bs_c \omega_0$) is the characteristic resistivity. Eq. (6) is the SOC expression for the ρ vs. T curves near the critical state.

Figures 2 and 3 show the resistivity ρ vs. T curves for the field direction parallel and perpendicular to the c axis of the crystal at various applied magnetic fields, respectively. During the flux flow, there is a uniform flux line profile in the sample as indicated in Fig. 1a [10]. At lower temperatures, however, the increased pinning force will balance the Lorentz force near the critical state (Fig. 1b), and the ρ vs. T curves for both orientations are fit well by Eq. (6) with $n = 0.5$ and $m = 2$ (Figs. 2a and 3a). The fitting parameter in Eq. (6), U_0 , has been found to be in the range of 0.02 - 0.1 eV for the field from 9 T to 0.2 T applied parallel to c axis, and 0.05 - 0.8 eV for the field perpendicular to the c axis.

These fittings correspond to Fig. 1b, which implies that the system is in criticality and avalanches occur at all sizes up to the sample size. It should be pointed out that, as indicated in Fig. 1b, the flux lines are driven out towards the direction of F_L . However, as temperature continue to decrease, F_p will exceed F_L , and flux motion starts to occur at the direction opposite to F_L as indicated in Fig. 1c. At this stage, the voltage measured is due to the $d\phi/dt$ difference caused by flux motion at both directions.

At even lower temperatures, the avalanches are beginning to slow down, and flux motion exhibits individual flux-creep behavior which can be well described by either the Anderson-Kim model or the collective creep model. At this stage, $F_p \gg F_L$ the field profile has an isosceles-like triangle (Fig. 1d). As can be seen in Fig. 2a and 3a, the fitting curves of Eq. (6) start to deviate from the experimental data, indicating a dynamical crossover between the flux avalanches and flux creep, which corresponds to Fig. 1c (This crossover has also been observed in our previous magnetization measurements [9]). As shown in Fig. 2b and 3b, the flux creep region emerges from this dynamical crossover. Note that the lower temperature parts of the R vs. T curves are fit by the Anderson-Kim equation: $\rho \sim \rho_0 \exp(-U_0(1-T/T_C)^m/kT)$ with $m \sim 1.5$.

In Fig. 4, we present a schematic of the R vs. T curve. Here, we divide the resistive broadening curve into three regions: flux flow with a uniform flux lattice, flux avalanches when the system is in criticality, and flux creep. Close to T_C , the Lorentz force dominates, causing the system to reach criticality. At lower temperatures, however, the pinning force begins to dominate and the Bean triangle is established against the Lorentz force. The avalanches slow down and the system enters the flux-creep regime.

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REFERENCES

- 1) T. T. M. Palstra, B. Batlogg, L. F. Schneemeyer, and J. V. Waszczak, *Phys. Rev. Lett.* **61**, 1662 (1988); T. T. M. Palstra, B. Batlogg, R. B. van Dover, L. F. Schneemeyer, and J. V. Waszczak, *Appl. Phys. Lett.* **54**, 763 (1989).
- 2) M. Tinkham, *Phys. Rev. Lett.* **61**, 1658 (1988).
- 3) M. V. Feigel'man, V. B. Geshkenbein, A. I. Larkin, and V. M. Vinokur, *Phys. Rev. Lett.* **63**, 2303 (1989).
- 4) J. Z. Sun, K. Char, M. R. Hahn, T. H. Geballe, and A. Kapitulnik, *Appl. Phys. Lett.* **54**, 663 (1989); D. Shi, H. E. Kourous, Ming Xu, and D. H. Kim, *Phys. Rev. B* **43**, 514 (1991).
- 5) D. H. Kim, K. E. Gray, R. T. Kampwirth, J. C. Smith, D. S. Richeson, T. J. Marks, J. H. Kang, J. Tlvacchio, and M. Eddy, *Physica C* **177**, 431 (1991); D. H. Kim, K. E. Gray, R. T. Kampwirth, and D. M. McKay, *Phys. Rev. B* **42**, 6249 (1990).
- 6) K. Kitazawa, S. Kambe, and M. Naito, in *Strong Correlation and Superconductivity*, edited by H. Fukuyama, S. Maekawa, and A. P. Malozemoff (Springer, Berlin, 1989), P 361.
- 7) M. P. Fisher, *Phys. Rev. Lett.* **62**, 1415 (1989).
- 8) X. Ling, D. Shi and J. I. Budnick, *Physica C* **185-189**, 2181 (1991).
- 9) Z. Wang and D. Shi, *Phys. Rev. B*, (Rapid Comm.) **48**, 4208 (1993); Z. Wang and D. Shi, *Phys. Rev. B* **48**, 9782 (1993); Z. Wang and D. Shi, *Phys. Rev. B* (Rapid Communi) (in press);
- 10) Z. Wang and D. Shi, unpublished, (1993).
- 11) P. Bak, C. Tang, and K. Wiesenfeld, *Phys. Rev. Lett.* **59**, 381 (1987); P. Bak, C. Tang, and K. Wiesenfeld, *Phys. Rev. A* **38**, 364 (1988).
- 12) C. Tang and P. Bak, *Phys. Rev. Lett.* **60**, 2347 (1988).
- 13) C. Tang, *Physica A* **194**, 315 (1993).

- 14) O. Pla and F. Nori, Phys. Rev. Lett. 67, 919 (1991).
- 15) C. P. Bean, Phys. Rev. Lett. 8, 250 (1962).
- 16) D. Shi, M. Tang, Y. C. Chang, P. Z. Jiang, K. Vandervoort, B. Malecki, and D. J. Lam, Appl. Phys. Lett. 54, 2358 (1989).
- 17) P. G. de Gennes, Superconductivity of Metals and Alloys (Benjamin, New York, 1966), p. 83.
- 18) P. W. Anderson and Y. B. Kim, Rev. Mod. Phys. 36, 39 (1964).

Figure Caption

FIG. 1. Schematics of the field profile with a small bias current applied through the sample and an external magnetic field: (a) $F_P \ll F_L$; (b) F_P balances F_L ; (c) $F_P > F_L$; (d) $F_P \sim F_g$.

FIG. 2. (a) Resistivity vs. temperature for a single crystal of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ in the SOC regime for various magnetic fields applied parallel to the c axis. The solid lines are fit to Eq. (6) with $n = 0.5$ and $m = 2$; (b) Arrhenius plot of the resistivity vs. temperature in the flux-creep regime for the same measurement shown in Fig. 2a. The solid curves are fit to the flux creep model of the form $\rho = \rho_0 \exp(-U_0(1 - T/T_C)^m)$ with $m = 1.5$.

FIG. 3. (a) Resistivity vs. temperature for a single crystal of $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_x$ in the SOC regime for various magnetic fields applied perpendicular to the c axis. The solid lines are fit to Eq. (6) with $n = 0.5$ and $m = 2$; (b) Arrhenius plot of the resistivity vs. temperature in the flux-creep regime for the same measurement shown in Fig. 3a. The solid curves are fit to the flux creep model of the form $\rho = \rho_0 \exp(-U_0(1 - T/T_C)^m)$ with $m = 1.5$.

FIG. 4. Schematic of resistivity vs. temperature for a type-II superconductor.

$B, j = \text{const} \quad , \quad j \ll j_c \quad T \downarrow$

(a)

$T \sim T_c$
 $F_p \ll F_L$
 Flux flow

(b)

$F_p \sim F_L$
 Flux avalanche

(c)

$F_p > F_L$

(d)

$F_p \gg F_L$
 Flux creep

Fig. 2

Fig. 3

Resistivity

Fig. 4

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