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Effect of flux avalanches on activation energy in type-II superconductors: Evidence for self-organized criticality

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The behavior of thermally activated flux avalanches is studied for both high-T_c superconductors (single crystals of $Bi_2Sr_2CaCu_2O_x$ and $YBa_2Cu_3O_x$) and a conventional type-II superconductor (Nb_3Sn multifilamentary wire). By combining two different mechanisms, namely, thermally activated and avalanche flux motion, we have developed a $U(j)$ relationship in a large regime of driving force for type-II superconductors. As a result of flux avalanches, the flux-motion activation energy is considerably reduced. We have found a dynamic crossover at which the flux-motion characteristic changes from spatially and temporally correlated flux avalanches to slow creep.

The origin of flux motion in the vortex state of superconductors was first identified as thermal activation by Anderson and Kim (AK model).[1] An early experimental study of the AK model was made by Beasley, Labusch, and Webb.[2] Since the discovery of high-T_c superconductors, several models have been developed,[3-5] based on thermal activation, to interpret the vortex behavior of these new oxides. These models, such as the thermally assisted flux-flow (TAFF) model[3] and the collective-creep (CC) model,[4] are applicable only at a small driving force ($j \ll j_c[T,H]$), where the hopping event has the characteristic of slow creep. However, in a real situation, particularly at a large driving force, flux avalanches are likely to occur as a result of high magnetic pressure; moreover, the hopping event is spatially and temporally correlated.

The avalanche effect in a sandpile has been described by a so-called self-organized-criticality (SOC) process formulated by Bak, Tang, and Wiesenfeld.[6,7] In a magnetic relaxation experiment, Ling, Shi, and Budnick[8] found that the current decay in single crystals of $Bi_2Sr_2CaCu_2O_x$, $YBa_2Cu_3O_x$, and Nb can be well described by the concept of SOC. They pointed out that spatial and temporal correlation is important in studying flux-motion behavior near the critical state. Since then, other investigations have also shown theoretical evidence of avalanche dynamics in the vortex state.[9,10] Recently, Tang[11] proposed that the initial depinning process is thermally activated, while the subsequent hopping process of depinned flux lines is governed by spatially and temporally correlated avalanches of flux lines. Wang and Shi[12] have reported experimental evidence that magnetic relaxation in single crystals of $Bi_2Sr_2CaCu_2O_x$ and $YBa_2Cu_3O_x$ can be well described by the SOC model. They showed that a flux line is always thermally activated regardless of the level of driving force, but the avalanche effect is pronounced and dominating at a large driving force. Wang and Shi observed that, instead of the slow and individual creep of a flux line in the AK model, flux motion exhibits avalanche behavior at a large driving force.

In this paper, we use the concept of SOC to explain the observed nonlinear dependence of the effective activation energy on the current density in type-II superconductors. By combining the AK theory and SOC theory, we have developed a $U(j)$ relationship for type-II superconductors. In the presence of avalanche effects, flux lines (or bundle) should overcome a barrier more easily. We propose that the effective flux-creep activation energy U_{eff} be modified by U_{aval}, which stands for the effective barrier as flux avalanches occur. We indicate that the effective flux-motion activation energy is considerably reduced by the flux avalanche effect at a large driving force. As the driving force decreases, the avalanches are weakened, and the current decay can be well described by the AK or the CC models. We note a dynamic crossover at which the system enters the pure thermally activated flux-creep regime where the avalanche effects are unobservably small.

We have investigated nonlinear $U(j)$ dependence by systematically measuring magnetic relaxation over a long time period for both high-T_c superconductors (single crystals of $Bi_2Sr_2CaCu_2O_x$ and $YBa_2Cu_3O_x$) and a conventional type-II superconductor (Nb_3Sn multifilamentary wire) in a wide temperature region. Magnetization measurements were carried out on a Quantum Design superconducting quantum interference device magnetometer. The samples were first zero-field cooled to a desired temperature T below the transition temperature T_c. We chose the applied field parallel to the *ab* plane for the single crystal of $Bi_2Sr_2CaCu_2O_x$, normal to the *ab* plane for the single crystal of $YBa_2Cu_3O_x$, and normal to the length of Nb_3Sn multifilamentary wire (Nb_3Sn wire). The magnetization M of the samples was measured as a function of time t. The initial data point of the magnetization was taken at $t_0 = 180$ s after the field was stabilized. The travel length of the sample in each scan was 3 cm to avoid field inhomogeneity.

According to the SOC model,[6,7] Tang[11] proposed that the time scale and the length scale of the velocity of flux lines are set by the avalanche size and the thermal activation rate ν, which is described by an Arrhenius expression:

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$$\nu = \nu_0 \exp(-U/kT) \,, \tag{1}$$

where ν_0 is the attempt frequency, and $U = U_0(1 - j/j_c)^\beta$,[2] where U_0 is the characteristic energy, j_c is the Bean critical current, and β is a constant exponent. Tang defined an avalanche size s as the total flux-line displacement involved in each avalanche. The avalanche size for an SOC-like system can be expressed as[7,11]

$$s = s_c(1 - j/j_c)^{-\alpha} \,, \tag{2}$$

where s_c is the characteristic size and α is a critical exponent. According to Tang,[11] $v = \nu s$, which is the velocity of flux line.[11,12] Combining Eq. (1) and Eq. (2), we can write the flux conservation equation[2,13] in one-dimensional form as

$$\begin{aligned} dB/dt &= -\nabla D \\ &= -\nabla(Bv) = -\nabla(B\nu s) \\ &= -\nabla[B s_c \nu_0 (1 - j/j_c)]^{-\alpha} \\ &\quad \times \exp[-U_0(1 - j/j_c)^\beta / kT] \,, \end{aligned} \tag{3}$$

where D is the flux flow density, and B is the magnetic field. Considering a slab of thickness d and integrating Eq. (3) over a sample volume, we obtain the decay rate dj/dt by using Bean's model[12]

$$\begin{aligned} dj/dt = &-(4Bs_c\nu_0/\mu_0 d^2)(1 - j/j_c)^{-\alpha} \\ &\times \exp[-U_0(1 - j/j_c)^\beta / kT] \,. \end{aligned} \tag{4}$$

In Eq. (4), the term $(1 - j/j_c)^{-\alpha}$ is associated with pure flux avalanches, while the term $\exp[-U_0(1 - j/j_c)^\beta / kT]$ originates from thermal effects.

Based on Eq. (4), we propose that the activation energy is altered by avalanche effects. We can write the standard rate equation as[2]

$$dj/dt = -(4B\omega\nu_0/\mu_0 d^2)\exp[-U_{\text{aval}}(j)/kT] \,, \tag{5}$$

where ω is the average hopping distance when flux avalanches are considered. We can define an effective activation energy for avalanche flux motion U_{aval} as

$$U_{\text{aval}} = kT[\ln(4B\omega\nu_0/\mu_0 d^2) - \ln|dj/dt|] \,. \tag{6}$$

Substituting Eq. (4) in Eq. (5), we can rewrite Eq. (6) as

$$U_{\text{aval}} - kTA + \alpha kT \ln(1 - j/j_c) + U_0(1 - j/j_c)^\beta \,, \tag{7}$$

where $A[=\ln(\omega/s_c)]$ is a constant in the temperature range considered. Our previous study[12] has suggested $\alpha = \beta - 1$. According to Beasley, Labusch, and Webb,[2] β is close to 1.5 for any smooth shaped barrier. In this study, we choose α and β to be 0.5 to 1.5 at a large driving force, respectively. Here, the term $\alpha kT \ln(1 - j/j_c)$ is associated with flux avalanches, and the term $U_0(1 - j/j_c)^\beta$ is connected with thermal effects. Thus, the activation energy is a function not only of thermal activation but also of the flux avalanches.

Equation (7) indicates that the effective activation energy will be reduced as a result of flux avalanches. The contribution of the avalanche term $\alpha kT \ln(1 - j/j_c)$ in Eq. (7) will decrease as j decreases at a small driving force. We therefore expect the system to enter the Anderson-Kim regime where the individual and uncorrelated creep of a flux line dominates the entire flux-motion process. In this situation, α reduces to a small value near zero and the exponent β reaches unity, as expected in the linear $U(j)$ law of the AK model (i.e., $U = U_0[1 - j/j_c]$).

Based on the previously developed methods,[14,15] we

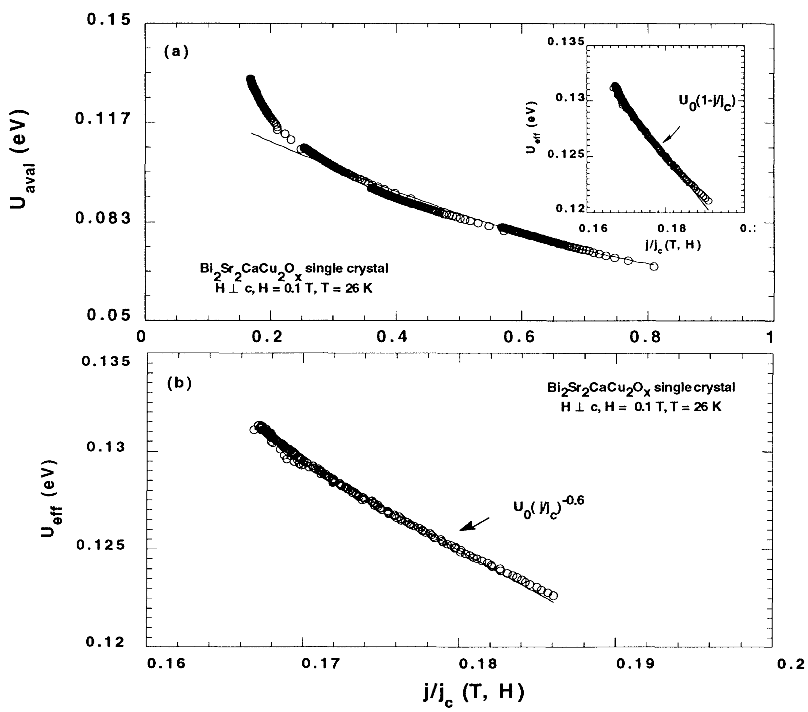

FIG. 1. (a) U_{aval} vs j/j_c curve for a single crystal of $Bi_2Sr_2CaCu_2O_x$ established by methods given in Refs. 14 and 15, where the curve is fit to Eq. (7) with $\alpha = 0.5$ and $\beta = 1.5$. The inset shows U_{eff} vs j/j_c at a small driving force, where the solid line is the fit of $U = U_0(1 - j/j_c)$. (b) The same curve shown in the inset of (a) but fit to the collective-creep model, $U = U_0(j/j_c)^{-0.6}$.

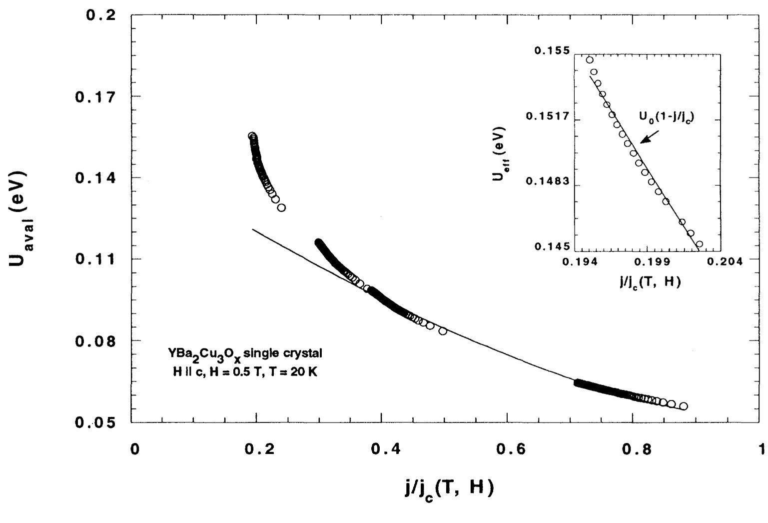

FIG. 2. U_{aval} vs j/j_c curve for a single crystal of $YBa_2Cu_3O_x$ established by methods given in Refs. 14 and 15, where the curve is fit to Eq. (7) with $\alpha=0.5$ and $\beta=1.5$. The inset shows U_{eff} vs j/j_c at a small driving force, where the solid line is the fit of $U=U_0(1-j/j_c)$.

have extracted the $U(j)$ relationship from the relaxation data. With these methods, the relaxation data taken at different temperatures (26, 30, 34, and 40 K) are constructed into a smooth $U(j)$ curve by adding $28.5kT$ to each set of the data. As can be seen in Fig. 1, the $U(j)$ curve at a large driving force agrees well with Eq. (7). The fitting yields $U_{\mathrm{aval}}=28.5kT+0.5kT\ln(1-j/j_c)+0.06(1-j/j_c)^{1.5}$ with only one fitting parameter, $U_0(=0.06\ \mathrm{eV})$. At a smaller driving force, however, the experimental data start to deviate from Eq. (7), indicating that the avalanche effects are significantly reduced. As the system enters the pure Anderson-Kim regime where $\beta\sim1$ and $\alpha\sim0$ (the avalanche term $\alpha kT\ln[1-j/j_c]\sim0$), the thermal term $(1-j/j_c)^\beta$ can be approximated as $1-j/j_c$, and the $U(j)$ curve becomes linear. Therefore, there is a dynamic crossover at which the system decays from the flux-avalanche region to the flux-creep region.

We note that the Anderson-Kim equation $U\sim(1-j/j_c)$ is a good approximation at a small driving force ($j\ll j_c[T=0]$ and $U\gg kT$). As shown in the inset of Fig. 1(a), a portion of the magnetic relaxation data at a small driving force can fit reasonably well to the AK model with the relation $U=U_0(1-j/j_c)$. However, we have found that the experimental data at a small driving force can be much better described by the CC model. As shown in Fig. 1(b), the same portion of the U-j curve in the inset of Fig. 1(a) is well fitted by the relation $U=U_0(j/j_c)^{-0.6}$, as predicted by the CC model.[4] These fittings indicate that both the AK and CC models are applicable only at small driving forces.

In addition to measuring the flux motion of $Bi_2Sr_2CaCu_2O_x$, we have done the same measurements on a single crystal of $YBa_2Cu_3O_x$ and Nb_3Sn wire. As shown in Figs. 2 and 3, exactly the same behavior has been observed in these superconducting systems. The $U(j)$ curves of both these systems can be well described by Eq. (7). These results clearly show that thermally activated flux avalanches are a universal characteristic of the vortex state in both high-T_c superconductors and conventional type-II superconductors.

It should be noted that, for convenience, we choose β to be either 1.5 or 1 (the corresponding α value is either

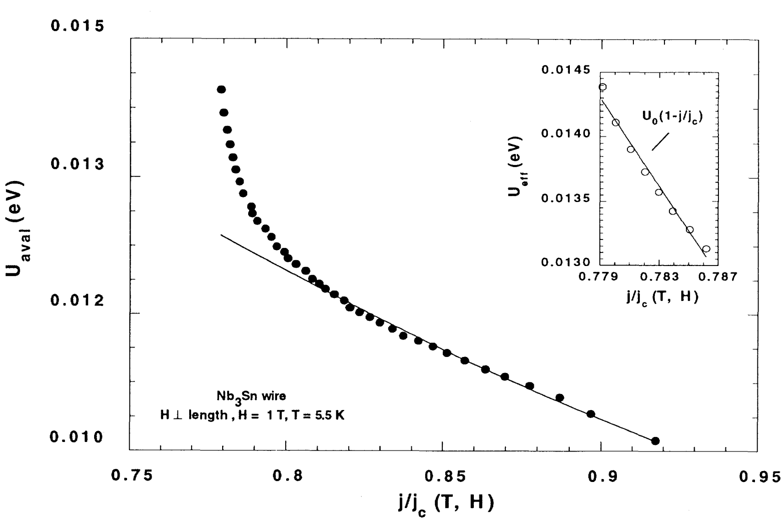

FIG. 3. U_{aval} vs j/j_c curve for Nb_3Sn wire established by methods given in Refs. 14 and 15, where the curve is fit to Eq. (7) with $\alpha=0.5$ and $\beta=1.5$. The inset shows U_{eff} vs j/j_c at a small driving force, where the solid line is the fit of $U=U_0(1-j/j_c)$.

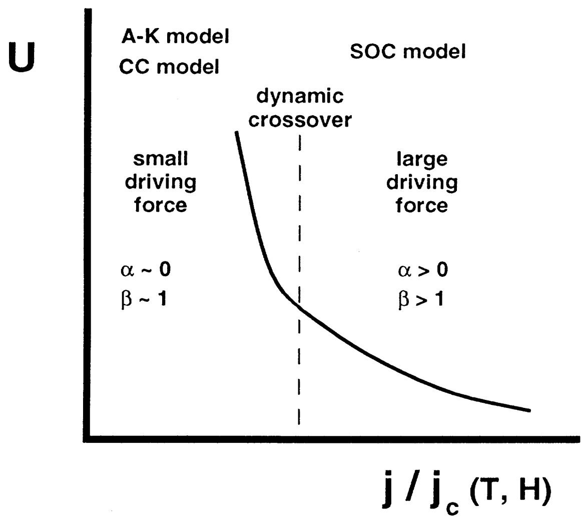

FIG. 4. Schematic illustration of the $U(j)$ curve representing flux motion through pure thermal activation (AK model and CC model) and thermally activated flux avalanches (SOC model).

0.5 or 0) in this study for the avalanche regime and Anderson-Kim regime, respectively. In fact, β remains 1.5 at a wide regime of driving force and quickly reduces to near unity at the dynamic crossover (equivalently, α decreases from 0.5 to near zero). In this study, we do not fit the data at the dynamic crossover where both α and β change rapidly in a narrow range of j.

In Fig. 4, we summarize our interpretation for the entire flux-motion dynamics. The $U(j)$ curve at a large driving force has a weak current density dependence, as observed in both high-T_c and conventional superconductors in this study and can be well explained by the concept of self-organized criticality. As flux avalanches occur, a thermally vibrating flux line, which may not be depinned in the absence of avalanches, can be activated through avalanche interaction with other moving flux lines. This is equivalent to a smaller activation energy than in the case of pure thermal effects. U_{aval}, as introduced in this study, may thus be appropriately defined as the activation energy for thermally activated flux avalanches. As driving force decreases, the avalanche time increases. As the driving force is significantly reduced, an avalanche seldom occurs and avalanche size is small; therefore, the avalanche effect is experimentally unobservable. In this situation, the system experiences a dynamic crossover and enters the pure thermally activated flux-creep regime. The $U(j)$ curve at a small driving force has a strong current density dependence. Both the AK model and CC model can be used to describe the $U(j)$ relationship in this region and flux motion indeed has the characteristic of creep, where flux lines are thermally activated and jump over the barrier individually or collectively.

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