Distribution of Flux-Pinning Energies in $YBa_2Cu_3O_{7-\delta}$ and $Bi_2Sr_2CaCu_2O_{8+\delta}$ from Flux Noise

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The spectral density of the magnetic flux noise measured in high-temperature superconductors in low magnetic fields scales approximately as the inverse of the frequency and increases with temperature. We use the temperature and frequency dependence of the noise to determine the pinning energies of individual flux vortices in thermal equilibrium. The distribution of pinning energies below 0.1 eV in $YBa_2Cu_3O_{7-\delta}$ and near 0.2 eV in $Bi_2Sr_2CaCu_2O_{8+\delta}$. The noise power is proportional to the ambient magnetic field, indicating that the vortex motion is uncorrelated.

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Much attention has been focused on the vortex pinning $U(T)$ of high-transition-temperature (T_c) superconductors. From studies of the resistive transition in a magnetic field, Palstra *et al.*[1] showed that flux creep in single crystals of $Bi_2Sr_2CaCu_2O_{8-\delta}$ (BSCCO) was thermally activated[2] with magnetic-field–dependent pinning energies ranging from 0.03 to 0.3 eV near T_c. In similar experiments, Sun *et al.*[3] showed that the activation energies in $ErBa_2Cu_3O_{7-\delta}$ were much greater when the applied magnetic field was perpendicular to the c axis than when it was parallel. Zeldov *et al.*[4] have studied the resistive transition in $YBa_2Cu_3O_{7-\delta}$ (YBCO) and reported activation energies as high as 6 eV in a magnetic field of 0.5 T. On the other hand, Hagen and Griessen[5] deduced a much lower value of the activation energy in YBCO from flux-creep measurements by Tuominen, Goldman, and Mecartney,[6] and Yeshurun, Malozemoff, and Holtzberg.[7] They found a distribution of activation energies with a peak near 0.06 eV. Subsequently, Griessen *et al.*[8] used the data of Yeshurun *et al.*[9] to show that the activation energies in a single crystal of BSCCO were also distributed, with a peak near 0.04 eV.

The above experiments were carried out in substantial magnetic fields with strong driving forces acting on correlated vortices. In this Letter, we describe an alternative probe of pinning energies, magnetic flux noise, which is present without applied currents or magnetic fields. We argue that this technique measures the pinning potential of individual uncorrelated vortices. We have measured flux noise in YBCO and BSCCO samples over the temperature range from 4.2 K to above T_c. The spectral density $S_\Phi(f)$ of the noise scales as $1/f^m$, where f is the frequency and $m \approx 1$. Assuming that individual vortices are thermally activated among pinning sites, we extend a model by Dutta, Dimon, and Horn[10] to derive the distribution of flux-pinning energies. In YBCO, this distribution shows a broad peak below 0.1 eV. The fact that $S_\Phi(f)$ scales linearly with an applied magnetic field B (0.1 mT $\leq B \leq$ 2.5 mT) supports our contention that the motion of the vortices is uncorrelated.

A detailed description of our experimental technique, including a diagram of the apparatus, appears in Ref. 11. A Nb-PbIn thin-film dc SQUID[12] (superconducting quantum interference device) is attached to a sapphire plate maintained at 4.2 K inside a vacuum can. The high-T_c sample is supported approximately 100 μm from the SQUID and parallel to it by a thermally isolated stage that regulates the sample temperature from 4.2 to 140 K. The cryostat is surrounded by a Mumetal shield that reduces the ambient magnetic field below 10^{-6} T. The motion of vortices in the high-T_c material is detected as a change in flux through the SQUID with a coupling coefficient of about 70%. We report results on two films of YBCO and a single-crystal flake of BSCCO. YBCO(1), which was cosputtered from three targets and postannealed,[13] was > 90% c-axis oriented with $T_c = 85$ K and a critical current density J_c of 5×10^6 A/cm^2 at 4.2 K. YBCO(2) was grown *in situ* epitaxially on a (100) MgO substrate by off-axis sputtering from a single target,[14] and had $T_c = 84$ K and $J_c \approx 4\times10^7$ A/cm^2 at 4.2 K. The BSCCO single-crystal flake was grown from a melt and was c-axis oriented with $T_c = 90$ K. Each film was about 300 nm thick and the BSCCO flake was about 40 μm thick.

All samples showed $1/f$-like flux noise over our observable frequency range, 1 to 10^3 Hz. To illustrate the temperature dependence of this noise, we plot S_Φ(1 Hz) versus temperature T in Fig. 1. The noise was $1/f$-like at all temperatures below T_c, except for random telegraph noise occasionally exhibited by YBCO(2) above 78 K and by BSCCO above 87 K; these events are not included in our analysis. Measurements of the mutual inductance between our SQUID and its modulation coil probe the dc magnetic susceptibility of the sample, and are sen-

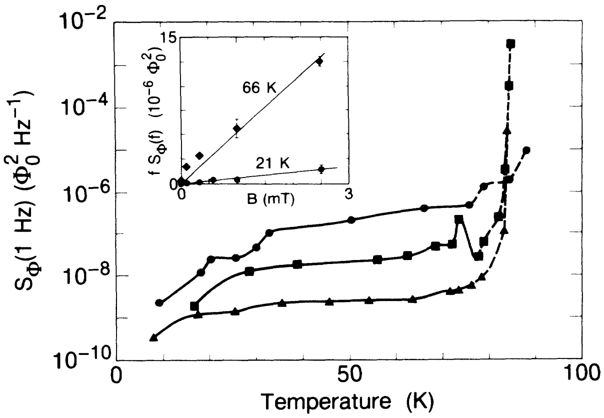

FIG. 1. Magnetic flux noise $S_\Phi(1\ \mathrm{Hz})$ vs temperature for three samples: squares, postannealed sputtered YBCO(1); triangles, *in situ* sputtered YBCO(2); circles, single-crystal BSCCO. Noise-power spectrum is $1/f$-like in all cases. Curves are piecewise cubic interpolants used to calculate $m(T)$ (solid and dashed segments) and $D(U_0)$ (solid segment only). Inset: Noise power $fS_\Phi(f)$ vs magnetic field B in which the BSCCO sample was cooled for two temperatures ($1\ \mathrm{Hz} \le f \le 100\ \mathrm{Hz}$). Lines are guides to the eye; both axes are linear.

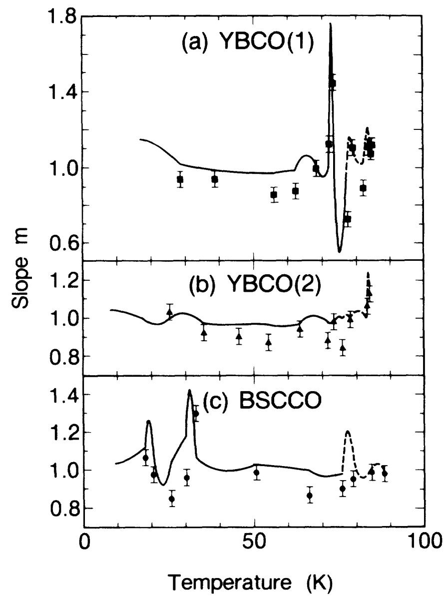

FIG. 2. Slope $m(T)$ of the noise-power spectrum vs temperature for the three samples (a) YBCO(1), (b) YBCO(2), and (c) BSCCO. Points are experimental data. Curves are predictions of Eq. (3) from the fits to noise in Fig. 1.

sitive to second phases with depressed T_c. These measurements indicate that the noise in the range of temperatures we analyze is not the result of such second phases.

We analyze the $1/f$ noise within the model of Dutta, Dimon, and Horn[10] modified to account for temperature-dependent activation energies. The central assumption of this model is that $1/f$-like noise arises from the incoherent superposition of many thermally activated switching processes. Consider a vortex hopping over a temperature-dependent barrier $U^i(T)$. The characteristic time for this process is

$$\tau^i(T) = \tau_0 \exp[U^i(T)/k_B T] = \tau_0 \exp[U_0^i \beta(T)]\,,$$

where τ_0^{-1} is a temperature-independent attempt frequency, U_0^i is the zero-temperature barrier height, and $\beta(T) \equiv U^i(T)/U_0^i k_B T$. Each independent process thus yields a Lorentzian power spectrum of the form

$$S_\Phi^i(\omega,T) \propto \tau^i(T)/\{1+[\omega\tau^i(T)]^2\}\,,$$

where $\omega = 2\pi f$. The spectral density of the noise from many such processes is

$$S_\Phi(\omega,T) \propto \int_0^\infty dU_0 D(U_0) \frac{\tau_0 e^{U_0\beta}}{1+\omega^2\tau_0^2 e^{2U_0\beta}}\,, \qquad (1)$$

where $D(U_0)dU_0$ is the number of processes with zero-temperature activation energies between U_0 and $U_0 + dU_0$. We assume τ_0 and $\beta(T)$ are the same for all processes. The kernel in Eq. (1) peaks sharply at an energy $\tilde{U}_0(\omega,T) = -\ln(\omega\tau_0)/\beta(T)$ and has a width of order $1/\beta(T)$. If we assume that $D(U_0)$ is slowly varying in the width of the kernel, we can take $D(U_0)$ outside the integral, which we readily carry out to find

$$D[\tilde{U}_0(\omega,T)] \propto \omega S_\Phi(\omega,T)\beta(T)\,. \qquad (2)$$

Thus, by measuring $S_\Phi(\omega,T)$ and taking an appropriate form for $\beta(T)$, we can obtain $D(U_0)$.

Our model makes an additional prediction, which can be tested. Since $D[\tilde{U}_0(\omega,T)]$ is weakly frequency dependent, Eq. (2) implies $S_\Phi(\omega,T) \propto 1/\omega^m$, where $m = -\partial \ln S_\Phi/\partial \ln\omega$ may deviate from unity. One can show from Eqs. (1), (2), and the expression for $\tilde{U}_0(\omega,T)$ that m must satisfy

$$m(\omega,T) = 1 + \frac{1}{\ln(\omega\tau_0)}\left[1 + \frac{\partial \ln S_\Phi}{\partial \ln T} \Big/ \left(\frac{\partial \ln\beta}{\partial \ln T}\right)\right]. \qquad (3)$$

Agreement between the measured values of $m(T)$ and the prediction of Eq. (3) will give us confidence that our model captures the physics of the flux-noise process.

In the limit of noninteracting vortices $[(\Phi_0/B)^{1/2} \gg \lambda]$, the pinning energy arises from a core interaction with temperature dependence[15] $U(T) \propto L[\Phi_0/\lambda(T)]^2$. Here L is the length over which the vortex is pinned, Φ_0 is the flux quantum, and $\lambda(T)$ is the penetration depth. The recent work of Hagen and Griessen[5] suggests that L is temperature independent. With this assumption, and the temperature dependence[15] $\lambda(T) \propto (1-t^4)^{-1/2}$ where $t = T/T_c$, we obtain $\beta(T) = (1-t^4)/k_B T$.

Figure 2 shows the measured values of $m(T)$ for each sample together with values calculated from Eq. (3) with $\omega/2\pi = 1$ Hz. We set $\tau_0 = 10^{-11}$ sec in agreement with values reported elsewhere.[1,5] The entire fit to $S_\Phi(T)$ in Fig. 1 (solid and dashed segments) is used in the calculation, since Eq. (3) is relatively insensitive to the particular functional form of $\beta(T)$. Although the measured and predicted values of m can differ by 10%, the major trends are reproduced, lending support to our model. A notable example appears in Fig. 2(a), where the most extreme departures from $m=1$ occur at 73 and 78 K. The predicted values of m mimic this behavior because $S_\Phi(T)$ exhibits a peak in this temperature range (Fig. 1). The noise peak must therefore be associated with a feature in $D(U_0)$. In plotting m, we have implicitly assumed that the vortex hopping distance l is temperature independent, so that the temperature dependence of $S_\Phi^i(\omega,T)$ arises solely from $\tau^i(T)$. If, instead, we allowed $l(T)$ to scale with T, the curves in Fig. 2 would be displaced downward, improving their agreement with the experimental data.

Figure 3 shows the distribution of pinning energies (in arbitrary units) computed from Eq. (2), using the fit to $S_\Phi(T)$ in Fig. 1. The dashed segment of the fit is not used in this calculation. In YBCO, this is the region near T_c where $D(U_0)$ depends strongly on the exact temperature dependence of $\beta(T)$. In BSCCO, the dashed segment marks the onset of a peak in $m(T)$ predicted from Eq. (3) that is not reflected in the measured slope (Fig. 2), perhaps indicating a noise process outside our model. The two YBCO films show a peak in $D(U_0)$ below 0.1 eV. To facilitate comparison of the peaks in the two films, we have replotted that for YBCO(1) in Fig. 3(a) on an expanded scale. One can understand the appearance of a low-energy peak by inspecting Eq. (2). Below 35 K, $S_\Phi(T)$ increases rapidly, yielding the onset of the peak in $D(U_0)$. As T increases further, $S_\Phi(T)$ levels off and the decrease of $\beta(T)$ dominates, rolling off $D(U_0)$. The peak occurs at an energy corresponding to $T\approx 35$ K: since $t^4 \ll 1$ at this temperature, the peak is at

$$\tilde{U}_0 \approx k_B T[-\ln(\omega\tau_0)] \approx 23 k_B T \approx 0.07\ \text{eV}.$$

In addition to the low-energy peak, YBCO(1) shows a peak near 0.35 eV (arising from the noise peak at 73 K) that is absent in YBCO(2). The higher-energy peak may be associated with grain boundaries or a-axis grains, both prevalent in YBCO(1) but not in YBCO(2), while the lower-energy peak may represent an intrinsic, intragranular pinning energy. The distribution $D(U_0)$ in BSCCO has a rapid onset near 0.03 eV and peaks near 0.2 eV. Our calculation yields a broader peak because the noise increases steadily from 35 to 75 K.

We have also studied the behavior of the noise when the sample is cooled in a small magnetic field B parallel to the c axis. The inset to Fig. 1 shows the results for BSCCO at two temperatures; YBCO films show similar behavior.[11] Although not apparent in the figure, the noise at a given temperature flattens off to a constant value as the applied field is reduced below 0.1 mT. We note that at the highest applied field, 2.5 mT, the average vortex spacing, $\sim(\Phi_0/B)^{1/2}$, of roughly 1 μm is greater than the vortex diameter of about one penetration depth ($\sim$0.3 and 0.4 μm at the two temperatures).[16] Thus, the average interaction between vortices is relatively small. Since we expect the number of vortices to be proportional to B, the fact that $fS_\Phi(f)$ is linear in B supports the idea that the noise arises from the uncorrelated motion of individual vortices.

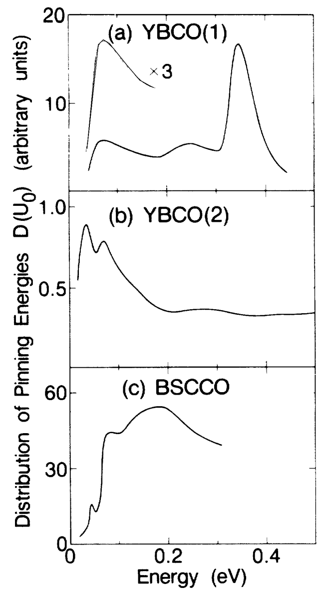

FIG. 3. Density of zero-temperature activation energies $D(U_0)$ vs energy U_0 for (a) YBCO(1), (b) YBCO(2), and (c) BSCCO. Arbitrary units on vertical scale are the same for all three samples. Shapes of the peaks depend slightly on the interpolation scheme chosen in Fig. 1.

In summary, we have shown that the flux noise observed in YBCO and BSCCO is consistent with a model based on thermal activation of single flux vortices. Further support for our analysis of $1/f$ noise into independent Lorentzian processes is provided by the occasional observation of random telegraph noise from a single switching process, which we will discuss in detail elsewhere. One such process may have an unusually large hopping distance under certain circumstances, making it stand out from the ensemble of similar processes that produces $1/f$ noise. The linear dependence of the noise power on the magnetic field in which the samples were cooled supports our assumption that the motion of the vortices is uncorrelated. Observation of $1/f$ noise in these materials over a wide temperature range implies that the pinning energies must have a distribution rather than a single value. We caution, however, that these noise measurements are insensitive to the presence of pinning sites of higher energy than those shown in Fig. 3, since flux pinned at these sites would be very unlikely to move during the time of the measurement. The low-energy peak observed in the YBCO films [Figs. 3(a) and 3(b)] is quite similar to that derived by Hagen and Griessen,[5] although their BSCCO data[8] peak at a much lower energy (0.04 eV) than ours, perhaps reflecting a difference in the microstructure of the samples. Recent zero-field critical-current measurements by Tahara *et al.*[17] on YBCO yielded pinning energies of roughly 0.1 eV. Evidently, at least some experiments in which vortices are driven sample the same pinning barriers as ours, in which vortices are near thermal equilibrium. The presence of the peak in YBCO(1) near 0.35 eV presumably represents a second pinning mechanism. Finally, the origin of the very large peak in the $1/f$ noise at T_c remains an open question. Calculation of $D(U_0)$ in this region is extraordinarily sensitive to the exact functional form of $\beta(T)$. The peak may possibly arise from mechanisms outside the scope of our model, such as the creation of vortex-antivortex pairs when their energy approaches k_BT, fluctuations which drive large regions of the sample normal, or the onset of cooperative vortex motion as $\lambda(T)$ diverges.

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