Suppression of Magnetic-Flux Noise in $YBa_2Cu_3O_{7-x}$ by a Supercurrent

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The magnetic-flux noise generated by a patterned film of $YBa_2Cu_3O_{7-x}$ is reversibly suppressed by the application of a supercurrent. The total noise power decreases by an order of magnitude, in quantitative agreement with a model involving thermally activated vortex hopping between pairs of pinning sites of nearly equal pinning energy. The model yields a force constant of 6×10^{-5} N/m for a vortex at a typical pinning site, and a hopping distance which increases with temperature from 13 nm at 4.2 K to 64 nm at 60 K. The number density of vortices is at least 0.02 μm^{-2}, even in a magnetic field of less than 1 μT.

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The study of magnetic vortex dynamics in superconductors has enjoyed a remarkable resurgence following the discovery of the high-transition-temperature (T_c) cuprates. In these materials, T_c is roughly an order of magnitude larger and vortex pinning energies an order of magnitude smaller than in low-T_c superconductors, opening previously inaccessible regimes of thermally activated resistivity [1], novel vortex phases [2], and giant flux creep [3]. Typical experiments probe the response of a high density of strongly interacting vortices to the Lorentz force exerted by a supercurrent. In a resistivity measurement [1,2], the vortices dissipate energy in response to a transport current; in a flux-creep experiment [3], they relax from the critical state, driven by a circulating shielding current. In both of these cases, only the net displacement of many vortices is measured, and the inferred vortex motion therefore vanishes as the driving force approaches zero. In this Letter we report an experiment, sensitive to the fluctuations of weakly interacting vortices about their mean positions, in which vortex motion exhibits a local *maximum* at zero driving force. By measuring the reduction in magnetic-flux noise caused by a supercurrent, we determine the vortex hopping distance, the distribution of activation energies, the number density of vortices, and the restoring force on a vortex at a typical pinning site.

The $YBa_2Cu_3O_{7-x}$ (YBCO) flux transformer with $T_c=77$ K on which we made our measurements (see Fig. 1) has been described in detail elsewhere [4]. It is supported on a thermally isolated hot stage [5] with its ten-turn input coil approximately 100 μm from a Nb-PbIn superconducting quantum interference device (SQUID) maintained at 4.2 K. Flux noise generated by the transformer is inductively coupled to the SQUID [4]. Mumetal and superconducting Pb shields surround the apparatus, which is cooled in a field of less than 1 μT. A Nb magnetic-field coil operated in a persistent-current mode allows us to apply a static magnetic field, which induces a circulating current in the transformer; zero stored current in the field coil corresponds closely to zero current in the transformer. In the results reported here, the largest applied magnetic field (of order 10^{-5} T) produced a transformer current of $I\approx3$ mA, corresponding to 5×10^4 A/cm^2 in the input coil. Such small fields do not directly affect the flux noise in YBCO films [6], implying that the phenomena we observe result from the supercurrent in the transformer.

The flux noise measured by the SQUID in our geometry is dominated by fluctuations in the supercurrent circulating in the transformer, driven by the motion of vortices. We call this mechanism indirect noise, to distinguish it from the direct noise process in which the flux directly linking the SQUID changes as a vortex moves [4,7]. When we induce a current $I=2$ mA as in Fig. 2(a), the total low-frequency noise power decreases by an order of magnitude from its value at $I=0$; the noise returns to its $I=0$ value when we remove the current. This reversibility demonstrates that the number of mobile vortices in zero applied field has not been altered. As we shall see, a sufficiently large current suppresses indirect noise, so that the residual noise at $I=2$ mA is due largely to direct noise from the cross under, consistent with the order-of-magnitude reduction observed [4] when indirect noise is eliminated by cutting the transformer. Figure 2(a) also indicates the presence of background noise sources other than the transformer, especially at high frequencies, but the difference spectra in Fig. 2(b) scale as $1/f$, as expected for vortex motion [5]. Therefore we subtract the large-current background from our noise measurements at each temperature, and obtain the current dependence of the indirect noise power $S_\Phi(1\text{ Hz})$ which is

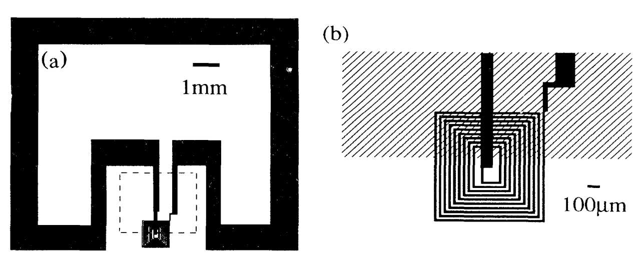

FIG. 1. YBCO flux transformer. (a) Pickup loop formed by wide lines, input coil centered on bottom edge, insulating $SrTiO_3$ layer indicated by dashed box. (b) Enlargement of input coil: The shaded region is $SrTiO_3$ and the vertical strip connected to the center of the coil is the cross under.

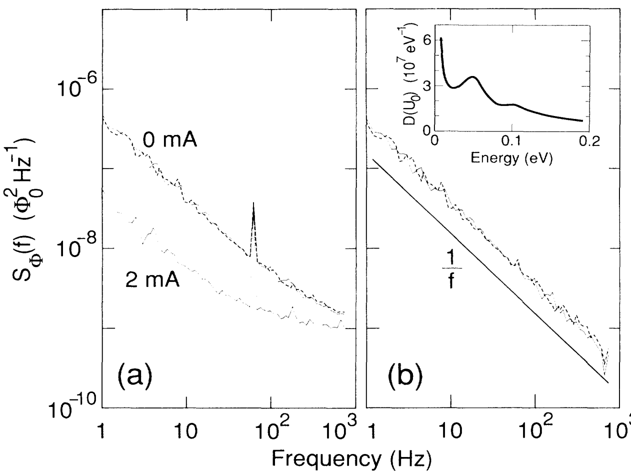

FIG. 2. (a) Total noise power vs frequency with transformer at 39 K. Upper solid curve: initial spectrum ($I=0$); lower solid curve: application of $I=2$ mA; dashed curve: subsequent return to $I=0$. Flattening at high frequencies is caused by Johnson noise from normal metal in apparatus. The spike is 60-Hz pickup noise. (b) Spectra for $I=0$ with spectrum for $I=2$ mA subtracted. The line indicates $1/f$ scaling. Inset: Distribution of activation energies from Eqs. (4) and (5). The peak near 0.05 eV is significant, but the weak 0.1-eV feature is not.

plotted in Fig. 3. The noise peaks symmetrically about $I=0$, and the width of the peaks increases slightly with temperature.

The reduction of noise by a current can be explained by our model [5,8] for $1/f$ noise in YBCO. This model postulates an ensemble of thermally activated bistable processes such as the one depicted in Fig. 4(a). In a transformer segment of width w_j, a vortex hops between pinning sites 1 and 2, separated by a distance l. The temperature-dependent activation energy for hopping out of either site is $U(T)$ [Fig. 4(b)]; we define $U_0=U(0)$. Neglecting other shielding currents, we take the current I to be uniformly distributed across the line so that it exerts a Lorentz force $F=I\Phi_0/w_j$ on each vortex, where Φ_0 is the flux quantum. The force per unit length of vortex is 2 or 3 orders of magnitude less than that in a typical flux-creep experiment [3]. Figure 4(c) shows that the force introduces a misalignment $\Delta U=Fl\cos\theta$ between the minima of the pinning potential, where θ is the angle between the Lorentz force and the vortex trajectory. Increasing current decreases the probability that the vortex will be activated out of site 2, reducing the noise. The lifetimes of states 1 and 2 are

$$\tau_1(T,I)=2\tau_0\exp[U_0\beta-\delta] \quad (1a)$$

$$\tau_2(T,I)=2\tau_0\exp[U_0\beta+\delta]\,, \quad (1b)$$

where the attempt time $2\tau_0$ and $\beta(T)=U(T)/U_0k_BT$ are assumed to be the same for all processes in the ensemble, and $\delta=I\Phi_0l(\cos\theta)/2w_jk_BT$. The factor of 2 in Eqs. (1) is chosen for consistency with Ref. [5]. For the same reason, we choose $U(T)/U_0=1-(T/T_c)^4$ and $\tau_0=10^{-11}$ s; our results are relatively insensitive to these parameters. The change in flux through the SQUID when the vortex hops is approximately [9] $\Delta\Phi=\Phi_l l\cos\theta$, where $\Phi_l=\Phi_0M_i/w_j(L_i+L_p)$, $M_i\approx 3$ nH is the mutual inductance between the input coil and the SQUID, and $L_i\approx 75$ nH and $L_p\approx 20$ nH are the inductances of the input coil and the pickup loop, respectively.

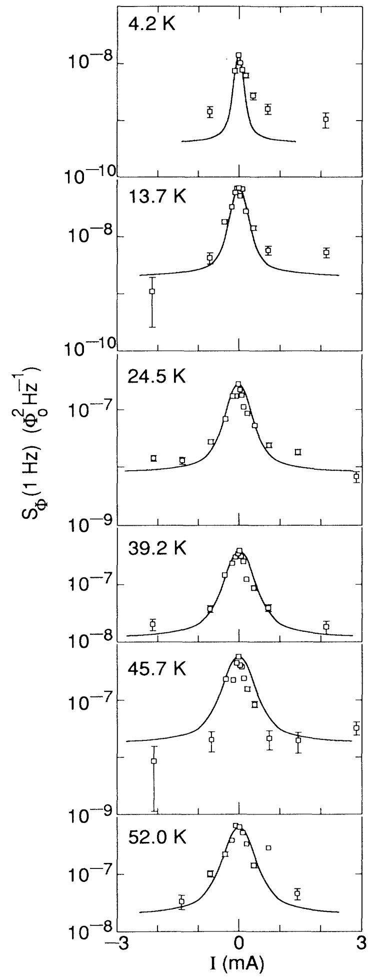

FIG. 3. Noise power S_Φ(1 Hz) vs current in transformer for six temperatures. The points are experimental data, from which the least noise measured at each temperature has been subtracted to remove background. The curves are the sum of predictions of Eq. (3) for each of the segments of the transformer. The central peak is due to input coil and the shoulders to pickup loop.

We can now see why current suppresses indirect noise without significantly affecting direct noise in our geometry. The noisiest indirect processes (largest $\Delta\Phi$) are those involving vortices in the input coil hopping across the line, in the direction of the Lorentz force. However, direct noise from the cross under arises primarily from vortices hopping radially with respect to the SQUID, perpendicularly to the Lorentz force, which thus has little

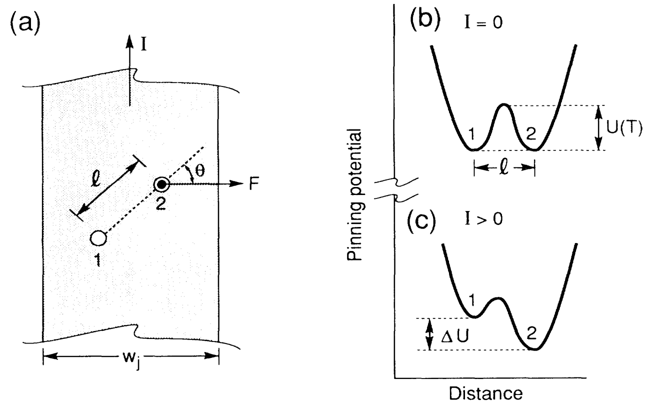

FIG. 4. (a) Schematic of single hopping process in line of width w_j. Current I exerts force F on the vortex which hops a distance l between pinning sites 1 and 2. The scale of l exaggerated. (b) Schematic pinning potential for $I=0$; (c) for $I>0$.

effect. In addition, the linewidth of the cross under is 5 times that of the input coil, making the local Lorentz force significantly weaker.

The power spectrum for a single hopping process is a Lorentzian given by [10]

$$S_\Phi^i(f,T,I)=\frac{4(\Delta\Phi)^2}{(\tau_1+\tau_2)[(\tau_1^{-1}+\tau_2^{-1})^2+(2\pi f)^2]}\ . \qquad (2)$$

The total noise for an ensemble of uncorrelated processes is

$$S_\Phi(f,T,I)=\int_0^\pi \frac{d\theta}{\pi}\int_0^\infty dU_0 D(U_0) S_\Phi^i(f,T,I)\ , \qquad (3)$$

where $D(U_0)dU_0$ is the number of processes with zero-temperature activation energies between U_0 and U_0+dU_0. In Fig. 3 the width of the peaks, which scales roughly as k_BT/l, increases only slightly with temperature; this suggests that l depends on energy, contrary to our earlier assumption [5]. To proceed, we assume that only the nearest pinning site interacts with each vortex, and take the pinning force to be $-k_0r$ (r is the distance between the vortex and the site), so that $l(U_0)=(8U_0/k_0)^{1/2}$. The spring constant k_0 is the only significant unknown parameter in our model. Other models of the pinning potential could also produce satisfactory agreement with the data, which imply only that l increases with U_0. Equation (3) can now be inverted for $I=0$, provided that $D(U_0)$ is slowly varying on the scale of β^{-1}, to yield

$$D(\tilde{U}_0)=fS_\Phi(f,T,0)\beta^2k_0/\Phi_f^2\ln(1/2\pi f\tau_0)\ , \qquad (4)$$

where the characteristic energy $\tilde{U}_0$ satisfies

$$\tilde{U}_0(f,T)=\frac{\ln(1/2\pi f\tau_0)}{\beta}+\frac{1}{2\beta}\ln\left(\frac{\tilde{U}_0\beta+1}{\tilde{U}_0\beta-1}\right)\ . \qquad (5)$$

Thus our zero-current noise measurements, which we extended to 60 K, yield [11] $D(U_0)$ as plotted in the inset of Fig. 2. We obtain the current dependence by solving Eq. (3) numerically. Actually, our flux transformer [4] is composed of three principal segments (pickup loop, input coil, and cross under), each with a different linewidth w_j and therefore a different current dependence. We compute the noise produced by the jth segment under the assumption that it contains a fraction l_jw_j/A of the processes in the ensemble, where l_j is its length and $A=\sum l_jw_j$. The total noise, plotted in Fig. 3, is the sum of these contributions. The shape of the curves is determined primarily by geometrical constants and by k_0; only the peak value depends sensitively on $D(U_0)$.

We obtain the best fit to our experimental data with $k_0=6\times10^{-5}$ N/m, from which we can calculate l. Higher-energy processes in the ensemble have longer hopping distances. Since $\tilde{U}_0$ increases from 8.5 to 190 meV over the temperature range from 4.2 to 60 K, the hopping distance of processes which contribute to the measured noise ranges from 13 to 64 nm. Our previous analysis [7] of random telegraph signals (RTS's) yielded 0.16 μm $\leq l \leq 32$ μm, supporting our contention that each RTS is a single long-range process, while $1/f$ noise results from many short-range hopping events. We note that the noise at 4.2 K in a second transformer [4] with lower-quality YBCO films ($T_c=59$ K) was also suppressed by a supercurrent, yielding a hopping distance of the order of 100 nm. Furthermore, both transformers exhibited RTS's over narrow ranges of temperature. We found that the switching rates were current dependent, but because of the often transient nature of the RTS's, we lack sufficient data to draw quantitative conclusions.

The total number of processes in the experimentally accessible energy range is $N_p=\int dU_0D(U_0)=3\times10^6$, where the integral has been taken from 8.5 to 190 meV. Provided that vortices interact with only the nearest pinning site and that the sites are randomly distributed, our model predicts that each vortex will participate in an average of four processes [12]. The number density of mobile vortices is thus $n_v=N_p/4A=0.02$ μm^{-2}, corresponding to an effective field $B_{\rm eff}=n_v\Phi_0=40$ μT if we ignore vortex polarity [13]. Accounting for processes outside the experimental energy range may increase $B_{\rm eff}$, but it is already much greater than the field B in which the transformer was cooled, implying that there is another mechanism for generating vortices in the film, such as the freezing-in of vortex-antivortex pairs as the film is cooled below T_c. Experiments on other samples [5,6,14] support this hypothesis; the measured noise, which is proportional to B and therefore to the number of vortices for $B\gtrsim100$ μT, becomes independent of field for $B<100$ μT. Certainly in the latter range, the mean vortex spacing is much larger than the penetration depth, justifying our neglect of vortex-vortex interactions.

Our model requires [8,15] that at $I=0$ both sites in Fig. 4(b) have nearly the same activation energy, as would be the case if the same type of defect were present at each site. The distribution in U_0 then arises from the distribution in l. The symmetry of each double well is consistent with our previous observation [7] of RTS's in other samples; the ratio of the activation energies for the two states in each RTS was indistinguishable from unity. The effect of a random inherent misalignment of the minima of the pinning potential would be to broaden the theoretical curve in Fig. 3, particularly at low temperatures. This may explain the discrepancy between theory and experiment at 4.2 K. Alternatively, vortex motion by configurational tunneling [16] could be significant at low temperatures, explaining both the discrepancy and the upturn in $D(U_0)$ at low energies. A second assumption implicit in our discussion is that there is no pinning site to the right of site 2 in Fig. 4(c) into which the vortex can hop. Even if this were not the case, however, the vortex would simply move under the influence of the Lorentz force until it encountered a barrier over which it could not be activated. The reversible decrease in noise with increasing current is a powerful argument for the existence of a distribution of activation energies, since the sample must contain such insurmountable barriers as well as those over which hopping occurs. The activation of vortices over these larger barriers may become significant under more extreme experimental conditions than those of our noise measurement, for example, in high fields near the critical current density or the critical temperature where flux creep becomes significant.

We have demonstrated that the presence of a circulating current in a YBCO flux transformer significantly reduces its noise, suggesting that the performance of practical devices could be improved by this means. The fact that the noise is reduced implies that most double wells are symmetric in energy. Our results rule out a recently proposed alternative theory [17] for magnetic-flux noise in high-T_c superconductors, based on universal conductance fluctuations, which predicts $S_\Phi \propto I^2$. The existence of a large number of mobile vortices despite the small ambient field ($B \ll B_{\rm eff}$) could also explain $1/f$ flux noise in low-T_c SQUIDs [18].

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[1] T. T. M. Palstra *et al.*, Phys. Rev. Lett. **61**, 1662 (1988); E. Zeldov *et al.*, Phys. Rev. Lett. **62**, 3093 (1989).
[2] M. P. A. Fisher, Phys. Rev. Lett. **62**, 1415 (1989); R. H. Koch *et al.*, Phys. Rev. Lett. **63**, 1511 (1989).
[3] Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. **60**, 2202 (1988); C. W. Hagen and R. Griessen, Phys. Rev. Lett. **62**, 2857 (1989).
[4] F. C. Wellstood *et al.*, Appl. Phys. Lett. **57**, 1930 (1990); M. J. Ferrari *et al.*, Appl. Phys. Lett. **58**, 1106 (1991).
[5] M. J. Ferrari *et al.*, Phys. Rev. Lett. **64**, 72 (1990).
[6] M. J. Ferrari *et al.*, IEEE Trans. Magn. **25**, 806 (1989).
[7] M. Johnson *et al.*, Phys. Rev. B **42**, 10792 (1990).
[8] P. Dutta, P. Dimon, and P. M. Horn, Phys. Rev. Lett. **43**, 646 (1979).
[9] J. R. Clem has calculated $\Delta\Phi$ exactly for specific geometries (unpublished).
[10] S. Machlup, J. Appl. Phys. **25**, 341 (1954).
[11] Equations (4) and (5) differ slightly from the results of Ref. [5] because l is no longer assumed to be the same for all processes. This also accounts for the upturn of $D(U_0)$ at low energies, which is quite similar to Fig. 3 of R. Griessen *et al.*, Physica (Amsterdam) **162C**, 661 (1989). The second term on the right-hand side of Eq. (5) is negligible here.
[12] M. J. Ferrari (unpublished).
[13] The actual magnetization may be zero if there are equal numbers of vortices and antivortices, but this is irrelevant for comparison to the field-cooled noise.
[14] M. J. Ferrari *et al.*, Nature (London) **341**, 723 (1989).
[15] M. B. Weissman, Rev. Mod. Phys. **60**, 537 (1988).
[16] S. Gregory *et al.*, Phys. Rev. Lett. **62**, 1548 (1989).
[17] L. Wang *et al.*, Phys. Rev. Lett. **64**, 3094 (1990).
[18] J. Clarke, W. M. Goubau, and M. B. Ketchen, J. Low Temp. Phys. **25**, 99 (1976).