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Random telegraph signals in high-temperature superconductors

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The local magnetization of $YBa_2Cu_3O_{7-x}$ and $Bi_2Sr_2CaCu_2O_{8+y}$ measured with a superconducting quantum interference device is shown to exhibit random telegraph signals (RTS's) over narrow ranges of temperature. We believe these signals arise from the thermally activated hopping of single magnetic vortices between two pinning sites. The spectral density of the RTS is Lorentzian; from the temperature dependence of the characteristic time, we deduce pinning energies of 0.17 and 0.20 eV for samples of $YBa_2Cu_3O_{7-x}$ and $Bi_2Sr_2CaCu_2O_{8+y}$, respectively, at reduced temperatures of 0.99 and 0.87. The amplitudes of various RTS's imply flux hopping distances varying from 0.2 to 30 μm. Multiple metastable states and transitions between "noisy" and "quiet" states are also observed.

Many recent experiments on high-transition-temperature (high-T_c) superconductors are interpreted in terms of the dynamics of magnetic flux vortices. Flux creep,[1,2] thermally activated resistivity,[3] dissipation in mechanically driven samples,[4] voltage noise,[5] and flux noise[6-8] are all manifestations of vortex motion, generally involving large numbers of vortices. Although the existence of individual static vortices in high-T_c materials has been demonstrated by flux decoration techniques,[9] the motion of single vortices has not previously been systematically studied experimentally. In this Rapid Communication, we describe measurements of random telegraph signals (RTS's) in the time-dependent magnetization of $YBa_2Cu_3O_{7-x}$ films and $Bi_2Sr_2CaCu_2O_{8+y}$ single crystals. These signals were observed, in at least one temperature range, in 5 of 10 samples, suggesting that they represent a common phenomenon in high-T_c materials. Gough *et al.*[10] have previously observed similar signals. We attribute these RTS's to the hopping of a single flux line between two pinning sites, and show that such processes have a Lorentzian power spectrum with a characteristic time τ. Analyzing this time as a function of temperature, we find the events to be thermally activated, and determine the depths U of the potential wells in which the flux lines are pinned. We estimate the distance over which a vortex hops from the amplitude of the RTS. Our observation of RTS's in the same samples[7,8] that exhibited flux noise with a power spectrum varying as $1/f$ (f is the frequency) strongly supports the model in which the $1/f$ noise arises from the incoherent superposition of many such flux hopping events.

The essence of the experimental apparatus,[6] which is in a vacuum can surrounded by liquid ^{4}He at 4.2 K, is shown in the inset to Fig. 3. A thin film Nb/Pb-In superconducting quantum interference device (SQUID) in a square washer configuration is supported a distance $d \approx 100$ μm from an unpatterned sample of $YBa_2Cu_3O_{7-x}$ or $Bi_2Sr_2CaCu_2O_{8+y}$. The SQUID is attached to a sapphire plate cooled by the bath, while the temperature of the sample can be raised above T_c. The experiment is cooled in an ambient magnetic field less than 10^{-6} T, and the mean distance between vortices is much greater than the penetration depth $\lambda \approx 0.2$ μm.

To give a brief survey of the phenomena, in Fig. 1 we show the time dependence of the magnetic flux Φ generated by three samples. The data in Figs. 1(a) and 1(b) are from $YBa_2Cu_3O_{7-x}$ No. 3, a 0.3-μm-thick c-axis film with $T_c = 89.8$ K grown epitaxially *in situ* on a (100) $LaAlO_3$ substrate by pulsed laser deposition.[11] Over most of the range of temperatures in which noise was observable,[8] 75–90.4 K, the power spectrum was approximately $1/f$. Over a narrow temperature range (88.4–88.6 K), however, the flux switched back and forth between two discrete levels at a rate that increased markedly with temperature. We interpret this signal as the hopping of one (or more) flux quanta between two pinning sites. The magnitude of the signal in Figs. 1(a) and 1(b) is $\Delta\Phi = (1.3 \times 10^{-3})\Phi_0$, where Φ_0 is the flux quantum. The magnitude of the fluctuations about each level is also roughly the same: this noise may be due to the motion of the vortex (or bundle) in its metastable state, or to the motion of other vortices in the film. This event is typical of the kind of RTS we most commonly encountered.

Figure 1(c) was obtained from $YBa_2Cu_3O_{7-x}$ No. 2, a

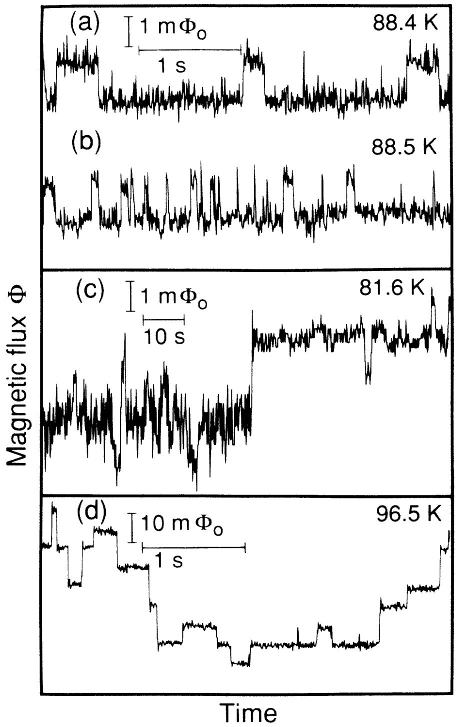

FIG. 1. Flux through SQUID vs. time generated by (a) laser-deposited $YBa_2Cu_3O_{7-x}$ No. 3 at 88.4 K, (b) same film at 88.5 K, (c) sputtered $YBa_2Cu_3O_{7-x}$ No. 2 at 81.6 K, and (d) $Bi_2Sr_2CaCu_2O_{8+y}$ No. 2 flake at 96.5 K. Note changes of scale in (c) and (d). Zeros of axes are arbitrary.

c-axis $YBa_2Cu_3O_{7-x}$ film grown epitaxially *in situ* on a (100) MgO substrate by off-axis sputtering from a single target.[12] This sample, previously described in Ref. 7, was about 0.3 μm thick with $T_c = 84$ K. The flux switches between two states separated by $(2.8\times10^{-3})\Phi_0$, but in this case the magnitude of the noise in state 1 (the lower level) is much higher than in state 2. We interpret this event as the hopping of a vortex (or bundle) between a pinning site where it is relatively mobile (state 1), producing a high noise level, and another site where it is much more restricted spatially. Figure 1(d) was obtained from a *c*-axis flake of $Bi_2Sr_2CaCu_2O_{8+y}$, about 150 μm thick. The transition temperature, determined magnetically, was 93 K; however, the existence of large levels of flux noise at higher temperatures indicates that small amounts of a second superconducting phase were present, with $T_c \approx 110$ K. The flux switches between a number of values, approximately equally spaced by $\Delta\Phi = (6.5\times10^{-3})\Phi_0$. A likely explanation for this behavior is that a fixed number of flux quanta occupy two pinning sites, and the various flux levels correspond to differing occupancies of these sites. The analysis below is based on this interpretation.

We now turn to a quantitative analysis of the RTS. From the amplitude, we can estimate the distance over which the flux lines hop. As shown in the inset in Fig. 3, a single flux quantum which hops radially a distance l causes the flux through the SQUID (Refs. 13 and 14) to change by $\Delta\Phi \approx \Phi_0(l/w)\alpha$, where $w = 400$ μm is the width of the SQUID loop, and we estimate[6] the coupling coefficient α to be approximately 0.7. If the vortex moves in a direction other than radial, $\Delta\Phi$ will be reduced; it follows that $l \geq w\Delta\Phi/\alpha\Phi_0$. In Table I, we list these lower limits on l for RTS's in various samples. Where we could observe the same process over a range of temperatures, we found l to be independent of temperature, implying that the vortex continues to hop between the same two sites. Of course, if the flux bundle actually contains not 1 but N flux quanta, l should be reduced to l/N. Because $\Delta\Phi$ remains constant over observational times of hours and also as the temperature is varied, we are led to believe that the hopping process involves a single flux quantum and we shall make that assumption in the remaining discussion. A hopping distance of micrometers, observed in several samples, is quite long, suggesting that the vortex is moving along a path of weak superconductivity, such as a twin or grain boundary.

We next address the question of whether the RTS arises from thermal activation, in which case the lifetimes $\tau_1(T)$ and $\tau_2(T)$ in each of the two potential wells are given by

$$\tau_i(T) = \tau_{Ai}\exp[U^{(i)}(T)/k_BT],\ i = 1,2\ . \quad (1)$$

Here, τ_{Ai} is the attempt frequency in the ith state and $U^{(i)}(T)$ is the temperature-dependent energy barrier for hopping out of that state. We note that the ratio $\gamma = \tau_1/\tau_2$ is exponentially sensitive to the difference in activation energies $U^{(1)}(T) - U^{(2)}(T)$, and in Fig. 2(a) we plot values of γ, obtained from the time traces for sample $YBa_2Cu_3O_{7-x}$ No. 3, versus T. Our measurements of γ are consistent with a *constant* value of 4.5 ± 1.0, even though τ_1 and τ_2 change by 2 orders of magnitude over the same temperature range. We conclude that the states 1 and 2 have very nearly the same activation energy, so that the asymmetry in their lifetimes can be attributed to different attempt frequencies τ_{A1}^{-1} and τ_{A2}^{-1}. We expect the corresponding power spectrum to be a Lorentzian of the form[15]

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

and in Fig. 3 we plot $S_\Phi(f)$ measured in $YBa_2Cu_3O_{7-x}$

TABLE I. Vortex hopping distances for different RTS's observed in five samples at various temperatures. These values are lower limits. $YBa_2Cu_3O_{7-x}$ No. 4 is sample 2 of Ref. 6, and $Bi_2Sr_2CaCu_2O_{8+y}$ No. 1 is described in Ref. 7.

Sample	$YBa_2Cu_3O_{7-x}$ No. 2		$YBa_2Cu_3O_{7-x}$ No. 3		$YBa_2Cu_3O_{7-x}$ No. 4	$Bi_2Sr_2CaCu_2O_{8+y}$ No. 1			$Bi_2Sr_2CaCu_2O_{8+y}$ No. 2		
T(K)	78.4	81.1	85.6	88.4[a]	50.9	89.9	90.5	91.1	35.3	50.6	95.1[a]
l(μm)	0.80	2.7	0.16	0.76	5.8	26	32	10	5.1	5.2	3.7

[a]Process observed over a range of temperatures. See text.

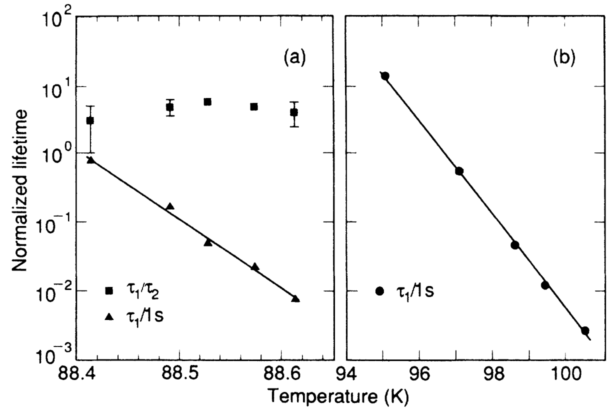

FIG. 2. Lifetimes vs temperature for (a) laser-deposited $YBa_2Cu_3O_{7-x}$ No. 3 film and (b) $Bi_2Sr_2CaCu_2O_{8+y}$ No. 2 flake. Solid lines are least-squares fits of Eq. (1) to $\tau_1(T)$ assuming $U(T)=U_0(1-t^4)$ and $\tau_{A1}=10^{-11}$ s. Fitting parameters are given in Table II.

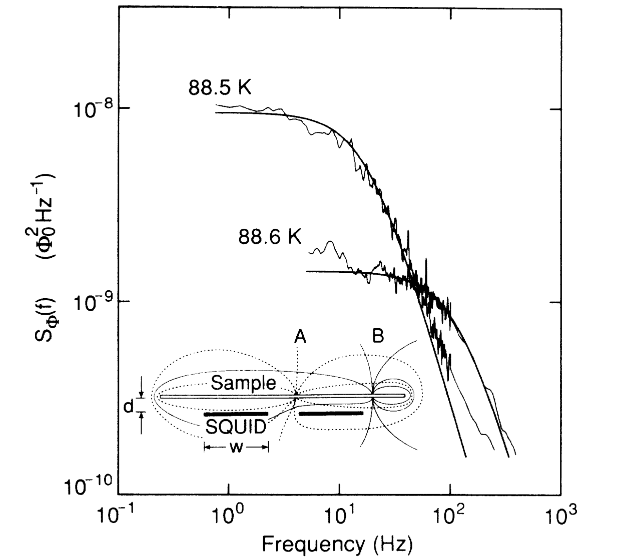

FIG. 3. Spectral densities of random telegraph signals from laser-deposited $YBa_2Cu_3O_{7-x}$ at 88.5 and 88.6 K. Light curves are measured noise. Heavy curves are Eq. (2) with $\Delta\Phi=(1.3\times10^{-3})\Phi_0$ and $\gamma=4.5$, as determined from time domain data, and $\tau_1=48$ and 7.3 ms, respectively. Departures at high frequencies are caused by noise from other vortices in the film and from the measuring system itself. Inset: Schematic cross section of sample and SQUID placed distance d apart. The width of the SQUID at its narrowest is w. Vortex pinned at site A couples flux $\Phi\approx\alpha\Phi_0$ (dotted field lines) into the SQUID, while one at site B couples negligible flux (solid field lines). We assume flux through SQUID decreases linearly with displacement of vortex from A to B.

No. 3 at two temperatures. The solid curves are obtained from Eq. (2) with fixed values of γ and $\Delta\Phi$, as determined from the time traces; τ_1 is the only fitting parameter. From fits of this kind, we obtain τ_1 versus temperature, shown plotted as triangles in Fig. 2(a). A similar treatment for $Bi_2Sr_2CaCu_2O_{8+y}$ No. 2 yields $\gamma\approx1$, and enables us to plot τ_1 versus temperature as shown in Fig. 2(b).

Having determined $\tau_1(T)$, we can estimate values for the zero-temperature flux pinning energy U_0. This analysis must involve the functional form of $U(T)$, but the temperature intervals over which values of $\tau_1(T)$ exist are too small to enable us to determine this unambiguously. If we were to assume that $U(T)$ is well approximated by a temperature-independent U_0, as proposed, for example, in Ref. 3, then a least-squares fit of Eq. (1) to the data from $YBa_2Cu_3O_{7-x}$ No. 3 would yield $U_0=16$ eV and $\tau_{A1}^{-1}\approx10^{900}$ Hz. Since this attempt frequency is unphysically high, we conclude that a temperature-independent pinning energy is inconsistent with our data. The appropriate functional form for $U(T)$ is a matter of some dispute. It is generally taken to be proportional to $[B_c^2(T)/2\mu_0]\xi^n(T)L^{3-n}$, where $B_c(T)$ is the critical field, $\xi(T)$ is the Ginzburg-Landau coherence length, L is a temperature-independent pinning length, and $n=3$, 2, or 1. We regard T_c as a fitting parameter, since the small region in which the vortex moves may have a transition temperature different from that measured for the sample as a whole, and restrict τ_{A1} to the physically meaningful range[16] 10^{-12} s $\leq\tau_{A1}\leq10^{-5}$ s. Fitting Eq. (1) to the measured values of $\tau_1(T)$, we find the values of U_0 and T_c listed in Table II, using the following temperature dependences of $U(T)$:

n=3. Using this value and the results[16] $\Phi_0=2\sqrt{2}\pi\times\lambda(T)\xi(T)B_c(T)$, where λ is the penetration depth, $\lambda(T)/\lambda(0)=(1-t^4)^{-1/2}$, and $B_c(T)/B_c(0)=1-t^2$, we find $U(T)=U_0(1+t^2)(1-t^4)^{1/2}$; here, $t=T/T_c$.

n=2. This value yields $U(T)=U_0(1-t^4)$. Fits to Eq. (1) for $\tau_{A1}=10^{-11}$ s are shown in Fig. 2, and are representative of the quality obtained of all values of τ_{A1} and n.

n=1. This model has had considerable success in explaining high-field results,[17] giving $U(T)=U_0(1-t^2)\times(1-t^4)^{1/2}$.

We see from Table II that U_0 increases as n decreases from 3 to 1. The $n=1$ values for $YBa_2Cu_3O_{7-x}$ No. 3 are so high as to be physically unlikely; since the model is derived from the shear energy of a strongly interacting vortex lattice,[17] it is probably inappropriate to our low-field experiment. On the other hand, we have no basis for preferring the $n=2$ values over the $n=3$ values; both activation energies correspond to a single vortex pinned over a length less than or equal to the sample thickness. We note that the values of $U(T_m)$, where T_m is the midpoint of the temperature range over which switching was observed, are insensitive to the temperature dependence of $U(T)$. Furthermore, since attempt times for vortex motion in high-temperature superconductors have been observed[2,3,7] to be small (10^{-12} s $\leq\tau_{A1}\leq10^{-10}$ s), for this parameter range we obtain from Table II $U(T_m)=0.175\pm0.015$ eV for $YBa_2Cu_3O_{7-x}$ No. 3 and $U(T_m)=0.20\pm0.02$ eV for $Bi_2Sr_2CaCu_2O_{8+y}$ No. 2. Thus, we can obtain reliable estimates of the pinning energy in the temperature range where the random telegraph signals appear, but have no meaningful way to extrapolate them to zero temperature without a model of $U(T)$ from another source.

TABLE II. Zero-temperature activation energies U_0 and local transition temperatures T_c deduced for RTS's in two samples for different values of attempt time τ_{A1} and different models of the temperature dependence of $U(T)$. The models are labeled by n, the power of the coherence length in the activated volume. A typical activation energy in the temperature range where the switching was observed is $U(T_m)$, where $T_m=88.5$ K for $YBa_2Cu_3O_{7-x}$ No. 3 and 97.8 K for $Bi_2Sr_2CaCu_2O_{8+y}$ No. 2.

	$n=1$		$n=2$		$n=3$		$U(T_m)$
τ_{A1} (sec)	U_0 (eV)	T_c (K)	U_0 (eV)	T_c (K)	U_0 (eV)	T_c (K)	(eV)
Sample $YBa_2Cu_3O_{7-x}$ No. 3							
10^{-5}	33	89.1	4.0	88.9	0.37	88.7	0.07
10^{-10}	23	89.8	4.1	89.4	0.56	89.0	0.16
10^{-11}	21	90.0	4.1	89.5	0.59	89.0	0.17
10^{-12}	21	90.1	4.1	89.6	0.63	89.0	0.19
Sample $Bi_2Sr_2CaCu_2O_{8+y}$ No. 2							
10^{-5}	0.93	107	0.39	104	0.12	101	0.08
10^{-10}	0.81	117	0.47	110	0.20	104	0.18
10^{-11}	0.81	120	0.48	112	0.22	105	0.20
10^{-12}	0.80	122	0.49	113	0.23	105	0.22

Our technique allows direct observation of the motion of single vortices as they hop reversibly between two pinning sites, providing a classic example of an RTS with a well-defined Lorentzian power spectrum, and lending strong support to our model for $1/f$ noise presented elsewhere.[7] We emphasize that the RTS's illustrated here are singular examples from a large family of such processes that more generally combine incoherently to produce $1/f$ noise. These particular RTS's dominate the overall noise in a narrow temperature window in which $2\pi f \tau_1(T)$ is of the order of unity, that is, when the knee frequency of the Lorentzian falls within the measured bandwidth. The most likely explanation for this dominance is that the hopping distances listed in Table I, typically 1–10 μm, are substantially larger than those contributing to the background $1/f$ noise. We have also shown that the hopping processes are thermally activated. For the particular processes illustrated here, the two pinning energies were virtually identical, but this symmetry need not apply to all such processes. Although we can rule out a temperature-independent pinning energy and probably one scaling as ξ, the observational temperature range is too narrow for us to be able to distinguish between $U(T)$ scaling as ξ^2 and as ξ^3. However, we are able to estimate the pinning energy in the temperature range where the process was observed. The sensitivity of U_0 to the model for $U(T)$ demonstrates that the inferred pinning energy depends very strongly on the method by which it is determined. Experiments in different regimes of temperature, and those which apply magnetic-field gradients,[1,2] or transport currents,[3] will probe different portions of the distribution of activation energies.[18] The values of U_0 in Table II exceed those determined from our analysis of $1/f$ noise[7] because the pinning sites that yield $1/f$ noise at low temperatures are different from those producing RTS's near T_c.

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