Vortex-Motion-Induced Voltage Noise in $YBa_2Cu_3O_{7-\delta}$ Single Crystals

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We have investigated vortex motion below the quasistatic melting transition in a detwinned $YBa_2Cu_3O_{7-\delta}$ single crystal by measuring the differential resistance and the voltage noise. With the magnetic field parallel to the copper-oxygen planes and the large, flat surface of the sample, the noise power spectrum permits us to deduce that the surfaces are the dominant source of the noise and that the vortices appear to be flowing in channels. In certain regimes, the noise power spectrum exhibits unusually sharp and distinct peaks which are periodic in frequency.

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In a type-II superconductor, in the mixed state, the sample is penetrated by an array of magnetic vortices each of which contains a quantized amount of magnetic flux. In an applied current, there will be a Lorentz force density $\vec{f} = \vec{J} \times \vec{B}$ on the vortices, where $\vec{J}$ is the current density and $\vec{B}$ is the flux density [1]. If the vortices are at rest, there will be no electric field and the resistance effectively zero. If the vortices are moving with a mean velocity $\vec{v}$, an electric field $\vec{E} = -\vec{v} \times \vec{B}$ appears and there is a finite resistance. At the microscopic level, there will always exist fluctuations [2] in the vortex motion either of thermal origin or due to the influence of defects in the sample. The electric field can then be separated into a time-averaged component $\vec{E}_{dc}$ and a fluctuating, noisy component $\delta\vec{E}$. Measurements of the averaged component permit one to study the macroscopic motion of the vortex ensemble as a whole: The study of the voltage noise $\delta\vec{E}$ gives one a powerful probe of the microscopic details of that vortex motion.

In the standard approach [3] the details of the dynamic regime are understood as arising from the motion of the vortex lattice through a cloud of pinning centers which attempt to rip and tear the lattice as it moves. Early noise measurements [4] provided support for the idea that the noise came from the motion of bundles of correlated vortices, carried along rigidly with the moving lattice. These bundles produced a shot-noise power spectrum with a characteristic rolloff frequency given by the inverse transit time of the vortices across the sample. The vortex bundle concept still remains central to more sophisticated models and simulations [3–5] which deal with the motion of vortices swimming through an atmosphere of pinning centers. However, in very clean superconductors in which volume pinning is expected to be weak, surface effects should play a dominant role. In particular, the interaction of vortices with the sample's surface and shape produce surface and geometrical barriers for flux entry and exit while defects at the surface result in surface pinning [6]. Consequently, in the weak pinning limit, vortex motion can, in principle, be quite different from the classical picture [7].

Clean, high T_c superconducting crystals, such as the detwinned $YBa_2Cu_3O_{7-\delta}$ (YBCO) crystal studied here, have very small critical currents and belong to the class of materials for which the surface terms should dominate [8]. In addition, the study of these materials has led to the development of several new concepts in vortex physics such as vortex liquids and glasses as well as a melting transition [9] between the solid and liquid phases. These new ideas justify revisiting the microscopic issues of vortex motion using noise measurements. In the Letter we report studies of the voltage noise created by the motion of the vortex lattice in YBCO in response to an applied dc current. The experiments were done in a parallel geometry with the field parallel to both the copper-oxygen planes of the crystal and the large surfaces of the flat sample. In this geometry, one expects the surface effects to be considerably enhanced. We will show that, except for very near the melting transition, vortex motion occurs via channels of flowing vortices in the sample. We can also show that the opening and closing of the channels is controlled by the surfaces of the sample. We believe that this type of vortex motion is characteristic of type-II superconductors with weak pinning.

Our measurements were performed on a detwinned crystal of YBCO grown by quenching the tetragonal phase during flux growth [10]. The absence of twins in our sample was checked by examining the crystal with polarized light. The sample had a T_c of 93.25 K ($\Delta T_c \approx 0.1$ K) as measured by the zero-field resistive transition. The sample was a regular parallelpiped with length (along the **a** axis) of 0.8 mm, width (along the **b** axis) of 0.4 mm, and thickness (along the **c** axis) of 0.02 mm. The volume voltage and current contacts were placed on the upper side of the sample with the voltage contacts separated by ~0.18 mm. The results shown in this Letter were obtained with the

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current along the **a** axis of the sample and the field along the **b** axis. The in-plane alignment is estimated to be ~2°. In this orientation the flowing vortices cross the sample parallel to the **c** axis.

In order to orient the reader as to where in the B-T plane the various measurements take place, we will first construct the phase diagram for the melting line and two other dynamic responses of the flowing vortex lattice from measurements of the differential resistance (dV/dI) and the voltage noise. Shown in Fig. 1 is the differential resistance (dV/dI) at a fixed temperature versus applied field for different applied dc and ac currents. In the technique, the differential resistance is measured by superimposing an ac current (56 Hz) on top of the dc current and the response at the ac frequency is measured with a phase-sensitive detector. The quasistatic melting field B_m can be identified with the sharp transition at about 4 T in the data taken at $I_{\mathrm{ac}} = 9\ \mu\mathrm{A}$ and $I_{\mathrm{dc}} = 0$. B_m is the field below which, for weak currents, the flow is dissipationless (pinned solid) and above which there is a finite resistance (vortex liquid). In this material the melting line coincides with the irreversibility line [11].

In the presence of a sufficiently large dc current, a nonzero differential resistance can be detected well below B_m (for example, see the data for $I_{\mathrm{dc}} = 0.3$ mA). Thus the flowing lattice can be either a solid or a liquid. This observation is relevant to the discussion of whether the irreversibility line is a melting transition or a depinning line. The data shown in Fig. 1 indicate that *a depinned and flowing lattice can melt.* However, this dynamic regime of vortex motion is not homogeneous. First, as shown in Fig. 1, there is a broad, S-shaped feature which occurs at about 3 T. This feature is related to the peak effect (PE) [12] which is quite often seen in type-II superconductors. Second, voltage noise measurements taken at the same time (not shown) indicate that the moving vortices produce a noise voltage which is maximal in the PE region and goes below our sensitivity limit at a field which coincides with the melting field B_m. These data are summarized in the inset in Fig. 1 where we have plotted three quantities as a function of temperature: B_m, the location of the peak effect, and the location of the collapse of the noise signal. In what follows, we will discuss data taken well below the PE line.

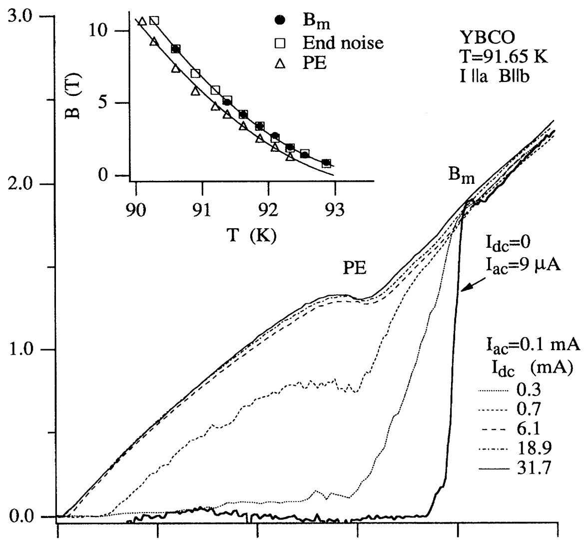

FIG. 1. The differential resistance dV/dI vs the field B, at 91.65 K, for different dc currents. The dV/dI trace at $I_{\mathrm{dc}} = 0$ and $I_{\mathrm{ac}} = 9\ \mu\mathrm{A}$ increases sharply at the quasistatic melting field ($B_m \approx 4$ T). At higher currents ($I_{\mathrm{dc}} > 0.7$ mA), the moving vortex assembly rapidly reaches a regime of homogenous flow as the field is increased. A feature noted PE appears at about 3 T. This feature is associated with the peak effect. Inset: B-T diagram constructed plotting B_m, the end of detected noise (not shown) and the local minimum in dV/dI at the PE feature. The lines in the inset are guides for the eye.

Figure 2 shows a typical current-voltage characteristic obtained in the solid phase below the PE line. Figure 2 also shows the associated low-frequency voltage noise power $W_{5\ \mathrm{Hz}}$ which was measured in parallel and at the same time. To avoid hysteretic effects, the sample was field cooled with an applied dc current in excess of the critical current. In the data shown in Fig. 2 we can distinguish four separate regimes labeled I–IV. They are as follows: (I) The possibly truly superconducting regime which occurs for $I_{\mathrm{dc}} < 7$ mA where the vortices are at rest for the time scale of our experiment and below our voltage resolution of 0.1 nV. (II) An early regime of vortex motion for $7 < I_{\mathrm{dc}} < 16$ mA which is strongly

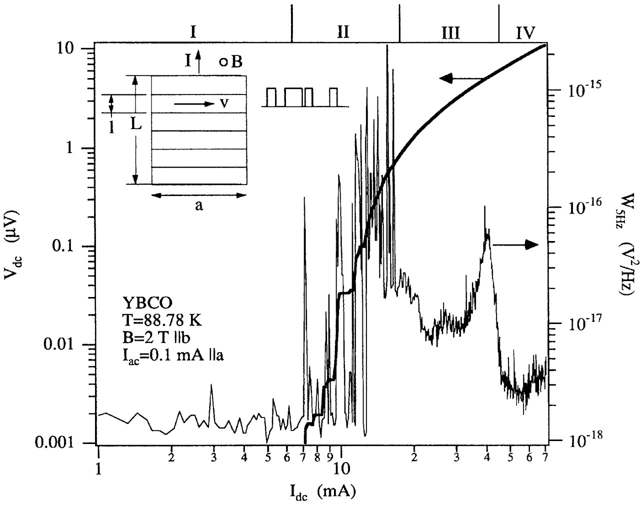

FIG. 2. The voltage-current characteristic and the voltage noise at 5 Hz in a detwinned YBCO crystal at 88.78 K and 2 T, plotted on a double logarithmic scale. Four regimes of vortex motion are distinguished and marked by numbers I–IV. Inset: simplified model for the vortex channel picture (see text for details).

nonlinear and where the voltage increases in steps. In this regime, each voltage step gives rise to a sharp noise peak. (III) and (IV) are regimes of homogeneous flow where the sharp noise peaks disappear. At currents $16 < I_{\mathrm{dc}} < 40$ mA the flow is weakly nonlinear (region III). At high currents 40 mA $< I_{\mathrm{dc}}$ a voltage is observed which is proportional to $R(I - I_c)$ and the flow becomes linear (region IV). The transition from nonlinear to linear (III to IV) is sometimes marked by a relatively large noise peak as can be seen in Fig. 2, but this is not always the case. At temperatures much higher than that used for the data in Fig. 2, the early regime of vortex flow (region II) cannot be detected with our resolution.

The steeply increasing current-voltage characteristic in regime II is one of the central results of this Letter. This behavior is similar to results found in type-I superconductors [13]. In the type-I superconductors, direct magneto-optical studies have been able to relate this type of current-voltage curve to the formation of channels of flux motion in the intermediate state. Such a picture suggests that each step in the current-voltage curve is the result of a new channel for vortex motion. The predictions from such a picture can be explored by using the simplified model sketched in the inset of Fig. 2. We imagine a situation where we have N channels, each with a width l. The distance between voltage contacts is $L = Nl$. We assume that the channels are independent of each other. When a channel is open, the vortices nucleate at one side and cross the sample thickness a with a fixed velocity v. We assume no fluctuations in the vortex density or vortex direction inside a channel. This results in a voltage $V = vlB$ for an open channel. If the channels open and close in a random fashion given by a Poisson distribution characterized by an average frequency λ, then a given channel would produce a random set of rectangular voltage pulses of height $V = vlB$ and of different time durations as is shown in the inset. In such a model the average length of time a channel remains open (that is, $1/\lambda$) can be either longer or shorter than the transit time for a vortex to cross the sample $\tau_T = a/v$. For the N independent channel model, it is straightforward to derive the voltage power spectrum which is the Lorentzian $W(f) = (V_{\mathrm{dc}}^2/N\lambda)[1 - (\pi f/\lambda)^2]^{-1}$, where V_{dc} is the mean voltage given by $BLv/2$. Note that this model assumes only velocity fluctuations and implies that there should be no field fluctuations [2].

Such a simple model might not be applicable in region II where the channel structure is rapidly changing with increasing current. However, in regions III and IV, the channel structure appears to be more regular. A test of this is a measure of the noise power spectrum. Shown in Fig. 3 is a measure of this spectrum for a current in region III. For $I_{\mathrm{dc}} = -18.4$ mA we find a Lorentzian form $W(f) = W(0)[1 - (\pi f/f_c)^2]^{-1}$, with $W(0)$ the low frequency noise level and f_c the corner frequency. We find similar spectra throughout regions III and IV. Also we always find that the corner frequency f_c is less than $1/\tau_T$. This means that the average time duration of the voltage pulses is longer than the average transit time of a vortex. This observation excludes models in which the voltage noise arises from density fluctuations which are rigidly carried across the sample as in a bundle picture. From our simple model, the width of a channel can be estimated to be $\sim 30a_0$ at the beginning of region III, where $a_0 \cong \sqrt{\phi_0/B}$ is the vortex spacing, and gradually diminishing to $\sim a_0$ in the linear region IV. The idea of channels seems to be capable of explaining our data, at least in the regime below the peak effect [14]. However, this then raises the question of the regularity of the channels and how they nucleate. These issues are addressed by the experiment we discuss next.

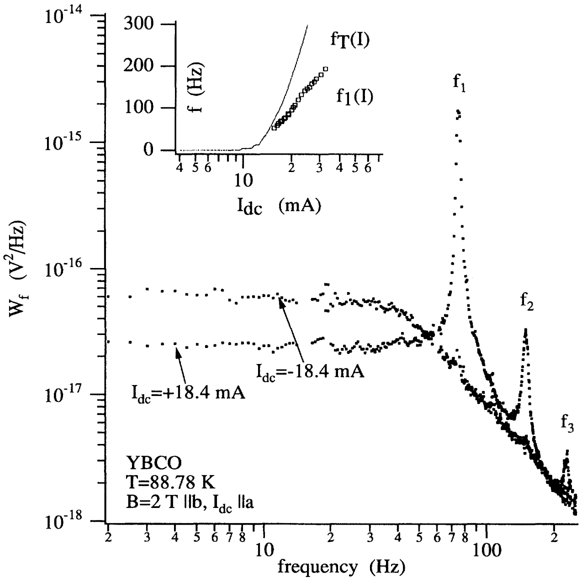

FIG. 3. The noise power spectrum for both polarities of an equal-magnitude dc current. As the polarity is changed, the surface where the vortices nucleate also changes. These data show the importance of the surface as the origin of voltage noise. The peaks in the power spectrum indicate unexpected periodic behavior. Inset: Frequency of the first peak, f_1, and the inverse of the transit time, f_T, vs the applied current.

Figure 3 shows how the noise power spectra depends on the sign of the driving current. In this geometry, changing the sign of the current exchanges the surfaces where the vortices nucleate and are destroyed. As discussed previously, for $I_{\mathrm{dc}} = -18.4$ mA one finds a Lorentzian with $f_c = 110$ Hz and $W(0) = 5.5 \times 10^{-17}$ V^{2}s. The dc voltage at this current is ~ 1 μV, which gives $1/\tau_T \sim 139$ Hz. However, if the current is reversed, a completely new phenomenon is observed. One finds three very sharp peaks in the noise spectra which are superimposed on the Lorentzian background. The peaks are a reproducible phenomenon. The peaks occur at frequencies that are in the ratio of 1:2:3. We have seen up to six peaks in various regimes. Shown in the inset of Fig. 3 is the current dependence of both $f_T = 1/\tau_T$ and the frequency of the first peak f_1. The peaks appear abruptly at ~16 mA and disappear at the end of region III.

The data in Fig. 3 make it very clear that the surfaces play an important role in generating the noise that one sees in this system. Given the low critical current, this is perhaps what one would have expected. At the surface, there should be a surface barrier [6] that will control the entry of vortices (but not their exit) and such a barrier might be the mechanism for the opening and closing of the channels. In our experiment, the two surfaces have been treated quite differently. One side has been glued to a sapphire substrate while the other has voltage and current contacts on it and is likely to be oxidized. Thus the fact that one surface nucleates vortices differently than the other is perhaps not too surprising. What is surprising and unexpected was the observation of noise peaks. These suggest some kind of coherent oscillation of the channels. Such an effect has been seen in type-I superconductors using magneto-optics. However, in type-II superconductors, to our knowledge, there have been no reproducible observations of such a phenomenon.

In conclusion, we report on voltage noise measurements on single crystal YBCO samples with the field in the plane of the sample. We have been able to show that the surfaces are the main source of the noise due to the motion of vortices and that the motion appears to proceed via flow in channels. Finally, we report the observation of sharp noise peaks, which we speculate are due to the coherent oscillation of the channels. These peaks demonstrate how far from uniform elastic flow the motion of vortices in clean YBCO can be.

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