Persistent Metastable States in Vortex Flow at the Peak Effect in $NbSe_2$

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Non-Gaussian flux-flow noise was measured in the "peak-effect" regime of $NbSe_2$. The form of the second spectra showed that neither flux bundles with Poisson statistics nor simple flow channels switching on and off could account for the noise. More complicated persistent flow patterns were needed. These metastable flow states were shown to correspond to different pinned configurations. [S0031-9007(96)01401-9]

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Statics and dynamics of magnetic flux line lattices (FLL) in type-II superconductors in the presence of quenched pinning disorder have attracted a great deal of attention in recent years [1]. Of special importance is the nature of FLL dynamics and its relation to the underlying spatial (and temporal) ordering in the pinned and moving states [2]. The appearance of the so-called peak effect (i.e., a sharp peak in the critical current for the onset of motion) in close proximity to an underlying FLL-melting transition is being studied extensively in both the high-T_c [3] and the conventional [4] systems.

There has also been much speculation on the nature of the vortex motion in the peak-effect regime [4]. Several recent studies in this regime [5–7] have found large flux-flow noise [8,9], whose statistical properties provide a useful new window on the dynamical effects in the flowing vortex condensate. Large non-Gaussian effects have been found, supporting some sort of plastic-flow picture [5]. However, the nature of the dynamical coherence in this regime has not been much explored. In particular, it has not previously been established whether the noise is a purely dynamical effect involving metastable flow patterns far from equilibrium, or rather a symptom of the many metastable pinned configurations available to the vortex condensate. In this Letter, we provide evidence unambiguously demonstrating that the noise arises from complicated configuration fluctuations which persist even when the vortices are not flowing.

Standard models of vortex flow noise have been based on independent vortices or independent vortex bundles [6,8]. Such models predict Poisson statistics with a single time constant for bundles traversing the sample. It is known, however, that such models are inadequate at least in some regimes [10]. Recent noise measurements on flux flow near the peak effect in Y-Ba-Cu-O have been interpreted in terms of independent channels of flow opening and closing, yielding Lorentzian spectra with much slower time constants [7]. Both pictures lead to specific predictions about higher-than-second-order moments of the voltage time series in a transport experiment. Specifically, both models can be shown to predict that the second spectrum, the spectrum of fluctuations in the ordinary first spectrum [11], is essentially independent of second-spectral frequency f_2. We present data from $2H$-$NbSe_2$ contradicting that prediction, requiring that there be multistate metastable flow patterns, e.g., interacting flow channels, in the peak-effect regime.

Regardless of the detailed nature of the different moving states, a central question is whether these are purely dynamical states (like, e.g., the fluctuations in turbulence) or metastable disordered states which are only probed by the nonlinear transport coefficients [as found, e.g., in some related charge-density-wave (CDW) noise effects] [12]. In this Letter, we will show using simple pulsed-current experiments that the metastable memory survives in the pinned state and thus reflects properties of that state.

All data presented here come from a single-crystal sample of the layered superconductor $2H$-$NbSe_2$ of size 1240 μm $\times$ 515 μm $\times$ 25 μm. Similar results for the dc experiments were obtained with a second sample. Gold wire leads were attached with low temperature InAg solder in a four-probe configuration with current flow in the *a-b* plane and magnetic field along the *c* axis. We found $T_c \sim$ 7.2 K with a width of about 225 mK. A small residual resistance in one of the samples below T_c indicated that the current and voltage leads were not completely independent, but the field dependence of the noise spectra rule out the contacts as a significant source of noise, as described below. Figure 1 shows the dependence of the critical current I_c on field ("peak effect") and a typical differential resistance curve at $H = 1.95$ T, where all of the detailed noise data presented here were taken.

The noise magnitude, spectral shape, and prominence of non-Gaussian effects observed were so similar to those found by Marley *et al.* [5] that we shall not comment extensively upon them. As before, the noise was large only on the low-field side of the peak. *This fact provides*

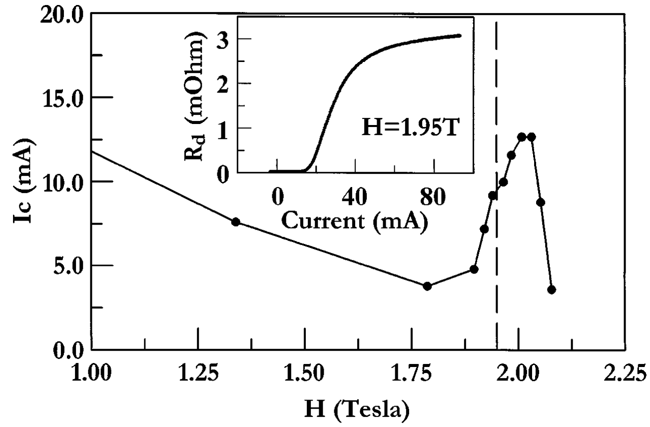

FIG. 1. Critical current I_c vs magnetic field shows a pronounced peak effect just below $H_{c2} \approx 2.3$ T. All noise data presented here were taken with $H = 1.95$ T (dashed line). Inset: ac differential resistance vs driving current at $H = 1.95$ T.

a very convenient test for noise artifacts, since essentially all such artifacts would be as large or larger on the high-field point with similar current and critical current to the low-field point. Except for at the very low end of the frequency range of our data, no such artifacts were detectable.

Solid symbols in Figs. 2 and 3 represent first and second spectra taken with dc sample current, I_s. The first spectra (Fig. 2) show a sharp increase in noise power as I_s is increased through I_c, and a change in the spectral shape from $1/f$ toward white noise as I_s is raised to a few times I_c. Similar behavior observed by Marley *et al.* [5] was interpreted as evidence for plastic flow crossing over to elastic flow as the flux lattice becomes less sensitive to pinning at high velocities [5]. The dc cross second spectra (solid symbols in Fig. 3) show remarkable dependence on I_s. At $I_s = 12$ mA, just above I_c, the second spectrum is large and roughly independent of f_2. As I_s is increased, the S_2 develop a $1/f$ dependence on f_2 in the regime at which S itself reaches its maximum. At higher current, S_2 decreases in amplitude.

The use of the second spectral technique allows a clear distinction between complicated kinetics involving many linked processes with different rates, and simpler superpositions of single-rate processes with a distribution of rates. The simple superpositions give nearly white second spectra. *The strong dependences of S_2 on f_2 immediately rule out models which invoke simple bundle transport or two-state channels.* Thus some sort of more complicated persistent flow patterns are required. Since S_2 acquires much more low-frequency weight in the regime in which S itself is large, and obvious tentative interpretation would be that as flow channels grow to occupy a large fraction of the sample, their interactions slow a much more complicated set of flow-pattern arrangements. The reasons for the drop in S_2 at a higher current are not fully understood, but are likely related to the less dramatic drop in S_1, which is believed to be related to healing of the vortex condensate at a higher flow rate [4].

The next question is whether these flow patterns should be understood as reflecting the underlying metastability of the pinned vortex state. The key experiment here resembles that for the analogous problem in CDW

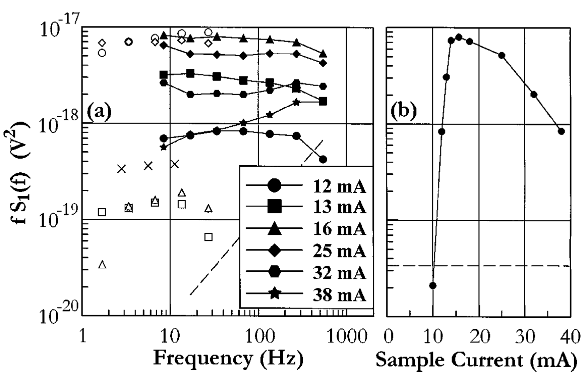

FIG. 2. (a) Solid symbols represent $\ln(2) f S_1(f)$ (first spectrum octave sums) taken with increasing dc bias. A horizontal line represents a $1/f$ spectrum. The dashed line represents one standard deviation of the (white) background noise for the dc experiment. Open symbols represent first spectra taken with pulse-train driving current—circles: 0 to $+1.8 I_c$, squares: 0 to $+0.5 I_c$, triangles: $-1.8 I_c$ to $+1.8 I_c$ diamonds: $-1.2 I_c$ to $+1.8 I_c$. The crosses were taken under the same conditions as the triangles, but using lock-in detection. The squares and triangles are indistinguishable from the background signal in this setup. (b) Power in an octave centered at $f_1 = 34$ Hz as a function of sample current, showing the peak in noise power just above I_c.

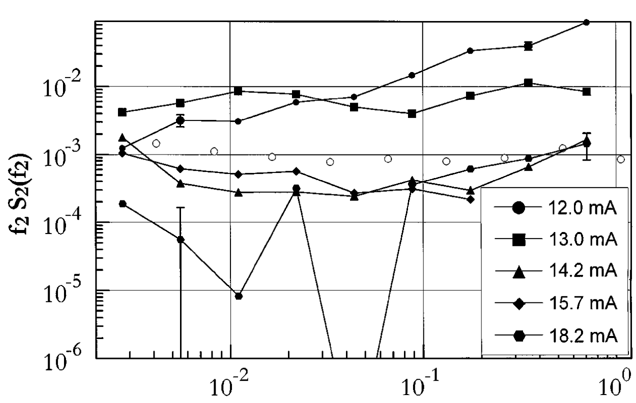

FIG. 3. Solid symbols represent $\ln(2) f_2 S_2(f_2)$ (*second* spectrum octave sums) taken with increasing dc bias (see text). Open circles represent data taken with a pulse train from 0 to $+1.8 I_c$. Each second spectrum is normalized to the average power in the corresponding first spectrum, giving a dimensionless measure of the (non-Gaussian) squared fractional fluctuations in the power in an octave of S_1. (Cross second spectra between adjacent octaves are used so that Gaussian noise would give zero.) Sample statistical error bars are calculated from the random imaginary cross second spectrum.

flow—testing whether the flow noise remembers its previous value after a period during which there is no flow [13]. If so, then the information determining the difference between the voltage and its temporal mean must be already contained in the pinned state. The experiment simply consists of substituting various pulse trains for the dc current. A bridge circuit and some analog filtering are then needed to allow amplification of the noise without overloading the amplifiers. All the pulse trains described here were obtained by adding different dc offset square waves with 50% duty cycle at 500 Hz (1 kHz for the lock-in measurement).

When a simple positive-going above-I_c pulse train was applied, the resulting low-frequency voltage noise spectrum was nearly identical to that obtained with a dc current, as shown in Fig. 2. Background taken with below-I_c pulse trains showed almost no noise. Thus the pinned state itself already contains information about the deviation of the *I-V* curve from its mean, and this information is not lost when the current is raised above I_c. The noise appears to come from rearrangements of the *pinned* condensate between metastable configurations. Unlike in turbulent models [10], the fluctuations cannot be just in velocity fields. Recent vibrating-reed measurements in $NbSe_2$ show dissipation even when the average motion of the vortices is smaller than the spacing between them, supporting this picture [14].

The nonlinearity of the mechanical dissipation [14], however, indicates that driven kinetics may be at least as important as thermal kinetics among the metastable states. Since the detailed noise spectrum in a flowing region should be sensitive to the configurations of neighboring regions regardless of whether they are flowing, the growth of S_2 as more of the sample is driven to slide also suggests that pinned regions do not sample new metastable steps as often as do flowing regions.

In some CDW regimes, although pinned states can contain the low-frequency noise information, the pinned states reached from the two opposite flowing configurations are so different that switching between these configurations eliminates the long-time correlations of the noise [15]. By applying an asymmetric square-wave bias, we tested whether something similar occurs in the $NbSe_2$ flux flow. The low-frequency noise persisted so long as at least one sign of the current bias exceeded I_c (see Fig. 2), indicating that the pinned states accessible from the two types of sliding state were not much different.

Finally, we have some data (Fig. 2) bearing on the symmetry of the fluctuations and the role of net current in driving the fluctuations. Using a symmetrical ac current bias substantially reduced the noise, whether detected directly or via a lock-in amplifier. (These measure different symmetry components of the noise, and their relative magnitude shows that most of the noise does not break the symmetry of the *I-V* curve [16].) We are now conducting experiments to quantify the role of the dc component of the current bias in driving the noise dynamics.

In conclusion, second spectra of peak-regime flux-flow noise show that there are complicated metastable flow patterns, especially in the regime for which the noise is largest. The persistence of the noise with various forms of ac drive current shows that the metastable flow states reflect underlying metastable pinned states, in partial contrast to suggestions that a metastable self-organized *flow* pattern is involved in low-frequency dissipation [14]. The extent to which driven effects may dominate the fluctuation kinetics remains to be quantified.

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