Flux Flow Noise and Dynamical Transitions in a Flux Line Lattice

A. C. Marley,[1,2] M. J. Higgins,[1] and S. Bhattacharya[1]
[1]*NEC Research Institute, Princeton, New Jersey 08540*
[1]*Department of Physics, University of Illinois, Urbana, Illinois 61801*
(Received 6 October 1994)

Generation of low frequency broadband noise is studied in the low-T_c superconductor $2H$-$NbSe_2$ near the "peak effect." A striking dependence on both current and magnetic field is observed in the power, spectral shape, and non-Gaussian nature of the noise. The noise is very large in the plastic flow regime of the dynamics, and small in both the elastic flow and fluid flow regimes. The results show a rapid decrease in the velocity correlation length, a measure of the spatial homogeneity of the moving flux line assembly, as the upper critical field is approached.

PACS numbers: 74.60.Ge, 74.40+k

Conjectures on possible phase transitions and the presence of exotic phases in clean and disordered magnetic flux line lattices (FLL) in a type-II superconductor have led to the recent resurgence of activities in this area [1]. Most of the experiments [2] have involved transport studies, not the usual way of detecting thermodynamic phase transitions. The results provide direct information only about the nature of dynamics and pinning. Those, in turn, may be related to the nature of ordering of the FLL phases, but only through strongly model-dependent interpretations, which remain ambiguous and controversial owing to the highly incomplete understanding of the dynamics of a disordered FLL.

Recent studies on dc transport [3,4] have suggested three distinct regimes of dynamics: elastic, plastic, and fluid, as the magnetic field H approaches the upper critical field H_{c2}. The shear modulus C_{66} of the FLL softens: $C_{66} = (H_{c2}^2/4\pi)(1 - 1/2\kappa^2)b(1 - b)^2(1 - 0.29b)/8\kappa^2$, where b $(=B/H_{c2})$ is the reduced field. This leads to increased strains in the FLL near the pins. Above a field $H_{\rm pl}$, the strain exceeds the elastic limit in some locations and plastic deformation [3–6] of the FLL occurs. It is speculated [4] that the FLL is broken up into chunks or filaments of dimension L_v, the *time averaged velocity correlation length.* The resulting defects and dislocations would lead to a decrease in the correlation volume of the FLL and thus to a rapid increase [7] in J_c. The increase in J_c continues up to the peak field H_p which is nearly coincident [3] with the Lindemann melting field.

The FLL is a prototype for collective transport in disordered systems for which $1/f$-like broadband noise (BBN) is expected to provide valuable information about the dynamics [8]. But a clear experimental demonstration is not available, although flux flow noise has been studied extensively for nearly three decades [9]. In this Letter we report the observation of a striking dependence of *all the characteristics of the BBN* on both the driving current I and the magnetic field H. The results demonstrate a crossover in the FLL dynamics from the elastic to the fluid through the intermediate plastic regime characterized by a large BBN. We measure a rapid decrease in L_v confirming directly, for the first time, earlier speculations [3,4] that changes in the velocity correlation length are responsible for changes in the dynamics.

All data shown were acquired on a single crystal sample of the layered low-T_c superconductor $2H$-$NbSe_2$ of dimension 870 μm $\times$ 780 μm $\times$ 150 μm. Similar data were obtained in two other samples. Typical parameters are $T_c \sim 7.2$ K, $\delta T_c \sim 40$ mK, and $R \sim 20$. Low resistance contacts were made with evaporated gold, and all measurements were made in the four-point configuration with I in the a-b plane and H along the c axis and in the a-b plane normal to I. Noise characteristics were measured at a fixed temperature, $T = 4.2$ K, at varying H and I. In order to obtain correlations with time-averaged dynamics, I-V curves and I-dV/dI curves were also measured; the latter were typically obtained with the standard ac method. We first summarize the main observations.

(1) Current dependence of noise power at different magnetic fields:—The inset of Fig. 1 shows the variation of the critical current I_c with H at $T = 4.2$ K for $H \parallel c$. The sharp rise of I_c marks the onset of plastic deformations [3] at $H_{\rm pl} = 1.81$ T, and the peak in I_c is the well-known "peak effect" at $H_p = 1.95$ T (H_{c2} is 2.2 T). The extreme weakness of pinning is shown by the smallness of the critical current density ($\sim$8 A/cm^2 at 1 T, for example). The main panel in Fig. 1 shows the variation of the noise power $fS(f)$ with $I_{\rm dc}$ for H in the "peak regime" (i.e., $H_{\rm pl} < H < H_p$). (The noise is plotted here in logarithmic scale for easier viewing). The data show the following: (i) The noise appears with the onset of resistance, ensuring that the noise is indeed due to flux motion; (ii) the noise power increases by many orders of magnitude to a maximum $S_{\rm max}$, slightly above I_c; and (iii) the noise power decreases at large I, i.e., a rapidly moving FLL is much less noisy.

(2) Field dependence of the maximum noise power.—Figure 2(a) shows the remarkable H dependence of $S_{\rm max}$ and of the critical current I_c in the vicinity of the peak effect [9]. First, below $H_{\rm pl}$ the noise is very small. Then,

0031-9007/95/74(15)/3029(4)$06.00

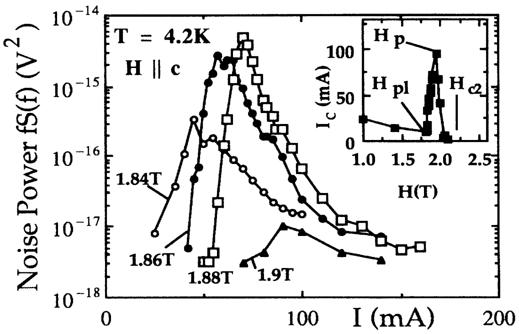

FIG. 1. Current dependence of noise power measured at $f = 34$ Hz at four fields in the peak regime. To improve averaging without loss of information, since the noise is broadband, the individual bins of the power spectrum $S(f)$ are summed from f to $2f$ giving $fS(f)$. All noise power and excess variance displayed in this paper are for $f = 34$ Hz. The inset shows the peak effect, i.e., the pronounced peak in the field dependence of the critical current. $H_{\rm pl}$ marks the onset of the peak regime, and H_p is the peak field.

a gigantic peak occurs between $H_{\rm pl}$ and H_p. Finally, the noise plummets to a very small value around H_p. The implications for the H dependence of the noise are as follows: (i) The large noise accompanies plastic flow and (ii) the peak in noise clearly occurs at a value of $H < H_p$. Figure 2(b) shows that the same qualitative result is obtained for $H \perp c$ and for both I_c and $S_{\rm max}$: $S_{\rm max}$ grows rapidly at $H_{\rm pl}$ and reaches a sharp maximum for a slightly larger H and drops below background levels at H_p. For $H \perp c$, the overall magnitude of noise and J_c is considerably larger.

(3) Current and field dependences of the non-Gaussian nature of the noise.—The non-Gaussian higher moments of the noise are expected to yield more insight into the nature and number of fluctuators. We use the fractional variance of the noise (i.e., the fluctuation of the noise power in a fixed frequency window measured in a given time interval, over many such time intervals) to measure the fluctuations of the fluctuators. The excess fractional variance Δ, above the Gaussian value, becomes large when a small number of fluctuators produce most of the noise [10].

We use $H \perp c$ to study the non-Gaussian nature of the noise because of the larger ratio of signal noise to background noise. Figure 3 inset shows the I dependence of Δ at $H = 5.4$ T. Δ typically peaks at the onset of motion, i.e., at the nominal I_c, and drops rapidly at larger currents. This peak $\Delta_{\rm max}$ occurs around I_c which is smaller than the value of I where the noise power peaks. But, most importantly, the overall scale of non-Gaussian nature is found to depend very strongly on H as well as I, as shown in the main panel. The data clearly show that (i) $\Delta_{\rm max}$, corresponding to the fewest fluctuators, coincides with $H_{\rm pl}$ and not with the peaks in either J_c or $S(f)$; (ii) moreover, $\Delta_{\rm max}$ (I) coincides with the onset of motion at I less than that for the peak in $S(f)$.

(4) Current and field dependences of the spectral shape function.—For each current value, the noise spectrum was measured spanning two decades in frequency (between a few Hz and a few hundred Hz). The data shown above represent behavior measured in a fixed f window. Although the same behavior is seen at all f in this range, there are some quantitative differences observed in subtle changes in the spectral function. Following time-honored methods, we characterize $S(f)$ by a power-law ($f^{-\alpha}$) form, which yields a good fit to the data. However, the exponent α is strongly I dependent. Figure 4 shows that α typically has at a value near 2 around where the noise peaks and then continues to decrease with increasing I and approaches a much smaller value near 0 at large I. Moreover, the spectrum at large I is nearly white at larger H as seen from the data for $H = 1.87$ T, in contrast with the data at $H = 1.83$ T. The same trend is also observed for the other geometry, i.e., $H \perp c$.

The data summarized above show unequivocally that the noise is localized in a narrow range of H and I that has previously [3,4] been speculated to be the plastic flow regime and that both the elastic solid and the fluid regimes are relatively noise-free. The data also show that the decreasing velocity correlation length L_v accounts for

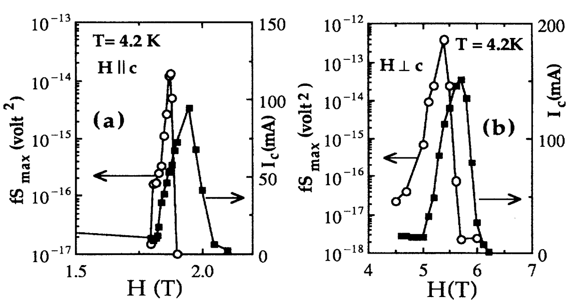

FIG. 2. Magnetic field dependence of the critical current and the maximum noise power for (a) $H \parallel c$ and (b) $H \perp c$. The peaks in noise power occur at fields below H_p in both geometries.

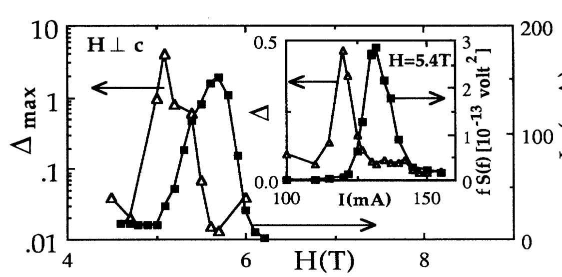

FIG. 3. The inset shows the current dependence of the noise power and the excess variance Δ which reaches its maximum value $\Delta_{\rm max}$ at I_c and decreases rapidly at higher I. The main panel demonstrates the strong H dependence of $\Delta_{\rm max}$ which peaks at $H_{\rm pl}$. See the text for discussions.

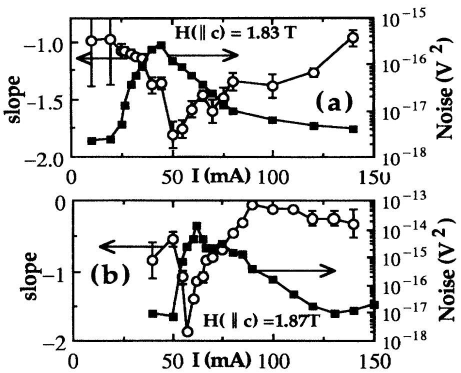

FIG. 4. The current dependence of noise power and the slope α of a power law ($f^{-\alpha}$) fit to the frequency spectrum for two values of H. The slope is near 2 at the peak of noise and decreases to a smaller value at large I. At the higher field in (b), near the flux liquid regime, the noise at large I is almost white.

the various dynamical regimes as the superconducting-to-normal phase boundary is approached.

The voltage measured in a transport study is a direct measure of the time rate of change of the magnetic flux, i.e., $V \sim N\langle v \rangle$, where N is the number of vortices moving and $\langle v \rangle$ is the average velocity; the fluctuations in the voltage are then related to the fluctuations in $N\langle v \rangle$. The noise is found to appear and disappear as a function of H for a given sample in a fixed geometry, arrangement of leads, etc. [9]. Furthermore, the appearance of noise corresponds precisely to anomalous I-V curves which signify different regimes of dynamics [3,4], showing that the noise is unambiguously related to flux transport in the sample.

It has been shown earlier that while metastability in the pinned state is a generic situation in these classes of systems, the moving state may, in some cases, be unique as long as the system remains elastic [11]. Thus the absence of noise for $H < H_{\mathrm{pl}}$ is entirely consistent with the view that the motion of the FLL, while instantaneously jerky, is nearly uniform on average. Although fluctuations can occur in the time scale of the washboard period ($t_0 = v/a_0$, where v is the velocity, and a_0 is the lattice constant), giving rise to a narrow band noise, similar to the charge-density wave (CDW) case [8], no noise is expected in the low f regime described here.

This near uniqueness of the moving state breaks down if the medium is no longer elastic, i.e., if plastic deformations occur [5,6]. We propose that the noise is due to transitions among the various metastable moving states of a plastically deformed FLL. Each of the metastable configurations consists of a different arrangement of mobile vortices whose number and velocity varies from one state to another. These transitions directly lead to the observed noise. We propose that the rapid decrease of noise at large current in Fig. 1 is due to the reduced effect of pinning and metastability of the FLL as the system heals back to the elastic regime.

We propose that for fluid flow at $H \geq H_p$ the noise is very small due to a different reason, i.e., the depletion in the size of the velocity correlation length L_v to typically the liquid correlation length $\sim a_0$, the lattice constant. As the lattice softens, L_v decreases as well and the moving FLL has a larger number of channels. The incoherent addition of fluctuations from many channels will lead not only to a depletion of noise but also to a rapid drop in Δ, as shown above. This implicitly proposes that the velocity-coherent regions themselves are the fluctuators (which may be identified with the Kim-Anderson flux bundles).

In the conventional scenario of the $1/f^{\alpha}$ noise, the noise spectrum is explained by postulating processes with a suitable distribution of relaxation times and the spectral shape is the result of a summation over many Lorentzians $S(f) \sim \int \tau g(\tau)\, d\tau/(1 + \omega^2\tau^2)$, where τ is the characteristic time. This restricts α between 2 and 0, at frequencies, respectively, above and below the characteristic frequency range. In our experiment α is indeed restricted between these values. The average characteristic frequency, which moves through our experimental frequency window as the slope changes from 2 towards 0, is much lower than the washboard frequency and corresponds well with the inverse transit time in the sample which ranges from 10^{-1} to 10^3 Hz in our experiment. The I dependence of α can be attributed to a decreasing τ with increasing I, i.e., increasing FLL velocity. We speculate that τ is related to the macroscopic rearrangement time of a particular vortex assembly. Moreover, as the FLL correlations decrease with increasing H between H_{pl} and H_p, L_v becomes smaller, yielding a smaller τ and thus a smaller α at large I, as in Fig. 4. In other words, the noise for fluid flow would be nearly white, consistent with the expected absence of long-time correlations.

In conclusion, the flux flow BBN shows a dramatic dependence on H and I in all its characteristics in the regime where the peak effect occurs. The results conclusively show that the large noise is due to plastic flow. Both the elastic solid and the flux liquid are much less noisy, but for different reasons. As shown in the general scenario developed above, the noise is caused by transitions of the moving FLL among *metastable moving states*. The absence of noise for the elastic solid is due to the near absence of metastability and for the fluid due to the smallness of the velocity coherence length L_v. All the experimental observations shown above, viz., the rapid decrease in the noise magnitude and its variance and, moreover, the change in the noise spectrum, as H increases towards H_{c2}, are consistent with a rapid decrease in the velocity correlation length L_v, the central measure of the (time-averaged) spatial coherence of the moving flux assembly. This provides a clear description of the long-sought transition of the dynamics from an interaction-dominated regime to a disorder-dominated one [1]. These results would provide insight into closely related phenomena in systems such as the CDW's and the Wigner solids [8].

We thank S. Coppersmith, H. J. Jensen, A. A. Middleton, G. T. Seidler, and C. Tang for discussions and X. S. Ling and M. B. Weissman for a critical reading of the manuscript. A. C. M. thanks NECI for support and hospitality and NSF Grant No. 93-05763 for partial support.

[1] D. S. Fisher, in *Phase Transitions and Relaxation in Systems with Competing Energy Scales,* edited by T. Riste and D. Sherrington (Kluwer Academic, Dordrecht, 1993).

[2] See, for example, D. E. Farrel, in *Physics of High Temperature Superconductors,* edited by D. Ginsberg (World Scientific, Singapore, 1994), Vol. IV.

[3] S. Bhattacharya and M. J. Higgins, Phys. Rev. Lett. **70**, 2620 (1993); Phys. Rev. B **49**, 10 005 (1994).

[4] S. Bhattacharya and M. J. Higgins (to be published).

[5] For a theoretical discussion of plastic deformation in charge-density waves (CDW's), see S. N. Coppersmith, Phys. Rev. Lett. **65**, 1044 (1990); Phys. Rev. B **44**, 2887 (1991). For a discussion on possible differences between FLL's and CDW's, see S. N. Coppersmith and A. J. Millis, Phys. Rev. B **44**, 7799 (1991). Even for the situations we call "elastic," plastic flow below our experimental detectability may occur at the onset of motion.

[6] Plastic deformation of a moving FLL has been observed in numerical simulations. See H. J. Jensen *et al.,* Phys. Rev. Lett. **60**, 1676 (1988); A. E. Koshelev, Physica (Amsterdam) **198C**, 371 (1992), and references therein.

[7] A decrease in the correlation volume leads to increased J_c; see A. I. Larkin and Yu. N. Ovchinnikov, J. Low Temp. Phys. **35**, 409 (1979).

[8] See, for example, A. C. Marley *et al.* [Phys. Rev. B **44**, 8353 (1991)] and A. C. Marley, I. Bloom, and M. B. Weissman [Phys. Rev. B **49**, 16 156 (1994)] for noise studies on CDW's, and Y. P. Li *et al.* [Phys. Rev. Lett. **67**, 1630 (1991), and references therein] for the Wigner solid in 2DEG.

[9] For a review, see J. R. Clem, Phys. Rep. **75**, 1 (1981); for recent work, see W. J. Yeh and Y. H. Kao, Phys. Rev. B **44**, 360 (1991), and references therein. For earlier work on noise near a peak effect in thin films, see F. Habbal and W. C. H. Joiner, J. Phys. (Paris) Colloq. **39**, C6-643 (1978).

[10] P. J. Restle, M. B. Weissman, and R. D. Black, J. Appl. Phys. **54**, 5844 (1983). This reference computes the variance, instead of excess variance, so a Gaussian signal is ~ 1.

[11] A. A. Middleton [Phys. Rev. Lett. **68**, 670 (1992)] shows the absence of metastability in the moving state for a quasi-one-dimensional CDW. For an elastic FLL, the same "no passing rule" may not apply due to the two spatial degrees of freedom as opposed to effectively one for the CDW. In any case, the metastability may be much weaker for a more rigid FLL without significant tears. The "elastic regime" may have few metastable states separated by large enough barriers, so the system would appear to have a unique state in the experimental time scale. Studies at lower H are necessary to understand how far this near-elastic regime extends.