PHYSICAL REVIEW B VOLUME 57, NUMBER 2 1 JANUARY 1998-II

Noise probes of underlying static correlation lengths in the superconducting peak effect

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(Received 23 June 1997; revised manuscript received 21 August 1997)

The sensitivity of low-frequency noise to ac magnetic-field perturbations is explored in the plastic flow regime near the ''peak effect'' in the clean type-II superconductor $NbSe_2$. Very small ac magnetic fields (on the order of 1 Oe in a dc field of about 20 000 Oe) substantially reduce the low-frequency spectral density by inducing rapid switching among metastable configurations present in the pinned state. This sensitivity to ac fields shrinks rapidly as H increases in the peak-effect regime, indicating reduced static correlation lengths as the peak is approached. [S0163-1829(98)50902-2]

In type-II superconductors with fairly weak vortex pinning there occurs a dramatic rise (the ''peak effect'') in the nominal critical current I_c (at which voltage reaches about 100 nV) near the boundary between a vortex solid and a vortex liquid. Since the early work of Pippard,[1] it has been clear that the peak effect in some way results from a softening of the vortex condensate, allowing the vortices to better find the randomly located pinning sites, but without entirely losing the collective effects needed to suppress flux creep. However, the properties of both the vortex flow above I_c and of the underlying vortex condensate which create the peak effect have been unclear.

Low-frequency broadband noise (BBN) has been used to elucidate the nature of the vortex flow in the material 2H-$NbSe_2$.[2,3] In the regime where I_c is an increasing function of field, H_0, the flow is very noisy [as also is found in Y-Ba-Cu-O (Ref. 4)] and the noise becomes highly non-Gaussian at the low-field edge of this regime[2] (see Fig. 1). Those results made sense in a model of plastic flow[5] with large *dynamical* correlation lengths, shrinking as H_0 is increased toward the value at the I_c peak. Further examination of the noise statistics revealed that the flow requires complex patterns, not simple flux bundles or channels switching on and off.[3]

Most importantly for our present purposes, in prior work the persistence of BBN when a pulse train of current was used instead of a dc current showed that the vortex configurations which slowly fluctuate exist in the pinned state, not just when the vortices are flowing.[3] Thus the BBN can be used to probe underlying pinned-state metastable configurations, even though the BBN is only detected when the vortices are flowing. With care, the sensitivity of BBN to changes in the vortex spacing of the ideal condensate can be used to extract correlation lengths corresponding to the extent of static rearrangements, as opposed to the velocity-velocity correlation lengths characterizing the nonequilibrium flow.[6]

In this paper, we explore the sensitivity of the BBN to small ac perturbations (δH) in H. We shall show that very small perturbations change the BBN by forcing the condensate to forget its previous metastable configuration. The BBN sensitivity to δH becomes especially large near the boundary between the peak regime and the main frozen condensate regime. We shall argue that the sensitivity to perturbations reflects the inverse of a *static* correlation length, which falls rapidly as the peak is approached from low H.

The key experimental idea, adapted from work on other systems,[7,8] is that periodic perturbations of the Hamiltonian for disordered systems generally speed up the fluctuation kinetics, since the system returns to a partially randomized configuration after each cycle. The typical result for $1/f$ noise is that for frequencies an order of magnitude or two less than the frequency of the perturbation, f_A, the spectral density $S(f)$ is reduced.[7,8] Near f_A, $S(f)$ can increase, due to the increase of fluctuations with characteristic rates near f_A.[7] It is helpful to think of a complicated energy landscape whose topography rapidly oscillates because of the applied perturbation, facilitating fluctuations among different valleys. (For simple collections of two-state systems, the perturbation can reduce the net fluctuations, creating deterministic periodic response,[9] but such effects are less likely for complex configurations.)

Our experiments were performed on a single crystal of size 1240 μm×515 μm×25 μm of the layered supercon-

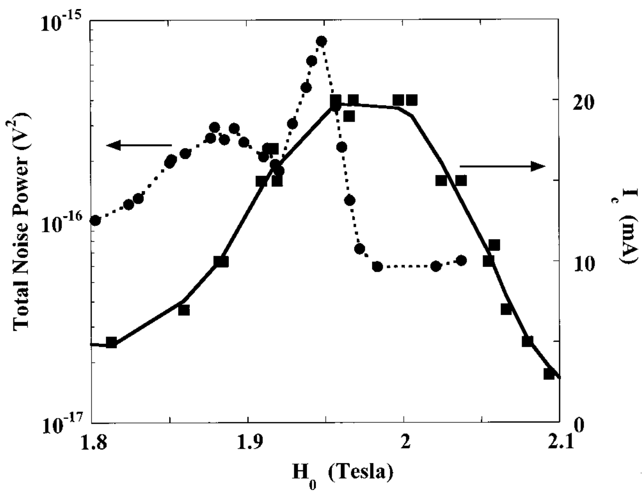

FIG. 1. Both I_c and noise power (from about 1 Hz to 2.25 kHz, measured at 20 mA) are shown vs H_0.

ductor 2H-$NbSe_2$, as used in previous work.[3] Gold wire leads were attached with low-temperature InAg solder in a 4-probe configuration with current flow in the a-b plane and the magnetic field along the c axis, perpendicular to the plane of the thin sample. We found $T_c \approx 7.2$ K, with a transition width of about 225 mK. The state of the vortex condensate can depend on whether an above-threshold current has been applied after sample cooling[10,11]—all data presented here intrinsically involved such currents and therefore do not explore the as-cooled state.

The dc field H_0 was supplied by a persistent superconducting magnet. The ac perturbation field, denoted $2^{1/2}H_1 \cos(2\pi f_A t)$ with $f_A \approx 110$ Hz, was applied with a small nonpersistent home-made superconducting magnet wound on a stainless steel form. We used a sample support made of Teflon, since eddy currents in the standard oxygen-free high conductivity copper support screened the sample from H_1 at 4.2 K. Room-temperature calibration of H_1 was corrected 16% for the effects of operating inside the larger-bore persistent magnet. (In an inadvertent preliminary experiment, which inspired this work, the ac field was supplied by a loose wire near the sample, with rather poorly characterized orientation and time dependence.)

All the BBN data presented in detail here were taken at 4.2 K in liquid He by conventional four-probe noise techniques, using a dc current source (Keithley 224). Results obtained with a variety of forms of ac current are too complicated to discuss in detail in this paper. The first stage of the low-noise amplification chain was a PAR 1900 transformer, which could be dc coupled since the four-probe dc voltage was very low. Standard low-noise amplifiers and antialias filters were used to condition the signal for Fourier analysis on a PC, with the useful analysis range typically being 1–50 Hz. In order to avoid saturating the post-transformer amplifiers with pickup from the ac magnetic field, a synchronized signal was subtracted at the input of one of the differential preamps.

I_c vs H_0 (see Fig. 1) closely resembled previous measurements,[3] with a very slight change of characteristic fields (here the peak is at $H_0 \approx 1.98$ T), probably due to slight changes in alignment on changing the sample support. The BBN voltage spectral density $S(f)$, measured for $I > I_c$, resembled that previously reported[2,3] in this and similar samples as a function of H_0 and of applied current I and showed the same dependences on the form of applied current (dc, ac, pulse train, etc.). The noise statistics, including second spectra, also resembled those previously reported.[2,3] Here we report in detail only on data taken on the left-hand side of the peak, in which the BBN is most easily detectable, focusing on the range between 1.823 and 1.920 T, for which the spectral density exponent γ in $S(f) \propto f^{-\gamma}$ ranged from 0.9 to 1.1.

The key experiment is to measure $S(f)$ at fixed $I > I_c$ as a function of H_1. The key effect, a reduction in $S(f)$ for $f < f_A$, is illustrated in Fig. 2 for data taken at $H_0 = 1.823$ T. $S(f)$ is most reduced at the lowest f, indicating that the perturbation disrupts long-time correlations, as expected. $S(1$ Hz$)$ can be reduced by a factor of 2 by $H_1 < 10^{-4}\ H_0$.

Under the conditions of these data, replacing the dc bias current with a 2 kHz pulse train (switching between $I = 0$ and $I = 12.5$ mA, the same I as in the dc data) has no significant effect on the BBN and no measurable effect on the fractional reduction due to H_1. [In another experiment, we found that similar effects on $S(f)$ occur even when small field changes are made only while the sample current is off.] These facts confirm that the BBN and its sensitivity to small field perturbations reflect fluctuations among metastable configurations shared by the pinned and sliding vortex condensate.[3]

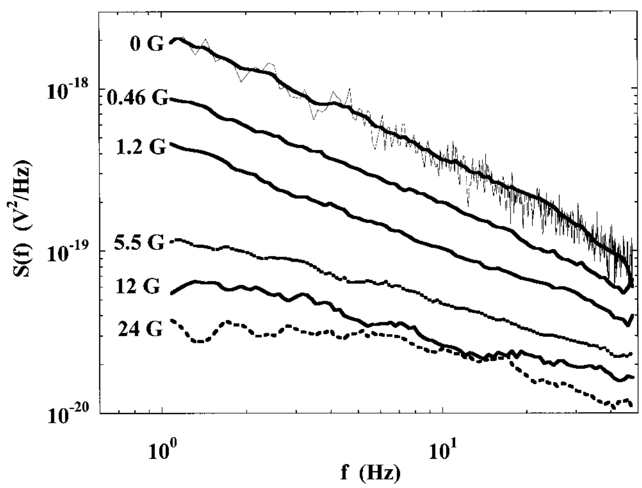

FIG. 2. $S(f)$ vs f for several H_1 are shown for $H_0 = 1.823$ T and $I = 12.5$ mA. Spectra are smoothed, with the raw spectrum also shown for $H_1 = 0$.

The typical time for a vortex to move across the sample under the conditions illustrated in Fig. 2 is 60 msec. Nevertheless the form of $S(f)$ shows that the long-time configurational memory must extend to times longer than the inverse of the lowest measured frequency, i.e., to >1 s. The vortex lattice retains more memory of its configuration after the vortices have been swept through the sample many times than after their concentration has been changed many times by a part in 10^4.

We shall argue later that the sensitivity of the BBN to H_1 is related to a correlation length of the vortex condensate. The dependence of this sensitivity on H_0 can help elucidate the relation between the peak effect and the underlying vortex phases. Some care is required to separate that dependence from the dependence on the dc measuring current, I.

Figure 3 shows the normalized noise power $S(4\ \text{Hz}, I, H_1)/S(4\ \text{Hz}, I, 0)$ as a function of H_1 for several currents as $H_0 = 1.838$ T, for which $I_c \approx 7$ mA. (A band around 4 Hz was used because it was the lowest f for which artifacts were consistently absent.) These data are typical for the region $1.81 < H_0 < 1.88$ T. We can conveniently parametrize these curves by defining $H_M(H_0, I)$ as the value of H_1 for which $S(4\ \text{Hz}, I, H_0, H_M)/S(4\ \text{Hz}, I, H_0, 0) = \frac{1}{2}$. Figure 4 shows H_M as a function of I, again for $H_0 = 1.838$ T, showing a minimum in H_M coincident with the maximum in $S(4$ Hz$)$ as a function of I. The coincidence of the minimum in H_M and the maximum in $S(4$ Hz$)$ as functions of current is a generic feature of the data in this region.

Figure 5 illustrates the dependence of H_M on H_0 and I. Between 1.807 T and 1.878 T, H_M increased a factor of 2 or 3, regardless of whether one selects data at fixed $I = 12.5$ mA or at I chosen to maximize $S(4$ Hz$)$. At higher H_0, the com-

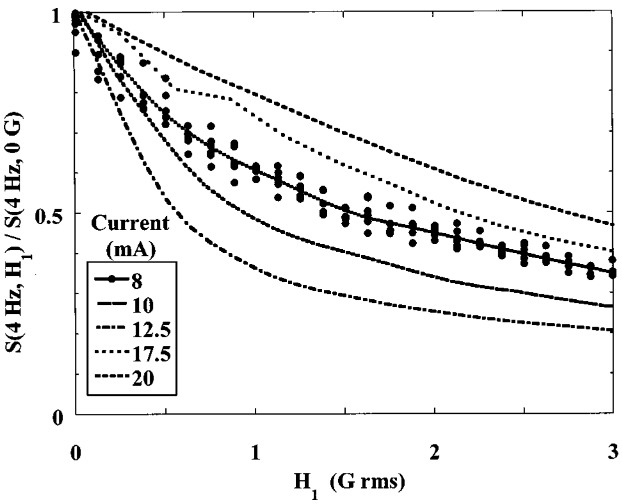

FIG. 3. $S(f)$, averaged over an octave around 4.1 Hz vs H_1, normalized to the value at $H_1=0$, at several currents, at $H_0=1.838$ T. The curves are smoothed, with raw data shown for the 8 mA data.

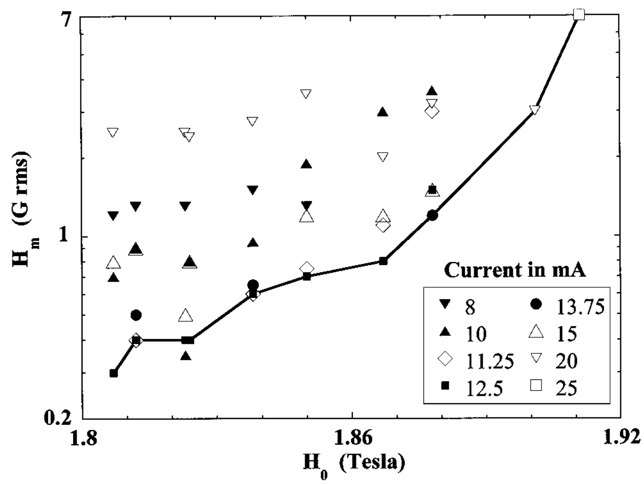

FIG. 5. H_M vs H_0, at several different I. The line connects measurements made with I chosen to produce the maximum S(4 Hz) at each H_0.

bination of history-dependent effects and strong dependence of I_c on H_0 made it more difficult to cleanly separate the direct effect on H_M of changing H_0 from the effect of changing I.

Very close to the peak in I_C, different effects were found. For $H_0=1.973$ T (near the peak itself), $\gamma<0.1$, and no effect of H_1 on the BBN was evident up to $H_1=30$ Oe. This result is to be expected, since if the characteristic fluctuation rates are already greater than f_A (as indicated by γ), the perturbation cannot increase them.

In the narrow regime near $H_0=1.94$ T with the largest BBN (see Fig. 1), with $\gamma\approx1.6$, the effect of H_1 was to *increase* S(4 Hz). The H_1 scale for the increase in S(4 Hz) was comparable to the scale for the decrease in S(4 Hz) at slightly lower H_0. Given the large γ in this regime, there is a very large extrapolated spectral weight *below* the observed frequency range. It is not surprising then that perturbations increasing the fluctuation rate would increase S(4 Hz) rather than decrease it, because the large very low frequency noise is moved up into the observed range.

We may understand the sensitivity of the configuration to

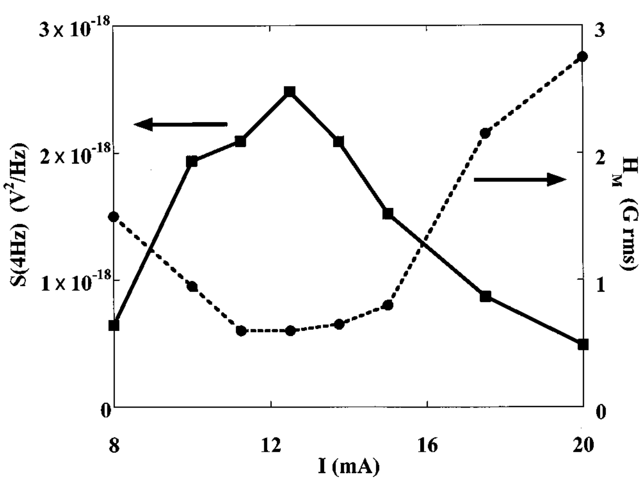

FIG. 4. H_M and S(4 Hz) vs I for $H_0=1.838$ T.

changes in H by considering what happens when the vortex density changes. Our arguments are meant only to serve as initial interpretive guides until a more serious theory can be developed.

We define a correlation length L_N as being the distance over which the vortex configuration changes (i.e., vortices find new pinning sites) in typical coherent rearrangements of the vortices. L_N must be at least as large as a Larkin-Ovchinnikov length,[12,13] the distance over which the vortex arrangement becomes distinct from simple periodic spacing. If a large fraction of the vortices within a coherently pinned region move a distance comparable to a vortex radius, they must find new pinning sites. If we express the Hamiltonian for the vortex condensate as a nonrandom interaction term plus a quenched random perturbation around the ordered lattice, the quenched random term is then thoroughly randomized. Thus if δH is large enough to add or remove a row of vortices in a region of dimensions L_N, i.e., if $H_1>(\varphi_0 H_0)^{1/2}/L_N$, those features of the vortex configuration which depend on disorder must be randomized. Likewise, it is clear that adding less than one vortex to a static correlation region ($H_1<\varphi_0/L_N^2$) cannot affect the configuration. To get a more accurate result between these two limits would require a more serious analysis of the metastable configurations.

H_M is then a measure, though not yet a well-characterized one, of the inverse of L_N, a static correlation length of the vortex condensate. Using the lower limit, L_N $(\varphi_0/H_M)^{1/2}$, at the onset of the peak effect $L_N>5$ μm. In this same regime, a standard calculation of the transverse Larkin length would give about 1 μm.[5] At any rate, L_N obviously shrinks as H_0 is increased toward the peak, as does the Larkin length itself. Whether the growing correlation length near the peak onset would actually diverge in very clean, homogeneous samples remains an open question.

The loss of sensitivity to magnetic perturbations together with the loss of slow relaxation rates at the peak is consistent with the previous surmise[2] that all correlation lengths become small near the peak, as the vortices approach a liquid-like state. The results for the narrow regime near the peak with especially large BBN with a steep spectrum are more intriguing. One possible suspect is a weak first-order phase transition, with no diverging correlation lengths (and hence no enhancement of the sensitivity to H_1), but with slow fluctuations between the phases. This effect will be explored in future work.

In conclusion, we have found an interesting probe of metastable frozen vortex states, the sensitivity of BBN to small field perturbations. The dependence of this sensitivity on dc field shows the existence of a large static correlation length on the low-field side of the peak, shrinking from a maximum near the peak-effect onset to a minimum at an anomalous noise regime just below the peak field.

We thank the Science and Technology Center for Superconductivity (NSF DMR 91-20000) for primary support of the Illinois work and NSF DMR 96-23478 for support for R.D.M. We thank B. Yanoff and B. Plourde for able technical assistance.

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