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FLUX-FLOW NOISE IN THE VICINITY OF THE PEAK EFFECT

Y. Paltiel, G. Jung *, Y. Myasoedov, M. L. Rappaport, and E. Zeldov
Department of Condensed Matter Physics, Weizmann Institute of Science
Rehovot 76100, Israel

S. Bhattacharya, M. J. Higgins
NEC Research Institute
4 Independence Way, Princeton, New Jersey 08540

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Strong flux-flow voltage noise, commonly observed in the vicinity of the peak effect in superconductors, is ascribed to a novel noise mechanism. Random injection of the strongly pinned metastable disordered vortex phase through the sample edges and its subsequent random annealing into the weakly pinned ordered phase in the bulk result in large critical current fluctuations causing large vortex velocity fluctuations. In the Corbino disk configuration vortices do not cross sample edges, the injection of the metastable phase is prevented, and accordingly the excess noise is absent.

Keywords: Flux flow noise; vortex dynamics; order-disorder phase transition.

1. Introduction

Flux-flow noise generated by the motion of magnetic flux in superconductors has been studied since the late 1960s, nevertheless, a comprehensive description of the phenomenon is still lacking; for a review of early results see Ref. 1. In general, flux-flow noise has been ascribed either to velocity or to density fluctuations of the moving flux structures.[1] The most popular shot noise model assumes that vortex density fluctuations rigidly flow across the sample at a constant velocity. The model predicts time-of-flight oscillations in the voltage power spectra and strong dependence of the noise on the voltage measuring circuit geometry, features that are observed seldomly in the experiment. Subsequent modifications of the original ideas brought the shot noise model closer to the experimental reality.[1−3] Nevertheless, recent SQUID assisted and flux-to-voltage noise cross-correlation experiments

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[*] permanent address: Department of Physics, Ben Gurion University of the Negev, Beer Sheva, Israel, also with Instytut Fizyki PAN, Warszawa, Poland. jung@hp1sesi.polytechnique.fr

revealed that noise spectra associated with the flux-flow dissipation can not be explained in the framework of the existing models.[4,5] This has lead to a new model based entirely on the velocity fluctuations due to a turbulent flow of the surface currents.[5] Although the model has passed successfully several experimental tests, it fails to explain the magnetic field and current dependent excess noise appearing in a specific and narrow region of the H-T phase diagram.[6−9]

In the low-T_c superconductors the low frequency excess noise occurs in the vicinity of the peak effect (PE) below H_{c2}, where the critical current I_c anomalously increases with field. In the high-T_c superconductors similar noise enhancement was found in the vicinity of the melting or order-disorder transitions.[9−13] This unconventional noise is inconsistent with the common flux-flow noise mechanisms due to its high intensity, which exceeds the usual flux-flow noise level by orders of magnitude, and strong non-Gaussian character.[6−8] In addition, studies of second spectra of the PE noise demonstrated fluctuations between different persisten metastable pinning configurations. [7,8]

In this letter we present evidence that the excess noise is due to strong velocity fluctuations resulting from a qualitatively different mechanism of random creation and annihilation of a metastable vortex phase.[14] The main conceptual difference is that in the existing models only random vortex penetration or irregular vortex motion in the bulk is considered. In contrast, we describe here a mechanism where random vortex penetration through surface barriers locally creates a new thermodynamics vortex matter phase characterized by tenfold larger critical current. This edge ‘contamination’ process is particularly prone to occur near the PE where a metastable disordered phase (DP), generated at the sample edges in the presence of a driving current, is sufficiently stable on the relevant experimental time scales.[14,15] Since DP is characterized by significantly larger critical current J_c^{dis}, as compared to J_c^{ord} of the ordered phase (OP),[16,17] the contamination process causes enhancement of the integrated critical current of the strip sample $I_c(t) = d\int_0^W J_c(x,t)dx \approx I_c^{ord} + dL_r(t)(J_c^{dis}(0,t) - J_c^{ord})[1 - e^{-W/L_r(t)}]$, where d and W are the thickness and width of the sample, and we have assumed here, for simplicity, an exponential decay of $J_c(x)$ with a characteristic decay length L_r.[14] Randomness in the DP injection and in the annealing process causes strong fluctuations of the instantaneous critical current, leading to pronounced voltage noise.

2. Experimental Results and Discussion

In order to address the question of the origin of the excess noise in the PE region we have investigated 2H-NbSe$_2$ single crystal samples using special contact configuration which allows for transport and voltage noise measurements in both the Corbino disk and strip-like geometry on the same crystals.[15] Figure 1(a) presents the voltage response V vs. the field $H \parallel$ c-axis. The applied currents were adjusted to provide the same current density at the average location of the voltage contacts in the two geometries. As a result the measured V and hence the corresponding

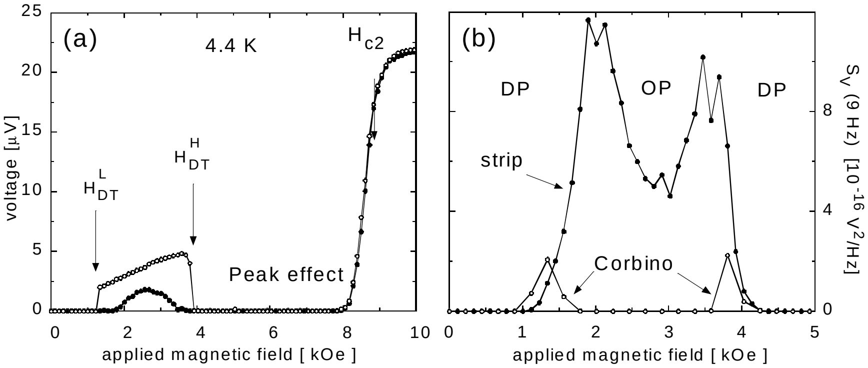

Fig. 1. (a) Voltage response vs. magnetic field at 4.4 K in Corbino (○) and strip (●) configurations. (b) Spectral density of the voltage noise at 9 Hz in Corbino (○) and strip (●) arrangements.

vortex velocity is identical at high fields. Upon decreasing the field from above $H_{c2}(T)$, the voltage decreases rapidly and vanishes in the PE region (4 to 8 kOe), where the critical current of the sample is larger than the applied current due to the presence of the strongly pinned *equilibrium* DP. The voltage recovers at intermediate fields before vanishing again at fields below about 1 kOe, where the reentrance of the equilibrium DP is found.[15] In the following we concentrate on the behavior at intermediate fields where the excess noise appears.

The marked difference in the observed dc response of the sample in the strip and Corbino geometry in Fig. 1(a) is a result of the edge contamination mechanism.[15,14] The DP, which is the equilibrium phase above H_{DT}^H, can exist as a metastable DP below H_{DT}^H along with the equilibrium OP. Therefore, below H_{DT}^H, in the presence of a driving current, the vortices penetrating through the rough sample edges locally destroy the lattice order and form a metastable DP near the edges. As the entire lattice flows deeper into the sample this "wrong" phase anneals gradually into the OP over a characteristic relaxation length L_r. The value of L_r depends strongly on the proximity to the H_{DT} transition: close to the transition the free energies of the DP and OP are comparable, hence the DP is rather stable and L_r is large. Deeper into the Bragg glass region the "wrong" phase becomes highly unfavorable and L_r is short. In addition to its strong field dependence, L_r is also very sensitive to the vortex velocity. At low currents the lifetime of the metastable DP is long and L_r is large. With increasing driving force the annealing process becomes progressively faster resulting in a rapid decrease of L_r with vortex velocity.

The electric field induced by vortex motion can be generally expressed as the product of magnetic induction and vortex velocity $\overrightarrow{\mathbf{E}} = \overrightarrow{\mathbf{B}} \times \overrightarrow{\mathbf{v}}$. Consistently, the I-V curve of a current driven vortex lattice can be expressed as a product of two terms, $V(I) = Rf(I - I_c)$. The first term R is proportional to the vortex density and in the asymptotic limit $I \gg I_c$ corresponds to the flux-flow resistance R_{ff}. The velocity-related term is expressed here as a general function f of the I–I_c argument. Voltage fluctuations result either from fluctuations of the critical current I_c (causing

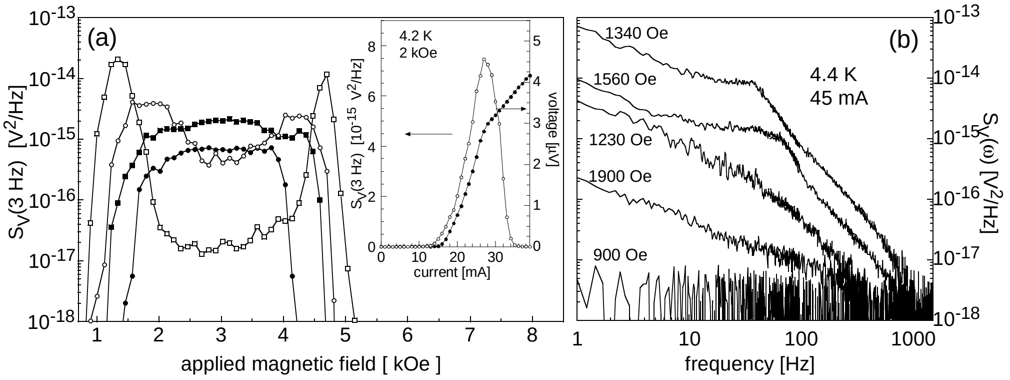

Fig. 2. (a) Voltage noise power density at 3 Hz vs. field at 4.2 K in the strip configuration for $I = 36$ mA (open square), 23 mA (open circle), 18 mA (full square) and 15mA (full circle). Inset: Noise power density at 3 Hz (left axis) and I-V characteristic (right axis) as a function of the current. (b) Representative noise power spectra at various fields in the vicinity of H_{DT}^{L}.

velocity fluctuations) or from fluctuations of the equivalent resistivity R (density fluctuations). In the small signal approximation $\delta V = \frac{\partial V}{\partial I_c}\delta I_c + \frac{\partial V}{\partial R}\delta R$, where δI_c and δR are the fluctuations of the critical current and resistivity, respectively. Since $\frac{\partial V}{\partial I_c} = -\frac{\partial V}{\partial I} \equiv -R_d$, we have $\delta V(I) = R_d(I)\delta I_c + \frac{V(I)}{R}\delta R$. Random injection of the metastable DP causes fluctuation of the integrated critical current $\delta I_c = \frac{\partial I_c}{\partial J_c^{dis}(0)}\delta J_c^{dis}(0)$. In the case of $L_r \ll W$ $\delta I_c \approx dL_r\delta J_c^{dis}(0)$ and the resulting noise power spectral density $S_V \approx R_d^2 d^2 L_r^2 S_{J_c^{dis}} + \frac{V^2}{R^2}S_R$ is strongly dependent on R_d and L_r behavior.

These predictions are consistent with the experimentally observed behavior of the excess noise, shown in Fig. 1(b) as a function of applied magnetic field. The noise attains maxima below H_{DT}^{H} and above H_{DT}^{L}, where L_r is large, and is reduced in the central region where L_r is small. The appearance of the two peaks demonstrates that the excess noise mainly occurs where the metastable DP contaminates a significant part of the sample. However, the most direct test of the described mechanism is the striking observation that in the Corbino geometry the excess noise is entirely absent in the central field range between H_{DT}^{H} and H_{DT}^{L}. This means that the mere motion of the vortex lattice within the bulk of the sample does not create an excess noise. Any bulk noise mechanism should have resulted in a similar noise level in the Corbino and strip geometries. One may even argue that plastic vortex flow,[6,9] could cause a larger noise level in the Corbino geometry due to the enhanced vortex shear by the $1/r$ radial current distribution, in contrast to the observations. The absence of the noise in the Corbino therefore clearly indicates the dominant role of the edge contamination in the noise process. The residual small and narrow noise peaks in the Corbino configuration can be ascribed to small deviations from a perfect Corbino disk configuration.

The general field and current dependence of the strip noise is presented in Fig.

2(a). The inset shows the noise as a function of current along with the I-V characteristic. The onset of the noise coincides with the onset of dc dissipation. With increasing current the I-V curve shows an upturn and approaches a linear behavior at elevated currents. The noise displays a large peak and vanishes rapidly at higher currents. The initial buildup of the noise follows the initial growth of R_d. The decay of S_V above the peak, however, is the result of a decrease of L_r with increasing vortex velocity. Above the noise peak the I-V characteristic approaches the linear behavior of the OP, where L_r is small. Since the ordered part of the sample does not contribute to the noise, the noise decreases rapidly and eventually vanishes as the width of the DP near the edge shrinks to zero. This feature clearly indicates that density fluctuations, the second term in the S_V expression, which in general should increase with increasing current following the $V(I)$ dependence, are negligibly weak with respect to the velocity fluctuations caused by the critical current fluctuations.

The above considerations allow us to analyze the noise behavior presented in Fig. 2(a). At low current, 15 mA, the excess noise is present only in the central field range where the vortex motion occurs. At 18 mA the field range of the observable vortex motion and of the corresponding noise expands, and by 23 mA, two noise peaks become apparent. In the central region the DP is less stable, L_r drops with I, and hence the noise decreases rapidly with the current. Closer to the transition fields, however, the metastable DP is much more stable and therefore at 23 mA L_r remains large and S_V is still increasing with current (see the inset). At 36 mA most of the sample is in the OP and the excess noise is restricted now only to narrow regions adjacent to the transition fields where the metastable DP survives even at high vortex velocities. The excess noise behavior can be, however, significantly more complicated due to possible L_r fluctuations and current dependence of δJ_c^{dis}, which we have neglected in the above simplified qualitative analysis.

Figure 2(b) shows representative noise power spectra in the vicinity of H_{DT}^L which display the typical power law behavior of the excess PE noise.[6−8] In addition, a pronounced kink, located at the frequency corresponding to the inverse transit time of vortices across the sample,[10,16] marks the change of the power exponent in the spectra. Such a behavior is generally consistent with the presented model of metastable DP flow, as confirmed by our numerical simulations that will be published elsewhere. However, processes of metastable DP generation as well as its annealing and disentanglement are not sufficiently known in order to extract more detailed information from the spectral behavior.

3. Conclusions

In summary, noise experiments in the Corbino configuration show that the flow of the vortex lattice in the bulk of the sample does not generate excess voltage noise commonly observed in the vicinity of the PE. In contrast, very strong noise enhancement is found in the same samples measured in the strip-like contact geometry. The excess noise results from strong vortex velocity fluctuations due to random injection of a metastable disordered vortex phase through the sample edges and its subsequent dynamic annealing.

Acknowledgments

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