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Velocity-fluctuations–dominated flux-flow noise in the peak effect

Y. Paltiel [1], G. Jung [1,2], Y. Myasoedov [1], M. L. Rappaport [1], E. Zeldov [1], M. Ocio [3], M. J. Higgins [4] and S. Bhattacharya [4,5]

[1] *Weizmann Institute of Science, Department of Condensed Matter Physics*
Rehovot 76100, Israel
[2] *Ben Gurion University of the Negev, Department of Physics*
Beer-Sheva 84105, Israel
[3] *Service de Physique de l'Etat Condensé, CE Saclay*
Orme Des Merisiers, 91191 Gif-sur-Yvette, Cedex, France
[4] *NEC Research Institute - 4 Independence Way, Princeton, NJ 08540, USA*
[5] *Tata Institute of Fundamental Research - Mumbai 400005, India*

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Abstract. – Strong excess flux-flow voltage noise commonly observed in the vicinity of the peak effect in superconductors has recently been ascribed to a novel unconventional noise mechanism. The mechanism consists in 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. This results in large critical-current fluctuations causing strong vortex velocity fluctuations. In this paper we present the evidence that flux-flow noise in the peak effect regime is dominated by vortex velocity fluctuations while density fluctuations, considered in the conventional flux-flow noise models, are negligibly weak.

Introduction. – The fluctuating component of the voltage induced by motion of magnetic-flux structures in a superconducting specimen, commonly referred to as the flux-flow noise, has been intensively studied for many years. Since its discovery in the 1960s, the flux-flow noise is regarded as a powerful tool enabling a deep insight into the dynamics of the vortex matter in superconductors. Nevertheless, a comprehensive description of the phenomenon is still lacking, for a critical review of early results see ref. [1]. The major unsolved controversy remains the question whether flux-flow noise should be attributed to the density or to the velocity fluctuations of the moving flux [1, 2].

The most popular "shot noise model" assumes that vortex density fluctuations rigidly flowing across the sample at a constant velocity constitute the source of the noise. Vortex density fluctuations are expected to manifest themselves in the time-of-flight oscillations of voltage noise power spectra as well as in a strong dependence of the noise on the geometry of the voltage measuring circuit. These features are seldom, if at all, observed in the experiments. Moreover, the intensity of the experimentally measured flux-flow noise frequently exceeds by orders of magnitude the predictions of the shot noise model. Subsequent modifications of the original ideas introduced the interrupted and chained motion to account for the realistic effects of the time of flight [1, 3]. The noise magnitude problem has been cured by incorporating the Anderson flux bundle concept in the shot noise model [1, 4]. The flux bundle scenario, although very useful in explaining the discrepancies between the theoretical picture and the experimental reality, see, *e.g.*, [4, 5], introduces esoteric huge flux bundles containing thousands of flux quanta shrinking to a fraction of a quantum with relevant changes of the experimental parameters [1, 4, 6].

Recently, more sensitive experiments involving direct SQUID detection of the flux noise and flux-to-voltage noise cross-correlation measurements clearly demonstrated that the noise spectra associated with the flux-flow dissipation cannot be explained in the framework of existing models [2, 6]. Critical analysis of the early experiments resulted in a new model based entirely on velocity fluctuations caused by a turbulent flow of surface currents [2]. Slightly different velocity fluctuations due to interactions of a perfect vortex lattice with pinning centers have been considered earlier in the analysis of flux-flow noise in pure metals [7]. However, none of the existing models explains a puzzling feature of the magnetic-field– and current–dependent excess flux-flow noise appearing in a specific and narrow region of the H-T phase diagram [8–12].

In low-T_c superconductors, the low-frequency excess noise occurs in the vicinity of the peak effect (PE) below $H_{\mathrm{c}2}$, where the critical current I_c anomalously increases with field [8–10]. In high-T_c superconductors, similar noise enhancement was found in the vicinity of the melting, or order-disorder transitions [11–15]. This unconventional noise is inconsistent with the common flux-flow noise mechanisms due to its high intensity, exceeding the usual flux-flow noise level by orders of magnitude, and strongly non-Gaussian character [1, 8–10].

Edge contamination model. – On the basis of a strong experimental evidence, we have recently proposed the edge contamination model (EC) attributing the excess flux-flow noise to a qualitatively different mechanism of random creation and annihilation of a metastable vortex phase [16–19]. The main conceptual difference between our approach and the existing models is that till now only random vortex penetration or irregular motion in the bulk has been considered. In the mechanism proposed by us, current-driven random vortex penetration through the sample edges locally creates a new metastable disordered vortex matter phase (DP). Such edge contamination process is particularly prone to occur near the peak effect where a metastable DP becomes sufficiently stable on the relevant experimental time scales [16, 17]. Since DP can be pinned more efficiently, it is characterized by significantly larger critical current than the weakly pinned ordered vortex phase (OP) [20, 21]. The contamination process thus causes an enhancement of the total integrated critical current of the sample. A strongly pinned metastable disordered vortex phase dynamically anneals in the bulk into an ordered phase with much smaller critical current. Randomness in the DP injection and randomness in its annealing into the OP result in strong fluctuations of the instantaneous critical current and a pronounced voltage noise. In this paper, we discuss experimental evidence that the excess flux-flow noise in the vicinity of the peak effect is almost entirely dominated by the velocity fluctuations caused by the fluctuations of the integrated critical current.

In a proper experimental arrangement one can neglect voltages induced by changes in the flux threading the loop composed of the sample and the voltage measuring leads. The electric field due to magnetic-flux motion can be written as $\boldsymbol{E} = -\boldsymbol{v} \times \boldsymbol{B}$. The flux-flow voltage noise $\delta V(t) = V(t) - V_0$, where $V_0 = vBL$ is the measured dc voltage drop and L is the distance between the voltage contacts, can be attributed either to the field fluctuations $\delta \boldsymbol{B} = \Phi_0 \delta n \frac{\boldsymbol{B}}{B}$, *i.e.*, to the fluctuations of vortex density n, or to the fluctuations of vortex velocity $\boldsymbol{v}$. In the small-signal approximation we can write $\delta V \approx L(\delta B v + B \delta v)$. The first term contains density fluctuations $\delta n = n(t) - n_0$, where $n_0 = B/\Phi_0$ is the equilibrium density of vortices. Density fluctuations can be directly evaluated by measuring the associated magnetic-field noise. The second term describes vortex velocity fluctuations $\delta v = v(t) - v_0$, where the equilibrium velocity $v_0 = V_0/BL$.

On the other hand, voltage produced by current driven vortices can be described phenomenologically by an equation of the $V(I)$ characteristics. As we have elaborated in detail elsewhere [22], the $V(I)$ curve in the vicinity of the peak effect can be correctly approximated by $V(I) = R[I - I_\mathrm{c}(V)]$. Here R is the resistance which corresponding to the flux-flow resistance $R_\mathrm{ff} \approx R_\mathrm{n} B/B_\mathrm{c2}$ in the high bias current limit, R_n is the normal-state resistance, B_c2 is the upper critical field, and $I_\mathrm{c}(V)$ is the integrated dc critical current which depends on vortex velocity v, or bias voltage V, according to the edge contamination model [16, 17, 22]. In the small-signal approximation one can again separate voltage fluctuations into two terms:

$$\delta V \approx \frac{\partial V(I)}{\partial I_\mathrm{c}} \delta I_\mathrm{c} + \frac{\partial V(I)}{\partial R} \delta R. \tag{1}$$

Assuming, for simplicity, that the $V(I)$ characteristics are linear above I_c, one finds by differentiating the $V(I)$ equation that $\frac{\partial V}{\partial I_\mathrm{c}} \approx -\frac{\partial V}{\partial I} \equiv -R_\mathrm{d}$. Within this approximation (1) becomes

$$\delta V(I) = -R_\mathrm{d}(I) \delta I_\mathrm{c} + \frac{V(I)}{R} \delta R. \tag{2}$$

We can associate voltage noise due to vortex velocity fluctuations with the fluctuations of the critical current δI_c, while flux density fluctuations can be represented by the fluctuations of the resistance δR.

As has been discussed previously, the critical current density in the EC scenario is position dependent, $J_\mathrm{c}^\mathrm{dc}(x) = (J_\mathrm{c}^\mathrm{dis} - J_\mathrm{c}^\mathrm{ord}) \exp[-x/L_\mathrm{r}] + J_\mathrm{c}^\mathrm{ord}$ [16, 17, 22]. Here $J_\mathrm{c}^\mathrm{dis}$ is the maximum critical current density of the disordered phase at the sample edge ($x = 0$), and $J_\mathrm{c}^\mathrm{ord}$ is the critical current density of the ordered phase. The total critical current of the sample $I_\mathrm{c} = d \int_0^W J_\mathrm{c}^\mathrm{dc}(x) \mathrm{d}x = (J_\mathrm{c}^\mathrm{dis} - J_\mathrm{c}^\mathrm{ord})[1 - e^{-\frac{W}{L_\mathrm{r}(V)}}] L_\mathrm{r}(V) d + I_\mathrm{c}^\mathrm{ord}$, where $I_\mathrm{c}^\mathrm{ord} = W d J_\mathrm{c}^\mathrm{ord}$, W is the strip width, and d is the sample thickness. The relaxation length L_r crucially depends on the vortex displacement velocity v [21, 23]. At low velocities, L_r is large, whereas at large driving force the disentanglement is very rapid, so that empirically $L_\mathrm{r} \simeq L_0(v_0/v)^\eta = L_0(V_0/V)^\eta$ [21]. Here η is typically in the range of 1 to 3, L_0, v_0, and V_0 are scaling parameters.

Experimental. – In the experiments we have measured simultaneously the voltage and magnetic-field noise associated with the current-driven vortex motion. The experiments were performed with Fe-doped (200 ppm) 2H-NbSe$_2$ single crystals with $T_\mathrm{c} = 5.6\,\mathrm{K}$, which display a significantly broader PE as compared to the pure crystals. However, additional experiments performed using samples with different doping rendered the same general behavior as the one described in this paper. This leads us to believe that the observed phenomena are general in the superconductors exhibiting PE and are not sample dependent.

Magnetic noise measurements were performed using miniature Hall probes based on two-dimensional electron gas (2DEG) structures which provide significantly better spatial resolution than SQUID sensors and operate better in a changing-temperature environment. For flux noise measurements we have designed and fabricated 2DEG Hall sensor arrays based on AlGaAs/GaAs heterostructures grown on undoped semi-insulating oriented GaAs substrates

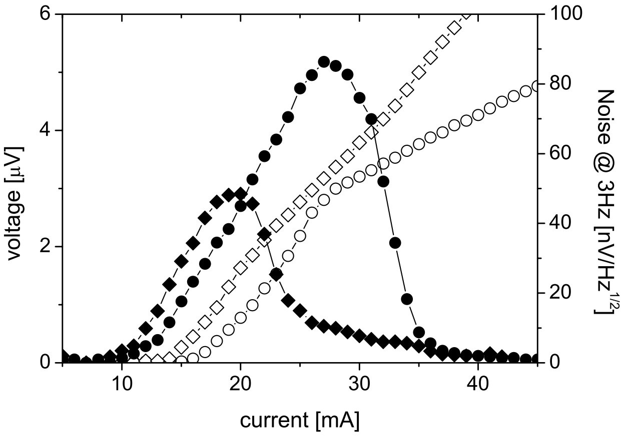

Fig. 1 – V-I characteristics (open symbols) and noise intensity (full symbols) at the frequency of 3 Hz ($S_V^{1/2}$) as a function of bias current at 4.2 K, 0.2 T (circles) and at 4.2 K, 0.3 T (diamonds).

by means of molecular-beam epitaxy [24]. The employed sensor configuration consisted of eleven $10 \times 10\,\mu\text{m}^2$ Hall sensors, connected in series with a $30\,\mu$m separation between them. The active 2DEG layer resides only about $0.1\,\mu$m below the structure surface. The sensitivity of our Hall sensors to the applied magnetic field was close to $100\,\text{m}\Omega/\text{gauss}$. After sufficiently long thermalization at low temperatures, the Hall sensor dc bias current level that causes onset of the excess shot noise was well above $200\,\mu$A, enabling us to operate safely at high current bias, which significantly improves the signal-to-noise ratio of the sensor. The ultimate sensitivity of our flux detection system was typically better than $2 \times 10^{-3}\,\text{gauss}/\text{Hz}^{1/2}$ at the frequencies above 5 Hz.

To perform simultaneous conduction and magnetic-noise measurements, the NbSe_2 crystal with attached contacts was placed directly on the top surface of the 2DEG Hall sensor array. The entire arrangement was immersed in a specially designed low-noise variable-temperature cryostat equipped with an external μ-metal magnetic screen and a persistent mode superconducting coil. In each experimental run, the sample has been zero-field–cooled to the required temperature before application of the magnetic field and bias current. The voltage measured in a four-point contact arrangement and the Hall probe signal were delivered to the top of the cryostat by twisted wire pairs, amplified by home-made low-noise voltage preamplifiers located within the cryostat head, and processed by the computer-assisted spectrum analyzer. The power spectra of the flux and voltage fluctuations were recorded simultaneously with the time domain records and dc voltage response. Instrumental noise originating from the measuring chain was eliminated by subtracting the reference spectra, recorded at zero current flow through the NbSe_2 crystal, from the acquired spectra. Possible contributions of the contacts to the measured voltage noise were excluded by using a high-impedance ballast resistors in series with the dc current source.

The detailed description of the excess noise behavior and its consistency with the EC model has been discussed by us elsewhere [18]. We have concluded that voltage fluctuations resulting from the EC mechanism are proportional to the product $L_\text{r}(B,I,T)R_\text{d}(I,T)$. The excess flux-flow noise level is therefore strongly current– and magnetic-field–dependent. The noise attains maxima at fields where the phase transition between the ordered and disordered vortex phase occurs because L_r diverges at the phase transition [18]. In fig. 1 we plot the

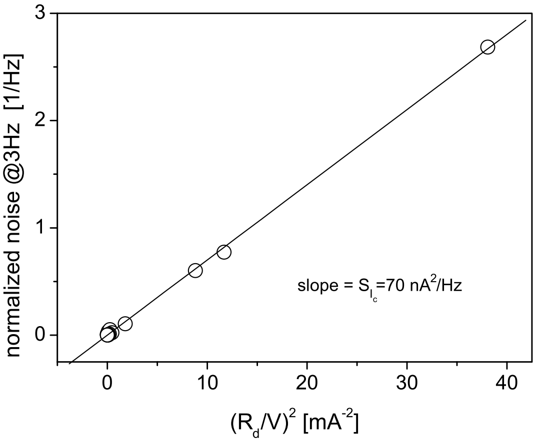

Fig. 2 – Normalized power density of voltage noise from fig. 1 plotted as a function of the ratio R_{d}^2/V^2. The linear fit to the data which crosses the zero indicates that the possible contribution of the vortex density fluctuations to the total voltage noise is negligible.

intensity of noise $S_V^{1/2}$ at a selected frequency of 3 Hz as a function of bias current along with the V-I characteristic. The onset of the noise coincides with the onset of dc current-induced dissipation. With increasing current, the V-I curve shows an upturn and eventually 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 the noise intensity above the noise peak, however, is the result of a decrease of L_{r} with increasing vortex velocity.

We have searched for the flux noise manifestations in the entire range of currents, magnetic fields, and temperatures at which the excess voltage noise appears. Within the sensitivity of our Hall-probe arrangement, of the order of mgauss/Hz$^{1/2}$ we could not detect any vortex density fluctuations. Even by biasing the sample at the very noise peak, where the voltage noise spectral intensity increases more than 4 orders of magnitude above the preamplifier background, we have seen no difference in the magnetic noise detected with and without the application of the driving current causing the motion and annealing of the vortex lattice.

In the face of the negative result, we have carefully checked that the Hall probe is properly coupled to the sample by measuring the Meissner effect at low fields and self-induced ac field response to an ac transport current. All tests proved unambiguously that the Hall sensors are properly coupled.

Is the absence of the flux noise consistent with the EC model and the general behavior of the total voltage noise? To find an answer, let us write the total spectral density of the voltage noise in terms of a normalized spectral density $S_v = S_V/V^2$. Using (2) and neglecting the cross-correlation term, we obtain

$$S_v = \frac{1}{R^2} S_R + \frac{R_{\mathrm{d}}^2}{V^2} S_{I_{\mathrm{c}}}, \tag{3}$$

where $S_{I_{\mathrm{c}}}$ and S_R are the spectral densities of critical current and equivalent resistivity fluctuations, respectively. Observe that plotting of the normalized voltage noise spectral density as a function of the ratio R_{d}^2/V^2 enables one to separate contributions of the vortex density and vortex velocity fluctuations to the total noise. The PSD value at zero R_{d}^2/V^2 corresponds to S_R

term, which is proportional to the vortex density fluctuations, while the slope of $S_V(R_\mathrm{d}^2/V^2)$ dependence enables one to evaluate the spectral density of critical current fluctuations S_{I_c}.

The experimental data from fig. 1 at 0.2 T are plotted in the above coordinate system in fig. 2. The data fit very well to a linear function crossing the zero. It clearly demonstrates that the excess noise due to a contamination mechanism is entirely dominated by the critical current fluctuations causing large voltage noise by inducing strong fluctuations of the velocity of moving vortices. According to (3), any significant density fluctuations would offset the linear fit upward, such that it would cross the y-axis at the value corresponding to S_R. This is clearly not the case in fig. 2. The fit line crosses the zero and the slope of the linear fit corresponds to the spectral density of the critical current noise of 70 nA^2/Hz.

Conclusions. – We conclude that the excess flux-flow noise in the vicinity of the peak effect is entirely dominated by vortex velocity fluctuations resulting from the critical current fluctuations due to random injection and random annealing of the metastable disordered vortex phase. This result may seem surprising in view of the experimental evidence of local vortex density noise associated with current-driven motion of vortices in high-T_c $\mathrm{Bi_2Sr_2CaCu_2O}_y$ (BSCCO) single crystals [15]. The flux noise in BSCCO system has been detected using a similar 2DEG Hall-probe arrangement with a similar sensitivity. The major difference between the two systems is the fact that in the low-T_c $\mathrm{Nb_2Se}$, the excess noise is associated with order-disorder transitions within the solid state of the vortex matter, whereas in high-T_c BSCCO the excess noise can be associated with thermally driven solid-to-liquid melting transition of the vortex matter. Moreover, the disorder-driven solid-solid transition in $\mathrm{Nb_2Se}$ occurs at temperatures of more than an order of magnitude lower and magnetic-fields order of magnitude stronger than the solid-liquid phase transition in BSCCO [15–17].

Since the vortex liquid has higher density than the solid, local melting transitions may result in strong density fluctuations. Nevertheless, it has been shown that the order-disorder phase transition in the solid vortex phase is also associated with a magnetization jump which should result in a similar density fluctuations [25, 26]. A possible reason for the lack of measurable density fluctuations at the solid-solid phase transition is the very slow dynamics with which the equilibrium magnetization is reached. In fact, to detect the magnetization step at the disorder-driven phase transition, a specific experimental technique such as vortex dithering had to be applied [25]. For this reason density fluctuations, if any, may appear at very low frequencies, much lower than the frequencies at which the excess voltage noise has been observed and beyond the spectral range of the experiment. The exact reason for the different aspects of excess noise in low- and high-T_c systems remains, however, an open question.

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