# Voltage noise and surface current fluctuations in the superconducting surface sheath

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We report the first measurements of the voltage noise in the surface superconductivity state of a type-II superconductor. We present strong evidence that surface vortices generate surface current fluctuations whose magnitude can be modified by the pinning ability of the surface. The simple two-stage mechanism governed by current conservation appears to describe the data. We conclude that large voltage fluctuations induced by surface vortices exist while the bulk is metallic. Furthermore, this experiment shows that sole surface current fluctuations can account for the noise observed, even in the presence of vortices in the bulk.

Separating bulk and surface effects is a ubiquitous problem in condensed matter physics. For example, Flicker noise in semiconductors[1] and $1/f$-like noise in metals[2,3] can occur from either bulk or surface localized sources. Similarly, one can cite the longstanding debate about surface versus bulk effects in driven nonlinear systems like charge density waves[4] or vortex lattice in superconductors.[5,6] Such a debate extends to the origin of the fluctuations responsible for their electronic noise. In any case, the key question is how to determine the relevant sources of disorder. From a technological point of view, noise is a limiting factor for most of the applications, and it is necessary to know its origin before expecting its minimization. It is also of theoretical interest to know if, when analyzing disordered systems, boundary effects are of first importance or if they can be neglected compared to the pure bulk treatment of the problem. A similar question has led to the proposition that bulk impurities play no major role in the broadband noise generation of charge density waves.[7] As a model system, the case of superconducting vortex lattices can be particularly instructing.

The dynamics of a bulk vortex lattice has been heavily studied in the literature. It is both understood and experimentally shown that the vortices, when submitted to an overcritical current $I > I_c$ and under steady-state conditions, move in the bulk of the sample with a well-defined average periodicity.[8] This motion is associated with a resistance $R_{ff} \leqslant R_n$ and an electrostatic field $E = -V_L \Lambda \omega$ ($V_L$ is the line velocity and $\omega$ the vortex field).[9] Experimentally, it was also shown that $E$ can be separated into its mean $\langle E \rangle$ and its fluctuating part $\delta E^*$.[10] The latter is the electric field noise. Combined with the V-I relation $V = R_{ff}(I - I_c)$, one can easily realize that this noise can be expressed as fluctuations in the bulk current $(I - I_c)$, or as fluctuations in the resistance $R_{ff}$. Most of the theories invoke bulk pinning centers through their interaction with the moving vortices, leading to vortex density fluctuations and to their associated $\delta R_{ff}^*$ fluctuations.[10] Alternatively, noise may arise from overcritical current fluctuations $\delta(I - I_c)^*$, while $R_{ff}$ is constant.[11,12] For the simple reason of current conservation, $\delta(I - I_c)^* = \delta I_c^*$. The fluctuations are thus linked to the underlying pinning mechanism. Cross-correlation magnetic flux noise experiments and rigorous analysis of the correlation terms are in favor of a

surface origin, at least in Pb-In samples.[12] If fluctuations are pure surface currents, it should be realized that the bulk is only a host which transports the (here noisy) information.

As a consequence, the study of pure surface current fluctuations coexisting with a "noise-free" (metallic) bulk should bring strong experimental evidence on the validity or irrelevancy of this scenario. In the surface superconductivity state, surface currents naturally coexist with a metallic bulk. This means that the $\delta R_{ff}^*$ term should be negligible above $B_{c2}$, so that only current fluctuations can account for the possible voltage noise. To our knowledge, the noise in the surface superconductivity state has not been reported so far. We show here that large voltage fluctuations do exist in this regime. Since it is made clear that they originate from the surface (approximately 0.01% of the total volume), a demonstration of the relevance of the two-stage surface/bulk noise mechanism is brought. These fluctuations exhibit the same magnitude as it is observed in the conventional vortex state of type II superconductors and can be modeled by similar arguments of statistical averaging.

The prediction of Saint James and De Gennes[13] that superconductivity persists in a surface sheath up to a field $Bc_3 \approx 1.69 Bc_2$ has been confirmed by many experiments. In particular, surface superconductivity is very frequently observed in low kappa superconducting metals. Consequently, a strip of pure Niobium ($T_c = 9.17$ K, Ginzburg-Landau parameter $\kappa \approx 1$, coherence length $\xi \approx 30$ nm)[14] has been chosen for this experiment. For all measurements, the magnetic field $\mu_0 B$ was applied perpendicular to the large faces. Note that, strictly speaking, superconductivity nucleates on the typical scale of $\xi$ over surfaces parallel to $\mu_0 B$. In practice, this condition is locally realized by nonzero normal component thanks to usual surface roughness, explaining the possibility of important surface superconducting currents close to the largest surfaces. Kulik calculated that this surface sheath is populated by quantized flux spots ("Kulik's vortices"[15]). It is very likely that the local surface disorder acts as the pinning potential for these short vortices (Ref. 16 and references herein), leading to a surface critical state. Therefore, the associated superficial critical current $i_c (A/m)$ comes from a pinning mechanism, and is consequently observed lower than its theoretical upper bound.[17] For $I \gtrsim I_c$

$\approx 2Wi_c$ ($W$=width), surface vortex depinning occurs. Any excess current ($I-I_c$) is transported in the bulk by normal electrons. It is important to realize that the associated transport equation $V=R_n(I-I_c)=R_nI_{bulk}$ implies that $I_c$ does not participate in the dc voltage response. In other words, the flux spots move in the surface sheath while being in their critical state most of the time.

This dynamic behavior corresponds to the mean motion and explains the main dc properties. In addition to this mean-field-like picture, one can speculate that, during the flux spots motion, many instabilities occur close the surface due to the local release of boundary conditions.[12] The surface current is time dependent and can be described by its mean value $i_c$ and its standard deviation $u^*$. The latter represents the statistical fluctuation's magnitude. One expects large fluctuations ($u^* \lesssim i_c$), correlated in a typical size $c$ larger than the intervortex distance $a_0$. The scale of the measurement is given by $S$, the surface contained between the contacts. $N=S/c^2$ statistically independent fluctuators have to be considered, and their statistical averaging reduces the apparent fluctuations to $\delta i_c^*=u^*/\sqrt{N}$. Up until now, only the surface current flowing in a very thin layer (about $\xi \approx 30$ nm compared to a sample thickness of $10^4 \times \xi$) is the fluctuating quantity. The measured voltage noise is $\delta V^*=R_n \delta I_{bulk}^*$. Now the current conservation implies that surface current fluctuations are counterbalanced by bulk current fluctuations $\delta I_{bulk}^*=\delta I_c^* \approx 2W\delta i_c^*$. Finally, the rms noise is given by

$$\delta V^* = R_n \delta I_c^* = R_n I_c \sqrt{c^2/S}. \qquad (1)$$

Experimental signatures of this mechanism would be the existence of large voltage noise, even without bulk vortices, i.e., in the surface superconducting regime, and the verification of this noise is controlled by the surface critical current.

One of the most critical points in this experiment is to identify properly the surface superconducting regime. Several experimental techniques were performed for this purpose (Fig. 1). Specific heat measurements give a robust localization of the second critical field, i.e., the field below which bulk superconductivity appears. Under liquid helium temperature ($T=4.2$ K), we find that the onset of the bulk superconducting signal is at $Bc_2=0.295\pm0.005$ T (Fig. 1, top), in good agreement with the value representative of pure niobium.[14] The magnetization curve shows the existence of small hysteretic currents $i_c$ above $Bc_2$ (Fig. 1, middle), which are characteristics of a surface superconducting state.[18] All the departure from the Ohmic normal state behavior is due to these surface currents.[19] At the same time, the differential resistance $R$ is $dV/dI \approx R_n$ at high current even if the normal state is not reached, as simply stated by $V/I \neq R_n$ (Fig. 1, bottom). Such a small difference between $R$ and $R_n$ can naturally be attributed to the smallness of the surface sheath volume, where the superconducting order parameter can relax. $Bc_3$ can be estimated from the disappearance of $i_c$, here at $0.52\pm0.02$ T. The obtained ratio $Bc_3/Bc_2=1.76\pm0.06$ is close to the theoretical value 1.69. Since the critical region where surface superconductivity takes place has been delimited, we can investigate if an excess noise exists in this regime and eventually analyze its behavior.
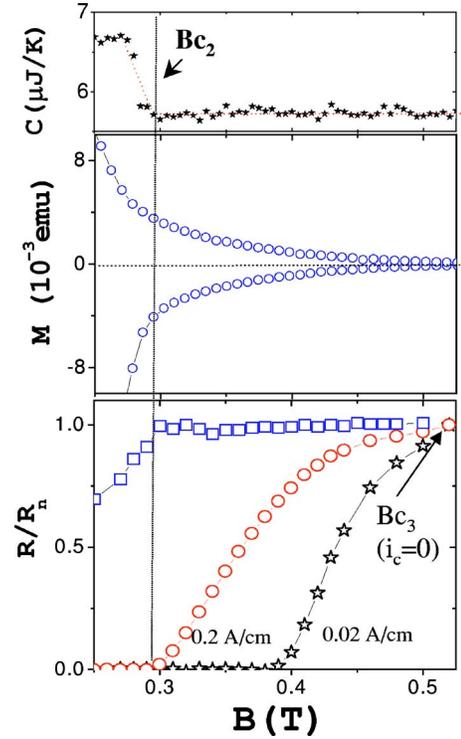


FIG. 1. (Color online) Evidence of surface superconductivity at $T=4.2$ K in the Niobium strip. Top: Specific heat as a function of $B$. Middle: Magnetization measured by a SQUID magnetometer. Note the hysteresis above $Bc_2$. Bottom: Resistance normalized by its normal state value. (stars: $i=0.02$ A/cm, circles: $i=0.2$ A/cm, squares: differential resistance for $i \gg i_c$). The non-Ohmic behavior is due to the surface critical current.

The principle of the conduction noise measurements is the following one. The temporal evolution of the voltage is digitally acquired after ultralow noise differential amplification (NF-SA 400F3) with usual care to eliminate external interference[20] (Fig. 2). It is then Fourier transformed and squared in order to obtain the Power Spectral Density of the voltage fluctuations $\tilde{V}^2(f)$. The final resolution at low frequency is $0.7$ nV/$\sqrt{\text{Hz}}$. Shown in Fig. 3 (top) is the variation of $\delta V^*=\sqrt{\int \tilde{V}^2(f)df}$, integrated over the low-frequency bandwidth (6–200 Hz), as a function of the magnetic field. For
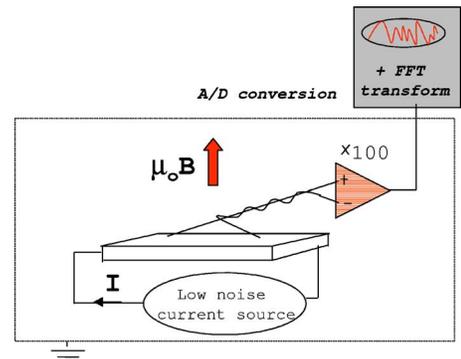


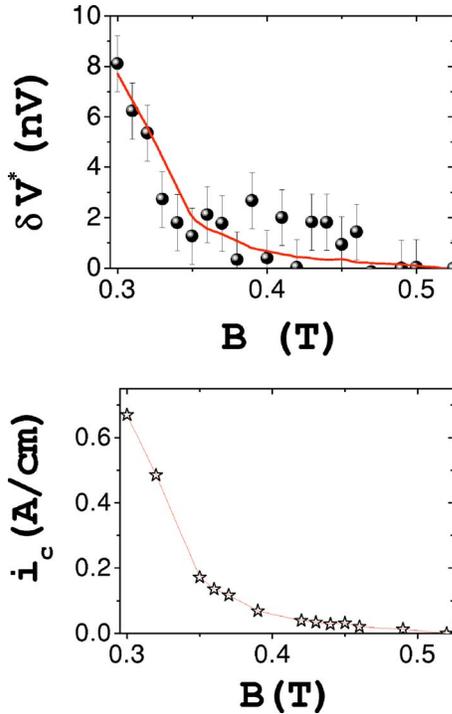FIG. 2. (Color online) Experimental setup used to measure the voltage noise in a Niobium strip (size $L=5^*W=1.5^*t=0.2$ mm$^3$).

FIG. 3. (Color online) Top: Variation of the voltage noise measured in the quasilinear regime of flux spots motion for $Bc_2 \lesssim B \lesssim Bc_3$ ($T=4.2$ K). Also shown is the master curve corresponding to the variation of $i_c(B)$. Bottom: Variation of the surface critical current for $Bc_2 \lesssim B \lesssim Bc_3$ ($T=4.2$ K). The dotted line is a guide for the eyes.

$B \gtrsim B_{c3} \approx 0.52$ T, no measurable noise is observed, meaning that the metallic part (and the contacts) of the sample can be considered as noise-free within our resolution. This confirms that $R_n$ is not a relevant fluctuating quantity in this experiment. For $B \lesssim B_{c3}$, the noise appears and grows when the field is decreased. Also shown in Fig. 3 (bottom) is the variation of the surface critical current $i_c$(A/cm) measured by V-I characteristics. In viewing the data, it is clear that both $\delta V^*$ and $i_c$ have a similar field dependence. This suggests a simple proportionality between $i_c$ and the amount of voltage noise. This is expected from Eq. (1) in the simplest case where $c$ is a constant, and a numerical application gives $c \approx 0.8 \pm 0.2$ $\mu$m. It is important to note that a similar analysis leads to $c \lesssim 1$ $\mu$m in the bulk vortex state of conventional type II superconductors.[12,20] The voltage noise in the surface superconducting state appears to have the same magnitude as in the conventional mixed state. The typical variation of $\delta V^*$ versus the transport current is shown in Fig. 4. This closely mimics the noise variation during the depinning transition a bulk vortex lattice.[10] Thus, as proposed in Refs. 12 and 20, there should be a general explanation of the moving vortex noise in terms of pure surface current fluctuations.

In order to confirm the role of the large surfaces for the noise generation, we have modified the top and bottom surface properties using a low-energy ion irradiation (Ar$^+$ ions with a kinetic energy of 600 eV and 30 min exposure). Because of the short range of the ions, the damage is restricted in the first nm of the subsurface region. Bulk properties
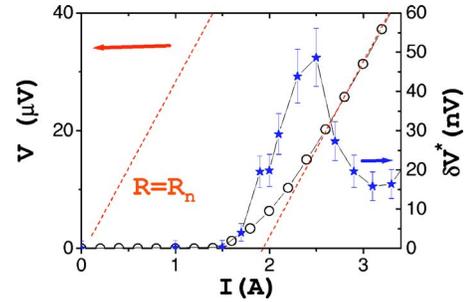


FIG. 4. (Color online) The voltage and the voltage noise as function of the current ($T=4.2$ K, $B=0.36$ T, irradiated surfaces). Note the depinning peak followed by the more quiet behavior characteristic of a depinning transition. The flux-flow noise (see Fig. 5) corresponds to the regime after the depinning peak. This corresponds to the steady state of the motion.

$(\rho_n, B_{c2}, T_c)$ are consistently measured as unchanged. The genuine irradiation effect on the surface superconductivity properties can be a matter of debate. AFM and MEB inspections confirm that the surface topography exhibits a strong increase of its roughness at a low spatial scale.[21] The increase of the surface roughness results in the stronger flux spots' pinning ability, but at the same time the strength of the surface sheath is reinforced because the roughening process multiplies the possibilities that superconductivity nucleates at the scale of the coherence length ($\xi \approx 30$ nm). Furthermore, as shown in Fig. 4, the third critical field has changed and increased up to at least 0.6 T, likely because of the concentration of impurities (implying a reduced electron mean-free path) near the surface. Whatever the genuine reason is, the central point is that an impressive increase of the surface critical current is observed (Fig. 5), whereas the bulk properties are unchanged. Interestingly for applications, one obtains large critical currents values ($i_c \approx 10$ A/cm or $J_c \approx 8 \times 10^4$ A/cm$^2$ if expressed like a current density at the sample scale) for fields much higher than $Bc_2$. As shown in Fig. 6, an associated increase of the noise is observed, giving more weight to the evidence of its pure surface origin. Furthermore, a quantitative analysis yields $c = 1 \pm 0.2$ $\mu$m after the irradiation, very close to the fluctuator size found for the virgin sample. This means that almost all the increase of noise comes from the increase of the current fluctuation magnitude, and that this latter is given by the critical current
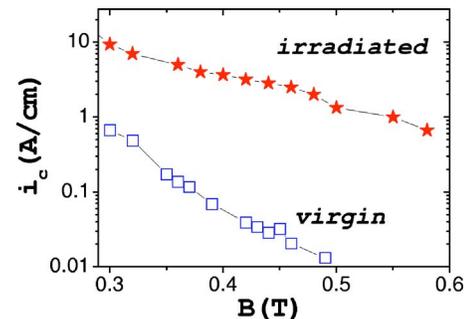


FIG. 5. (Color online) Surface critical current for $Bc_2 \lesssim B \lesssim Bc_3$ for the virgin and for the irradiated samples ($T=4.2$ K). Note the huge increase of $i_c$ after the surface irradiation.
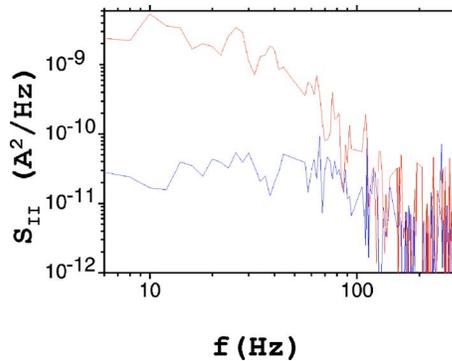
FIG. 6. (Color online) Typical excess of flux-flow noise (the units correspond to the spectral density of the elementary surface current fluctuations $S_{II} = S_{vv} S / (2WR_n)2$ ($T = 4.2$ K, $B = 0.36$ T). Top curve: irradiated sample. Bottom curve: virgin sample. The integration of these spectra over the 6–200 Hz bandwidth gives $i_c c$, the value of the elementary fluctuation (in Amperes). $c$ is deduced from this value.

value. A more detailed discussion of the effect of surface irradiation for the pinning and vortex noise in the surface superconducting regime and in the mixed state $B \lesssim B_{c_2}$, including the statistical study of the noise spectra, will be discussed widely elsewhere.

To conclude, voltage noise due to flux spots motion in the superconducting surface sheath has been observed. Current conservation induces bulk noisy current, whereas the noisy sources were shown to be clearly localized close to the surface. Noise is found to be of the same magnitude as in the conventional mixed state of type II superconductors, and it behaves similarly. This emphasizes the fundamental role of the boundaries in the nonlinear response of vortices.

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[21] The roughness has been controlled by AFM measurements. We have found 0.7 nm rms before the irradiation and 2.2 nm rms after the irradiation (measurements averaged over a length of 1 $\mu$m).