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Voltage noise of $YBa_2Cu_3O_{7-\delta}$ films in the vortex-liquid phase

P.J.M. Wöltgens [1], C. Dekker [2], S.W.A. Gielkens [3], H.W. de Wijn *

Faculty of Physics and Astronomy, and Debye Institute, PO. Box 80000, 3508 TA Utrecht, The Netherlands

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Abstract

The voltage noise of $YBa_2Cu_3O_{7-\delta}$ films is measured in the resistive vortex-liquid phase which occurs above the vortex-glass transition in high magnetic fields. The excess voltage-noise spectral density S_V is found to vanish critically at the vortex-glass transition temperature T_g according to $S_V \propto (T-T_g)^x$, with $x = 1.8 \pm 0.3$, and to have a $1/f$ frequency dependence. A model is constructed on the basis of critical slowing down of the vortex dynamics. The model adequately accounts for the experiments, and suggests that x can be identified with the critical exponent ν of the vortex-glass correlation length.

1. Introduction

Noise spectroscopy is a proven and valuable technique to study the kinetics of vortices in superconductors [1]. In high-T_c superconductors, magnetic-flux noise [2] as well as voltage noise [3–7] have been examined mainly in the regime near zero magnetic field. The results have quite naturally been interpreted in terms of thermal activation over barriers and microscopic defects, or by the use of a perculation noise model. The present paper is concerned with experiments on the low-frequency voltage noise in $YBa_2Cu_3O_{7-\delta}$ films in the regime of high magnetic fields, where the vortices are sufficiently densely packed to exhibit collective behavior. In high fields, a resistive vortex-liquid phase occurs at temperatures above a continuous phase transition to a superconducting vortex-glass phase. This transition was first conjectured theoretically by Fisher [8], and in the last few years abundant experimental evidence for its existence has accumulated [9,10].

The principal findings of the present paper are that the excess voltage-noise spectral density in the vortex-liquid phase

(1) vanishes with decreasing temperature according to a critical power law with a critical exponent $x = 1.8 \pm 0.3$, and

(2) exhibits a nearly $1/f$ frequency dependence (Section 2). To account for these results, an approximate model is constructed (Section 3). The basic ingredient is that the vortex dynamics is governed by the formation of vortex-glass domains, which upon approach of the phase transition increase in size and accordingly in lifetime. The domain size is on average given by the vortex-glass correlation length,

* Corresponding author.

[1] Present address: IBM Research, Thomas J. Watson Research Center, PO Box 218, Yorktown Heights, NY 10598, USA.

[2] Present address: Department of Applied Physics, Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands.

[3] Present address: Faculteit Technische Natuurkunde, Universiteit Twente, PO Box 217, 7500 AE Enschede, The Netherlands.

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which diverges at the transition. At any temperature, however, a broad distribution of domain sizes is assumed. The noise spectrum may then be derived in the spirit of the treatment by Dutta and Horn [11] of low-frequency fluctuations in the presence of a broad distribution of time constants.

2. Experiments

The specimens were high-quality c-axis-up $YBa_2Cu_3O_{7-\delta}$ films of 3000 Å thickness, which were obtained by laser ablation onto $SrTiO_3$ substrates. The films were photolithographically patterned to four-probe patterns with a central stripe of 150×20 μm^2. A gold layer was subsequently deposited onto the contact pads, which after annealing provided a contact resistance well under 1 Ω. The results presented in Section 2 are those for a representative film, for which the resistance vanished in zero magnetic field at $T_c = 91.0$ K.

The experimental setup is shown schematically in Fig. 1. It employs a four-terminal configuration, in which the superconducting sample is biased with a DC current supplied by a battery-operated current source. The noise voltage was fed into a low-noise 1:100 transformer, amplified with an ultra low-noise preamplifier, and analyzed with an Advantest 9211 A fast-Fourier transform digital spectrum analyzer. The excess noise spectral density S_V as a function of the frequency was obtained by subtracting background contributions such as Nyquist noise and 50 Hz interference, and multiplying by the transfer function of the setup inclusive of the transformer. This

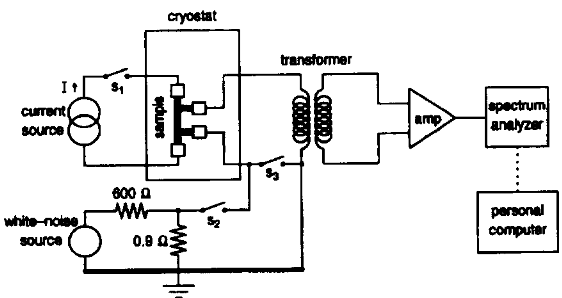

Fig. 1. Schematic layout of the experimental setup.

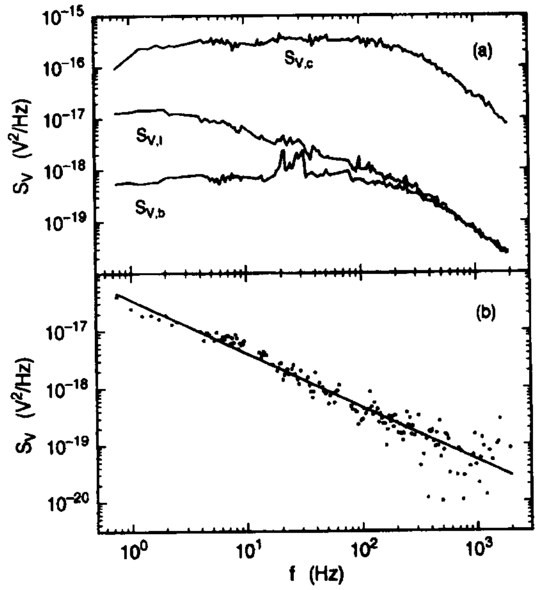

Fig. 2. (a) Set of noise spectra measured at $H = 2.0$ T and $T = 90.11$ K, consisting of a current spectrum $S_{V,I}$ for $I = 2.00$ mA, a background spectrum $S_{V,b}$, and a calibration spectrum $S_{V,c}$ for $P_{V,c} = 3 \times 10^{-16}$ V²/Hz. (b) The excess voltage-noise spectral density S_V derived from the spectra in (a) by use of Eq. (1). The solid line represents a $1/f^{0.93}$ dependence.

was realized by the use of a procedure in which three noise spectra are collected [12]:

(1) The noise spectrum $S_{V,I}$ measured with the driving DC current I switched on (switches S_1 and S_3 closed, switch S_2 open);

(2) The background spectrum $S_{V,b}$ taken with no DC current running through the sample (S_1 and S_2 open, S_3 closed);

(3) A calibration spectrum $S_{V,c}$ reflecting the system's frequency response, measured by injecting a known white-noise power $P_{V,c}$ into the grounding point of the primary electrical circuitry in the absence of DC current (S_2 closed, S_1 and S_3 open). The excess noise spectral density S_V at any frequency is then derived from

$$S_V = \frac{S_{V,I} - S_{V,b}}{S_{V,c} - S_{V,b}} P_{V,c}. \tag{1}$$

Fig. 2(a) shows a typical set of $S_{V,I}$, $S_{V,b}$ and $S_{V,c}$. The spectrum $S_{V,c}$ is determined primarily by the signal transformer, while $S_{V,b}$ mainly consists of the

Nyquist noise of the primary circuitry. In $S_{V,I}$ and $S_{V,b}$ a few sharp peaks associated with residual low-frequency interference and acoustic vibrations show up, which, however, largely cancel out in Eq. (1). The excess voltage-noise spectral density S_V computed with Eq. (1) is shown as a function of the frequency in Fig. 2(b).

The excess noise spectral density S_V has been examined as a function of the frequency f (0.5 Hz–2 kHz), the DC current I (10^{-1}–10 mA), the temperature T (80–150 K), and the magnetic field H along the c-axis (2.0 and 5.0 T). As for the frequency dependence, S_V is found to decrease with the frequency very closely as $1/f$. An example of the

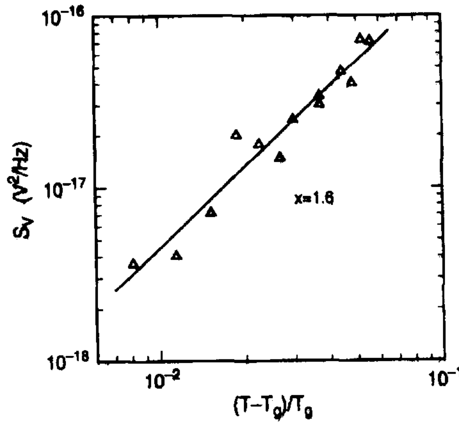

Fig. 4. Voltage-noise spectral density S_V at 1 Hz vs. $(T-T_g)/T_g$ for $I=4.00$ mA and $H=2.0$ T. The corresponding critical exponent x is derived by fitting Eq. (2).

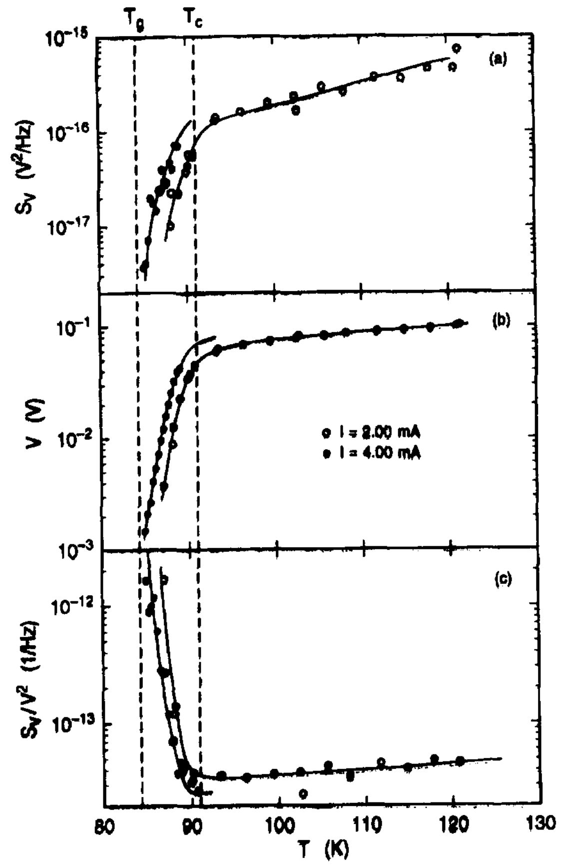

Fig. 3. (a) Voltage-noise spectral density S_V at 1 Hz vs. the temperature T for $H=2.0$ T. (b) Voltage V vs. the temperature for the data in (a). (c) The combination S_V/V^2 at 1 Hz vs. T as derived from (a) and (b), demonstrating the critical nature of S_V below T_c.

frequency dependence of S_V was already shown in Fig. 2(b). Averaging over all spectra, we find a dependence according to $1/f^n$, with $n=0.97 \pm 0.06$. No systematic dependence of n on I, T and H was observed in the above ranges. In the following we therefore specify numerical values of S_V with reference to 1 Hz.

In Fig. 3(a), we present S_V as a function of the temperature for two bias currents. Note that S_V becomes approximately four times larger when doubling the current, as expected for a quadratic current dependence. The important result from Fig. 3(a) is that S_V vanishes with decreasing temperature at the vortex-glass phase transition temperature T_g. It should be noted that this behavior is not related to the disappearance of the resistance at T_g in a simple way [cf. Fig. 3(b)]. This is best appreciated by plotting the normalized noise S_V/V^2 up to temperatures well into the normal phase [Fig. 3(c)]. In the entire regime above $T_c \approx 91$ K, S_V/V^2 can be associated with resistance fluctuations (cf. Ref. [6]). It is relatively small, and varies only weakly with the temperature. As soon as the vortex-liquid phase below T_c is entered, however, S_V/V^2 breaks away from this more or less constant level, exhibiting a steep rise with decreasing temperature.

To test whether the drop of S_V conforms to a critical power law, the measured S_V have been plotted in log–log plots versus $(T-T_g)/T_g$ for several currents and fields. An example is given in Fig.

4. Indeed, the temperature dependence of S_V can be described by

$$S_V \propto (T - T_g)^x, \qquad (2)$$

in which x represents the critical exponent of the voltage-noise spectral density. Here, the precise value for T_g derived from critical scaling (see below) was inserted. Eq. (2) was found to be obeyed for all combinations of bias currents and magnetic fields (cf. Table 1). Averaging over all available data, we arrive at $x = 1.8 \pm 0.3$. The fact that Eq. (2) reproduces the data clearly manifests that the voltage noise in the vortex-liquid phase is related to critical dynamics of the vortices near T_g. This constitutes the primary conclusion of this paper. It is noted that critical behavior of the noise near T_g has not been reported before.

For an accurate determination of the vortex-glass phase transition temperature T_g as well as the critical vortex-glass exponents z and ν, supplementary nonlinear current-voltage (I–V) isothermes were taken. A representative set is shown in Fig. 5. These measurements were carried out using the AC method of Ref. [9]. To extract T_g, z and ν, the measured I–V curves were subjected to a critical-scaling analysis [8]. This entails that T_g, z and ν are varied until all I–V isotherms collapse onto a unique scaling function $\mathscr{F}$ as prescribed by

$$\frac{\rho}{|T - T_g|^{\nu(z-1)}} = \mathscr{F}\left(\frac{J}{T|T - T_g|^{2\nu}}\right). \qquad (3)$$

Here, J is the current density, while $\rho = E/J$, in which E is the electric field, represents the resistivity. As it turns out, T_g and z are quite strongly correlated. For a more precise determination of these parameters, therefore, use was made of the additional

Table 1
Critical exponent x for a selection of bias currents and magnetic fields, derived from fits of Eq. (2)

H (T)	I (mA)	x
2.0	2.00	1.6 ± 0.1
2.0	4.00	1.7 ± 0.1
5.0	2.00	2.3 ± 0.3
5.0	4.00	1.6 ± 0.3

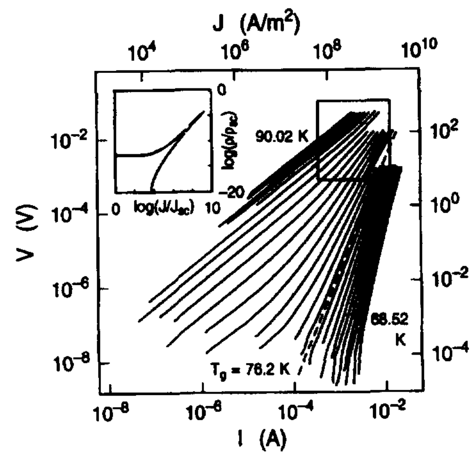

Fig. 5. Log–log plot of I–V isotherms taken near T_g in a magnetic field of 5.0 T. Consecutive isotherms are 0.80 K apart. The dashed line is the pure power-law prevailing at T_g. The box on the upper right delimits the region where the noise measurements were carried out. The inset shows the scaling collapse of the isotherms for $T_g = 76.2$ K, $z = 4.9$, and $\nu = 1.7$. The scaling quantities are $J_{sc} = T|T - T_g|^{2\nu}$ and $\rho_{sc} = |T - T_g|^{\nu(z-1)}$.

condition that at T_g Eq. (3) goes over into the pure power law $E \propto J^{(z+1)/2}$. The critical-scaling collapse pertaining to the I–V isotherms of Fig. 5 is shown in the inset. For the critical exponents we thus deduced $z = 4.9$ and $\nu = 1.7$, which values are in good agreement with earlier studies [9,10,13]. The transition temperature was found to be $T_g = 84.3 \pm 0.1$ K in a magnetic field of 2.0 T along the c-axis, decreasing to 76.2 ± 0.1 K in a field of 5.0 T.

3. Model

To describe the above observations, we have developed a model based on the generally accepted notion that the voltage is induced by the motion of vortices. The general assumption of critical scaling of the average vortex-glass domain size is adequate to derive the temperature dependence of the noise power. The model must, however, rely on heuristic arguments in case dependences on the domain size must be made explicit, such as is needed to evaluate the frequency dependence.

As the vortex-glass phase transition is continuous, the vortex dynamics in the vicinity of this transition is governed by critical fluctuations [8]. Upon approach of the transition from the vortex-liquid phase, local vortex-glass domains of limited size and lifetime develop. The average size of these domains is given by the vortex-glass correlation length ξ, which diverges critically with decreasing temperature at the vortex-glass transition according to

$$\xi \propto 1/(T-T_g)^{\nu}. \tag{4}$$

The lifetimes of these domains depend as a power law on their size, so that on average

$$\tau \propto \xi^{z}. \tag{5}$$

The vortex dynamics thus slows down critically upon approach of T_g. The critical exponents z and ν are universal for vortex-glass transitions in a variety in systems.

We have modeled the $1/f$ noise to result from domains with a broad distribution of sizes, and accordingly lifetimes. If $D(l)$ is the distribution function of the domain sizes l, the spectral density of the voltage fluctuations is given by

$$S_V(f) \propto \int D(l)\mathscr{L}(f, l)\,\mathrm{d}l, \tag{6}$$

where

$$\mathscr{L}(f, l) = \frac{4\tau_l}{1+(2\pi f\tau_l)^2} I(l). \tag{7}$$

represents the Lorentzian spectrum brought about by a single single fluctuator consisting of a vortex-glass domain of size l and lifetime τ_l. The function $\mathscr{L}(f, l)$ is normalized to $I(l)$, the total noise power of the fluctuator, i.e., $\int\mathscr{L}(f, l)\mathrm{d}f = I(l)$. The approach is similar to the one by Dutta and Horn [11] except that the distribution function is specified as a function of l rather than characteristic time scales and that explicit allowance is made of the l dependence of the noise power.

To proceed from Eq. (6), it is necessary to make assumptions concerning $D(l)$, τ_l, and $I(l)$. In glassy systems, the distribution $D(l)$ presumably is quite broad. Yet, the *average* of the domain size l is quite well known in the critical regime, where it may be identified with the correlation length ξ. The critical dynamics is furthermore not expected to affect the functional form of $D(l)$ apart from overall scaling of l in relation to ξ. Recalling that $\int lD(l)\mathrm{d}l = \xi$ and $\int D(l)\mathrm{d}l = 1$, we may thus write

$$D(l) = \xi^{-1}\mathscr{D}(l/\xi), \tag{8}$$

where $\mathscr{D}$ is independent of the temperature (with the possible exception of temperatures so close to T_g that ξ becomes macroscopic). The scaled distribution function $\mathscr{D}(l/\xi)$ is assumed to be broad in relation to the width of the Lorentzians, so that it can be approximated by its average and taken outside the integral in Eq. (6). Note that Eq. (8), which rests on scaling arguments, is quite general and valid for any dimensionality.

Evaluation of Eq. (6) furthermore requires explicit knowledge of τ_l and $I(l)$ as a function of l at a *fixed* temperature. It is plausible that τ_l varies with l similarly to the way its average value depends on ξ when the temperature is varied. That is,

$$\tau_l = Cl^{z'}, \tag{9}$$

where $z \approx z' \approx 4.9$. Note that z' is not a critical exponent, which is why we have primed it for distinction from the genuine critical exponent z occurring in Eq. (5). The effects of $I(l)$ are unfortunately difficult to handle, because no detailed a priori knowledge is available of the mechanism providing the elementary voltage fluctuator. In the vortex liquid, the voltage simply is proportional to the current times the vortex density (which is approximately constant) [1]; in a vortex glass the voltage depends on the current in a substantially more complex way [cf. Eq. (3)]. So the question arises what *fluctuation* in the voltage is brought about by the freezing or thawing of a vortex domain. The considerable complexity of this problem leaves us with no other option than to insert a simple heuristic relationship. We adopt $I(l) \propto l^a$, with a a coefficient (again noncritical) to be estimated from experiment. Summing up, we have

$$S_V \propto \frac{1}{\xi}\int \frac{Cl^{z'+a}}{1+(2\pi fCl^{z'})^2}\mathrm{d}l, \tag{10}$$

so that, by substitution of Eq. (4), we finally arrive at

$$S_V \propto \frac{(T-T_g)^{\nu}}{f^{(z'+a+1)/z'}}. \tag{11}$$

According to Eq. (11), S_V vanishes critically according to $S_V \propto (T - T_g)^{\nu}$ upon approaching T_g, where $\nu = 1.75$ from the critical-scaling analysis of the I–V curves. This is in very good agreement with the experimental finding that S_V vanishes critically at T_g with an exponent $x = 1.8 \pm 0.3$. The critical exponent x for the noise may indeed be identified with the static critical exponent ν. As pointed out above, the frequency dependence specified in Eq. (11) is susceptible to substantial uncertainty. Comparison with the observed $1/f^{0.96 \pm 0.06}$, however, seems to indicate that the domain-size dependence of $I(l)$ is only weak.

It is finally pointed out that an equally adequate description may be provided by the concept of unconventional critical scaling [14]. This involves thermally activated dynamics over barriers of height $B_l \propto l^{\psi}$ at characteristic times $\tau_l \propto \exp(B_l/k_B T)$. Inserting this τ_l into Eq. (7) we arrive at $S_V \propto k_B T(T - T_g)^{\psi\nu}/f$ instead of Eq. (11). With $\psi \approx 1$, this result is in conformity with the experiments. It is believed, however, that unconventional scaling is unlikely in the case of a vortex glass, where the critical dynamics results from a competition between vortex interactions and entropy, leading to a second-order phase transition.

4. Conclusions

In summary, we have observed that the excess voltage-noise spectral density S_V in the vortex-liquid phase

(1) vanishes critically upon approaching T_g with an exponent equal to the vortex-glass static critical exponent ν, and

(2) has a $1/f$-like frequency dependence. To account for these results, we have developed a model based on the critical dynamics of vortex-glass domains. It shows that the temperature dependence of S_V indeed reflects the critical slowing down of the dynamics of these domains upon approach of the vortex-glass phase transition. The frequency dependence of S_V following from the model is roughly in accord with the observed $1/f$ when assuming a broad distribution of the domain lifetimes and not too strong a dependence of the elementary voltage fluctuator on the domain size.

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