Investigation of vortex dynamics in Josephson junction arrays with magnetic flux noise measurements

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Abstract

We have measured the magnetic flux noise in a two-dimensional Josephson junction array in nominally zero magnetic field, in the vicinity of the superconducting transition. This transition is of the Berezinski-Kosterlitz-Thouless (BKT) type, driven by the unbinding of thermally excited vortex-antivortex pairs. At temperatures just above the BKT transition temperature $T_c$, the flux-noise power spectrum $S(\omega)$ is white up to a temperature dependent cross-over frequency $\omega_\xi(T)$. We identify $\omega_\xi$ with the characteristic time related to the scale at which the cross-over from free vortex response to a response dominated by bound pairs occurs. The signature of free vortices is thus white noise while bound vortex pairs give rise to a $1/\omega$ dependence.

Key words: superconductivity, Josephson junction arrays, magnetic flux noise

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1 Introduction

The Berezinski-Kosterlitz-Thouless (BKT) transition [1] is the subject of many investigations, both experimental and theoretical [2–5]. Two-dimensional Josephson junction arrays (JJA) in zero magnetic field represent an excellent experimental system to investigate the BKT transition. The easily controllable parameters in the fabrication process, and the precision achieved with photolithographic techniques make good quality and reproducible samples available.

Many experimental techniques are used to investigate the nature of the transition [6]. Most of them consist of measuring the sample by means of invasive methods, and to take the limit of zero drive excitation. In this work we use a non invasive method, which provides a 'clean' way of measuring the transition.
By measuring the magnetic flux noise in a triangular JJA we have obtained the frequency power spectrum $S_\phi(\omega)$ at various temperatures in the transition zone. We relate the different characteristics of $S_\phi(\omega)$ with the principal features of the transition.

2 Theoretical background

Two-dimensional JJA constitute physical realisations of the XY-model, they are therefore ideally suited for an experimental investigation of the BKT transition. The analysis of experimental data is only slightly complicated by the fact that the single junction coupling energy $E_J(T)$ is temperature dependent, necessitating the introduction of a reduced temperature $\tau = k_BT/E_J(T)$, where $k_B$ is Boltzmann’s constant.

In zero magnetic field, the ground state of a JJA at zero temperature is completely ordered, i.e. all the phases are aligned [7]. At any non-zero temperature, thermal fluctuations give rise to different kinds of excitations which destroy long range phase coherence. The first excitations to appear are spin waves. When the temperature fluctuations become more important, vortex-antivortex (V-AV) pairs are created in the system. The array remains superconducting (existence of quasi long range order) up to the transition temperature $T_c$. At $T_c$ the largest pairs of V-AV dissociate, and the first free vortices appear. Above $T_c$ the free vortex density will raise with increasing temperature and is proportional to $\xi_+^{-2}$, where $\xi_+(\tau) \propto \exp[b/(\tau - \tau_c)^{1/2}]$ is the BKT correlation length. In this regime the response of the system at sufficiently long length scales [compared with $\xi_+(T)$] is determined by free vortices, while V-AV pairs are responsible of the behavior at shorter length scales. For a simple diffusion process $r_\omega \approx (D/\omega)^{1/2}$, where $D$ is the diffusion constant, is the typical diffusion distance in time $\omega^{-1}$[3,8]. Then, by measuring the system for a given time scale (i.e., at a given frequency $\omega$) we are testing a spatial scale $r_\omega$. In the frequency domain, the low frequency response comes from the contribution of signals extending over large scales, while higher frequencies are associated with smaller distances. At $T = T_c$ the correlation length $\xi_+(T)$ approaches infinity, which in the frequency domain corresponds to the limit $\omega = 0$. Above $T_c$ pairs of characteristic size $\xi_+(T)$ dissociate. We can therefore expect that the frequency $\omega_\xi$ associated with the length scale $\xi_+(T)$ will mark a regime crossover. Finally, we notice the exponentially decaying behavior of $\xi_+(T)$, implying that $\omega_\xi(T)$ should be an increasing function of $T$.

The flux noise power spectrum $S_\phi(\omega)$ (i.e., the Fourier transform of the flux-flux correlation function) permits us to characterize the behavior of the vortex fluctuations over a very broad frequency range. Many theoretical works can be found in the literature which predict different dependencies for $S_\phi(\omega)$. All of
these models predict two regimes: at low frequencies a frequency independent white noise which becomes $\omega^{-\alpha}(\alpha > 0)$ dependent at higher frequencies. Citing only some of these works, the predicted value for $\alpha$ varies among $3/2$, $1$ or $2$, depending on the assumed model [9–12].

3 Results and discussion

The power spectra of a proximity effect Pb/Cu/Pb triangular JJA at a number of temperatures close to $T_c$ were measured. With physical vapor deposition and subsequent photolithography star-shaped islands of Pb were deposited on a Cu layer of $\sim 2000\text{Å}$ [5]. The lattice constant $a$ is $15\text{µm}$, and the junction width is $1\text{µm}$.

The experimental setup is shown in Fig. 1. An astatic detection coil was mounted over the sample, the first winding lying $\sim 20\text{µm}$ above the sample. A DC-SQUID detects magnetic flux fluctuations seen by the coil, and transforms them in voltage. A dynamic signal analyzer collects and analyzes the SQUID response, and makes a fast Fourier transform (FFT) giving directly the power spectrum $S_\phi(\omega)$ of the signal.

The resulting power spectra as a function of frequency $f = \omega/2\pi$ at different temperatures below the BKT transition temperature are presented in Fig. 2a, a selection of spectra above $T_c$ is shown in Fig. 2b. Above $T_c$, for frequencies $\omega$ up to a characteristic temperature dependent frequency $\omega_\xi$ the noise is Johnson like (or white). For $\omega > \omega_\xi$ the noise becomes proportional to $1/\omega$. If we consider free vortices as uncorrelated entities, the white noise spectrum observed for $\omega < \omega_\xi$ appears to be a reasonable result. At smaller length scales the dynamics is strongly influenced by the presence of V-AV pairs, and a different type of spectrum is expected. As evidenced by our results this spectrum is of the $1/\omega$ form. It should be emphasized that we find both $\omega^0$ and $\omega^{-1}$ spectra, while other like $\omega^{-2}$ or $\omega^{-3/2}$ are not observed.

In the following we focus on the free vortex dominated white noise contribution to $S_\phi(\omega)$ below $\omega_\xi$ (the behavior of $S_\phi(\omega)$ associated with V-AV pairs will be discussed elsewhere). From the fluctuation-dissipation theorem relating $S_\phi(\omega)$ to the real part of the conductivity, it is straightforward to show, using a Drude-like approach to describe the free vortex ‘charges’, that at low frequencies

$$S_\phi(\omega) = CT/n_v(T)$$

(1)

where $n_v(T)$ is the free vortex areal density and $C$ a temperature independent constant. In a very narrow critical temperature range above $T_c$ one expects...
\[ n_v(T) \propto \xi_{+}^{-2}(T), \] whereas a simple activated behavior \( n_v(T) \propto \exp(-\Delta/kT) = \exp(-B/\tau) \) should become manifest outside the critical region, at temperatures well above \( T_c \). The second exponential form relies on the observation that the energy \( \Delta \) required to nucleate a vortex is proportional to \( E_J(T) \). In Fig. 3 the quantity \( T/S_{\phi}(\omega) \) extracted from the white noise 'plateaus' of Fig. 2b is plotted logarithmically as a function of \( 1/\tau \). The data exhibit an almost Arrhenius-like behavior with a vortex nucleation energy \( \Delta = B E_J \approx 1.6 E_J \). There is no trace of critical behavior \([n_v(T) \propto \xi_{+}^{-2}(T)]\), which should be reflected in a downward curvature of the data as \( \tau \) approaches \( \tau_c \). This indicates that, in order to observe genuine critical behavior, \( S_{\phi}(\omega) \) should be measured at frequencies much lower than those accessible in our experiments. This observation rises some questions regarding the validity of the analysis, based on \( r_\omega \approx \xi_{+}(T) \) to study \( \omega_\xi \), carried out in [13].

4 Conclusions

From the results presented here we conclude that it is possible to characterize the features of the BKT transition by inspecting the flux noise spectra for different temperatures. When \( T > T_c \) the spectrum presents two easily distinguishable parts: for frequencies \( \omega \) lower than a crossover frequency \( \omega_\xi(T) \) we observe white noise, the signature of free vortices, while for \( \omega \geq \omega_\xi(T) \) the spectrum decays as \( 1/\omega \), signature of bound V-AV pairs. As the temperature grows, the characteristic frequency \( \omega_\xi(T) \) increases, as expected. At \( T_c \) an infinite vortex correlation length implies that the crossover frequency vanishes and the \( 1/\omega \) spectrum is present at all frequencies. The same functional frequency dependence is observed for temperatures slightly below \( T_c \), where the intensity of the noise decreases with \( T \).

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Fig. 1. Experimental configuration: an astatic coil is mounted over the sample to detect magnetic flux noise fluctuations. A DC SQUID amplifies the fluctuations which are then fed into the FFT.
Fig. 2. Flux noise as a function of frequency $f$ at temperatures slightly below (a) and slightly above (b) the BKT transition. On a log-log plot straight lines have slope -1.
Fig. 3. Arrhenius plot of $k_B T/S_\phi(\omega)$ as deduced from the noise 'plateaus' of Fig. 2b at $\omega < \omega_\xi$. The straight line is a fit through the data. The temperature dependence of the crossover frequency $\omega_\xi$ is shown in the inset.