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OBSERVATION OF QUANTUM NOISE EFFECTS IN A RESISTIVELY SHUNTED JOSEPHSON JUNCTION

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ABSTRACT

The measured spectral density of the voltage noise in current-biased resistively shunted Josephson junctions in which quantum corrections to the noise are expected to be important is found to be in excellent agreement with theoretical predictions. The contribution at the measurement frequency of zero point fluctuations mixed down from frequencies near the Josephson frequency is clearly demonstrated.

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Koch et al.[1] calculated the spectral density of the voltage noise in a current-biased resistively shunted Josephson junction. For measurement frequencies much less than the Josephson frequency and for a heavily overdamped junction they found

$$S_V(0)/R_D^2 = 4k_BT/R + (2eV/R)(I_0/I)^2 \coth(eV/k_BT). \tag{1}$$

Here, I_0 and R are the critical current and shunt resistance, R_D is the dynamic resistance, and I and V are the current and voltage. Equation (1) assumes that the noise arises from equilibrium noise currents in the shunt resistor with a spectral density

$$S_I(\nu) = (2h\nu/R)\coth(h\nu/2k_BT) \equiv (4h\nu/R)\{\tfrac{1}{2}+[\exp(h\nu/k_BT) -1]^{-1}\} \tag{2}$$

at frequency ν. The first term on the right hand side of Eq. (1) is noise generated at the measurement frequency, while the second term represents noise mixed down from frequencies near the Josephson frequency. In the limit $eV \gg k_BT$, the second term becomes $(2eV/R)(I_0/I)^2$ and represents zero point fluctuations. In this paper, we report an experimental test of this theory.

The Pb/In - In_2O_3 - Pb junctions and Cu (3wt.% Aℓ) shunt resistors were fabricated using photolithographic techniques. The junctions were 2.5 μm in diameter, and typical parameters were I_0=0.5 mA, R=0.5Ω, C=0.5 pF, and $\beta_c=2\pi R^2CI_0/\Phi_0 \approx 0.2$, where C is the estimated junction capacitance. The value of R was measured with the critical current reduced to zero by an applied magnetic field or trapped flux. The voltage noise across the current-biased junctions was amplified with cooled 70-, 106-, and 180-kHz LC-resonant circuits coupled in turn to a low-noise preamplifier. The noise was mixed down to frequencies below 500 Hz, and the spectral density measured with a computer. The gain of the amplifier-mixer-computer chain was calibrated against the Nyquist noise of a resistor.

The total measured noise was corrected for preamplifier noise and the 1/f noise generated by the junctions (the latter was at most 10% at the low voltage biases, and negligible at the high voltage biases). The temperature rise due to Joule heating in the junction was estimated at each temperature by reducing the critical current to zero, and measuring the Nyquist noise. Heating effects were significant only at relatively high voltages where $eV > k_BT$, and it was necessary to correct only the first term in Eq. (1).

In Fig. 1 we plot $S_V(0)/R_D^2$ vs. T for four values of V (open circles) with the preamplifier noise subtracted. The solid circles are the measured noise after the heating and 1/f corrections have been made. The upper solid line is the prediction of Eq. (1), while the upper dashed line is the predicted noise in the absence of zero point fluctuations. The solid triangles are the measured mixed-down noise, computed by subtracting $4k_BT/R$ from the solid circles. The lower solid line is the prediction of the second term on the right hand side of Eq. (1), while the lower dashed line is the predicted mixed-down noise in the absence of zero point fluctuations. The data are in good agreement with Eq. (1), and show clearly the necessity of including the zero point term.

We can compute the spectral density of the current noise in the resistor by multiplying the mixed down noise by $2(I/I_0)^2$, and setting $2eV=h\nu$. The result is plotted in Fig. 2 for two temperatures. The agreement between the data and the predictions of Eq. (2) (solid lines) is excellent. The predictions of the theory in the absence of the zero point term (dashed lines) fall substantially below the data at the higher frequencies.

Our results confirm the existence of the zero point term in the spectral density of the current noise of a resistor in thermal equilibrium, and demonstrate that the zero point fluctuations produce the limiting noise in a resistively shunted junction. Furthermore, the good agreement with Eq. (1) justifies our use of a Langevin treatment to predict quantum noise effects in an overdamped current-biased junction, at least in the free-running mode $I>I_0$.

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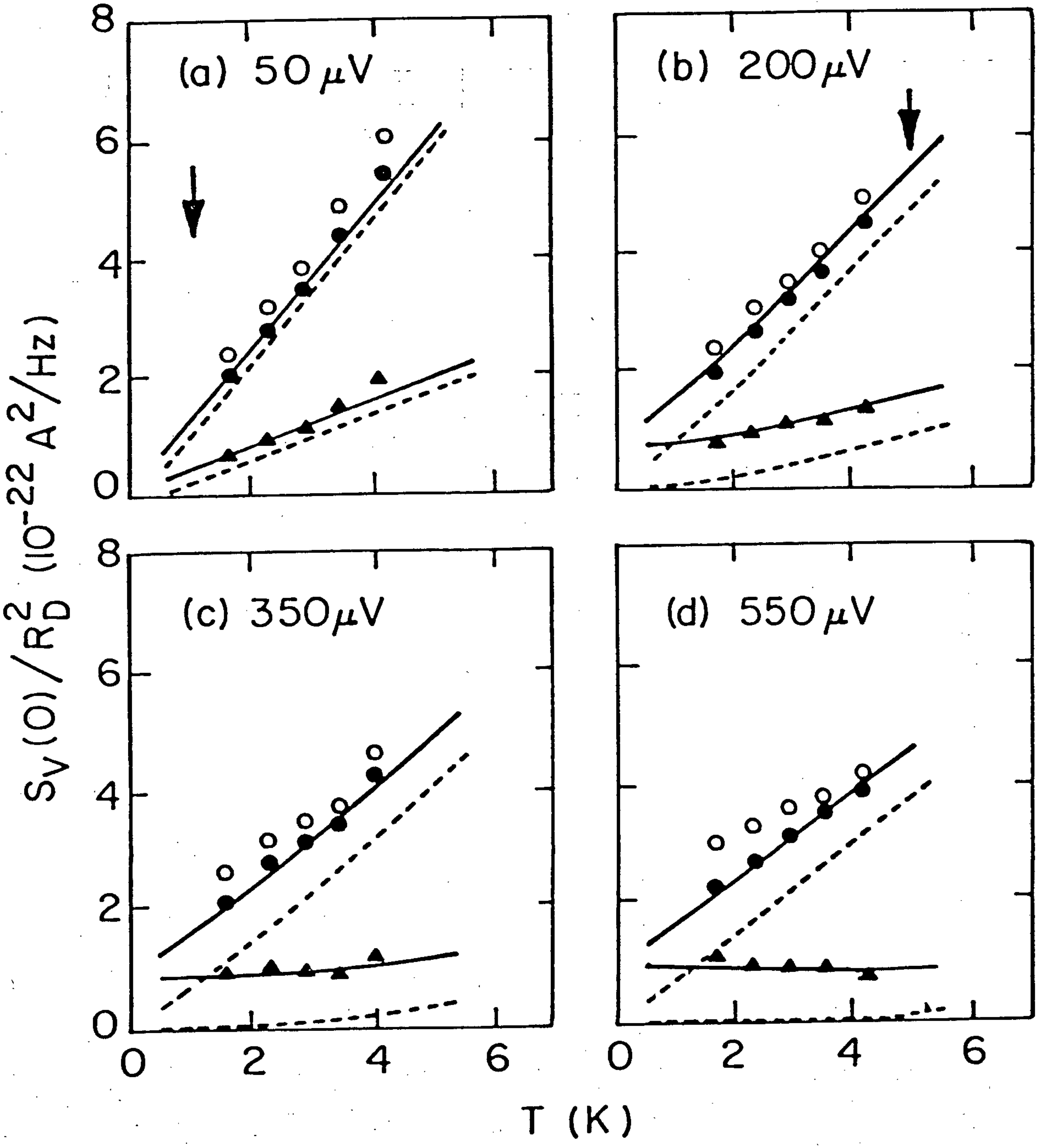
REFERENCE

1. R. H. Koch, D. J. Van Harlingen, and J. Clarke, Phys. Rev. Lett. 45, 2132 (1980).

FIGURE CAPTIONS

Fig. 1 $S_v(0)/R_D^2$ vs. T for 4 bias voltages. Open circles show the total measured noise; solid circles show the noise remaining after correction for 1/f noise and heating. Upper solid line is prediction of Eq. (1), upper dashed line is prediction of Eq. (1) excluding zero point fluctuations. Solid triangles are measured mixed down noise, lower solid line is mixed down noise predicted by Eq. (1), lower dashed line is predicted mixed down noise excluding zero point fluctuations. Arrows indicate $2eV=k_BT$.

Fig. 2 Measured spectral density of current noise in shunt resistor at 4.2k and 1.6K. Solid lines are predictions of Eq. (2), dashed lines are predictions omitting zero point term.



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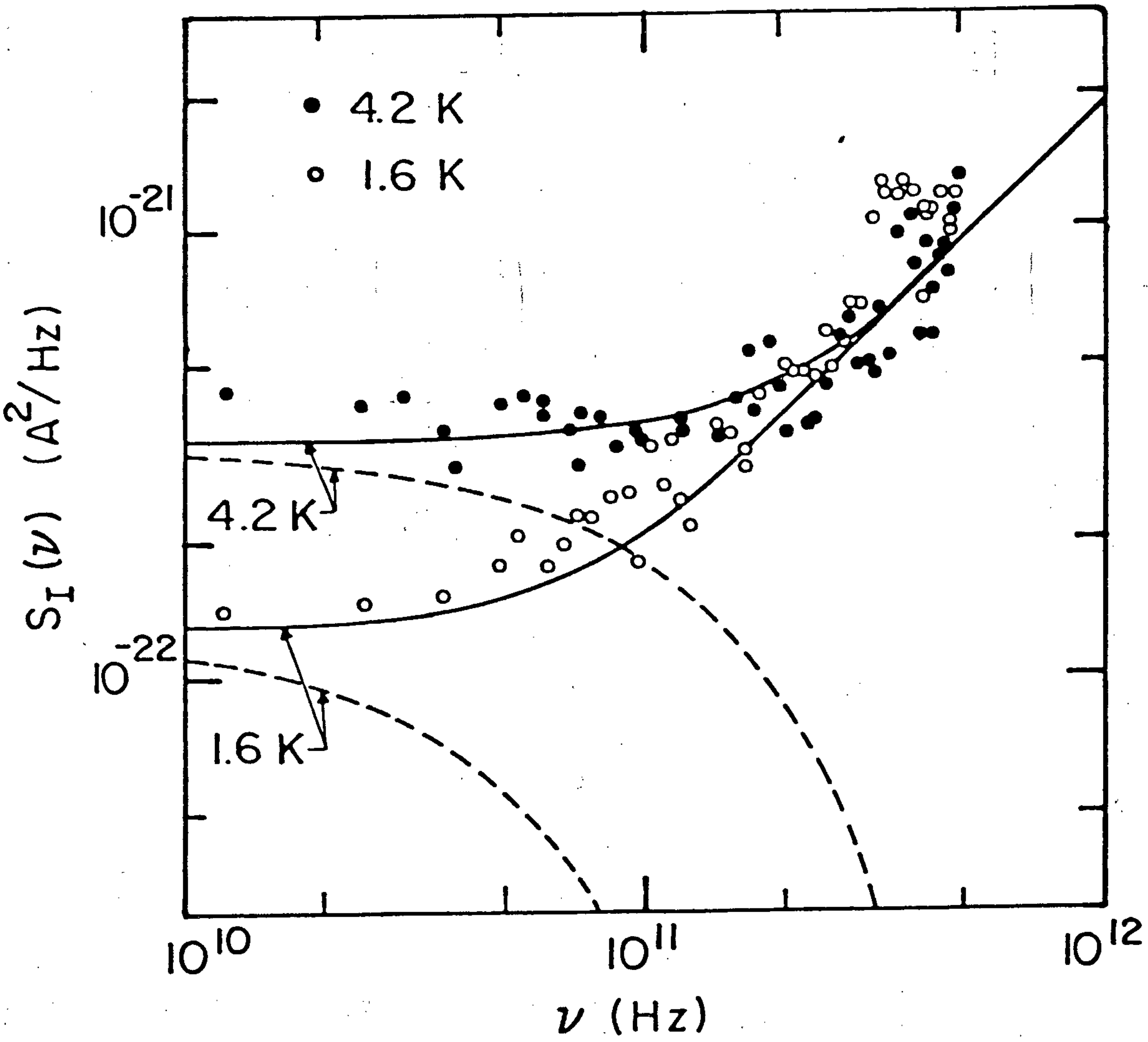

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