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CURRENT NOISE IN JOSEPHSON POINT CONTACTS

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FOREWORD

This report is published by The Aerospace Corporation, El Segundo, California, under Air Force Contract F04701-71-C-0172.

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Approved

AHSilver

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W. E. Belote, 1st Lt. USAF
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CURRENT NOISE IN JOSEPHSON POINT CONTACTS

The power spectrum for fluctuations of quasiparticle and pair tunnel currents has recently been calculated by Scalapino[1] and by Stephen[2] and was shown in both cases to be directly related to the I-V characteristics of the junction. For a Josephson junction carrying both pair and quasiparticle currents the predicted power spectrum is

$$P(\omega) = \langle i(\omega)^2 \rangle = (e/\pi)\{I_q(V)\coth(eV/2kT) + 2I_p(V)\coth(eV/kT)\}. \qquad (1)$$

The expression is applicable for $\omega < eV/\hbar$ and $\omega < kT/\hbar$, with V the junction dc potential and $I_q(V)$ and $I_p(V)$ the dc-current contributions by quasiparticles and pairs, respectively. Equation (1) is of the shot-noise type with the coth factor arising from the sum of the contributions by forward and backward currents. In the limit $eV \gg kT$,

$$P(\omega) \rightarrow (1/2\pi)(2eI_q + 4eI_p), \qquad (2)$$

which is the shot-noise expression in a more familiar form. Note the double-charge factor from the pair-current contribution. For $eV \ll kT$,

$$P(\omega) \rightarrow (1/2\pi)4kT(I_p + I_q)/V, \qquad (3)$$

which has the form of Johnson noise with $(I_p + I_q)/V$ the total dc conductance of the junction. For supercurrents at low voltages this conductance can become very large and thus result in considerable "excess" noise when compared with normal currents. In terms of the dynamic junction impedance R_D, the current fluctuations are directly related to voltage fluctuations:

$$\langle v^2(\omega)\rangle = \langle i^2(\omega)\rangle R_D^2/(1 + \omega^2\tau^2), \qquad (4)$$

where $R_D = (dI/dV)^{-1}$ and τ is the circuit time constant associated with the capacitance and the "normal" resistance of the junction. For the current-driven case considered here, the external circuit resistance is much larger than R_D and is negligible in Eq. (4).

Dahm et al.[3] investigated the voltage fluctuations by measuring the line width of the Josephson radiation emitted from tin and lead thin-film junctions. The radiation linewidth is the result of frequency modulation by the fluctuating junction voltage. These authors found the linewidth generally in excess of but limited towards the lower side by that calculated with a power spectrum of Eq. (1) for a range of sample currents and temperatures. Individual samples at a fixed temperature, however, showed a dependence on current of higher power than linear as indicated in Eq. (1). This result was attributed to excessive radio-frequency power in the junction. All the data was obtained for $eV \ll kT$, where the limit expressed in Eq. (3) is applicable.

By directly measuring the voltage fluctuations across Josephson point-contact junctions with a low-noise amplifier, the present authors in a previous publication[4] were able to show that the lower limit of junction noise currents is given by Eq. (2) for voltages $eV \gtrless kT$ and sample critical currents between 6×10^{-7} and 4×10^{-4} A. The "excess" noise to be expected for the same current levels on the basis of Eq. (3) for $eV < kT$ did not consistently become apparent in the scatter of experimental data. We here present data obtained with an improved experimental technique which clearly show the correct dependence of current fluctuations on voltage predicted by Eq. (1) for sample voltages $eV > kT$ down to $eV \ll kT$.

The junctions consisted of niobium wire tips pressed in liquid helium (4.2°K) against a flat oxidized Nb surface. The junctions were driven in the current mode through a resistor R_o (see inset of Fig. 1) large compared with the impedance of the junction. A typical I-V characteristic is shown in Fig. 1. The characteristic resembles closely that theoretically expected for a highly damped junction which has been discussed by Stewart[5] and McCumber.[6] The noise voltage was measured with a correlator-amplifier of the type described by Brophy et al.[7] The amplifier output is proportional to the squared voltage input in a band pass 30 kHz wide centered at 150 kHz. This frequency was chosen to avoid a $1/f$ noise contribution observed below about 100 kHz. The amplifier was calibrated by measuring the change with temperature of thermal voltage fluctuations of resistors in place of the sample ($2°K < T < 4.2°K$). Amplifier noise was near $2 \times 10^{-21}\ V^2/Hz$ corresponding to the Johnson noise of a 10-Ω resistor at 4.2°K, and was subtracted from the data. A recorder plot of the squared voltage output of a sample is shown in Fig. 1, where the zero reference line is the amplifier output at infinite sample conductance ($V = 0$). In order to determine the current fluctuations the junction impedance was determined separately by modulating the driving dc current with a small ac signal at 150 kHz. The corresponding amplifier output is shown by the dashed line in Fig. 1 and is directly proportional to R_D^2.[8] The dashed curve was calibrated by determining R_D from the slope of the right-hand straight-line portion of the I-V characteristic.

By comparing the curves labeled $\langle v^2 \rangle$ and R_D^2 it is evident that the mean squared voltage fluctuations are to a large extent proportional to R_D^2 as would be expected from a constant current source. However, variation of the current source with voltage is clearly indicated, particularly towards the limits of the displayed voltage region. For comparison with theory, Fig. 2 shows the current fluctuation calculated by using Eq. (4) and plotted (in units of $2eI_{dc}$) versus the applied dc voltage (in units kT/e) for a number of samples.[9] For the data shown, $T = 4.2°K$. I_{dc} is the measured

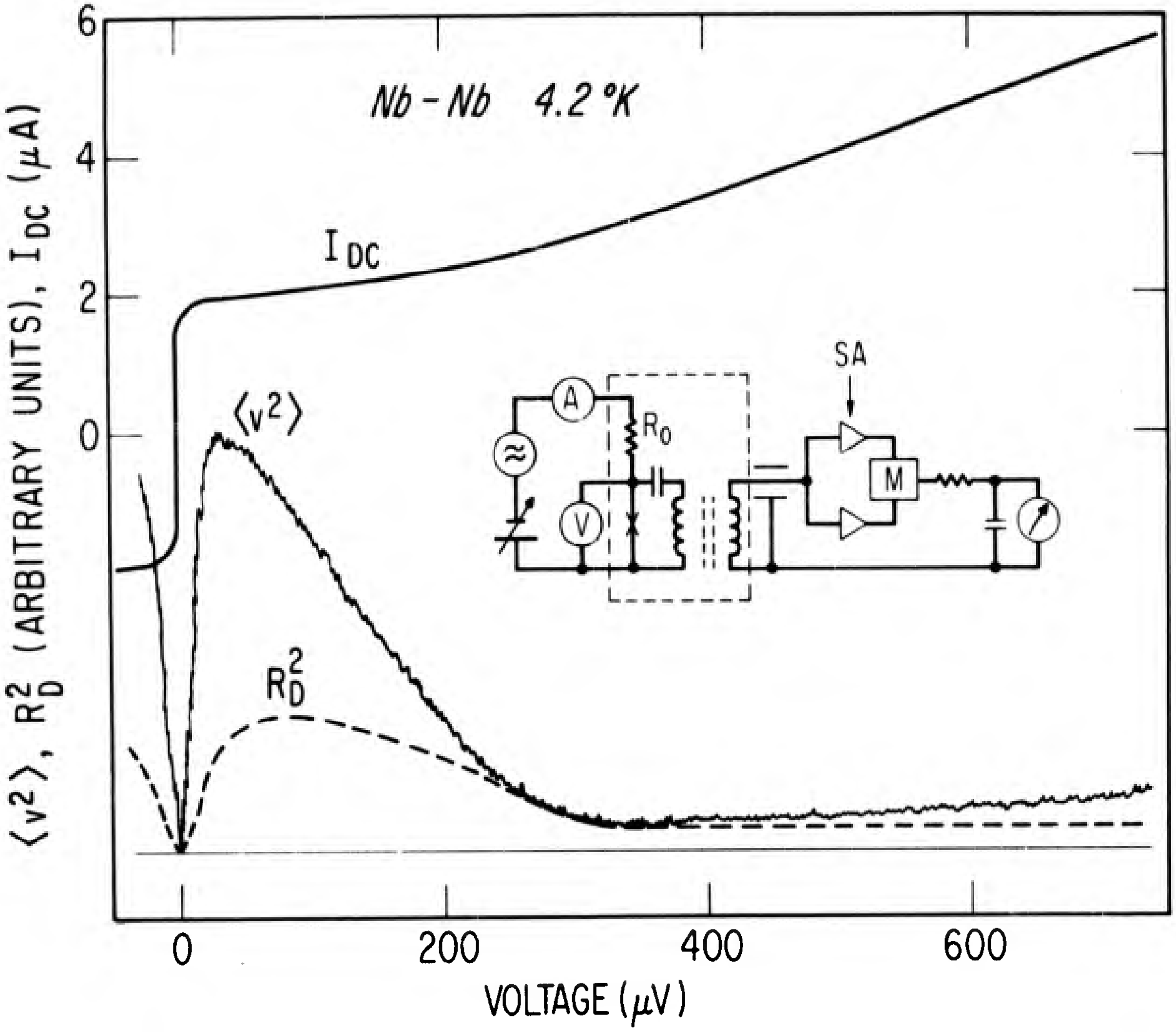

Fig. 1. Recorder plots of dc-sample, I_{dc}, mean squared noise voltage, $\langle \upsilon^2 \rangle$, and squared dynamical resistance, R_d^2 as functions of dc-sample voltage. The inset sketches the circuitry of the setup. SA referes to selective amplifiers, and M to the multiplier. The portion of the circuit enclosed by the dashed region is submerged in liquid helium.

current comprising the sum of quasiparticle and pair contributions. The solid lines represent Eq. (1) for the two limits $I_{dc} = I_q$ or $I_{dc} = I_p$. The actual data for a particular sample should fall somewhere between these two curves. Our results clearly follow the predicted voltage dependence for $eV/kT < 1$. Scatter, however, is too large to permit the determination of the relative contributions of pairs and quasiparticle currents at $eV/kT > 1$.[10]

The various samples covered a range of critical currents between 1 and 10 μA. Furthermore, on several samples I_{dc} was depressed by application of a magnetic field with a corresponding reduction of the noise current level. The data thus are consistent with the predicted current dependence. We were not able to test predicted temperature dependence for the entire voltage range. The reason for this was the fact that the I-V characteristics changed with lowering of temperature. The slope for $V < 200$ μV rapidly approached zero ($R_D \to \infty$) and operation at a particular voltage became unstable. Some samples tended to show a slight hysteresis effect as expected[5,6] for junctions whose time constant becomes comparable with or larger than the inverse of the so-called plasma frequency $\omega_J = [2eI_c/\hbar C]^{1/2}$, where C is the capacitance of the junction and I_c is the critical current. However, for $V > 300$ μV the I-V characteristics remained constant with temperature (1.6°K < T < 4.2°K) and the corresponding portion of the curve, representing the squared noise voltage in Fig. 1, was found to be independent of temperature. In reduced voltage units, $eV/kT > 0.8$ for $V > 300$ μV and $T \leq 4.2$°K. Consequently, as indicated by the solid lines in Fig. 2, one does not expect an appreciable temperature dependence in this limit.[11]

Not all our point-contact junctions showed the noise properties discussed above. For a number of samples the increase of noise current with decrease in sample voltage was only partially observed and sometimes not at all. This was particularly true for critical currents $I_c \gtrsim 10$ μA. Occasionally, the noise-current level would rise according to Eq. (1) for $eV < kT$ down to $eV < 0.4kT$ and then either decrease or remain constant for lower voltages.

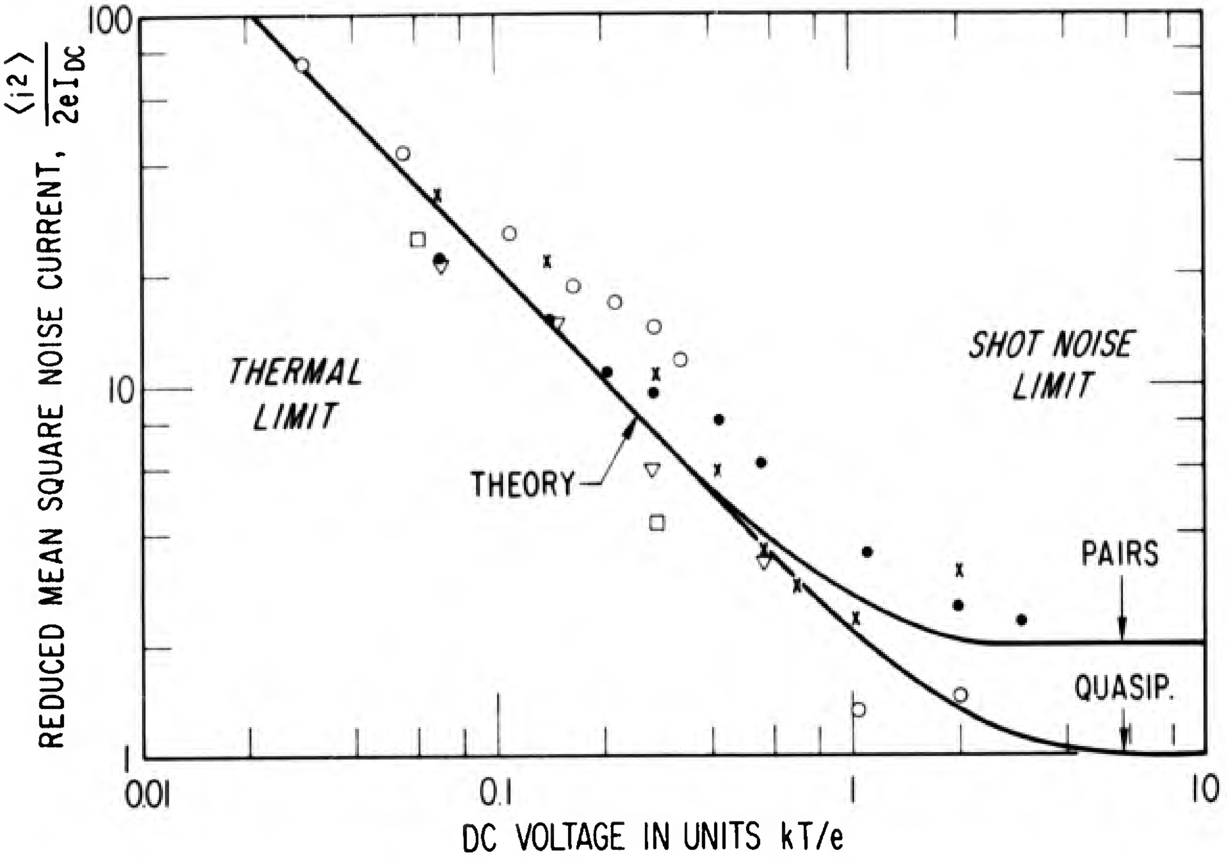

Fig. 2. Comparison of measured voltage dependence of mean squared noise currents with theory for various samples. Here kT/e ≈ 360 µV (T = 4.2°K) and 1 µA ≥ I_{dc} < 10 µA. Temperature dependence could only be investigated for voltages (in reduced units) in excess of 0.8 where the mean squared noise current was found to be independent of temperature. Data points with eV/kT > 0.8 accordingly shift to the right (not shown) inversely in proportion to the temperature.

We suggest that these observations are related to scattering into intermediate states in the junction which would compete with the direct tunneling of pairs between the condensed states of both superconductors on which the increase in noise current with decrease of level separation is based.

FOOTNOTES

1. D. J. Scalapino, University of Virginia Report No. AD 661848, 1967 (unpublished), PG-1. Available from Clearing House for Federal Scientific and Technical Information, Springfield, Va. 22151.

2. M. J. Stephen, Phys. Rev. 182, 531 (1969).

3. A. J. Dahm, A. Denenstein, D. N. Langenberg, W. H. Parker, D. Rogovin, and D. J. Scalapino, Phys. Rev. Lett. 22, 1416 (1969).

4. H. Kanter and F. L. Vernon, Jr., Appl. Phys. Lett. 16, 115 (1970).

5. W. C. Stewart, Appl. Phys. Lett. 12, 277 (1968).

6. D. E. McCumber, J. Appl. Phys. 39, 3113 (1968).

7. J. J. Brophy, M. Epstein, and S. L. Webb, Rev. Sci. Instrum. 36, 1803 (1965). Our correlator-amplifier consisted of two selective amplifiers (the signal amplifier portions of the two PAR HR-8) whose outputs were multiplied (PAR 230) and smoothed with a low-pass filter of RC = 1 sec.

8. For this measurement the amplifier sensitivity was reduced orders of magnitude below that used for the actual noise measurement. The ac signal produced a peak voltage change of less than 5 μV and was normalized in Fig. 1 to coincide with the minimum of the sample noise curve.

9. Because for our junctions $\tau \approx 10^{-12}$ sec, the frequency-dependent term of Eq. (4) was negligible.

10. The scatter of the data $\langle i^2 \rangle / 2eI_{dc} \sim 1$ is due to experimental accuracy, limited by amplifier noise and drift. For $\langle i^2 \rangle / 2eI_{dc} \gtrsim 10$, however, the indicated experimental deviations from theory are real. Reasons for this deviation are not known. Smooth curves connecting the data points for the various samples accurately represent the experimental results except for the open circles between $0.4 < eV/kT < 0.9$ and the open squares between $0.08 < eV/kT < 0.2$, where no data were taken since the samples had in these regions $R_D > 1$ kΩ and showed instability. The noise properties for a particular sample were reasonably constant during its lifetime which was limited by the time the helium charge lasted.

11. An estimate of the maximum possible contribution of Johnson currents by the Ohmic portion of the sample gives $\langle i^2 \rangle$ thermal $\sim \langle i^2 \rangle$ shot for $eV > kT$ if $I_c R \sim kT/e$ (where $T = 4.2°K$) $= 3.6 \times 10^{-4}$ V, the minimum value observed on our samples.