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Intrinsic excess noise in a transition edge sensor

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Abstract

The noise in the measurement of the resistance of a transition edge sensor slightly above the zero resistance state contains a noise component associated with fluctuations in the superconducting order parameter. This noise has been calculated by Nagaev a dozen years ago in the context of the formation of fluctuating Cooper pairs in the normal state slightly above the transition. With reasonable assumptions concerning the properties of TESs it is found that this noise is comparable to Johnson noise only when the temperature is very close to the transition. We discuss the noise from pair fluctuations and methods to decrease its magnitude by pair breaking mechanisms should it be a problem.

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1. Introduction

It has been well known since the late 1960s that the resistance of a normal metal does not decrease discontinuously to zero at the transition to the superconducting state. Rather, the DC electrical conductivity of a normal metal above the transition changes gradually, being modified by the existence of fluctuating Cooper pairs. Aslamazov and Larkin (AL) [1] were the first to calculate the effect of these fluctuations showing that the normal-state DC conductivity is enhanced by the formation and dissociation of Cooper pairs. Shortly thereafter, Maki [2] (later modified by the inclusion of a cut-off by Thompson [3]) found another effect of the ephemeral Cooper pairs, namely, their existence influences the conductivity of the normal electrons. This has come to be called the Maki–Thompson (MT) conductivity. Other authors considered the influence of a magnetic fields and of impurity scattering. In general, the experimental results are in rough agreement with the calculations, a brief review of which can be found in texts such as Tinkham [4].

While the influence of fluctuating Cooper pairs on the DC conductivity of a normal metal at temperatures slightly above the superconducting transition was understood more than 30 years ago, no one at that time considered the effect of fluctuations near the transition on the conductivity at finite frequencies. Since noise in excess of Johnson noise and of intrinsic temperature

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fluctuations has been reported by many groups working with transition edge sensors, one obvious question to ask is whether fluctuating Cooper pairs could be making a contribution to noise observed in these devices.

About a dozen years ago Nagaev [5] addressed the technically challenging problem of performing a microscopic calculation of the excess noise in a superconductor due to fluctuational Cooper pairing. The paper that describes this work appears to have been largely overlooked in that there has only been one citation of the paper since its publication. The discussion below relates Nagaev's results to questions of noise in TES detectors.

In a two-dimensional superconductor where the thickness, d, is much less than the coherence length, the AL DC conductivity is given by the expression

$$\sigma_{\mathrm{AL}} = \frac{e^2}{16\hbar d}\frac{1}{\tau} \tag{1}$$

where $\tau = (T - T_{\mathrm{c}})/T_{\mathrm{c}}$. In clean superconductors the MT DC conductivity can be as much as an order of magnitude larger than the AL term. It can be written for $\tau > \tau_{\mathrm{c}}$ as

$$\sigma_{\mathrm{MT}} = 2\sigma_{\mathrm{AL}} \ln\left(\frac{\tau + \tau_{\mathrm{c}}}{\tau_{\mathrm{c}}}\right) \tag{2}$$

τ_{c} being the reduced shift of the transition temperature

$$\tau_{\mathrm{c}} = (T_{\mathrm{c0}} - T_{\mathrm{c}})/T_{\mathrm{c}}$$

produced as a consequence of pair breaking. In this expression, T_{c0} is the transition temperature the metal would have were there no pair breaking interactions present. Also, to account for pair breaking [6], τ in Eq. (1) should be replaced by $(\tau + \tau_{\mathrm{c}})$. When pair breaking is present, the DC conductivity from fluctuating pairs diverges not at T_{c} but below T_{c} by the amount $(T_{\mathrm{c0}} - T_{\mathrm{c}})$.

The ratio of the AL conductivity to that of the normal state is

$$\frac{\sigma_{\mathrm{AL}}}{\sigma_{\mathrm{N}}} = \frac{e^2 R_{\square}}{16\hbar}\frac{T_{\mathrm{c}}}{T - T_{\mathrm{c}}} = 1.52 \times 10^{-5}\ R_{\square}\frac{1}{\tau} \tag{3}$$

where $R_{\square}$ is the resistance per square. For typical TESs having an $R_{\square}$ of 0.1 Ω or less, the ratio is very small and one might expect that noise deriving from the same fluctuations as the DC conductivity would be small as well, when compared to the standard Johnson noise.

2. Results

Nagaev [5] calculated the noise in the weak coupling BCS model through the use of two-particle Green functions within the Keldyish diagrammatic technique. The results are expressed in a number of separate terms that have their origins in different effects, all of which have analogs in the DC conductivity. His calculations are limited to weak electric fields, E, and all the noise terms are proportional to E^2. Of the various terms the one that is analogous to the MT DC conductivity is the largest. In comparison, all the other terms are small.

Nagaev calculated the spectral density of the *current density* fluctuations. For comparison with experiment, this is best converted to the spectral density of the *total current* fluctuations. We do this for a square film. The spectral density for the current of the MT term can be written, for $\hbar\omega \ll k(T - T_{\mathrm{c}})$ and $(T - T_{\mathrm{c}}) \ll T_{\mathrm{c}}$, as

$$S_{pf}(\omega) = \frac{\pi^2}{128}\frac{De^4E^2}{\hbar}\frac{\tau_\phi\ T_{\mathrm{c}}^2}{k(T - T_{\mathrm{c}})^3}\frac{\arctan(\omega\tau_\phi/2)}{\omega\tau_\phi/2}. \tag{4}$$

The quantity D is the diffusion coefficient and τ_ϕ is the phase coherence time of the electrons. To illustrate the size of the noise in a TES predicted by Eq. (4), we take $D = 0.1\ \mathrm{m^2/s}$, $\tau_\phi = 10^{-8}$ s, $E = 10^{-2}$ V/m, $T_{\mathrm{c}} = 100$ mK, and $(T - T_{\mathrm{c}}) = 0.5$ mK. Then for $\omega\tau_\phi < 1$, the spectral density is $S_{pf}(\omega) = 3.6 \times 10^{-26}\ \mathrm{A^2 s/rad}$ and

$$S_{pf}(f) = 2 \times 10^{-24}\ \mathrm{A^2/Hz}.$$

This is 50 times smaller than the spectral density of the Johnson noise in the normal state at 0.1 K. For a film having a thickness $d = 100$ nm and the value of D used above, $R_{\square} = 0.06\ \Omega$, and

$$S_J = 4kT/R_{\square} = 1 \times 10^{-22}\ \mathrm{A^2/Hz}.$$

For a uniform film, one would not expect to see manifestations of intrinsic pair fluctuations in the noise, unless $(T - T_{\mathrm{c}})$ were of the order of 0.1 mK.

One can ask how representative of TESs are the values chosen parameters in Eq. (4), in particular,

τ_ϕ. Recent work on mesoscopic systems for a review, see Ref. [7] has provided some information on τ_ϕ in metals below 1 K. In alloys with large impurity scattering, τ_ϕ can be as low as 10^{-11} s at low temperature, but such a value seems unlikely for films of the quality of TESs. Measurements [8] indicate that τ_ϕ for clean gold films at 0.1 K is between 10^{-7} and 10^{-8} s.

Experimentally, TESs do not have normal to superconducting transitions as sharp as predicted for an ideal film. The rounding on the normal side of the transition is larger than expected from fluctuation theory. It would seem likely that this broadening is the result of minor spatial variations in the properties of the films, which produce small differences in the transition temperature depending on position. At any point on the transition curve some regions of the film have very small values of $(T - T_c)$ and produce, because of the $1/(T - T_c)^3$ term in Eq. (4), very large contributions to the noise. Qualitatively, one might expect the noise to rise as the temperature is decreased through the resistive transition, as is observed experimentally [9–11]. While the temperature dependence of the observed noise is consistent with pair fluctuations, the lack of variation of excess noise with electric field [10], does not conform to the expected E^2 dependence of Eq. (4).

Should pair noise be observable in a TES, then it can be removed by pair breaking mechanisms introduced by magnetic impurity scattering or an applied magnetic field. Both affect the frequency spectrum of fluctuating Cooper pairs. Nagaev did not explicitly include a magnetic field in his calculations. In general, the effect of a field on pair breaking can be taken into account[3] by replacing T_c with the renormalized transition temperature

$$T_c \to T_c + \frac{\pi\alpha}{4k} \tag{5}$$

where α depends upon field orientation with respect to the film of the sensor and is given by

$$\alpha = \frac{1}{6}\frac{De^2B^2d^2}{\hbar} \quad \text{for parallel field and} \tag{6}$$

$$\alpha = DeB \quad \text{for perpendicular field.} \tag{7}$$

For a film having the parameters used above, $D = 0.1\ \text{m}^2/\text{s}$ and $d = 100$ nm, a parallel field of 0.5 mT or a perpendicular field of 0.003 mT would produce a shift in T_c the order of 3 mK. Upon replacing T_c in the term $(T - T_c)^3$ in the denominator of Eq. (4) by $T_c + \pi\alpha/4k$, the pair noise is dramatically reduced for T near T_c. Ullom et al. [12] have observed a strong decrease of the noise in perpendicular fields the order of 0.1 mT, but, again, this may have another explanation than that discussed here.

Within Nagaev's formalism, magnetic impurities affect the noise through τ_ϕ and T_c. Webb et al. [8] found that when a Au film initially with $\tau_\phi = 3 \times 10^{-9}$ s was implanted with 2.8 ppm of Fe, the coherence time dropped to less than 10^{-10} s at 0.1 K. The effect that a particular magnetic impurity has on the pair fluctuation noise at a superconducting transition is expected to depend upon the transition temperature compared to the Kondo temperature. At temperatures well below the Kondo temperature, an impurity forms a non-magnetic singlet in its host, and enhanced scattering is predicted to be no longer present.

3. Conclusions

At any second-order transition, intrinsic fluctuations in the order parameter must exist. In the measurement of resistance of a metal near a transition to the superconducting state, additional noise must be present at some level. The question is, what is that level? Whether or not pair fluctuations, as considered by Nagaev, contribute to the noise that is experimentally observed in inhomogenously broadened transitions remains to be determined. It may be that pair noise is suppressed by effects not included by Nagaev, such as spatial gradients in the order parameter invoked above to broaden the transition. Spatial inhomogeneities can lead to spin–orbit scattering and reduced fluctuations. Should pair fluctuations be found to impair the performance of a TES, there are means for reducing their magnitude. Pair

[3] See Ref. [4, Section 10.2].

fluctuations are strongly suppressed by magnetic impurities and by a magnetic field.

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