Observing temperature fluctuations of a mesoscopic electron system

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Almost a century ago, Johnson and Nyquist1,2 presented evidence of fluctuating electrical current and the governing fluctuation dissipation theorem (FDT). Whether, likewise, temperature T can fluctuate is a controversial topic and has led to scientific debates for several decades3–5. To resolve this issue, there was an experiment initially in 19926,7 where the authors found controversial topic and has led to scientific debates for several decades3–5. To resolve this issue, there was an experiment initially in 19926,7 where the authors found
to acquire statistics of temporal temperature of the absorber (brown) connected to three superconducting leads (blue). The right one is a tunnel contact of the thermometer and the other tunnel junction on the left the hot electron injector. The third one pointing down and 50 nm away from the thermometer, is a direct clean metal-to-metal contact grounded at the sample stage. It provides a fixed chemical potential for the absorber and induces proximity superconductivity to the thermometer facilitating its proper operation. The measuring setup for the thermometer junction shown on the right side of Fig. 1 consists of a parallel on-chip LC resonator, coupled to input V1 and output V2 rf lines, operating at f0 = 620 MHz which also admits DC biasing at voltage Vth. The measured signal S21 obtained from the ratio of V2/V1, yields the conductance of the thermometer junction. It is typically measured at 10 kHz sampling rate in order to acquire statistics of temporal temperature of the absorber.

In order to calibrate the thermometer we measure S21 averaged over typically 1 s time interval at different bath temperatures of the cryostat, traceable to primary Coulomb blockade thermometry CBT. An example of dependence of thus obtained ⟨S21⟩ on Vth is shown on a wide bias range in Fig. 2. The drop of ⟨S21⟩ at about ±200 μV is due to the superconducting gap Δ in aluminum. The main feature, the zero bias anomaly (ZBA) at Vth = 0 which is indicated by the central red arrow,

At low frequencies we have

\[ S_T(0) = \frac{2k_B T^2}{G_{th}}, \]  

and the spectrum has Lorentzian cut-off at \( \omega_c = G_{th}/C \).

These results hold also for a system coupled to several equilibrium baths, if one takes \( G_{th} \) to represent the sum of all the individual thermal conductances to these baths. For the rms fluctuations we obtain the well-known result

\[ \langle \delta T^2 \rangle = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} S_T(\omega) = k_B T^2 / C, \]
In our case we monitor the fluctuating temporal fluctuations of the quantity of interest. A key element in the calorimeter is a thermometer with sufficient bandwidth to provide temporal temperature traces, of which an example is shown above the absorber. The measurement setup including the colored scanning electron micrograph of the sample in the center. The L = 1 μm long Cu absorber (brown) coupled to two superconducting Al leads (blue) via tunnel barriers (bronze). The clean metal-to-metal contact to another superconducting Al lead pointing down at an inclined angle provides the proximity effect for the thermometer and a fixed chemical potential for the absorber. The circuit on the sample stage at low temperature (LT) within the dashed area presents the RF readout of the thermometer junction composed of an LC resonator and probed by RF transmission measurement between ports V1 and V2. The rest of the setup at room temperature (RT) is for DC biasing of both the injector (V) and thermometer (Vth).

FIG. 1. The setup for measuring temperature fluctuations. (a) The calorimeter principle applied to the electronic system in this work. The normal-metal absorber in the center is subjected to the fluctuating heat current from the phonon bath below. Additionally we have an option to create nonequilibrium by injecting "hot" electrons as indicated by red arrows on the left. A key element in the calorimeter is a thermometer with sufficient bandwidth to provide temporal temperature traces, of which an example is shown above the absorber. (b) The measurement setup including the colored scanning electron micrograph of the sample in the center. The L = 1 μm long Cu absorber (brown) coupled to two superconducting Al leads (blue) via tunnel barriers (bronze). The clean metal-to-metal contact to another superconducting Al lead pointing down at an inclined angle provides the proximity effect for the thermometer and a fixed chemical potential for the absorber. The circuit on the sample stage at low temperature (LT) within the dashed area presents the RF readout of the thermometer junction composed of an LC resonator and probed by RF transmission measurement between ports V1 and V2. The rest of the setup at room temperature (RT) is for DC biasing of both the injector (V) and thermometer (Vth).

presents the basis of our thermometer. This dip originates from proximity induced supercurrent due to the presence of clean contact. Now it is placed 50 nm away from the tunnel junction which is to be contrasted to 500 nm in our earlier work [11]; this way the sensitivity of the thermometer is enhanced substantially. Quantitatively, the temperature dependence of the transmission ⟨S21⟩ at this dip is depicted in Fig. 2b. It manifests approximately linear dependence at sub 200 mK down to below 20 mK temperatures, emphasised by the zoom in the inset of this figure. Owing to the competing quasiparticle tunneling, there is eventually back-bending of the characteristics at temperatures above 300 mK; this leads to temporal loss of sensitivity in this temperature range. Depending on the range of interest, we employ either linear or nonlinear calibration to convert ⟨S21⟩ to temperature. As tested and demonstrated in Ref. [11], the temperature measured by ⟨S21⟩ of the ZBA thermometer in a similar setup is that of the absorber electrons that we indeed want to monitor. Time domain measurements allow detecting temporal fluctuations of the quantity of interest. In our case we monitor S21(t), yielding the instantaneous temperature of the absorber at 10 kHz sampling rate over a chosen time interval. We collect data under given conditions typically for up to 1 hour. As a result we obtain the total fluctuations (variance) ⟨δS21, tot⟩ in a bandwidth of Δf ≈ 10 kHz. This signal is composed of the amplifier and other instrumental noise ⟨δS21, bg⟩ ("bg" stands for background), in addition to the noise of interest from the actual sample, ⟨δS21⟩ = ⟨δS21, tot⟩ − ⟨δS21, bg⟩. Here we assume uncorrelated noise from the different sources. The way we determine the ⟨δS21, bg⟩ is explained in the Methods section. Our quantitative results depend critically on the precision of determining this background noise. Taking the linear calibration as in the inset of Fig. 2b, with the responsivity R ≡ |d⟨S21⟩/dT|, we have for the temperature of the absorber ⟨δT2⟩ = R−2⟨δS21⟩. We exhibit in Fig. 3 the total quantity in the experiment, low-frequency temperature fluctuations √S2 T = √⟨δT2⟩/2Δf as a function of bath temperature in equilibrium. From now on we denote Θ ≡ √S2 T which can also be associated to the noise-equivalent temperature NET0, where with subscript 0 we refer to the fundamental temperature fluctuations discussed here. The data symbols correspond to the averaged bare noise, where the best guess of the background has been subtracted. The shaded area depicts the uncertainty in determining Θ precisely due to this subtraction. Overall, we observe first increase of Θ upon lowering T and then gradual turn down of it at the lowest temperatures. The dominant contributions to Gth arise from electron-phonon coupling at higher temperatures and radiative heat transfer by thermal photons [14] towards low T as

\[ G_{th} = 5 \Sigma V T^4 + \alpha g T. \]  

Here Σ, V are electron-phonon coupling constant [15] and volume of the absorber, respectively. For the photonic contribution [10], GQ = gT is the quantum of thermal conductance with g = πk_B^2/6ℏ. We assume the coupling coefficient α to have values ≪ 1. Equation (2) predicts then

\[ \Theta = \sqrt{2k_B T^{-1}} \quad \text{(high T)} \]

\[ \Theta = \sqrt{2k_B T^{-1/2}} \quad \text{(low T)}, \]

with cross-over between the two regimes at the tem-
FIG. 2. The transmission measurement of the RF thermometer. (a) Wide bias range transmission $\langle S_{21} \rangle$ averaged over 100 repetitions at each bias point $V_{th}$ at bath temperature $T \sim 100$ mK and $-120$ dBm input power. The two red arrows indicate the working points for actual ZBA thermometry at $V_{th} = 0$ and background measurement at $V_{th} = 85 \mu$V, respectively. (b) The thermometer calibration against the bath temperature $T$ in equilibrium. The inset shows the low temperature end together with the linear fit used for the temperature fluctuation measurements.

The measured temperature $T_{co} = (\frac{\alpha g}{m \gamma})^{1/3}$. Using the literature value $\Sigma = 2 \times 10^9 \text{WK}^{-5}\text{m}^{-3}$ [12], the measured volume $V = 1.0 \times 10^{-21} \text{m}^3$ and an educated guess $\alpha \approx 10^{-3}$ [13] according to earlier investigations, we obtain a predicted $\Theta$ versus $T$. Our simple model above predicts a maximum of $\Theta$ at $\sim 35$ mK with the value of about $30 \mu$K/$\sqrt{\text{Hz}}$. This is outside the shaded area of $60 - 130 \mu$K/$\sqrt{\text{Hz}}$ of the measured signal in Fig. 3. A possible origin of this discrepancy lies in that we assume the absorber to be in the normal state. However, the clean absorber-superconductor contact leads to a proximity induced superconductivity in the absorber. This suppresses the density of states around the Fermi level, on the scale of the Thouless energy $E_{Th} = \hbar D/L^2 \sim 10 \mu$eV, resulting in a decreased electron-phonon coupling. Here, $D \sim 0.01 \text{m}^2/\text{s}$ is the diffusion constant of the Cu film. As a consequence, for electron temperatures $T \lesssim E_{Th}/k_B \sim 100$ mK, the thermal conductance $G_{th}$ is decreased [17] and, hence, the temperature noise $\Theta$ is increased. Furthermore, the temperature calibration, i.e., the responsivity $R$ of the thermometer gets more unreliable towards the lowest temperatures. The overall magnitude at $T > T_{co}$, determined by the electron-phonon heat conductance (no fit parameters) is thus in fair agreement with the experiment within the uncertainty of the measurement as explained. The cross-over, more of phenomenological origin, is also consistent with the experiment with the chosen value of $\alpha = 10^{-3}$. Another possible contribution to this cross-over may arise from the fact that the fluctuations $\delta T$ of temperature become comparable to $T$ itself in the lowest temperatures.

Let us next consider the nonequilibrium fluctuations [19-21]. In the measurements up to now the injector junction on the left in Fig. 1b has been unbiased in order to ensure equilibrium. By applying a voltage $V$ to it, the system can be driven into nonequilibrium. The well-known influence of such biasing of a superconductor-normal metal junction is that it serves as a local refrigerator of the normal-metal absorber thanks to the energy gap of the superconductor, i.e., it acts as an evaporative cooler [18]. This effect is manifested in the bias dependence of the average temperature of the absorber, obtained from the values of $\langle S_{21} \rangle$ in Fig. 4.

Injecting electrons does not only change the average temperature of the absorber but, due to the stochastic nature of tunneling, it leads to noise of heat current as
tion noise regime well below the superconducting gap, the injectively. For typical voltages and temperatures in the
and S stand for normal metal and superconductor, re-
density of states for superconductor and subscripts N
where $n$ is exponentially suppressed [10]. In con-
quantitatively by assuming constant voltage noise independent
of the low temperature Caltech CITLF2 cryogenic SiGe
low noise amplifier ($\delta S_{21, \text{bg}}$) by carefully off-tuning the
the carriers form a local Fermi-Dirac distribution: all
the heat diffusion time of electrons in the absorber,
$\tau_{\text{diff}} = \gamma \rho / L$, is very short. Here, $c = \gamma T$,
the specific heat due to conductance electrons with
$\gamma \sim 2^8 \text{ Wm}^{-3} \text{K}^{-2}$, $\rho \sim 10^{-8} \Omega \text{m}$ is the resistivity of
the Cu, $l = 1 \mu\text{m}$ is the length of the absorber, and
$L_0 = 2.44 \times 10^{-8} \text{ W} \Omega \text{K}^{-2}$ is the Lorenz number.

METHODS

Background measurements

We measure the instrumental noise dominated by that
of the low temperature Caltech CITLF2 cryogenic SiGe
low noise amplifier ($\delta S_{21, \text{bg}}$) by carefully off-tuning the
the interesting fluctuations from the sample itself. This
is achieved by simultaneously (i) biasing the thermome-
rence away from the ZBA regime ($V_{\text{th}} \sim 85 \mu\text{V}$), and
(iv) measuring at frequencies either below or above
the resonance at $f_0$. An example of the correspond-
parametric background noise measurement, in form
$\langle \delta S_{21, \text{bg}}^2 \rangle$ versus $\langle S_{21} \rangle$ is presented in Fig. 3. We see a
typical increase of noise when the attenuation increases
left. This dependence can be understood quanti-
tatively by assuming constant voltage noise independent
of $S_{21}$. The measured transmission can be written as

$$S_{21} = 20 \log (v/\bar{v}),$$

where $v$ is the output of the last stage amplifier, $\bar{v} = \sqrt{50}\, \Omega \times 1\, \text{mW} \approx 224\, \text{mV}$. Noise of $v$ translates then
into variations of $S_{21}$ in linear regime as

$$\delta S_{21} = \frac{20 \, \delta v}{\ln 10 \, v},$$

well [22]. Quantitatively the low frequency heat current
noise is given by

$$\delta S_{\text{shot}} = \frac{1}{e^2 R_T} \int dE (E - eV)^2 n_S(E)$$

$$\{f_S(E - eV)[1 - f_S(E)] + f_S(E)[1 - f_S(E - eV)]\},$$

where $n_S(E) = |E| / \sqrt{E^2 - \Delta^2}(|E| - \Delta)$ denotes the
density of states for superconductor and subscripts N
and S stand for normal metal and superconductor,
respectively. For typical voltages and temperatures in the
regime well below the superconducting gap, the injec-
tion noise $\sqrt{S_{Q}^{\text{eq}}}$ is exponentially suppressed [10]. In con-
trast, the equilibrium noise due to phonons, $\sqrt{S_{Q}^{\text{eq}}}$, is of a

roughly constant magnitude $\sim 10^{-20} \text{W}/\sqrt{\text{Hz}}$. Therefore
it is not surprising that the temperature noise in Fig. 1 does not change much at sub-gap voltages $V < 200 \mu\text{V}$,
in particular as the temperature of the absorber is not
changing dramatically in this bias range. For these un-
correlated sources the temperature noise is predicted to
obey $S_T = (S_{Q}^{\text{eq}} + S_{Q}^{\text{ph}})/G_{\text{th}}$. The sudden decrease of
temperature noise $\Theta$ at $V > 200 \mu\text{V}$ is natural since
$G_{\text{th}}$ increases rapidly when the absorber heats up in this
regime (see Fig. 4a). We consider the sharp peak at the
gap (Fig. 4b) to be an artefact arising from unavoid-
able voltage noise of injector, which directly transforms
to temperature noise due to the strong voltage depen-
dence of temperature at this point.

Finally, what is the temperature that fluctuates? In
fact, it is the parameter of the distribution of the elec-
trons in the absorber that we monitor. It qualifies as tem-
perature for the following reasons. (i) Number of parti-
cles is large, about $10^9$. (ii) Due to fast electron-electron
internal relaxation over a time scale of $\sim 10^{-9} \text{ s}$ [22],
the carriers form a local Fermi-Dirac distribution: all
other relaxation rates, most notably the electron-phonon
time ($\sim 10^{-5} \text{ s}$) are much slower [21]. Furthermore,
the temperature of the absorber is spatially uniform,
since the heat diffusion time of electrons in the absorber,
$\tau_{\text{diff}} = \gamma \rho l^2 / L_0 \approx 10^{-10} \text{ s}$ is very short. Here, $c = \gamma T$,
is the specific heat due to conductance electrons with
$\gamma \sim 2^8 \text{ Wm}^{-3} \text{K}^{-2}$, $\rho \sim 10^{-8} \Omega \text{m}$ is the resistivity of
the Cu, $l = 1 \mu\text{m}$ is the length of the absorber, and
$L_0 = 2.44 \times 10^{-8} \text{ W} \Omega \text{K}^{-2}$ is the Lorenz number.

FIG. 4. Temperature and its fluctuations under nonequilib-
rium conditions. (a) Average temperature of the absorber
when the injecting junction is biased at different voltages $V$.
The data sets correspond to bath temperatures 12, 27, 35,
43, 52, 67, 83, 100, 117, 135, 166, 198, and 233 mK from bot-
tom to top. (b) Nonequilibrium temperature fluctuations at
selected temperatures as a function of injector bias.
FIG. 5. Background noise measurements. All the data are taken outside the zero bias regime of the thermometer and at nonresonant frequencies to exclude the actual noise from the sample. The inset of (a) shows an example of $\langle S_{21}\rangle$ measured around the resonance frequency indicated by the central upward arrow. The data points in the main frame of (a) depict parametric plot $\sqrt{\langle \delta S_{21,bg}^2 \rangle} = a 10^{-\langle S_{21}\rangle/20}$ versus $\langle S_{21}\rangle$ at the bias voltages $V_{th} = 85$ µV and at frequencies below the resonance down to 614 MHz indicated by a downward arrow. The red solid line shows the predicted dependence yielding the noise temperature of the amplifier of $T_n = 4.9$ K as the only fit parameter of the curve (constant noise voltage at the input). (b) The full range measurement of the background as in (a) but now both above and below the resonance. We observe two features that we need to consider when making an accurate evaluation of the $\langle \delta S_{21,bg}^2 \rangle$. First, at large attenuations, due to the fact that the changes are not fully linear in the sense of Eq. (7), the exponential dependence of Eq. (8) is not obeyed strictly. Therefore we resort to polynomial fits in two regimes, to capture the dependence over the full range. Second, there is a weak dependence of the amplifier noise on frequency; thus the data taken below and above the resonance differ from each other slightly. What we do then, e.g., in Fig. [3] is that we take the mean between the two background measurements as the reference and indicate by the shaded area the uncertainty incurred due to the difference between the two extremes. We thus assume that the frequency dependence of the noise is more or less smooth in the narrow range of $\sim 10$ MHz around $f_0$, and interpolate the data accordingly.

and can be written with the help of Eq. (6) for the rms values as

$$\sqrt{\langle \delta S_{21,bg}^2 \rangle} = 20 \ln 10 \frac{\sqrt{\langle \delta v^2 \rangle}}{v} 10^{-\langle S_{21}\rangle/20}.$$  

Based on the fit parameter $a$ in Fig. [5] and the total gain of 60 dB of the amplifier chain, we find the input voltage noise to be $\sim 12$ nV corresponding to the noise temperature of the amplifier of $T_n \sim 5$ K which is in line with its specifications by the manufacturer.

Figure [5] presents background measurements at frequencies both below and above the resonance over a wide range of attenuation $\langle S_{21}\rangle$. We observe two features that we need to consider when making an accurate evaluation of the $\langle \delta S_{21,bg}^2 \rangle$. First, at large attenuations, due to the fact that the changes are not fully linear in the sense of Eq. (7), the exponential dependence of Eq. (8) is not obeyed strictly. Therefore we resort to polynomial fits in two regimes, to capture the dependence over the full range. Second, there is a weak dependence of the amplifier noise on frequency; thus the data taken below and above the resonance differ from each other slightly. What we do then, e.g., in Fig. [3] is that we take the mean between the two background measurements as the reference and indicate by the shaded area the uncertainty incurred due to the difference between the two extremes. We thus assume that the frequency dependence of the noise is more or less smooth in the narrow range of $\sim 10$ MHz around $f_0$, and interpolate the data accordingly.

**Experimental details**

The sample (Fig. [1]) was fabricated on standard oxidized Si substrate using Ge process for achieving robust deposition mask [25, 26]. The electron-beam lithography was used to pattern the structure for three-angle shadow evaporation of metals. First we deposit 20 nm of Al making the leads followed by oxidation in pure $O_2$ (1 min at 1 mbar). Next another Al layer of 20 nm thickness again provides the clean superconducting contact at the distance of 50 nm from the thermometer junction, and finally we deposit 35 nm Cu to form the absorber. The resonator is a spiral on a separate chip made of 100 nm thick Al by simple one angle evaporation. The heart of the measuring setup is shown in Fig. [1] with inductance $L = 100$ nH, $C_1 = 10.3$ fF and $C_2 = 59.3$ fF as coupling capacitors, and $C = 0.2$ pF. The rest of the RF circuitry follows closely to what is presented in Ref. [24].

**AUTHOR CONTRIBUTIONS**

The experiment was proposed by J. P. and its realization was conceived by all the authors. B. K. performed the experiment, and designed and fabricated the samples. Data analysis and modeling were performed by B. K. and J. P., with contributions on the noise analysis by F. B. and P. S. The manuscript was written by B. K. and J. P.
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