Energy resolution of electronic states delivered by Pauli exclusion and shot noise

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Conventional transport-based spectroscopy of the non-equilibrium electronic states is achieved via an energy-selective sensor. Here we focus on a fundamentally different approach, which relies solely on the fermionic statistics of the electrons. The effect of Pauli’s correlations between the electrons is non-vanishing in spontaneous current fluctuations permitting local measurement of the electronic energy distribution (ED) via shot noise. We demonstrate the power of this approach measuring the local ED in a biased diffusive metallic wire by means of a normal metal tunnel junction. Working in the ohmic regime of the tunnel junction we are able to measure the usual double-step ED with the energy resolution limited by the bath temperature. The observed evolution of the ED in external magnetic field allows the measurement of the inelastic relaxation time mediated by a well-known effect of unintentional magnetic disorder.

Nanoscale temperature mapping and control of nonequilibrium configurations has attracted much interest recently. The prominent examples range from thermometry in a living cell1 to thermal imaging of quantum systems2 and nanoscale devices3. Along with direct thermal measurements and NVC- and SQUID-based thermometers,4 primary shot noise thermometry is also attractive due to its self-calibrating nature.5 Historically, it was first used for the study of hot-electron regime in metallic resistors7–9 and was later on extended to primary electronic thermometry10 and to the studies of graphene.11–15

Shot noise power of the current fluctuations $S_I$ in a two-terminal conductor, however, doesn’t provide neither local nor energy resolution. The reason is that random fluctuations of the occupation numbers of the electronic quantum states are averaged both in the energy interval where electron scattering is possible, and along the length of the device.16 This fundamental constraint set by current conservation makes accessible only the device-averaged nonequilibrium noise temperature $T_N$. To circumvent these charge conservation restrictions, one can measure the dynamical response of thermal noise to an ac excitation to extract inelastic relaxation times17, or implement the special design of the experiment to guide currents in a magnetic field.18

Energy-resolved measurements in mesoscale devices typically rely on the spectral sensitivity of the used detector. This spectral sensitivity inherent, e.g., to superconducting electrodes or quantum dots (QD) with discrete electronic levels, allowed to use them as sensors for the measurements of energy distribution (ED) inside current-driven mesoscopic metallic wires20–22 and for the edge-channel spectroscopy in the integer quantum Hall regime.23,24 In these experiments, EDs were obtained by measuring average current through the tunnel junction (TJ) and through the QD, respectively. Strikingly, energy-resolved local information is also accessible without using any spectral-sensitive detector. Rather than in the average current it is concealed in current fluctuations measured with a local probe. In this case, energy sensitivity is provided solely by the Pauli exclusion principle, which couples EDs in the equilibrium reservoir and in the studied device in the expression for the shot noise. Noteworthy, there is no external limiting energy scale in this approach besides bath temperature.

In this paper we demonstrate how the Pauli exclusion principle, which influences the current fluctuations magnitude, delivers energy resolution of electronic states. To illuminate the main idea of the experiment we first consider two electron reservoirs with EDs $f_1$ and $f_2$ coupled, for the moment, by a tunnel junction (TJ) with an energy-independent transmission probability. The average partial tunneling current in the energy strip $\delta \varepsilon$ from the $i$-th to the $j$-th reservoir for a single conduction channel is

$$\delta I_{i \rightarrow j} \propto f_i (1 - f_j) \delta \varepsilon.$$ 

Here, the factor $f_i$ stands for the occupation probability of the state incident from the $i$-th reservoir, whereas the second factor $(1 - f_j)$ reflects the requirement that, simultaneously, the counter-propagating state in the $j$-th reservoir is empty. The latter restriction is imposed by the Pauli exclusion and distinguishes electrons, which obey the Fermi-Dirac (FD) statistics, from classical independent particles. Nevertheless, the expression for the average partial tunneling current through the TJ $\delta I = \delta I_{1 \rightarrow 2} - \delta I_{2 \rightarrow 1} \propto (f_1 - f_2) \delta \varepsilon$ is identical to the classical case. Thus, the quasiparticle statistics remains
hidden in the average current. The situation is different as soon as the fluctuations are considered. Since the two currents $\delta I_{1,2}$ and $\delta I_{2,1}$ are mutually uncorrelated events with Poisson distributions, the corresponding Schottky-like contributions to the current noise spectral density just add up:

$$\delta S_I = 2e\left[\left|\delta I_{1,2}\right| + \left|\delta I_{2,1}\right|\right] \propto \left[f_1 + f_2 - 2f_1f_2\right] \delta \varepsilon.$$ 

Hence, the noise spectral density contains the product of the electronic EDs on the two sides of the TJ. This coupling of the EDs originates directly from the Pauli exclusion and enables the energy resolution in the shot noise measurement. Provided one takes into account the transmission eigenvalue distribution, similar reasoning applies not only for the TJ but for any multimode conductor with transport occurring at constant energy. In this general case, the expression for the $\delta S_I$ should be additionally multiplied by the Fano-factor of the conductor’s shot noise. Equally important, in the nonequilibrium configuration zero average current through the conductor can coexist with its noise which by far exceeds the Johnson-Nyquist value. For the simplest case of a temperature difference across the conductor this was recently demonstrated for InAs-nanowires and for atomic scale junctions.

In the following we will demonstrate the measurements of ED in micrometer-scale nonequilibrium metallic wires, see fig. 1(a) for the sketch of the experiment setup. The sensor reservoir is described by the equilibrium ED $f_1 = f_0(\varepsilon - eV, T_0)$, and the probed conductor locally by some nonequilibrium ED $f_2 = f(\varepsilon)$. Here, $f_0(\varepsilon, T) = \left[\exp\left[\varepsilon / (k_B T)\right] + 1\right]^{-1}$ is the FD distribution, $V$ is the bias voltage across the TJ connecting the two reservoirs, and $T_0$ is the bath temperature. Changing $V$ effectively scans $f_1$ relatively to the studied nonequilibrium $f$, see figs. 1(b) and 1(d). The current across the TJ is

$$I \propto \int [f_0(\varepsilon - eV) - f(\varepsilon)] \delta \varepsilon,$$

and the differential conductance, $G = dI/dV$, is therefore constant and polarity-independent, see fig. 1(c). Here, the transmission probability of the TJ and the density of states in the reservoirs are assumed independent of the energy, which is the case in our experiment. At the same time, the $V$-dependent contribution to the partial current noise spectral density

$$\delta S_I \propto f_0(\varepsilon - eV) \left[1 - 2f(\varepsilon)\right] \delta \varepsilon$$

leads to the peculiar $S_I(V)$-dependence with

$$\frac{dS_I}{dV} \propto 1 - 2f(eV). \tag{1}$$

For the locally-equilibrium ED $f = f_0(\varepsilon, T)$ with $T \gg T_0$ this relation would link the transition between occupied and empty states in $f$ with the crossover in $S_I(V)$ from thermal noise at small $|V|$ to linear with bias shot noise at larger $|V| \gg k_B T$, see Ref. Similarly, for the nonequilibrium $f(\varepsilon)$ with possibly many step-like features, each step is associated with the change of the slope in the $S_I(V)$-dependence.

Consider, for simplicity, the case of negligible inelastic scattering in the studied wire achieved at low enough $T_0$. Upon the application of a transport current $I_{sd}$ through the wire ED $f(\varepsilon)$ acquires an intermediate step, see fig. 1(d) with the height depending on the position along the wire and the polarity of the $I_{sd}$. At bias voltages $V$ when the step in FD distribution $f_0$ crosses the steps in $f$, the derivative $dS_I/dV$ changes its value which is expressed as two kinks in the $S_I(V)$-dependence, see fig. 1(e). The presence of electron-electron ($e-e$) scattering in the wire leads to the smoothing of the step in $f$ and, correspondingly, to the smoothing of the kinks.

The colored SEM image of a typical device is presented in fig. 1(f). The 3 $\mu$m-long 25 nm-thick and 100 nm-
wide copper wire (brown) is evaporated above 20 nm-thick Al electrodes (blue) which were first controllably oxidized for 2 min with pure oxygen pressure of 1 mbar to form a TJ (red cross). The wire is well coupled to two thicker side aluminum reservoirs which are 125 nm-thick and were intentionally made as wide as possible. These reservoirs are used to turn the wire out of equilibrium with a transport current $I_{\text{sd}}$. For sensing purposes, we used Al electrode located either at one-quarter distance between two reservoirs (device D1) or in the middle of the wire (device D2). The unused Al electrode on both devices was left unbounded. The typical TJ’s resistance is around 25–30 kΩ by far exceeding the sum of the wire’s resistance (27 Ω) and its reservoirs resistance ($\approx 1$ Ω to the ground) ensuring negligible heat leakage to the sensor reservoir. In order to avoid any superconducting effects of Al electrodes, during the noise measurements we applied perpendicular magnetic field at least sufficient to completely suppress superconductivity (120 mT). In the similar fashion we also studied the middle in the length of 3 μm-long 25 nm-thick and 150 nm-wide Al wire realized in an all-aluminum TJ device (device D3, see Supplemental Material Fig. S1) with TJ’s resistance of 5 kΩ and the wire’s resistance of 10 Ω. The noise measurement details may be found in Supplemental Material.

For all three devices we first characterize the TJs in terms of conventional transport and noise properties. For devices D1 and D2 the $I$-$V$ characteristics in $B = 0$ demonstrated the typical normal-metal-insulator-superconductor (NIS) behavior with drastic decrease of subgap conductance with decreasing temperature, and conductance peaks at $\approx 190 \mu$eV, reflecting the maxima in the density of states of the superconducting Al. The device D3 showed the typical SIS behavior (see Supplemental Material Fig. S2 for the $I$-$V$ curves of both devices). All three devices demonstrated almost linear $I$-$V$ curves in finite magnetic field suppressing superconductivity with negligible contribution of interaction effects (see Supplemental Material Fig. S3). In terms of noise in the normal state, devices D1 and D3 demonstrated the standard Fano-factor $F = 1$, common for TJs. In device D2 we measured a linear behavior typical for TJs, however, with $F = 0.6$ which might be a result of a pinhole. This junction also acts as a current noise-to-ED converter, yet with a slightly smaller sensitivity owing to the reduced shot noise.

Knowledge of the Fano-factor of the TJ allows one to infer

$$f(eV) = \frac{1}{2} - \frac{1}{F} \frac{d(k_B T_N)}{d(eV)},$$

where $T_N = S_1 R_T / 4k_B$ is the TJ’s noise temperature and $R_T$ is its resistance. This relation is valid when $k_B T_N$ is much less than the characteristic energy scale on which the local ED $f(\varepsilon)$ changes significantly. Fig. 2 demonstrates the dependence $T_N(V)$ in the devices D1 and D2 in large magnetic field 5 T. The dotted lines on the panels (a) and (b) are measured in the absence of the transport current through the metallic wire, $I_{\text{sd}} = 0$. In this case, the $T_N(V)$-dependence is typical: it is symmetric with respect to the $V$ inversion and displays the parabolic transition from the Johnson-Nyquist noise at low $|V|$ to the linear shot noise at higher $|V|$. The finite transport current $I_{\text{sd}}$ changes $T_N(V)$ drastically, see solid lines. For the TJ realized at one-quarter of the way between two reservoirs, fig. 2(a), $T_N(V)$ becomes asymmetric with the kink-like features at $V = \mp V_{\text{sd}}/4$ and $V = \pm 3V_{\text{sd}}/4$ with upper signs corresponding to $I_{\text{sd}} > 0$ and lower signs corresponding to $I_{\text{sd}} < 0$. These features coincide with the expected kinks positions, as indicated by arrows in fig. 2(a) for $I_{\text{sd}} > 0$. In the case when the TJ is realized in the middle of the nonequilibrium conductor, fig. 2(b), the $T_N(V)$-dependence is symmetric, however with a near-zero bias plateau-like region. Note, how this observation illustrates Fig. 1: scanning the 1/2-plateau in $f(\varepsilon)$ with bias voltage $V$ doesn’t change $T_N$. Here, again, the plateau’s boundaries coincide with expected kinks position, see arrows in fig. 2(b). Overall, Fig. 2 reveals energy and spatial sensitivity of our approach.

![FIG. 2. Noise temperature vs. bias voltage for the TJs realized at two different positions along the wire at $T_{\text{bath}} = 30$ mK in a magnetic field of $B = 5$ T. (a) In the asymmetric case, $T_N$ depends on the polarity of $I_{\text{sd}}$ in accordance with $f(\varepsilon)$, reflecting the locality of the extracted ED. (b) $T_N$ is symmetric for the central positioning of the TJ. Dotted lines in both panels demonstrate $T_N$ measured at $I_{\text{sd}} = 0$.](image)
up to $B \sim 5$ T, where the effect of magnetic field saturates. Similar behavior is known from copper, where it was deduced from the features in differential conductance of a TJ due to Coulomb blockade utilizing the special design of the sensor electrode. The observed behavior is consistent with the presence of dilute magnetic impurities; impurity-induced energy exchange in small magnetic fields freezes out at increasing $B$. Besides from minute concentrations of magnetic impurities, the similar effect might also result from the presence of paramagnetic oxygen at the copper film surface.

Fig. 3(c) demonstrates EDs at one-quarter distance between two reservoirs in copper device D1 measured at $T_{\text{bath}} = 30$ mK for two representative values of a $B$-field. Again, the step-feature is almost indistinguishable in a smaller field $B = 1$ T, however the ED is far from the thermal one. As in D2, ED evolves with increasing $B$ reaching saturation in $\sim 5$ T. In fig. 3(f) we demonstrate the ED in the middle of aluminum device D3, similarly obtained at two values of magnetic field. Unlike the case of copper, here the ED is independent of the magnetic field and is of a double-step form already in small $B$. We note that it is also observable at higher $T_{\text{bath}} = 0.5$ K (see Supplemental Material Fig. S5). While the surface aluminum atoms may form a bath of magnetic moment similar to the copper case, the observed difference between two materials may indicate a smaller density of the magnetic moments and/or their weaker coupling to the conduction electrons in aluminum.

Extracted EDs provide access to $e-e$ scattering time in the copper wires as a function of $B$. The ED inside a quasi-one-dimensional conductor obeys the Boltzmann equation:

$$\frac{1}{\tau_D} \frac{\partial f(x,E)}{\partial x} + I_{\text{coll}}(x,E,f) = 0.$$

Here, $I_{\text{coll}}(x,E,f)$ is the collision integral describing inelastic scattering processes, $\tau_D = L^2 / D$ is the diffusion time of electrons along the wire and $D$ is the diffusion coefficient. The coordinate $x$ along the wire is expressed in units of its length $L$. Taking into account only $e-e$ scattering and assuming the interaction is local, one gets

$$I_{\text{coll}}(x,E,f) = \int dE' K(\varepsilon) f_{E'}(1 - f_{E'+\varepsilon}) \times \left[ (1 - f_{E}) f_{E'+\varepsilon} - f_{E} (1 - f_{E'-\varepsilon}) \right],$$

where $K(\varepsilon)$ is the interaction kernel. The dominant role of exchange interaction of electrons with magnetic impurities suggests $K(\varepsilon) = \tau_{ee}^{-1} / \varepsilon^2$, where $\tau_{ee}$ is the rate of $e-e$ scattering. Using the numerical relaxation method, we solve the Boltzmann equation and obtain the ratio $\tau_{ee}/\tau_D$ which fits the experimental EDs best. For the copper device D2 the corresponding best fits are shown by dashed lines in panels (a-d) of fig. 3.

In fig. 4(a) we plot the obtained $\tau_{ee}$ in dependence of the magnetic field for both copper devices, see the symbols. At increasing $B$ from 0.3 T to 6 T, $\tau_{ee}$ grows monotonically and saturates at high $B$. This evolution may be understood as follows. For the $B$-dependent $e-e$ scattering rate we assume

$$\frac{1}{\tau_{ee}(B)} = \frac{1}{\tau_{\text{sf}}(B)} + \frac{1}{\tau_0},$$

where $\tau_{\text{sf}}$ is the spin-flip rate due to $B$-dependent scattering involving magnetic impurities, and $\tau_0$ is the $B$-independent scattering rate, e.g., due to the direct Coulomb interaction. For the spin-flip rate, we use the expression similar to that in thermal equilibrium:

$$\frac{\tau_{\text{sf}}(B)}{\tau_{\text{sf}}(B = 0)} = \frac{\sinh (g \mu_B B / k_B T^*)}{g \mu_B B / k_B T^*},$$

where $\mu_B$ is the Bohr magneton, $g$ is the gyromagnetic factor of the magnetic impurities. The effective temperature in our strongly non-equilibrium case should scale with the bias voltage on the metallic wire $T^* \sim V_{sd} / k_B$. This expression closely describes our data, assuming $g = 2$, $T^* / (eV_{sd} / k_B) = 0.46$ and 0.39 and $\tau_0/\tau_D = 1.02$ and 0.96, respectively, for the devices D1 and D2. We compare the obtained values for $\tau_{ee}$ with the theoretical prediction of ref. 21 in Supplemental Material.

We note that, experimentally, the double-step feature smooths out at increasing $V_{sd}$. This is illustrated on the inset of fig. 4(b), where EDs measured in D3 are plotted as functions of the normalized energy $\varepsilon / (eV_{sd})$ for various values of $V_{sd}$. Smoothing of EDs is an obvious consequence of the direct Coulomb interaction which starts to
dominate at increasing excess quasiparticle energy. For the kernel of Coulomb interaction \( K_{\text{Coulomb}}(\varepsilon) \propto \varepsilon^{-3/2} \) \( \tau_0 \) depends on the exact \( \varepsilon_{\text{I}}^{(3)} \) which, in turn, depends both on the energy of the quasiparticle and on the position along the wire. To estimate \( \tau_n \), we formally use the same kernel as before, however, with the bias-dependent scattering time \( K(\varepsilon) = \tau_n^{-1}(\varepsilon_{\text{sd}})/\varepsilon^2 \). For device D3, the results are shown in fig. 4(b). The dependence \( \tau_{ee}(\varepsilon_{\text{sd}}) \) is stronger than the expected in 1D \( \tau_{ee} \propto \varepsilon_{\text{sd}}^{-1/2} \), probably indicating the transition of the wire to effectively larger dimensionality in terms of energy relaxation.

FIG. 4. (a) Scattering time as a function of magnetic field in devices D1 (crosses) and D2 (circles) at \( \varepsilon_{\text{sd}} = 0.24 \text{ mV} \). The dashed lines effective temperatures are \( T = (e\varepsilon_{\text{sd}}/k_B) = 0.46 \) and 0.39, correspondingly. (b) Scattering time as a function of \( \varepsilon_{\text{sd}} \) in device D3 in \( B = 5 \text{ T} \). The inset demonstrates thermalization of ED at increasing bias voltage.

Overall, our data evidence the power of the local shot noise measurement for the energy resolution of the electronic states out of equilibrium. There are two necessary conditions for this approach to work. One is the elasticity of charge transport through the TJ, which would then preserve spectral information. The second one requires the much smaller thermal conductance of the TJ compared to that of the studied conductor, similarly to the analogous electrical requirement for conventional voltimeters. To probe low-resistance conductors, these conditions, alongside with TJs, are fulfilled for elastic InAs nanowire-based sensors, allowing additionally thermoelectric or spin-to-charge conversion studies.

We note that the demonstrated approach is also applicable to the study of non-equilibrium configurations associated with spin (or valley, etc.) currents. Naturally, in this case the local noise probe should additionally conserve the respective quantum number. Theoretically, it is known that the current noise reflects the degree of spin imbalance in the reservoirs. Experimentally, this concept was recently investigated in the study of the spin accumulation driven shot noise across a tunnel barrier with a spin polarized injection contact. In this respect, potentially, our approach may be useful for investigating the microscopic details of spin (or valley, etc.) relaxation.

In summary, we experimentally demonstrated the local sensing of the non-equilibrium ED in a diffusive metallic wire based on the shot noise measurements with a tunnel junction. In fundamental contrast to transport based techniques, our approach relies solely on the Pauli exclusion principle and works in the absence of the energy-selective features in conductance. Consequently, the energy resolution of such a measurement is only limited by the bath temperature. The spatial resolution is virtually unlimited with state-of-the-art noise scanning techniques. The approach is quite universal and equally suitable for the measurements of the non-equilibrium configurations created by charge, spin and valley etc. currents.

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Supplemental Material

Device and measurement techniques

Supplemental Material Fig. 1. **SEM microphotograph of the device D3.** All-aluminum TJ (in the middle) is realized between 3 $\mu$m-long 25 nm-thick and 150 nm-wide Al wires.

To characterize our devices in terms of the electronic elastic mean free path (mfp) we do as follows. The diffusion coefficient $D$ is first obtained from the Einstein’s relation $\sigma = \nu_F e^2 D$. Then, the mfp is obtained from $D = 1/3 \nu_F l$ with $\nu_F$ the Fermi velocity. For Cu devices D1 and D2 we find $D = 120 \text{ cm}^2/\text{s}$, $\tau_D = 0.8 \text{ ns}$, $l_{\text{mfp}} = 23 \text{ nm}$; for Al device D3 – $D = 200 \text{ cm}^2/\text{s}$, $\tau_D = 1.2 \text{ ns}$, $l_{\text{mfp}} = 30 \text{ nm}$.

The noise spectral density was measured using the home-made low-temperature amplifier (LTamp) with a voltage gain of about 10 dB and the input current noise of $\sim 2-6 \times 10^{-27} \text{ A}^2/\text{Hz}$. The voltage fluctuations on a 6.4 k$\Omega$ load resistor were measured near the central frequency 7 MHz of a resonant circuit at the input of the LTamp. The output of the LTamp was fed into the low noise 75 dB gain room temperature amplification stage followed by a hand-made analogue filter and a power detector. The setup was calibrated using the equilibrium Johnson-Nyquist noise thermometry. Unless otherwise stated, the measurements were performed in a cryogen free Bluefors dilution refrigerator BF-LD250 at a bath temperature of 30 mK.

**Energy relaxation time estimation**

According to Ref. 5, energy relaxation time in a 1D case is given by

$$\frac{\hbar}{\tau_E} = \frac{e^2}{\hbar} \frac{L_\epsilon}{\sigma_1 \epsilon}, \quad L_\epsilon = \sqrt{\frac{\hbar D}{\epsilon}},$$

where $\sigma_1$ is the 1D conductivity. For our copper wires, using $D = 120 \text{ cm}^2/\text{s}$ and $\sigma_1 = 10^{-7} \text{ m}/\Omega$, we estimate (at $\epsilon = 0.24 \text{ meV}$)

$$\tau_E \approx 6 \text{ ns}, \quad L_\epsilon \approx 200 \text{ nm}.$$ 

The contribution from the triplet channel (spin density fluctuations) is practically of the same value and may further decrease $\tau_E$, making it comparable to the experimental value.
Supplemental Material Fig. 2. *I*-*V* curves of the copper and aluminum devices. (a) In D2, the *I*-*V* characteristics of the TJ in *B* = 0 demonstrates the typical NIS behavior with drastic decrease of subgap conductance with decreasing temperature, and conductance peaks at ~190 µeV, reflecting the maxima in the density of states of the superconducting Al. (b) In D3, the *I*-*V* curve in *B* = 0 demonstrates the typical SIS behavior.

Supplemental Material Fig. 3. (a) Differential resistance and (b) shot noise of the tunnel junction in the device D1 measured at *T*<sub>bath</sub> = 30 mK in *B* = 0.3 T. The nonlinearity of *dV/dI* is approximately 5%.
Supplemental Material Fig. 4. **Local noise measurement in the Cu strip.** The linear dependence $T_N(V_{sd})$ at $V_{sd} \lesssim 1$ meV at $T_{bath} = 30$ mK demonstrates the absence of $e$-$ph$ energy relaxation at corresponding excess energies of quasiparticles (qp). At higher qp energies the $T_N(V_{sd})$-dependence becomes sublinear indicating the power flow from electron system to the phonon one. The inset shows the measurement scheme. Data in 0.3 T and in 6 T are almost indistinguishable.

Supplemental Material Fig. 5. **Local noise thermometry of the Al strip.** (a) (Symbols) Average noise temperature as a function of bias voltage across the heater at $T = 4.2$ K (red) and $T = 0.56$ K (blue). (Solid lines) Numerical simulation taking into account geometry of the sample gives $\Sigma_{e-ph} = 2.3 \times 10^{11}$ W/m$^3$K$^3$. This value allows one to estimate the $e$-$ph$ scattering length $l_{e-ph} = \sqrt{(\sigma L)/(3\Sigma_{e-ph}T)}$ to be 2.3 $\mu$m at $T_{bath} = 0.56$ K which is only slightly less than the length of the constriction $l = 3 \mu$m. This fact allows the observation of double-step feature at $T_{bath} = 0.56$ K as shown in panel (b). $\mathcal{L} = (\pi^2/3)(k_B/e)^2 = 2.44 \times 10^{-8}$ W$\Omega$K$^{-2}$ is the Lorenz number. In the simulation electronic heat conduction is assumed to satisfy the Wiedemann-Franz law $\kappa = \sigma \mathcal{L} T$. (b) ED in Al wire at $T = 0.56$ K at $V_{sd} = 1.2$ mV (violet) and $V_{sd} = 1.8$ mV (yellow).