Pauli-Heisenberg Oscillations in Electron Quantum Transport

Karl Thibault,[1,*] Julien Gabelli,[2,†] Christian Lupien,[1,‡] and Bertrand Reulet[1,§]

[1] *Département de physique, Université de Sherbrooke, Sherbrooke, Québec, J1K 2R1, Canada*
[2] *Laboratoire de Physique des Solides, Univ. Paris-Sud, CNRS, UMR 8502, F-91405 Orsay Cedex, France*

I. INTRODUCTION

Conduction of electrons in matter is ultimately described by quantum mechanics. Yet at low frequency or long time scales, low temperature quantum transport is perfectly described by this very simple idea: electrons are emitted by the contacts into the sample which they may cross with a finite probability[1,2]. Combined with Fermi statistics, this partition of the electron flow accounts for the full statistics of electron transport[3]. When it comes to short time scales, a key question must be clarified: are there correlations between successive attempts of the electrons to cross the sample? While there are theoretical predictions[1] and several experimental indications for the existence of such correlations[4–6], no direct experimental evidence has ever been provided.

In order to probe temporal correlations between electrons, we have studied the correlator between current fluctuations $i(t)$ measured at two times separated by τ, $C(\tau) = \langle i(t)i(t+\tau)\rangle$, where $\langle . \rangle$ denotes statistical averaging. We calculate this correlator by Fourier transform of the detected frequency-dependent power spectrum of current fluctuations generated by a tunnel junction placed at very low temperature. The very short time resolution required to access time scales relevant to electron transport is achieved thanks to the ultra-wide bandwidth, 0.3-13 GHz, of our detection setup.

We report the measurement of the frequency-dependent noise spectral density of both thermal noise (no dc bias, various temperatures) and shot noise (lowest temperature, various voltage biases), from which we determine the current-current correlator in time domain $C(\tau)$. In complex quantum systems, the method we have developed might offer direct access to other relevant time scales related, for example, to internal dynamics, coupling to other degrees of freedom, or correlations between electrons.

In the following, the noise spectral density is expressed in terms of noise temperature : $T_N(f) = S(f)/(2k_BG)$.

II. RESULTS

Thermal noise spectroscopy. On Fig. 1, we show measurements of the noise temperature T_N vs. frequency for various electron temperatures T between 35 and 200 mK, when the sample is at equilibrium, *i.e.* with no bias ($V = 0$). We observe that at low frequency one has $T_N(0) = T$ which is the classical Johnson-Nyquist noise. At high frequency $hf \gg k_BT$, all experimental curves approach the zero temperature curve (theoretical dotted black line) which corresponds to the so-called vacuum fluctuations $S_{vac}(f) = Ghf$. Our data are in very good agreement with the theoretical predictions given by[7] :

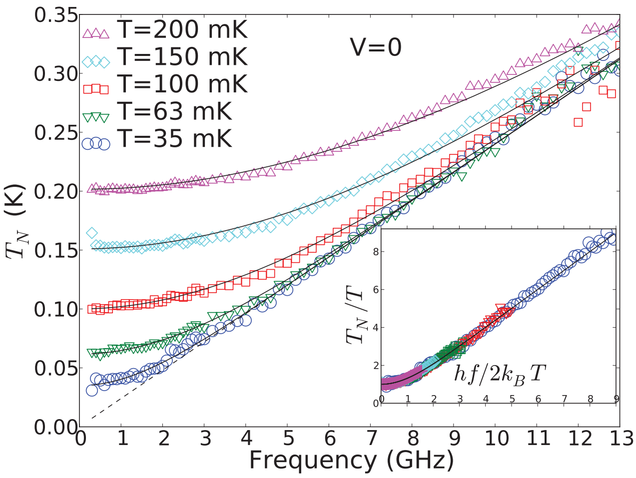

FIG. 1. **Equilibrium noise temperature vs. frequency for various electron temperatures T.** Symbols are experimental data and solid lines are theoretical expectations of Eq. (1).
Inset : Experimental rescaled noise temperature T_N/T vs. rescaled frequency $hf/(2k_BT)$.

$$S_{eq}(f,T) = Ghf \coth\left(\frac{hf}{2k_BT}\right). \tag{1}$$

Shot noise spectroscopy. Fig. 2 shows the measurements of T_N vs. frequency for various bias voltages V. The data are taken at the lowest electron temperature $T = 35$ mK. At low frequencies, *i.e.* $hf < eV$, one observes a plateau corresponding to classical shot noise $S = eI$. When $hf \gg eV$, the vacuum fluctuations take over and $S = S_{vac}(f)$. Black lines on Fig. 2 are the theoretical predictions of the out of equilibrium noise spectral density[8]

$$S(f,V,T) = \frac{1}{2}\left[S_{eq}\left(f+\frac{eV}{h},T\right) + S_{eq}\left(f-\frac{eV}{h},T\right)\right]. \tag{2}$$

Current-current correlator in time domain. The current-current correlator in the time domain is given by the Fourier Transform of Eq. (2) :

$$C(t,T,V) = C_{eq}(t,T)\cos\left(\frac{eVt}{\hbar}\right). \tag{3}$$

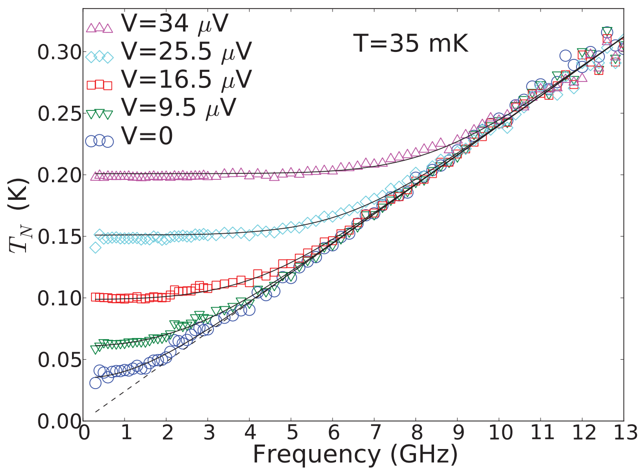

FIG. 2. **Out of equilibrium noise temperature vs. frequency for different dc voltage biases V at $T = 35$ mK.** Symbols are experimental data and solid lines are theoretical expectations.

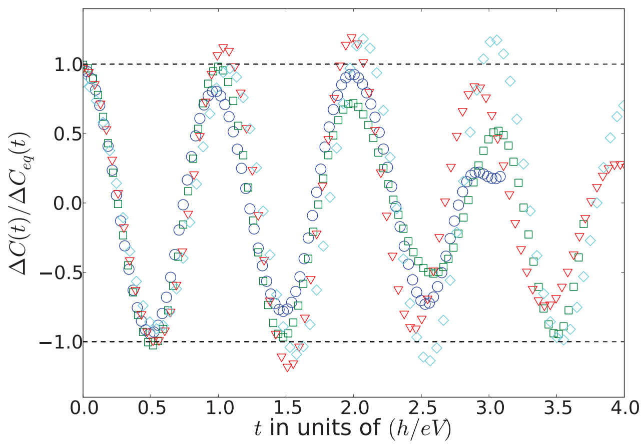

FIG. 3. **Rescaled current-current correlator in time domain vs. reduced time eVt/h for various bias voltages $V =$ 25.5, 30.6, 35.7 and 40.8 μV.**

However, $S_{eq}(f)$ diverges as $|f| \to \infty$, so $C_{eq}(t, T)$ diverges at all times. To circumvent this problem, we define the *thermal excess noise* and its corresponding time domain correlator :

$$\Delta S(f, T, V) = S(f, T, V) - S(f, T = 0, V)$$
$$\Delta C(t, T, V) = \Delta C_{eq}(t, T) \cos\left(\frac{eVt}{\hbar}\right), \quad (4)$$

We show experimental data for $\Delta C(t, V)/\Delta C_{eq}(t, T)$ as a function of the rescaled time h/eV on Fig. 3. This rescaling clearly demonstrates the oscillation period being h/eV, in agreement with Eq. (4).

III. INTERPRETATION

These oscillations are the result of both the Pauli principle and Heisenberg incertitude relation. To see this, let us consider a single channel conductor crossed at $t = 0$ by two electrons of energy E and E'. According to Pauli principle, the energies must be different, $E \neq E'$. But how close can E and E' be? According to Heisenberg incertitude relation, it takes a time $t_H \simeq h/(|E - E'|)$ to resolve the two energies, so E and E' cannot be considered different for times shorter than t_H. This means that if one electron crosses at time $t = 0$, the second one must wait. Since $|E - E'| < eV$, one has $t_H > h/eV$: there is a minimum time lag h/eV between successive electrons. The regular oscillations we observe on ΔC are a direct consequence of this blockade and reflect the fact that electrons try to cross the sample regularly at a pace of one electron per channel per spin direction every h/eV. The decay of $\Delta C(\tau)$ we observe at long time reflects the existence of a jitter which is of pure thermal origin.

At high bias voltage, $eV \gg k_B T, hf$, the oscillation period h/eV becomes so small that the electrons no longer have to wait before tunneling. This high energy regime is the classical limit where the current flowing through the junction is characterized by a Poisson distribution. The noise spectral density is thus given by the Schottky limit $S = eI$. At low bias voltage, there are correlations between successive tunneling electrons and the resulting current distribution is no longer Poissonian.

* Karl.Thibault@USherbrooke.ca
† Julien.Gabelli@U-PSud.fr
‡ Christian.Lupien@USherbrooke.ca
§ Bertrand.Reulet@USherbrooke.ca

[1] T. Martin and R. Landauer, Phys. Rev. B **45**, 1742 (1992).
[2] M. Büttiker, Phys. Rev. B **46**, 12485 (1992).
[3] G. B. Lesovik and L. S. Levitov, Phys. Rev. Lett. **46**, 538 (1994).
[4] M. Reznikov, M. Heiblum, H. Shtrikman, and D. Mahalu, Phys. Rev. Lett. **75**, 3340 (1995).
[5] A. Kumar, L. Saminadayar, D. C. Glattli, Y. Jin, and B. Etienne, Phys. Rev. Lett. **76**, 2778 (1996).
[6] N. Ubbelohde, K. Roszak, F. Hohls, N. Maire, R. J. Haug, and T. Novotný, Scientific Reports **2**, 538 (2012).
[7] H. B. Callen and T. A. Welton, Phys. Rev. B **83**, 34 (1951).
[8] A. J. Dahm, A. Denenstein, D. N. Langenberg, W. H. Parker, D. Rogovin, and D. J. Scalapino, Phys. Rev. Lett. **22**, 1416 (1969).