Frequency-dependent shot noise in single-electron devices

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Shot noise (SN), consequence of the granularity of electron charge, has been intensively investigated within the last decades [1]. Coulomb blockade devices, where electrons are flowing through tunnel barriers one by one, are then of great interest for SN studies.

To characterize noise, its spectral density $S(\omega)$ is usually compared to the spectral density of a Poissonian process $2q<I>$. The ratio at zero frequency $F = S(0)/2q<I>$ is called Fano Factor. If $F < 1 (> 1)$, SN is sub-(super-) Poissonian. If F = 1, SN is Poissonian.

The home-made simulator SENS (Single-Electron Nanodevices Simulation) has been used previously to analyze the behavior of Si quantum dot (QD)-based double-tunnel junctions (DTJs) [2] and single-electron transistors (SETs) [3]. It consists in the self-consistent solution of 3D Poisson-Schrödinger equations, depending on the bias and number of electrons in the dot. Tunnel transfer rates are computed from the resulting wave functions. Then, a Monte-Carlo (MC) algorithm or the master equation coupled with Korotkov's method [4] are used to determine the electronic characteristics, such as current and SN.

Korotkov's method is very powerful to quickly reach accurate frequency-dependent spectral densities. However, the physics at the origin of the SN behavior is hidden within a complex mathematical formalism.

In contrast, the MC algorithm, though time consuming, allows us to follow the time evolution of the system. According to the number of electrons in the QD and the corresponding transfer rates, the time between two events is randomly picked. Then, the tunnel event is also randomly chosen (an electron goes in or out of the QD). A glance at resulting time/current characteristics, as well as a comparison between tunnel transfer rates, helps to understand the behavior of shot noise.

In Fig. 1, the time evolution of the number of electrons going through a barrier in a DTJ shows a situation known as "bunching", i.e., a lot of events happen in a short time, followed by a long time without any event. This is the signature of a super-Poissonian SN.

In a previous article [5], the zero frequency super-Poissonian noise has been explained through the study of the tunnel transfer rates in a 3-state case (0-1-2 electrons in the QD) schematized in Fig. 2a. Symmetry between in (Γ_{in}) and out (Γ_{out}) transfer rates for a given number of electrons, linked with a dissymmetry of the transfer rates of the forthcoming events, as shown in Fig 2b, induce the "bunching" phenomenon.

The MC algorithm of the SENS simulator also allows determining the frequency-dependent spectral densities. First, we calculate the current autocorrelation function $C_I(\tau)$. In the concrete case of a particular DTJ shown in Fig. 3, different behaviors are observed depending on the transport regime. The autocorrelation function remains positive (negative) for super-(sub-) Poissonian Fano factor. Close to the Poissonian case, the autocorrelation function goes from negative to positive values before reaching zero.

The spectral densities of current $S(f)$ are then calculated from the autocorrelation functions. The corresponding results are given in Fig. 4. MC calculations fit nearly perfectly with Korotkov's method. For all cases, spectral densities are given by the Fano factor at low frequency and the Poissonian regime ($S(f) = 2q<I>$) is finally reached at high frequency. Remarkably, in the case of a Fano factor close to 1 (Fig. 4b), the transport becomes sub-Poissonian in the [10^5 Hz - 10^8 Hz] range, thus indicating the presence of some specific dynamics in such frequency range associated to the values of the transfer rates.

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This frequency behavior can be explained by considering transfer rates and characteristic times for each transition in the simple 3-state case (not shown here).

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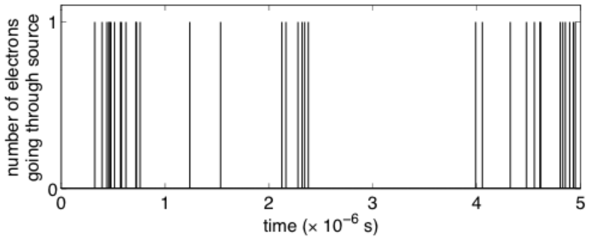

Fig. **1**. Time evolution of the number of electrons going through the device in a case of a super-Poissonian noise $F = 4.67$. The mean current is 0.76 pA.

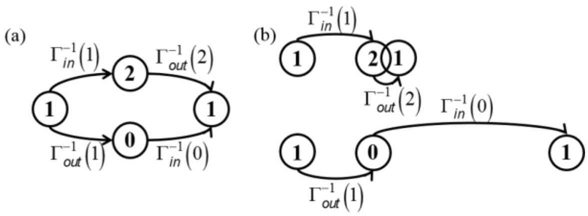

Fig. **2**. Schematic description of (a) all possible transitions in a 3-state case, and (b) the particular case leading to bunching with $\Gamma_{in}(1) = \Gamma_{out}(1)$ and $\Gamma_{out}(2) >> \Gamma_{in}(0)$. The numbers in circles are the numbers of electrons in the quantum dot.

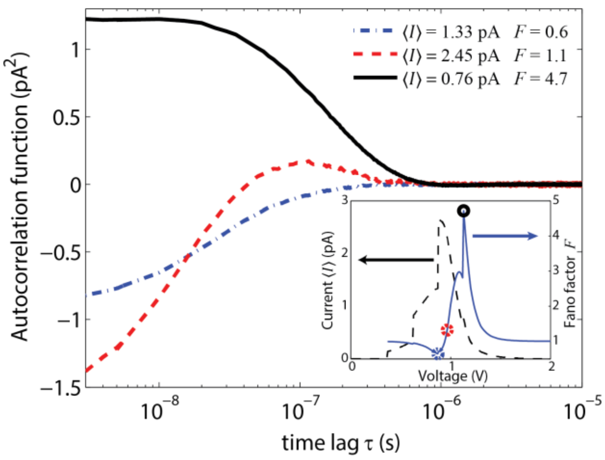

Fig. **3**. Current autocorrelation function for super-, sub- and Poissonian noise. Inset: Current-voltage and Fano factor-voltage characteristics for a given DTJ. The Fano factors studied are indicated by circles.

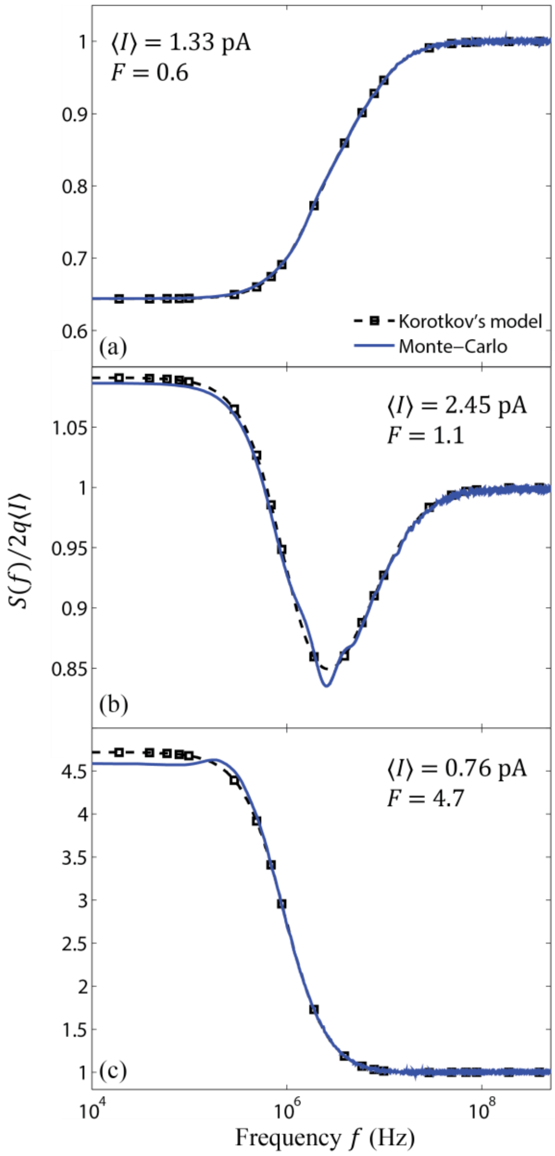

Fig. **4**. Spectral density of current as a function of frequency obtained in the case of (a) sub- (b) Poissonian (c) super-Poissonian Fano factor.