Quantifying many-particle Coulomb correlation through the super-poissonian noise of electron current in resonant structures

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Electron transport in mesoscopic systems has been understood mainly from a single-particle description. In principle interacting many-electron systems are well assessed through many-body Schrödinger equation, but its solution is a very hard problem even in the case of few electrons correlated by coulomb interaction. In any case the quantum many-body effects can impact dramatically macroscopic measurement. The first emergency was in 1911 when K. Onnes astonished the word by discovering the super-conductivity. Since then, numerous techniques have been developed to simulate quantum correlations, and many models have been sought for to explain the transport properties of many-body systems.

Here we focus on how the many-body Coulomb interaction might affect noise in resonant structures. Specifically, the correlation between an electron trapped in the resonant state during a dwell time τ_d and the ones remaining in the cathode has been investigated. The reason why this correlation occurs is because of the potential energy perturbation on the other electrons due to the trapped electron. As an example of resonant structure, we considered a double barrier resonant tunneling diode (RTD) [1], [2]. As depicted in figure 1, an electron tunneling into the well from the cathode raises the potential energy of the well by an amount of e/C_{eq}, where e is the electron charge and C_{eq} the structure capacitance. As a consequence, the density of state in the well is shifted upwards by the same amount. This can affect the noise in two different ways: if the resonant energy is over the conduction band edge of the cathode, the raised density of state is accessible to electrons staying in the tail of the cathode occupation factor. Therefore the majority of the electrons in the cathode results blocked approximately for a dwell time τ_d. This suppresses the randomization of the injection and consequently augments the sub-poissonian noise already present in the limit of partition noise only [2]. Conversely if the resonant energy is under the conduction band edge of the cathode, the raised density of state is accessible to electrons staying near the maximum of the cathode occupation factor. Therefore the majority of the electrons in the cathode can tunnel in the well. Thus the Coulomb interaction tries to regroup the electrons providing an enhancement of the randomization of the injection and consequently gives a super-poissonian noise.

To quantitatively analyze this pure quantum many-body effect we employed two different approaches. The first is based on an algorithm recently developed by Oriols [3]. This provides a way to compute many-particle trajectories within the Bohm's picture, from single-particle time dependent Schrödinger equation with time dependent potential energy that account for correlations. By means of this powerful algorithm, and the generalization of Ramo-Shockley theorem to compute the current [4], and the very inclusion of Coulomb interaction in the many-particle Hamiltonian beyond the mean field [5], we were able to correctly simulate the current and noise in the RTD.

The second approach is based on a completely analytical model of the RTD proposed in [6]. This model was improved by including scattering [7] in a consistent way with the Breit-Wigner formulation [8]. Accordingly with the formalism proposed in [9] based on sequential tunneling and accounting for the coulomb interaction within a Hartree approximation, we were able to derive a general formula for the Fano factor

$$\gamma = 1 - 2\frac{\left(\Lambda_Q - \Lambda_C + \Gamma' - \Gamma_R\right)\left(\Lambda_Q + \Gamma_R\right)}{\left(\Lambda_Q + \Gamma'\right)^2} \qquad (1)$$

where Λ_Q and Λ_C are the quantum and Coulomb interaction energies respectively and read as a generalization of the interaction energy proposed in [2]. Γ' is the reduced total width of the resonant level and Γ_R the width associated to the right barrier.

As shown in figure 2 the analytical model of DC current is in excellent agreement with the quantum Monte Carlo simulation and the Fano factor reproduces correctly the sub-poissonian and super-poissonian noise regime [1], [2]. Comparing both approaches, due to the excellent agreement, it is shown that the analytical one is capable to perfectly catch and quantify quantum many-particle effects that emerge in the super-poissonian noise regime. Furthermore the variation of the pick height, compared with that of other relevant relative quantities (see figure 3), is in general one or more orders of magnitude larger. It makes this feature extremely important in order to extract parameters from measurement carrying many-body information.

In conclusion we analyzed quantum many-body interaction in the transport and noise of resonant structures by means of two different approaches: quantum Monte Carlo simulation and an analytical model. This result has two merits. On the one hand it shows that the analytical approach is able to capture relevant many-particle information (such many-particle density of states) not easily accessible from other DC transport. On the other hand it furnishes a way to predict quantitatively these effects and is useful for the design of resonant structure.

References:

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Figure 1 (top right): Potential energy for a RTD without (dashed line) and within (solid line) an electron in the well. Red lines are the correspondent resonant states.

Figure 2 (bottom left): Quantum Monte Carlo simulation of DC current (symbols), analytical model (solid blue line) and Fano factor (1) (dashed red line).

Figure 3 (bottom right): Fano factor maxima locus (dashed red line); Fano factor minima locus (dashed dot blue line); relative pick current magnitude curve (black solid line).