Super-Poissonian noise in a Coulomb-blockade metallic quantum dot structure

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The shot noise of the current through a single electron transistor, coupled capacitively with an electronic box, is calculated, using the master equation approach. We show that the noise may be sub-Poissonian or strongly super-Poissonian, depending mainly on the box parameters and the gate. The study also supports the idea that not negative differential conductance, but charge accumulation in the quantum dot, responds for the super-Poissonian noise observed.

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Deviations of the shot noise (SN) from the full (Poissonian) value in nanostructures have been the subject of a great number of works, both experimental[1–9] and theoretical.[2,10–16] Mathematically, the measure of these deviations is the Fano factor F_n, defined as the ratio of the actual noise spectral density to the full SN value $2eI$, where e is the elementary charge and I is the average current. Physically, it is widely accepted that the Pauli exclusion and the charge interaction are the two correlations, which cause observed SN deviations. While the Pauli exclusion always causes a suppression of SN, the charge correlation may suppress or enhance the noise, depending on the conduction regime. The typical non-Poissonian behaviors of SN can be found in resonant tunneling diodes (RTD), where the noise is partially suppressed (sub-Poissonian noise) at low bias voltages (preresonance) and becomes very large (super-Poissonian) in the negative differential conductance (NDC) region.[2,3,6,8,12] For Coulomb blockade quantum dot (QD) structures, a suppression of SN is widely demonstrated, both experimentally[1,4,9] and theoretically.[10,11,13,14] Recently,[16] we have shown that in a system of two metallic QDs, coupled in series, the SN is always sub-Poissonian even in NDC regions. However, in some particular QD structure, as that considered in Ref. 5, a positive correlation in the electronic motion through QDs, leading to a super-Poissonian noise, might be developed. In this paper we will show that even in a simple structure of a symmetrical single electron transistor (SET), coupled capacitively to an electronic box, as that measured in Ref. 17, the super-Poissonian noise can be easily realized even in a positive differential conductance (PDC) region. Furthermore, in consistency with Refs. 6 and 7, our study supports the idea that the charge accumulation, not NDC, is ultimately responsible for the super-Poissonian noise observed.

The equivalent circuit diagram of the structure studied is drawn in Fig. 1(a), where the left QD (D) forms a SET, while the right QD (B) acts as an electronic box. Two QDs are coupled to each other by a capacitance C_m, but the electron tunneling between them is forbidden. The current through the SET depends not only on the bias voltage V and the gate voltage V_g, but also on the charge state in the box. Such a SET-to-box coupling may produce a NDC as experimentally observed in Ref. 17.

Within the framework of the Orthodox theory[18] the state $|i\rangle$ of the system under study is entirely determined by the numbers of excess electrons in two QDs, n in D and m in B. At a given (n,m) state, the free energy of the system can be written as

$$F = Q_d^2/2C_d^* + Q_b^2/2C_b^* + Q_dQ_b/C_p^* - (C_1 + C_3)V^2/2 - C_gV_g^2/2 - n_qeV, \qquad (1)$$

where $C_d^*=\Sigma/C_b$; $C_b^*=\Sigma/C_d$; $C_p^*=\Sigma/C_m$ with $\Sigma=C_dC_b-C_m^2$, $C_d=C_1+C_2+C_m+C_g$, $C_b=C_3+C_m$; $Q_d=C_1V+C_gV_g+ne$; $Q_b=C_3V+me$; and n_q is the number of electrons that have entered the structure from the top lead (the bottom one is grounded). Any electron transfer across junctions results in a change in free energy F. In the system of interest there are six possible sequential electron transfers across three junctions (1, 2, and 3) upward (+) or downward (−). The change in free energy associated with these transfers can be deduced from Eq. (1) as follows:

$$\Delta F_1^{\pm} = e^2(1 \mp 2n)/2C_d^* \mp me^2/C_p^* \mp eC_gV_g/C_d^* \mp (C_1/C_d^* + C_3/C_p^* + 1)eV$$

$$\Delta F_2^{\pm} = e^2(1 \pm 2n)/2C_d^* \pm me^2/C_p^* \pm eC_gV_g/C_d^* \pm (C_1/C_d^* + C_3/C_p^*)eV$$

$$\Delta F_3^{\pm} = e^2(1 \mp 2m)/2C_b^* \mp ne^2/C_p^* \mp eC_gV_g/C_p^* \mp (C_1/C_p^* + C_3/C_b^* + 1)eV. \qquad (2)$$

At zero temperature the rate of a sequential electron transfer across any ν junction ($\nu=1,2,$ or 3) is well-known[18]

$$\Gamma_\nu = \theta(-\Delta F_\nu)|\Delta F_\nu|/(e^2R_\nu), \qquad (3)$$

where θ is the step function, R_ν is the tunneling resistance of the ν junction, and ΔF_ν is the corresponding change in free energy defined in Eq. (2).

Using expressions (2) and (3), in principle, one can solve the master equation (ME) or perform Monte Carlo simulation to yield the current as a function of bias voltage V(I-V characteristics) and further to calculate the noise. The Monte Carlo method is very useful for complicated structures at finite temperature, but it is not efficient for the system under study. Moreover, in this work we will discuss only the zero-temperature case and therefore the ME method should be used. Denoting $p(i)$ as the probability of the state $|i\rangle$

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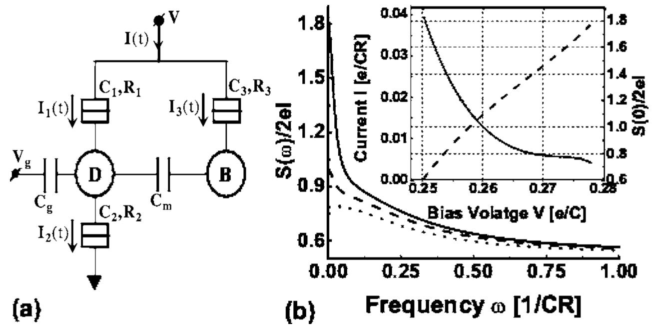

FIG. 1. (a) Equivalent circuit diagram of the structure under study. (b) The normalized noise $S(\omega)/2eI$ calculated from Eq. (8) is plotted as a function of frequency for some values of bias voltages V (from top): 0.25, 0.26, and 0.27. Inset: The current I (7) (dashed line, see the left axis) and the Fano factor (10) (solid line, see the right axis) as a function of bias voltage in the range $V_2 < V < V_3$ (see the text). The structure parameters: $C_m = C_3 = C_2 = C_1 \equiv C$, $R_3 = R_2 = R_1 \equiv R$, without gate.

$\equiv (n_i, m_i)$ of the system, the ME can be written in the matrix form[10]

$$d\hat{p}(t)/dt = \hat{M}\hat{p}(t), \tag{4}$$

where $\hat{p}(t)$ is a column matrix of elements $p(i,t)$ and $\hat{M}$ is an evolution matrix with elements defined as follows: $M(i,j) = \Gamma_2^+(j) + \Gamma_1^-(j)$ (if $n_j = n_i - 1$ and $m_j = m_i$); $\Gamma_2^-(j) + \Gamma_1^+(j)$ (if $n_j = n_i + 1$ and $m_j = m_i$); $\Gamma_3^+(j)$ (if $n_j = n_i$ and $m_j = m_i + 1$); $\Gamma_3^-(j)$ (if $n_j = n_i$ and $m_j = m_i - 1$), and $M(i,i) = -[\Gamma_1^+(i) + \Gamma_1^-(i) + \Gamma_2^+(i) + \Gamma_2^-(i) + \Gamma_3^+(i) + \Gamma_3^-(i)]$.

Solving the ME (4) under condition $\Sigma_i p(i,t) = 1$, we can further calculate the net current

$$I(t) = q_1 I_1(t) + q_2 I_2(t) + q_3 I_3(t), \tag{5}$$

where $I_\nu(t) = e\Sigma_i [\Gamma_\nu^+(i) - \Gamma_\nu^-(i)] p(i,t)$ is the statistical average current through the ν junction ($\nu = 1, 2$, or 3), the factors q_ν are defined as:[19] $q_1 = (C_m C_2 + C_2 C_3)/\Sigma$; $q_2 = (C_m C_1 + C_m C_3 + C_1 C_3)/\Sigma$; and $q_3 = C_m C_2/\Sigma$ with Σ given in Eq. (1). Here it should be noted that as discussed in detail by Blanter and Büttiker (see Ref. 13, p. 24), to ensure the current conservation, for the time-dependent currents (5) as well as for the noise expression shown below we have to consider not only the currents $I_1(t)$ and $I_2(t)$, but also the displacement current $I_3(t)$ associated with the charge state in the metallic box.

Next, the noise spectrum $S(\omega)$ of the current I can be calculated in the way similar to that developed in Refs. 11 and 16

$$S(\omega) = 2\sum_\nu q_\nu^2 A_\nu + 4e^2 \sum_{\nu\mu} \sum_{ij} q_\nu q_\mu [\Gamma_\nu^+(i) - \Gamma_\nu^-(i)] \times \hat{B}_{ij} [\Gamma_\mu^+(j|\mu^-) p_{\rm st}(j|\mu^-) - \Gamma_\mu^-(j|\mu^+) p_{\rm st}(j|\mu^+)]. \tag{6}$$

Here, $A_\nu = e(I_\nu^+ + I_\nu^-)$ with $I_\nu^\pm = e\Sigma_i p_{\rm st}(i)\Gamma_\nu^\pm$; the conditional probability $p(i \leftarrow j|\tau)$ for having state $|i\rangle$ at the time $t=\tau > 0$ under the condition that the state was $|j\rangle$ at an earlier time $t=0$ obeys the same ME as for the probability $p(i,t)$; the stationary probability $p_{\rm st}(i)$ is defined as $p(i \leftarrow j | \tau \to \infty) = p_{\rm st}(i)\delta_{ij}$; $\hat{B} = {\rm Re}\{(i\omega\hat{I} - \hat{M})^{-1}\}$; $\langle j | \nu^\pm \rangle$ is the state obtained from the state $|j\rangle = (n_j, m_j)$ by transferring an electron across the ν junction upward (+)/downward (−); the tunneling rates $\Gamma_\nu^\pm$ and the factors q_ν are defined in Eqs. (3) and (5), respectively. Similarly, we can also obtain the noise expression for currents through junctions, I_1 or I_2.[16]

Thus, using the tunneling rates (3), in principle, we can solve the ME (4) and further to calculate the current (5) and the noise (6). In practice, however, this ME cannot be exactly solved with all possible states except some simple cases at low bias voltages. Let us consider such a simple case, when the SET is symmetrical, $C_1 = C_2 \equiv C$ and $R_1 = R_2 \equiv R$, and the box parameters are as follows: $C_3 = C$, $R_3 = R$, and C_m belongs to the range $(\sqrt{6}-1)C/5 \leqslant C_m \leqslant (\sqrt{3}+1)C$. The gate is neglected. With all these assumptions, in the way similar to that developed in Refs. 16 and 20 we can solve the ME (4) as well as calculate the current (5) and the noise (6) exactly in some ranges of low bias. Neglecting lengthy, but elementary, algebraic calculations the final results for the current can be reviewed as follows: (1) the Coulomb blockade region has the threshold voltage of $V_0 = (e/2C)(C_m + C)/(5C_m + 3C)$; (2) in the next range of bias voltage, $V_0 \leqslant V \leqslant V_1 \equiv (e/2C)(C_m + 2C)/(5C_m + 4C)$, the current has been found as $I = e\Gamma_2^+(1)\Gamma_1^+(0)/[\Gamma_2^+(1) + \Gamma_1^+(0)]$, where two states $|1\rangle \equiv (-1, 0)$ and $|0\rangle \equiv (0,0)$ are written for short; (3) the current is equal to zero in the range of bias $V_1 \leqslant V \leqslant V_2 \equiv (e/2C)(3C_m + C)/(5C_m + 3C)$ (second Coulomb blockade gap); and (4) in the last range of bias, $V_2 \leqslant V \leqslant V_3 \equiv (e/2C) \times (3C_m + 2C)/5C_m + 4C)$, where the ME (3) can be still solved exactly, the current is given by

$$I = \frac{(a+b)cdh + bcdg}{cdh + bcd + (a+b)dh + (g+h)cb}, \tag{7}$$

where we introduce $a = \Gamma_1^+(0); b = \Gamma_3^+(0); c = \Gamma_2^+(1); d = \Gamma_1^+(2); g = \Gamma_2^+(3)$; and $h = \Gamma_3^-(3)$. Two states $|2\rangle \equiv (0, -1)$ and $|3\rangle \equiv (1, -1)$ are also written for short.

Now, we can calculate the noise (6) in two ranges of bias, $V_0 \leqslant V \leqslant V_1$ and $V_2 \leqslant V \leqslant V_3$, where the current is finite and already known. As an example, we show the noise expression obtained in the last range of bias, $V_2 \leqslant V \leqslant V_3$

$$S(\omega) = 2(q_1^2 A_1 + q_2^2 A_2 + q_3^2 A_3) + 4e^2 D_r B D_c. \tag{8}$$

Here, $A_1 = A_2 = eI$ [I defined in Eq. (7)]; $A_3 = 2e^2 bcdh/[cdh + bcd + (a+b)dh + (g+h)cb]$; D_r is a row-matrix of four elements: $q_1 a + q_3 b, q_2 c, q_1 d$ and $q_2 g - q_3 h$; D_c is a column matrix of four elements: $q_2(a+b)cdh/Q, (q_1 acdh - q_3 bcdh)/Q, (q_2 bcdg + q_3 bcdh)/Q$, and $q_1(g+h)bcd/Q$ with $Q = cdh + bcd + (a+b)dh + (g+h)bc$; and $\hat{B} = {\rm Re}(i\omega\hat{I} - \hat{M})^{-1}$ with

$$i\omega\hat{I} - \hat{M} = \begin{pmatrix} i\omega + a + b & -c & 0 & 0 \\ -a & i\omega + c & 0 & -b \\ -b & 0 & i\omega + d & -g \\ 0 & 0 & -d & i\omega + g + h \end{pmatrix}. \tag{9}$$

The expression (8) gives the SN of the net current I as a

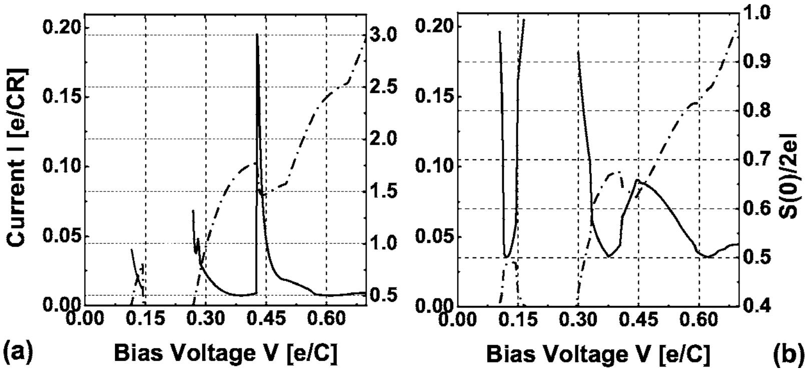

FIG. 2. Numerical results: The current, calculated from Eq. (5) (dashed line, see the left axis) and the Fano factor, $F_n=S(0)/2eI$, calculated from Eq. (6) (solid line, see the right axis), are plotted against the bias voltage V. The structure parameters are the same as in Fig. 1(b) except C_m, which is equal to $2C$ in (a) and $10C$ in (b).

function of frequency ω and of bias V. In the right-hand side of this expression [as well as expression (6)] the first term associated with the self correlation of a given tunneling event with itself describes the noise in the high-frequency limit[11] and the second term is due to the finite-time correlation between two different tunneling events.

In Fig. 1(b), for example, we present the normalized noise $S(\omega)/2eI$ as a function of frequency, calculated at some bias voltages, for the structure with parameters given in the figure. Here and below, for symmetrical SETs of equal capacitances C and tunneling resistances R, it is convenient to choose the elementary charge e, the capacitance C, and the resistance R as basic units. The voltage, the current, and the frequency in figures are then measured in units of e/C, e/CR, and $(CR)^{-1}$, respectively. It seems from Fig. 1(b) that the normalized noise obtained for the net current always decreases as the frequency increases and within the framework of the model considered there exists a large frequency limit: $S(\omega)/2eI \geqslant 0.5$.

Particularly, in the limit of zero frequency, when all the noises, for the net current and for currents through partial junctions, are coincident,[16] we found an explicit expression for Fano factor[21]

$$F_n \equiv S(0)/2eI = 1 + 2\left\{\frac{ach(a+h)(d+g+h)+bdg(a+b+c)(g+h)}{[dh(a+b+c)+bc(d+g+h)][h(a+b)+bg]} - \frac{cd[bc+dh+(a+b+c)(d+g+h)][h(a+b)+bg]}{[(dh(a+b+c)+bc(d+g+h)]^2}\right\}, \tag{10}$$

where the quantities a, b, c, d, g, and h are defined in Eq. (7). Clearly, this expression (10) shows that F_n may be greater or smaller than 1, depending on relative values of two terms with opposite signs in the braces. In other words, we have exactly shown that at least for the simple case under study the SN may be super-Poissonian or sub-Poissonian, depending on the structure parameters and bias voltage. Such an interesting noise behavior can be seen in the inset of Fig. 1(b), where, as an example, we present the current I (7) and the corresponding Fano factor F_n (10) (valid in the range of bias $V_2 \leqslant V \leqslant V_3$) for the same structure as in the main figure. While the current monotonously increases (with a PDC), the noise is super-Poissonian ($F_n > 1$) at $V \leqslant 0.26$ and becomes sub-Poissonian at higher biases.

To extend calculations to higher biases and different varieties of structure parameters, we solve the ME (4) and calculate the current (5) and the noise (6) numerically. In Fig. 2(a) we present obtained results of the current I (dashed line) and Fano factor F_n (solid line) for the structure with the same parameters as in Fig. 1(b) except the SET-to-box capacitance C_m. Apparently,[22] the I-V characteristics obtained is very similar to that reported in Ref. 17 with a clear second Coulomb gap. Compared to this experiment, the calculation has been extended to higher bias voltages, where one more NDC region has been recognized. Along with such an I-V curve the Fano factor F_n strongly varies with the bias V and reaches super-Poissonian peaks, $F_n=1.31$ and 3.01, at $V=0.27$ and 0.43, respectively. Note that the lower value of V belongs to a PDC region, while at the higher one we have a NDC. Statistics of numerical results for structures with different varieties of parameters show that the noise-versus-bias behavior is very sensitive to the SET-to-box capacitance C_m. A change in C_m can make a super-Poissonian noise sub-Poissonian and inversely. This can be seen, for example, by comparing two figures, Figs. 2(a) and 2(b). The structures studied in these figures are the same except the capacitance C_m, which is equal to $2C$ in (a) and $10C$ in (b). While two I-V curves (dashed lines) are not much different from each other and, particularly, the NDC regions are still clearly maintained in both figures, in Fig. 2(b) the noise is sub-Poissonian in the whole range of bias voltages under study. The study demonstrates that by changing only C_m it is possible to get the noise as large as $F \approx 100$. Such a giant enhancement of noise has been suggested in a quantum shuttle at the shutting threshold.[23]

Results similar to those in Fig. 2 have been also obtained when we change only the box parameter C_3 or R_3. Noting again that the SET is still symmetrical, our study thus demonstrates an important role of the box in affecting both the I-V characteristics and the noise behavior of the SET.

All the results presented in Figs. 1 and 2 are for the case without gate. The gate leads to an additional term in the free energy F (1) and simply makes numerical calculations a little lengthier. As an example, the current (dashed line) and normalized zero-frequency noise (solid line), calculated at the bias $V=0.44$, are plotted against the gate parameter C_gV_g in Fig. 3 for the same structure as in Fig. 2. The Fano factor decreases from the value of 1.59 (super-Poissonian) in the

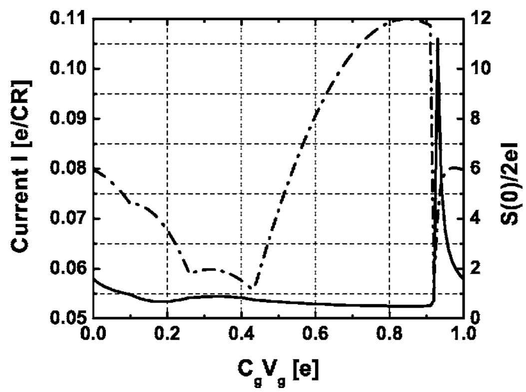

FIG. 3. The gate effect: The current (dashed line) and Fano factor (solid line) are plotted against the gate parameter C_gV_g for the same structure as that studied in Fig. 2(a) at bias voltage $V=0.44$.

case without gate ($C_gV_g=0$) to the sub-Poissonian value of 0.5 at $C_gV_g=0.85$ and then sharply rises to a large value of ≈ 11.2. Note that as the gate parameter C_gV_g varies the changes of conductance and of noise are not always in accordance with each other: the noise may be either suppressed or enhanced in NDC regions. Experimentally, for the structure measured in Ref. 7, it was noted that the super-Poissonian peaks can be observed in only specific ranges of gate voltage.

The fact that a super-Poissonian noise is not necessarily accompanied by a NDC has been claimed by Song *et al.*[6] and by Safanov *et al.*[7] Comparing the *I-V* curves and the noises measured in a super-lattice diode and in a RTD, Song *et al.* concluded that not NDC, but charge accumulation in the well, responds for the super-Poissonian noise observed in RTD. Safanov *et al.*, measuring the noise in resonant tunneling via interacting localized states, observed a super-Poissonian noise in the range of bias, where there is no NDC. They have also pointed out that the effect on noise of the Pauli exclusion principle and the Coulomb interaction are similar in most mesoscopic systems. For our structure of study, in solving the ME, we are able to exactly analyze the charge states of the dot and the box at bias voltages, where the super-Poissonian peaks are observed. Studies strongly support the idea[6,7] that the charge accumulation in the dot causes the super-Poissonian noise observed.

In conclusion, we have calculated the current and the SN in a SET capacitively coupled to an electronic box, using the ME approach. In a particular case we were able to derive exact expressions for the *I-V* characteristics as well as the noise as a function of both frequency and bias voltage. For different varieties of structure parameters, including the gate, in a large range of bias voltage the calculation has been performed numerically. The obtained results show that the noise may be sub-Poissonian or strongly super-Poissonian, depending mainly on the box parameters and the gate. The super-Poissonian noise observed in the structure is not necessarily accompanied by an NDC. The study supports the idea that not NDC, but charge accumulation in the dot, responds for the super-Poissonian noise observed. Such an accumulation may be produced in correlation with charge states in the box.

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this problem can be found in Refs. 10 and 11 and in C. Flindt, T. Novotny, and A.-P. Jauho, Phys. Rev. B **70**, 205334 (2004).

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