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Noise Enhancement due to Telegraphic Switching in a Two-Level Quantum Dot Coupled to Spin-Polarized Leads

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Current fluctuations in a two-level quantum dot coupled to the spin-polarized leads are studied by means of the Markovian master equation. It is shown, that transitions between spin configurations of the system cause switching between different current channels, which generates the super-Poissonian noise enhancement and the correlation between subsequent waiting times separating the successive tunneling events.

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1. Introduction

It was first shown by Bułka [1] that in Coulomb-blockaded quantum dots attached to the spin-polarized leads the noise enhancement to super-Poissonian values can be observed. It results from the competition between tunneling processes for electrons with different spin polarizations, which are associated with different timescales of tunneling. This phenomenon was later referred to as the dynamical channel blockade [2]. The super-Poissonian shot noise associated with this mechanism has been experimentally observed in organic magnetic tunnel junctions [3].

Later, it was shown that in single-level quantum dots with a finite value of the Coulomb coupling and energy-dependent tunneling rates the another mechanism of the noise enhancement can occur – the telegraphic switching between the fast and the slow current channels [4]. This phenomenon, in contrast to the dynamical channel blockade, can be associated with the presence of the correlation between subsequent waiting times separating the successive tunneling events. However, the effect is pronounced only for a strong energy-dependence of the tunneling rates which is not a common feature of quantum dot systems. Here I show that the telegraphic switching can be observed also in two-level quantum dots even without energy dependence of the tunneling coupling (apart from its spin dependence). This significantly extends the range of physical systems in which the telegraphic switching phenomena can be predicted.

2. System and methods

I consider transport through a two-level quantum dot coupled to the separate non-interacting spin-polarized left (L) and right (R) leads with electrochemical potentials μ_α and spin polarizations p_α with $\alpha \in \{L, R\}$

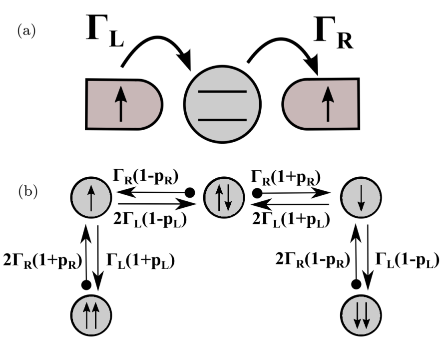

Fig. 1. (a) Scheme of a two-level quantum dot attached to two spin-polarized leads. (b) The five-state effective model of the dynamics of the system. $\Gamma_\alpha(1+p_\alpha)$ and $\Gamma_\alpha(1-p_\alpha)$ denote the tunneling rates for spin ↑ and ↓ electrons.

(Fig. 1a).The Hamiltonian of an isolated dot reads

$$\hat{H}_D = \sum_i \sum_\sigma \epsilon_i c^\dagger_{i\sigma} c_{i\sigma} + \frac{U}{2} \sum_{i,j} \sum_{\sigma,\sigma'} n_{i\sigma} n_{j\sigma'}, \tag{1}$$

where $i, j \in \{1, 2\}$, $\sigma, \sigma' \in \{\uparrow, \downarrow\}$, ϵ_i is the energy of the i-th level, U is the intradot Coulomb interaction and $n_{i\sigma}$ is the particle number operator. Parameters of the system are chosen in the following way: $\epsilon_1 \approx \epsilon_2 \approx -U$ and $\mu_L, -\mu_R, U - \mu_L, U + \mu_R \gg k_B T$. In such a regime only a single and a double occupancy of the dot is allowed. The separation between electrochemical potentials of the leads and dot energy levels is high in comparison to $k_B T$, such that transport can be considered as unidirectional. In the weak tunnel coupling regime the transport can be studied by means of the Markovian master equation [5]. Here there is no coherent coupling between the dot levels, therefore the diagonal and the off-diagonal elements of the density matrix are decoupled and only the former influence the transport (cf. Ref. [5] where such a decoupling is discussed). In result transport can be described by the classical rate equation

$$\dot{\rho}(t) = \mathcal{L}\rho(t), \tag{2}$$

where $\rho(t)$ is the column vector containing the state prob-

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abilities and $\mathcal{L}$ is the square matrix representing the Liouvillian. Furthermore, I assume that both levels are identically coupled to the leads. In such a case transport through the system can be studied by the effective five-state model which describes transitions between spin configurations of the dot (Fig. 1b). Let me explain values of the transition rates in the model by an example. When the level 1 is occupied by a spin $\uparrow$ electron, the spin configuration $(\uparrow\downarrow)$ can be generated through the transition of a spin $\downarrow$ electron either to the level 1 or 2. Thus the rate of the transition $(\uparrow) \to (\uparrow\downarrow)$ is equal to the tunneling rate $\Gamma_L(1-p_L)$ multiplied by 2. On the other hand, due to the Pauli exclusion principle, configuration $(\uparrow\uparrow)$ can be generated only by the tunneling of a spin $\uparrow$ electron to the level 2, and the rate of the transition $(\uparrow) \to (\uparrow\uparrow)$ is equal to the single tunneling rate $\Gamma_L(1+p_L)$. The similar reasoning applies to other transitions.

Fluctuations of the current flowing from the dot to the right lead are characterized by the full counting statistics (FCS) [6] and the waiting time distribution (WTD) [7]. Both methods are based on the following splitting of the Liouvillian:

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{J},$$

where the operator $\mathcal{J}$ describes the tunneling from the dot to the right lead. It includes all non-diagonal elements of the matrix $\mathcal{L}$ containing the tunneling rates Γ_R. The scaled cumulants of the n-th order of the zero-frequency FCS, denoted as c_n, can be determined using the following equation [8]:

$$\left(\frac{\mathrm{d}}{\mathrm{d}l^n}\lambda(l)\right)_{l=0} = c_n, \tag{3}$$

where $\lambda(l)$ is the scaled cumulant generating function, which is a dominant eigenvalue of the expression $\mathcal{L}_0+\mathcal{J}e^l$. In practice, cumulants can be most easily obtained without direct determination of $\lambda(l)$ by using the characteristic polynomial approach presented in Ref. [8].

WTD is characterized by the cumulants of the function $w(\tau)$, which describes the distribution of waiting times between the subsequent electron tunnelings. The Laplace transform of $w(\tau)$ reads [7]

$$w(s) = \frac{\mathrm{Tr}(\mathcal{J}(s-\mathcal{L}_0)^{-1}\mathcal{J}\rho_0)}{\mathrm{Tr}(\mathcal{J}\rho_0)}, \tag{5}$$

where ρ_0 is the vector of the stationary state (the solution of the equation $\mathcal{L}\rho(t) = 0$). The n-th order cumulants κ_n of the distribution $w(\tau)$ are given by the expression [7]

$$\kappa_n = (-1)^n \left(\frac{\mathrm{d}^n \log(w(s))}{\mathrm{d}s^n}\right)_{s=0}. \tag{6}$$

In particular, the cumulants κ_1 and κ_2 are equal to the mean waiting time $\langle\tau\rangle$ and the variance of waiting times $\langle\Delta\tau^2\rangle$. One can also determine the cross-correlation (covariance) of two subsequent waiting times [4]

$$\langle\Delta\tau_1\Delta\tau_2\rangle = \left(\frac{\partial}{\partial s}\frac{\partial}{\partial z}\log(w(s,z))\right)_{s,z=0}, \tag{7}$$

where

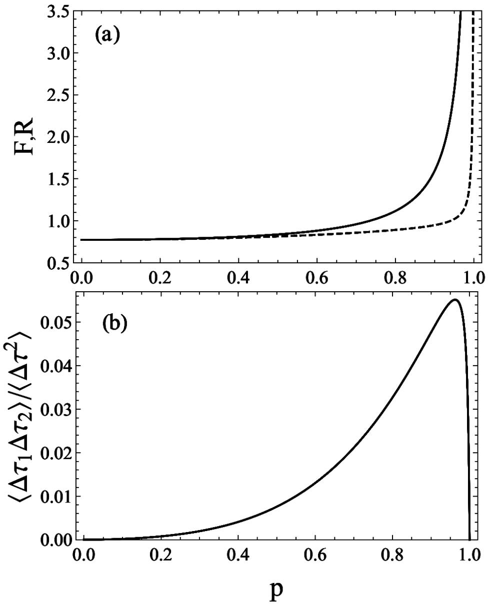

Fig. 2. Dependence of (a) the Fano factor F (solid line), the randomness parameter R (dashed line) and (b) the cross-correlation of the waiting times on the spin polarization of the leads $p = p_L = p_R$ for $\Gamma_R = 10\Gamma_L$.

$$w(s,z) = \frac{\mathrm{Tr}(\mathcal{J}(z-\mathcal{L}_0)^{-1}\mathcal{J}(s-\mathcal{L}_0)^{-1}\mathcal{J}\rho_0)}{\mathrm{Tr}(\mathcal{J}\rho_0)}, \tag{8}$$

is the Laplace transform of the distribution of two subsequent waiting times $w(\tau_1,\tau_2)$.

3. Results

I consider two quantities characterizing the full counting statistics and the waiting time distribution, respectively, the Fano factor F and the randomness parameter R

$$F = \frac{c_2}{c_1} = \lim_{t\to\infty}\frac{\langle\Delta n(t)^2\rangle}{\langle n(t)\rangle}, \tag{9}$$

$$R = \frac{\kappa_2}{\kappa_1^2} = \frac{\langle\Delta\tau^2\rangle}{\langle\tau\rangle^2}, \tag{10}$$

where $\langle n(t)\rangle$ is the mean number of electron transferred in the time interval t, and $\langle\Delta n(t)^2\rangle$ is the variance of this number. I focus on the case of $p_L = p_R = p$. For high values of p one can observe the super-Poissonian noise enhancement: $F > 1$ (see Fig. 2a). Additionally, the randomness parameter is not equal to the Fano factor which indicates that the subsequent waiting times are correlated [4] (when the waiting times are uncorrelated, both parameters are always equal [9]). This is confirmed by the direct calculation of the cross-correlation of subsequent waiting times (Fig. 2b).

The mechanism of the noise enhancement, which also generates the correlation of the waiting times, can be understood using the model presented in Fig. 1b. For high values of p transport is predominated by tunneling of spin $\uparrow$ electrons in two transport channels corresponding to the transitions $(\uparrow\uparrow) \leftrightarrow (\uparrow)$ and $(\uparrow\downarrow) \leftrightarrow (\downarrow)$. These processes are associated with the different timescales of the tunneling (especially for high asymmetry of the lead couplings). Transitions $(\uparrow) \leftrightarrow (\uparrow\downarrow)$, associated with the tunneling of spin $\downarrow$ electrons, cause the slow switching between these transport channels. Such a phenomenon, referred to as the telegraphic switching, is already known to generate both the super-Poissonian noise and the correlations between subsequent waiting times [4]. Additionally, the system may be trapped in the configuration $(\downarrow\downarrow)$ which leads to the current blockade. At $p \approx 1$ this mechanism becomes the most important, which decreases the value of the waiting time cross-correlation (Fig. 2b).

4. Conclusions

I have shown, that in a two-level quantum dot attached to spin-polarized leads the transitions between spin configurations of the system may induce switching between different transport channels, which generates the super-Poissonian noise enhancement and the correlation between subsequent waiting times. This mechanism differs from the dynamical channel blockade which does not generate the waiting time correlations [4]. The results illustrate, that the analysis of the waiting time correlation is a useful tool enabling to distinguish between different mechanisms of the noise enhancement.

Experimentally, the waiting times correlations can be studied directly using the single electron counting techniques [10]. Alternatively, as shown in Ref. [4], their presence can be revealed indirectly by considering the second-order current correlation function and the zero-frequency current skewness, which should be accessible using the standard current measurements.

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