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Electron transfer properties of double quantum dot system in a fluctuating environment*

Lujing Jiang(姜露静)[1,†], Kang Lan(蓝康)[1,2,†], Zhenyu Lin(林振宇)[1], and Yanhui Zhang(张延惠)[1,‡]

[1] School of Physics and Electronics, Shandong Normal University, Jinan 250014, China
[2] School of Physics, State Key Laboratory of Crystal Materials, Shandong University, Jinan 250100, China

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Using the innovative method of the additional Bloch vector, the electron transfer properties of a double quantum dot (DQD) system measured by a quantum point contact (QPC) in a fluctuating environment are investigated. The results show that the environmental noises in transverse and longitudinal directions play different roles in the dynamical evolution of the open quantum systems. Considering the DQD with symmetric energy level, the Fano factor exhibits a slight peak with the increase of transverse noise amplitude σ_{T}, which provides a basis for distinguishing dynamical phenomena caused by different directional fluctuation noises in symmetric DQD structures by studying the detector output. In the case of asymmetric DQD, the dependence of a detector current involving the level displacement is distinct when increasing the transverse noise damping coefficient τ_{T} and the longitudinal noise damping coefficient τ_{ε} respectively. Meanwhile, the transverse noise damping coefficient τ_{T} could significantly reduce the Fano factor and enhance the stability of the quantum system compared with the longitudinal one. The Fano factors with stable values as the enhancement of noise amplitudes show different external influences from the detector measurement, and provide a numerical reference for adjusting the noise amplitudes in both transverse and longitudinal directions appropriately in a microscopic experimental process to offset the decoherence effect caused by the measurements. Finally, the research of average waiting time provides unique insights to the development of single electron transfer theory in the short-time limit.

Keywords: double quantum dots, fluctuating environment, electron transfer, noise

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1. Introduction

With the rapid development of quantum information technology, solid-state quantum computing based on semiconductor quantum dot system has become a research focus in quantum measurement and quantum information processing.[1–9] In the practical quantum computation, the system inevitably interacts with the surrounding environments, which leads to the loss of the coherence of the quantum system.[10–14] Recently, it has become an urgent problem to study the decoherence process caused by the coupling of the quantum system and the external environment, and research on the non-Markovian dynamics of the open quantum system has attracted extensive attention.[15–26] Studying the process of electron transport[27–34] in an open quantum system is of great significance for understanding the dynamical evolution of the system, restraining the decoherence and improving the efficiency of quantum computation.

In recent years, driven by the potential application of quantum information science, the double quantum dot (DQD) system with its unique quantum properties and strong controllability has become an effective model for quantum measurement and quantum transport.[35–38] As a measuring instrument, the quantum point contact (QPC) is widely used to measure the position of electron in the DQD owing to its high sensitivity.[39–43] The disturbance of the external environment leads to many interesting phenomena in the dynamical evolution of open quantum systems. A great many theoretical works and experiments related to quantum dots have made breakthroughs, which inspires us to research the dynamical properties of the quantum systems.

The information about the probability distribution of n electrons tunneling to the collector electrode can be obtained from full counting statistics (FCS).[44–53] The first-order cumulant of the number of electrons transferred during transport represents the average current of the system, and the shot noise which represents the fluctuation of the system is indicated by the second-order cumulant. The intensity of shot noise is usually expressed numerically by the value of the Fano factor, $F = 1$, $F < 1$, and $F > 1$, which correspond to the distributions of Poissonian, sub-Poissonian, and super-Poissonian.[54–59] As indexes reflecting system dynamics in the short-time limit, single electron transfer probability and the average waiting time can effectively show the electron transfer properties.[60]

In the previous work,[58] we studied the dynamics of a DQD system interacting with a Gaussian white noise (GWN)

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†These authors contributed equally.
‡Corresponding author. E-mail: yhzhang@sdnu.edu.cn
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environment; however, the effects of noises in transverse and longitudinal directions on the system were not considered respectively. Based on the previous work, we further calculate the detector current and Fano factor, which reveal the influences of transverse and longitudinal noises on the electron transfer properties in symmetric ($\varepsilon_0 = 0$) and asymmetric ($\varepsilon_0 \neq 0$) DQDs. In the case of a symmetric DQD, the Fano factor presents a weak unimodal structure with the influence of transverse noise amplitude $\sigma_{\rm T}$, which can provide a basis for distinguishing the dynamical evolution of fluctuating noise in different directions by investigating the detector outcome. For the case of an asymmetric DQD, the average current increases differently with the augmentation of the transverse noise damping coefficient $\tau_{\rm T}$ and longitudinal noise damping coefficient τ_ε, which provides a reference for adjusting noise parameters to obtain different directional environment information. Moreover, the increase of level displacement rises with the suppression of electron transfer in DQD, which causes a reduction of the detector barrier to slow down the single electron transfer of QPC. The probability of single electron transfer would take less time to reach its stationary value with the increase of the transverse noise amplitude $\sigma_{\rm T}$ than that with the increase of the longitudinal noise amplitude σ_ε, illustrating that the transverse noise amplitude $\sigma_{\rm T}$ plays a major role in the electron transfer of the detector. It should be noted that whether in symmetric or asymmetric cases, the Fano factor always follows the super-Poissonian distribution because of the cotunneling effect. Our results not only provide a method for quantum measurement experiments to obtain environmental information, but also provide theoretical support for the study of noise properties in non-Markovian dynamics.

2. Theoretical framework

First, we consider a DQD, as shown in Fig. 1. The Hamiltonian of the DQD can be described as[47]

$$H_{\rm S} = \frac{\varepsilon_0}{2}(a_{\rm L}^\dagger a_{\rm L} - a_{\rm R}^\dagger a_{\rm R}) + T_0(a_{\rm L}^\dagger a_{\rm R} + a_{\rm R}^\dagger a_{\rm L}), \tag{1}$$

where ε_0 and T_0 represent the level displacement and the tunneling amplitude of the DQD, $a_{\rm L}^\dagger$ ($a_{\rm L}$) and $a_{\rm R}^\dagger$ ($a_{\rm R}$) are the creation (annihilation) operators of the left and right dots of the DQD. We assume that only one electron can occupy the DQD system with the basis $\{|L\rangle, |R\rangle\}$.[63]

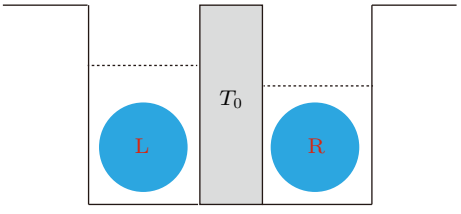


Fig. 1. A double quantum dot two-level system.

The dynamical evolution of the density matrix of the DQD satisfies

$$\frac{\rm d}{{\rm d}t}\rho(t) = L_0\rho(t), \tag{2}$$

where $L_0\rho(t) = -\frac{\rm i}{\hbar}[H_{\rm S}, \rho(t)]$ describes the unitary evolution of the system, and L_0 is the unitary evolution operator of the system

$$L_0 = \begin{pmatrix} 0 & 0 & {\rm i}T_0 & -{\rm i}T_0 \\ 0 & 0 & -{\rm i}T_0 & {\rm i}T_0 \\ {\rm i}T_0 & -{\rm i}T_0 & -{\rm i}\varepsilon_0 & 0 \\ -{\rm i}T_0 & {\rm i}T_0 & 0 & {\rm i}\varepsilon_0 \end{pmatrix}. \tag{3}$$

The reduced density matrix of the system is represented by the column vector, $\rho(t) = [\rho_{\rm LL}(t), \rho_{\rm RR}(t), \rho_{\rm RL}(t), \rho_{\rm LR}(t)]^\dagger$, and the evolution of the elements of the reduced density matrix can be written as

$$\begin{aligned} \dot\rho_{\rm LL}(t) &= -{\rm i}T_0[\rho_{\rm LR}(t) - \rho_{\rm RL}(t)], \\ \dot\rho_{\rm LR}(t) &= {\rm i}\varepsilon_0\rho_{\rm LR}(t) - {\rm i}T_0[\rho_{\rm LL}(t) - \rho_{\rm RR}(t)]. \end{aligned} \tag{4}$$

The diagonal elements of the reduced density matrix $\rho_{\rm LL}(t)$ and $\rho_{\rm RR}(t)$ represent the probabilities of finding the electron in the left and right quantum dot, respectively, and the off-diagonal elements $\rho_{\rm LR}(t)$ and $\rho_{\rm RL}(t)$ describe the coherence between states $|L\rangle$ and $|R\rangle$, $\rho_{\rm RR}(t) = 1 - \rho_{\rm LL}(t)$, and $\rho_{\rm RL}(t) = \rho_{\rm LR}^*(t)$.

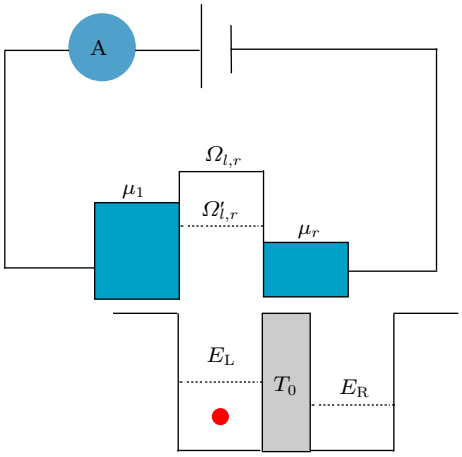


Fig. 2. The DQD system coupled with a QPC. μ_l and μ_r denote the chemical potentials of the left and right reservoirs, and $V = \mu_l - \mu_r$ is the bias voltage in QPC.

In order to study the electron transfer properties in the DQD, QPC is introduced to measure the position of the electron in the DQD, as shown in Fig. 2. The Hamiltonian of the system is written as[63]

$$\begin{aligned} H &= H_{\rm S} + H_{\rm PC} + H_{\rm I}, \\ H_{\rm PC} &= \sum_l E_l a_l^\dagger a_l + \sum_r E_r a_r^\dagger a_r + \sum_{l,r}(\Omega_{l,r} a_r^\dagger a_l + {\rm H.c.}), \\ H_{\rm I} &= \sum_{l,r} \delta\Omega_{l,r}\sigma_z(a_r^\dagger a_l + a_l^\dagger a_r), \end{aligned} \tag{5}$$

where $H_{\rm PC}$ is the Hamiltonian of the QPC, $a_l^\dagger$ (a_l) and $a_r^\dagger$ (a_r) are the creation (annihilation) operators of the left and right reservoirs in the QPC. $H_{\rm I}$ describes the interaction between

the DQD system and QPC, $\delta\Omega_{l,r} = \Omega_{l,r} - \Omega'_{l,r}$, depends on the electron occupying the left or right quantum dot.[39] When the electron transfers from the left quantum dot to the right quantum dot, the tunneling barrier of the detector changes, resulting in the hopping amplitude changing from $\Omega_{l,r}$ to $\Omega'_{l,r}$.

By introducing a QPC, the dynamical evolution of the reduced density matrix of the system is given by[6]

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho(t) = L_0\rho(t) + L_\mathrm{d}\rho(t), \tag{6}$$

where L_d describes the decoherence caused by the interaction of the system coupled to a QPC detector with the decoherence rate $\Gamma_\mathrm{d} = D + D' - 2\sqrt{DD'}$, $D = 2\pi|\Omega_{l,r}|^2\rho_l\rho_r(\mu_l - \mu_r)$, $D' = 2\pi|\Omega'_{l,r}|^2\rho_l\rho_r(\mu_l - \mu_r)$, where $\rho_{l,r}$ is the density of states in the reservoirs. L_d can be written as

$$L_\mathrm{d} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & -\frac{\Gamma_\mathrm{d}}{2} & 0 \\ 0 & 0 & 0 & -\frac{\Gamma_\mathrm{d}}{2} \end{pmatrix}. \tag{7}$$

Considering the influence of the detector, the reduced density matrix elements of the system are expressed as

$$\begin{aligned} \dot{\rho}_{\mathrm{LL}}(t) &= -\mathrm{i}T_0[\rho_{\mathrm{LR}}(t) - \rho_{\mathrm{RL}}(t)], \\ \dot{\rho}_{\mathrm{LR}}(t) &= \mathrm{i}\varepsilon_0\rho_{\mathrm{LR}}(t) - \mathrm{i}T_0[\rho_{\mathrm{LL}}(t) - \rho_{\mathrm{RR}}(t)] - \frac{\Gamma_\mathrm{d}}{2}\rho_{\mathrm{LR}}(t). \end{aligned} \tag{8}$$

The number of tunneling electrons is recorded by using the reduced density matrix $\rho^{(n)}_{ij}(t)$. The index n is the number of electrons in the QPC that reach the right reservoir during time t. The cumulative moment generation function of the electron satisfies[52]

$$\rho^{(n)}_{ij}(x,t) = \sum_{n=0}^{\infty}\rho^{(n)}_{ij}(t)\,\mathrm{e}^{-nx}, \tag{9}$$

where x is a statistical parameter. The quantum master equation for the generalized particle number resolution of the system is written as[61]

$$\dot{\rho}^{(n)}(t) = L\rho^{(n)}(t) + L_\mathrm{J}\rho^{(n-1)}(t). \tag{10}$$

The operators L and L_J respectively describe the continuous evolution of the system and the quantum jump in electron transfer, and can be expressed as

$$\begin{aligned} L &= \begin{pmatrix} -D & 0 & \mathrm{i}T_0 & -\mathrm{i}T_0 \\ 0 & -D' & -\mathrm{i}T_0 & \mathrm{i}T_0 \\ \mathrm{i}T_0 & -\mathrm{i}T_0 & -\mathrm{i}\varepsilon_0 - \frac{D+D'}{2} & 0 \\ -\mathrm{i}T_0 & \mathrm{i}T_0 & 0 & \mathrm{i}\varepsilon_0 - \frac{D+D'}{2} \end{pmatrix}, \\ L_\mathrm{J} &= \begin{pmatrix} D & 0 & 0 & 0 \\ 0 & D' & 0 & 0 \\ 0 & 0 & \sqrt{DD'} & 0 \\ 0 & 0 & 0 & \sqrt{DD'} \end{pmatrix}. \end{aligned} \tag{11}$$

We consider a DQD system measured by a QPC in fluctuating environment. First, we only consider the influence of noise in transverse direction on the system; the random fluctuation in Hamiltonian of the DQD system can be expressed as

$$H(t) = H_\mathrm{S} + H_\delta(t) = \frac{\hbar}{2}\varepsilon_0\sigma_z + \hbar T_0\sigma_x + \hbar T(t)\sigma_x, \tag{12}$$

where H_S is the Hamiltonian of the DQD without environmental effect, and $H_\delta(t)$ is the fluctuation caused by the coupling between the DQD system and transverse noise, $T(t)$ is the random fluctuation of the tunneling amplitude in the two-level system, and σ_z and σ_x denote the Pauli matrices. According to the statistical properties of GWN, the noise in transverse direction can be represented by the second-order cumulant

$$\langle\delta T(t)\delta T(t')\rangle_\delta = \sigma_\mathrm{T}^2\,\mathrm{e}^{-\tau_\mathrm{T}(t-t')}, \tag{13}$$

where σ_T and τ_T respectively denote the amplitude and damping coefficient of the transverse noise. Based on the properties of GWN, the exact dynamical evolution equation of the DQD system is given by a time-convolutionless master equation[58]

$$\begin{aligned} \frac{\mathrm{d}}{\mathrm{d}t}\rho(t) &= L_0\rho(t) + L_\mathrm{d}\rho(t) \\ &\quad + \int_0^t \mathrm{d}t'\langle L_\delta(t)\,\mathrm{e}^{L_0(t-t')}L_\delta(t')\rangle_\delta\,\mathrm{e}^{-L_0(t-t')}\rho(t). \end{aligned} \tag{14}$$

The first and second terms on the right respectively describe the unitary evolution of the DQD system and the decocoherence caused by QPC measurement, and the third term corresponds to the fluctuation of the transverse noise on the system. The super operator $L_\delta(t)$ corresponding to the fluctuation of the system caused by the transverse noise can be written as

$$L_\delta(t) = \begin{pmatrix} 0 & 0 & -\mathrm{i}\delta T(t) & \mathrm{i}\delta T(t) \\ 0 & 0 & \mathrm{i}\delta T(t) & -\mathrm{i}\delta T(t) \\ -\mathrm{i}\delta T(t) & \mathrm{i}\delta T(t) & 0 & 0 \\ \mathrm{i}\delta T(t) & -\mathrm{i}\delta T(t) & 0 & 0 \end{pmatrix}. \tag{15}$$

With only the longitudinal noise taken into account, the Hamiltonian of the DQD system can be written as

$$H(t) = H_\mathrm{S} + H_\delta(t) = \frac{\hbar}{2}\varepsilon_0\sigma_z + \hbar T_0\sigma_x + \frac{\hbar}{2}\varepsilon(t)\sigma_z, \tag{16}$$

where $\varepsilon(t)$ is the random fluctuation of the level displacement in the two-level system. According to the statistical properties of GWN, the noise in the longitudinal direction can be represented by the second-order cumulant

$$\langle\delta\varepsilon(t)\delta\varepsilon(t')\rangle_\delta = \sigma_\varepsilon^2\,\mathrm{e}^{-\tau_\varepsilon(t-t')}, \tag{17}$$

where σ_ε and τ_ε respectively denote the amplitude and damping coefficient of the longitudinal noise. According to Eq. (14), the corresponding system fluctuation operator $L_\delta(t)$ caused by the longitudinal noise is different from that caused by the transverse noise

$$L_\delta(t) = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & \mathrm{i}\delta\varepsilon(t) & 0 \\ 0 & 0 & 0 & -\mathrm{i}\delta\varepsilon(t) \end{pmatrix}. \tag{18}$$

The master equation of particle number resolution describing electron transfer of the QPC with the effect of transverse and

longitudinal noises is[58]

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho^{(n)}(t) = L\rho^{(n)}(t) + L_{\mathrm{J}}\rho^{(n-1)}(t) + \int_0^t \mathrm{d}t' \langle L_\delta(t)\, \mathrm{e}^{L_0(t-t')} L_\delta(t') \rangle_\delta \mathrm{e}^{-L_0(t-t')} \rho^{(n)}(t). \quad (19)$$

In order to describe the influences of transverse noise and longitudinal noise on the electron transfer properties of the system clearly, we introduce the method of additional Bloch vector to represent the cumulants in the transport process; the traditional Bloch vectors are[51]

$$\begin{aligned} \mathcal{I}(x,t) &= \rho_{\mathrm{LR}}(x,t) + \rho_{\mathrm{RL}}(x,t), \\ \mathcal{J}(x,t) &= \frac{1}{\mathrm{i}}[\rho_{\mathrm{LR}}(x,t) - \rho_{\mathrm{RL}}(x,t)], \\ \mathcal{K}(x,t) &= \rho_{\mathrm{LL}}(x,t) - \rho_{\mathrm{RR}}(x,t), \end{aligned} \quad (20)$$

and the additional vector is

$$\mathcal{R}(x,t) = \rho_{\mathrm{LL}}(x,t) + \rho_{\mathrm{RR}}(x,t). \quad (21)$$

The cumulative moment generation function of the electron can be obtained by deriving the additional Bloch vector with respect to x[52]

$$\langle N^{(k)} \rangle = (-1)^k \frac{\partial^k}{\partial x^k} \mathcal{R}(x,t)|_{x=0}. \quad (22)$$

The influences of environmental noises on the electron transfer of the system are studied by calculating the average current

$$I(t) = -\frac{\partial}{\partial x} \dot{\mathcal{R}}(x,t)|_{x=0}. \quad (23)$$

The intensity of shot noise is determined by the value of the Fano factor, $F = (\langle N^2 \rangle - \langle N \rangle^2)/\langle N \rangle$. The transfer probability of n electrons in time t can be expressed as

$$P_n(t) = (-1)^n \frac{\partial^n}{\partial x^n} \mathcal{R}(x,t)|_{x=\infty}. \quad (24)$$

In addition, as an important physical quantity representing dynamical information in the short time limit, the average waiting time can be obtained by integrating the probability of transferring zero electron P_0, $\langle \tau \rangle = \int_0^\infty P_0(t)\mathrm{d}t$.

3. Results and discussion

In this section, we separately analyze the electron transfer dynamics for the cases of symmetric and asymmetric DQDs affected by the fluctuation noises in transverse and longitudinal directions. The dynamics of electron transfer between right and left dots in a closed symmetric DQD ($\varepsilon_0 = 0$) system only depends on the initial position of the electron ($\rho_{\mathrm{LL}}(0) = 1$ or $\rho_{\mathrm{RR}}(0) = 1$). If detector measurements and environmental effects are taken into account, the probabilities of an electron occupying the two dots of DQD in the long-time limit should be consistent, namely, $\rho_{\mathrm{LL}}(t_\tau) = \rho_{\mathrm{RR}}(t_\tau) = 0.5, t_\tau \to \infty$. As for the case of an asymmetric DQD ($\varepsilon_0 \neq 0$), the probabilities of an electron occupying in the long-time limit are related to the level displacement ε_0. However, the zero point of level displacement would shift, which results in interesting dynamical phenomena due to the influences of longitudinal noise. In this paper, we assume that the electron is located in the left quantum dot at the initial moment of $t = 0$, namely, $\rho_{\mathrm{LL}}(0) = 1$, $\rho_{\mathrm{RR}}(0) = 0$. Due to the environmental effects, the level displacement and coupling strength produce stochastic fluctuations that satisfy the statistical properties of GWN. Correspondingly, the eigen energy levels of the DQD system ($\Omega_{\mathrm{L}}^2 = \varepsilon(t)^2 + 4T(t)^2$) would change, resulting in the electron transfer process no longer satisfying the unitary dynamics. Thus, the environmental effects in both the transverse and longitudinal directions play significant roles in the dynamical evolution by considering the eigen energy levels of the DQD.

3.1. Electron transfer affected by transverse noise

Figure 3 shows the evolutions of average current I and the Fano factor F with different decoherence rates Γ_{d} and transverse noise parameters σ_{T} , τ_{T} for symmetric and asymmetric DQDs in the long-time limit. We find that the average current always presents an enhancement behavior with the increase of Γ_{d} induced by the QPC in Fig. 3(a). The increase of the output current is due to the electron transfer in DQD being inhibited, which leads to a relatively low QPC barrier and makes the electrons pass through the barrier more easily in the detector. We can see the interesting phenomenon in Fig. 3(b) where the Fano factor increases rapidly with Γ_{d} and reaches a very high peak value in the case of the asymmetric DQD because of the slow switching between different current channels connecting with the left and right reservoirs of the detector.[57,58] Meanwhile, the Fano factor in the symmetric case is much smaller than that in the asymmetric case. Whether the DQD is symmetric or not, the Fano factor always presents a super-Poissonian distribution due to the cotunneling effect caused by the tunneling of electrons between different energy levels in the detector.[57,62]

As shown in Fig. 3(c), the average current increases with the transverse noise amplitude σ_{T} for different level displacement ε_0 and finally tends to be stable in the case of the asymmetric DQD. It also can be seen from the observation that in the region of $\sigma_{\mathrm{T}} < 0.5T_0$, the average current decreases with the level displacement. This is mainly because the augmentation of ε_0 causes the increase of the eigen energy level in the DQD system. Consequently, it is difficult for the electron to transfer to the eigen energy level in the DQD, which puts the barrier of QPC into a higher-energy state, and hinders the electron transfer in the detector. In order to better understand the relation between the average current and transverse noise in the symmetric case, we specially enlarge the ordinate in Fig. 3(d_2) to investigate the evolution of the Fano factor. According to the results of the detector output, the Fano factor that represents the fluctuation of the average current exhibits a

weak unimodal structure with the increase of transverse noise amplitude σ_T in Fig. 3(d_2), confirming that the average current is slightly affected by the σ_T in the symmetric case. Besides, the Fano factor decays obviously with the enhancement of σ_T and tends to be identical at the different level displacement ε_0 in Fig. 3(d_1). For the asymmetric DQD, the presence of the transverse noise damping coefficient τ_T leads to the increase of the average current in Fig. 3(e), namely, the number of electrons reaching the collector of the detector increases in unit time. In the region of $\tau_T > 6T_0$, the evolutions of the average current with τ_T tend to identity in the case of the symmetric and asymmetric DQDs. There is no relatively distinct change in the evolution of the average current with the transverse noise damping coefficient τ_T in symmetric DQD, which corresponds to the Fano factor in Fig. 3(f_2). Different from Fig. 3(d_2), the Fano factor shows a tiny decrease with the increase of τ_T in Fig. 3(f_2), which can provide an effective way to distinguish dynamical phenomena caused by different transverse noise parameters σ_T and τ_T in symmetric DQD structures by studying the detector outcome. In addition, the transverse noise damping coefficient τ_T could gradually decrease the Fano factor in Fig. 3(f_2), which suppresses the shot noise to enhance the stability of the quantum system.

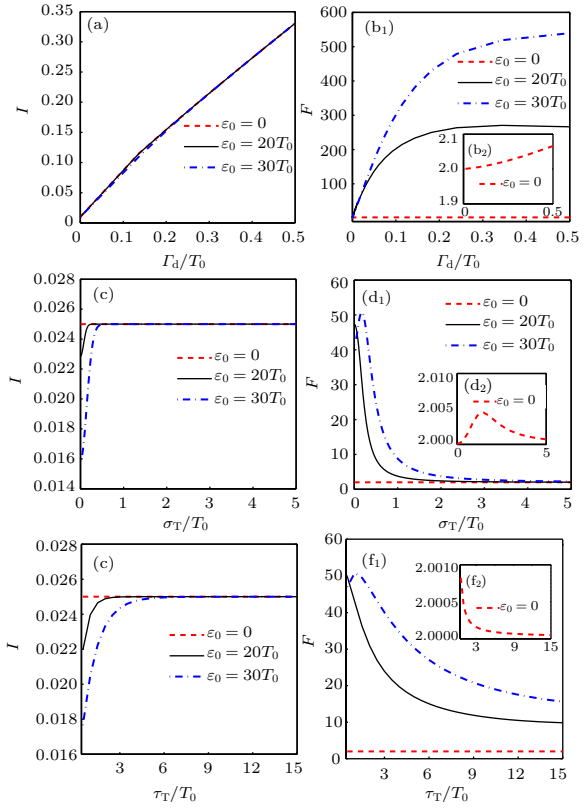


Fig. 3. The evolution of (a) the average current I and (b) the Fano factor F with decoherence rate Γ_d at different level displacement ε_0 in the long-time limit, with parameters $\sigma_T = 0.3T_0$ and $\tau_T = T_0$. The evolution of (c) the average current I and (d) the Fano factor F with the transverse noise amplitude σ_T at different level displacement ε_0 in the long-time limit, with parameters $\tau_T = T_0$ and $\Gamma_d = 0.01T_0$. The evolution of (e) the average current I and (f) the Fano factor F with the transverse noise damping coefficient τ_T at different level displacement ε_0 in the long-time limit, with parameters $\sigma_T = 0.3T_0$ and $\Gamma_d = 0.01T_0$.

Figure 4 shows the influence of the transverse noise on the probability of single electron transfer P_0 as a function of the time t for different damping coefficient τ_T and amplitude σ_T in the short-time limit. As shown in Fig. 4(a), the increase of σ_T reduces the time of P_0 reaching stability, meaning that σ_T promotes the transfer of a single electron in the detector. Different from the strong dependence of σ_T, there are no obvious distinctions in the probability of single electron transfer P_0 at different τ_T in Fig. 4(b). It is not difficult to see that the influence of σ_T on single electron transfer probability P_0 is greater than that of τ_T. Therefore, it is the best way to acquire the noise properties by the sensitivity of the single electron transfer probability P_0 to σ_T.

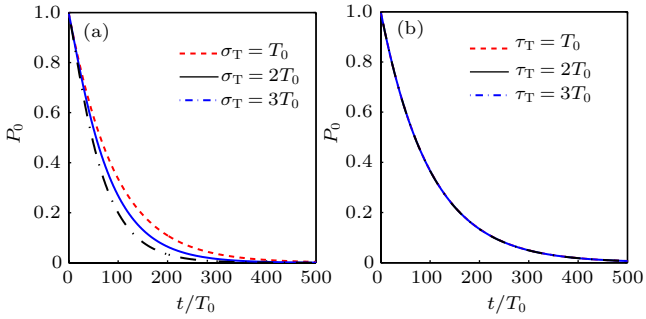


Fig. 4. Asymmetric DQD ($\varepsilon_0 \neq 0$). (a) The probability of single electron transfer P_0 versus time for different amplitude σ_T, other parameters are chosen as $\Gamma_d = 0.01T_0$, $\tau_T = T_0$. (b) The probability of single electron transfer P_0 versus time for different damping coefficient τ_T with $\Gamma_d = 0.01T_0$ and $\sigma_T = 0.3T_0$.

Figure 5 shows the evolution of average waiting time $\langle\tau\rangle$ with transverse noise for symmetric and asymmetric DQDs in the short-time limit. When the transverse noise amplitude $\sigma_T < 15T_0$, for the same σ_T, the average waiting time $\langle\tau\rangle$ in the asymmetric case is larger than that in the symmetric case, meaning that the increase of level displacement ε_0 can impede the electron tunneling of the detector in the short-time limit of Fig. 5(a). However, in the region of $\sigma_T > 15T_0$, the evolutions of $\langle\tau\rangle$ with σ_T in the symmetric and asymmetric cases are the same. This reminds us that it is important to choose the appropriate value of σ_T for the purpose of obtaining the electron tunneling properties of the detector. It is shown that the change of σ_T causes a tiny peak of $\langle\tau\rangle$ in the case of the symmetric DQD of Fig. 5(a_2). In addition, the existence of the transverse noise damping coefficient τ_T leads to the slight decrease of $\langle\tau\rangle$ in the asymmetric case of Figs. 5(b_1) and 5(b_2), demonstrating that τ_T weakly accelerates the single electron transfer in the detector compared with the transverse noise amplitude σ_T. Similar to Fig. 5(a), we find that the larger the ε_0 is, the slower the electron transfer in QPC will be. The sensitivity of the average waiting time on the level displacement provides an effective way to control the velocity of electron transfer in open quantum systems.

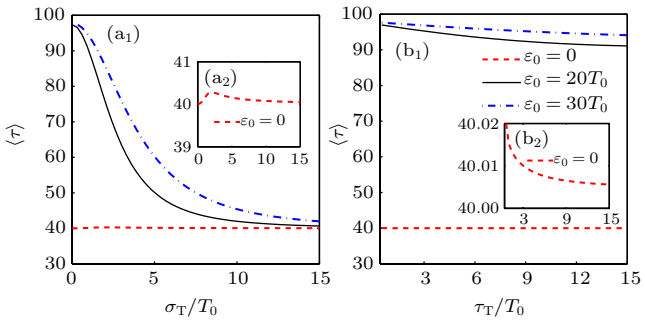


Fig. 5. (a) The average waiting time $\langle\tau\rangle$ versus amplitude σ_T at different level displacement ε_0, other parameters are chosen as $\Gamma_d = 0.01T_0$, $\tau_T = T_0$. (b) The average waiting time $\langle\tau\rangle$ versus damping coefficient τ_T at different level displacement ε_0 with $\Gamma_d = 0.01T_0$ and $\sigma_T = 0.3T_0$.

3.2. Electron transfer affected by longitudinal noise

Figure 6 shows the evolutions of average current I and Fano factor F with different decoherence rates Γ_d and longitudinal noise parameters τ_ε and σ_ε for symmetric and asymmetric DQDs in the long-time limit. As we can see in Fig. 6(a), the enhancement of the coupling between the DQD and QPC causes an increase of the average current whether the DQD is symmetric or not, and the Fano factor following super-Poissonian distribution reaches a very high value with the increase of the decoherence rate in the asymmetric case of Fig. 6(b_1), which shows a similar evolution as in Fig. 3(b_1). Compared with the asymmetric case, as the decoherence rate increases, the Fano factor increases slightly in the symmetric case of Fig. 6(b_2), revealing that the continuous measurement of the detector could destroy the stability of the DQD system.

We find that the detector current in the asymmetric DQD gradually increases with the influence of longitudinal noise amplitude σ_ε and reaches a stable value coinciding with the symmetric DQD in Fig. 6(c). It suggests that the level displacement ε_0 of the DQD system should be flexibly selected in order to get the different current values of the transmission probability. Corresponding to the Fano factor in Fig. 6(d_2), the average current is not affected evidently by the increase of σ_ε in the symmetric DQD. Figure 6(d_1) shows that the increase of σ_ε leads to the reduction of the Fano factor, which could restrain the shot noise. This implies that the stability of the DQD system can be improved by adjusting the range of σ_ε. Moreover, due to the peak value of Fano factor shifts with the increase of ε_0, the stability of open quantum systems dynamical evolution can be maintained by setting the level displacement ε_0. Different from the previous work,[58] we focus on the case of large noise damping coefficient τ_ε in this paper. The evolutions of the average current and Fano factor show the same tendency at large longitudinal noise damping coefficient in the case of the asymmetric DQD in Figs. 6(e) and 6(f). We find that the average current in the symmetric case is larger than that in the asymmetric case at the same value of τ_ε, indicating that the increase of level displacement reduces the number of electrons passing through QPC in unit time. Figure 3(f_1) shows that the Fano factor shifts up with the increase of the level displacement, which leads to the instability of the DQD system.

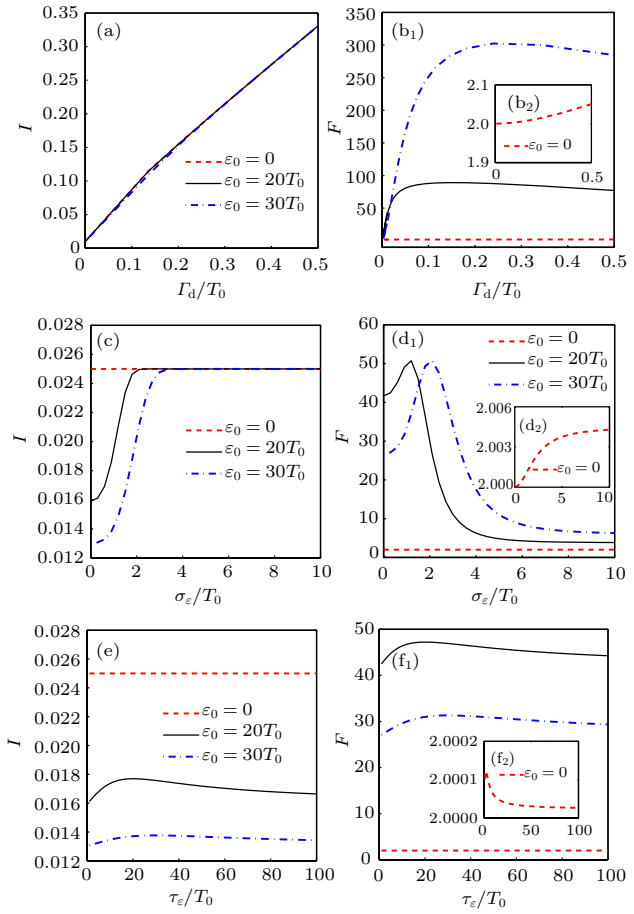


Fig. 6. The evolution of (a) the average current I and (b) the Fano factor F with decoherence rate at different level displacement ε_0 in the long-time limit, with parameters $\sigma_\varepsilon = 0.3T_0$ and $\tau_\varepsilon = T_0$. The evolution of (c) the average current I and (d) the Fano factor F with the longitudinal noise amplitude at different level displacement ε_0 in the long-time limit, with parameters $\tau_\varepsilon = T_0$ and $\Gamma_d = 0.01T_0$. The evolution of (e) the average current I and (f) the Fano factor F with the longitudinal noise damping coefficient at different level displacement ε_0 in the long-time limit, with parameters $\sigma_\varepsilon = 0.3T_0$ and $\Gamma_d = 0.01T_0$.

Figure 7 shows the influences of the longitudinal noise on the probability of single electron transfer P_0 as a function of the time for different damping coefficient τ_ε and amplitude σ_ε in the short-time limit. It is obvious that the increase of σ_ε causes P_0 to reach a stable value more quickly in Fig. 7(a). This is because σ_ε speeds up the electron tunneling in the detector. As shown in Fig. 7(b), the change in τ_ε has no obvious effect on P_0, meaning that the influence of τ_ε on the system evolution is relatively weak in the short-time limit. According to the comparative analysis, we find that the transverse noise plays a crucial role in the electron transfer of the detector. Therefore, it is not the best way to obtain the longitudinal environment information by P_0; we need to further calculate the average waiting time to analyze the effect of longitudinal noise on electronic behavior in the system.

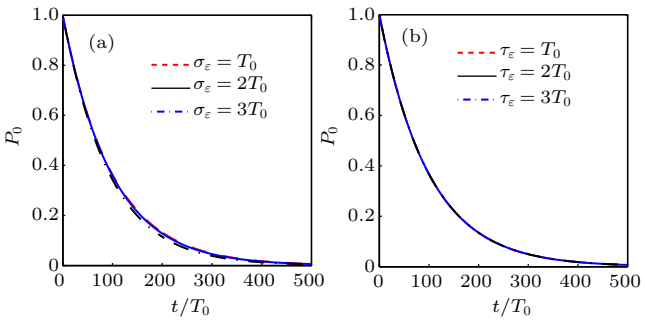


Fig. 7. Asymmetric DQD ($\varepsilon_0 \neq 0$). (a) The probability of transferring single electron P_0 versus time at different amplitude σ_ε, other parameters are chosen as $\Gamma_\mathrm{d} = 0.01T_0$, $\tau_\varepsilon = T_0$. (b) The probability of transferring single electron P_0 versus time at different damping coefficient τ_T with $\Gamma_\mathrm{d} = 0.01T_0$ and $\sigma_\varepsilon = 0.3T_0$.

Figure 8 shows the evolution of average waiting time $\langle\tau\rangle$ with longitudinal noise for symmetric and asymmetric DQDs in the short-time limit. It can be seen from Fig. 8(a) that the average waiting time $\langle\tau\rangle$ gradually decreases with the increase of longitudinal noise amplitude σ_ε in the asymmetric case. We attribute the decreasing behavior of average waiting time to the promotion of single electron transfer by σ_ε. Meanwhile, we find that the mean waiting time presents a weak increasing trend with the increase of σ_ε in the symmetric case of Fig. 8(a_2), which is different from that in the asymmetric case. The dependence of the average waiting time on the σ_ε provides a precise way for the experiment to obtain the information of the longitudinal environment compared with τ_ε in the short-time limit. In Figs. 8(b_1) and 8(b_2), the evolution of the average waiting time $\langle\tau\rangle$ changes slightly with the increase of τ_ε. It can be seen that the enhance of level displacement ε_0 would slow down the single electron transfer in the QPC by analyzing the change of $\langle\tau\rangle$ at different ε_0 in Fig. 8(a). However, if setting the electron in the right quantum dot at the initial time, we could get the opposite result.[58]

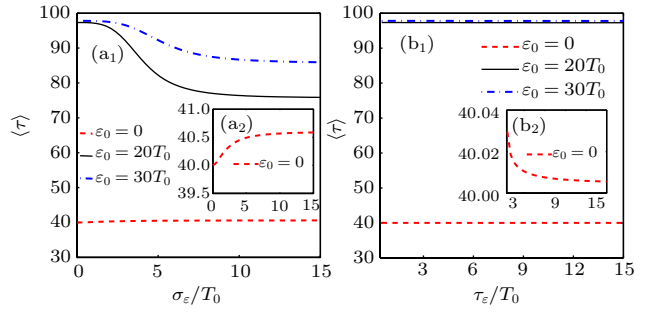


Fig. 8. (a) The average waiting time $\langle\tau\rangle$ versus amplitude σ_ε at different level displacement ε_0, other parameters are chosen as $\Gamma_\mathrm{d} = 0.01T_0$, $\tau_\varepsilon = T_0$. (b) The average waiting time $\langle\tau\rangle$ versus damping coefficient τ_ε at different level displacement ε_0 with $\Gamma_\mathrm{d} = 0.01T_0$ and $\sigma_\varepsilon = 0.3T_0$.

4. Conclusion

Based on the FCS theory and the method of additional Bloch vector, we separately analyze the influences of transverse noise and longitudinal noise on the electron transfer properties in symmetric and asymmetric DQDs. In the case of the symmetric DQD ($\varepsilon_0 = 0$), because both the Fano factor and the average waiting time show a slight peak with the augmentation of the transverse noise amplitude σ_T, it is convenient to distinguish the different dynamical features induced by environmental noise in different directions by investigating the detector outcome. For the case of asymmetric DQD ($\varepsilon_0 \neq 0$), the amplitude of transverse noise σ_T causes a distinct reduction of the Fano factor and improves the stability of the system compared with the longitudinal noise. Compared with the longitudinal noise amplitude σ_ε, the transverse noise amplitude σ_T would accelerate the probability of single electron transfer to reach the steady value, indicating that the transverse noise amplitude σ_T plays a dominating role in the electron transfer of the detector. Meanwhile, the increase of level displacement ε_0 would slow down the electron transfer, which provides an effective way to control the behavior of electron tunneling in microdevices. The Fano factor always follows the super-Poissonian distribution because of the cotunneling effect, regardless of whether the DQD is symmetric or not. Next, we will investigate the photon emission properties of DQD system in a fluctuating environment. The results of this paper can help us study the effect of environmental noise on the luminous mechanism of the DQD system.

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