Correlated hybridization induced super-Poissonian noise in quantum dots

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Transport through molecules or quantum dots is sensitive to not only the localized interactions on the conductor but also the hybridization to the external leads. In this study, we investigate the noise properties of a single level quantum dot with correlated hybridizations to the leads. In contrast to the featureless dot-lead coupling used in previous studies, we show that the correlated hybridization can give rise to the electron bunching in the transport. As a result, the noise Fano factor may be enhanced to super-Poissonian when the tunneling strength depends strongly on the electron number on the dot. This super-Poissonian noise appears at high bias voltage which enables the transfer of electrons via the doubly occupied state.

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I. INTRODUCTION

In the past decade, our understanding of the quantum transport in nanoconductors has been greatly improved by measuring the zero-frequency shot noise power.[1] A convenient figure of merit for the shot noise is the Fano factor which is defined as the ratio of the zero-frequency current noise and the Poissonian value $F=S/S_P$, where the Poisson value $S_P=2eI$ with e the carrier charge and I the averaged current. The Poisson value characterizes the current noise when the carrier transport can be described by the Poisson process. Previous studies have shown that shot noise in noninteracting conductors is always sub-Poissonian, i.e., $F<1$.[1] Therefore, much interest is drawn to study the microscopic interaction effects in conductors where an enhanced or super-Poissonian ($F>1$) noise is observed.[2–6] Several mechanisms[3–10] have been proposed to explain the super-Poissonian noise observed in quantum-dot systems. For example, both the interlevel Coulomb interaction[7] and the level-dependent coupling strengths[8,11] can lead to the dynamical channel blockade[12,13] and give rise to the super-Poissonian noise in the Coulomb-blockade regime.

The transport through a molecule or a quantum dot with a single level has been a subject of intensive investigations since it provides the simplest model system with nontrivial interaction effects. Thielmann *et al.*[14] have systematically studied the noise Fano factor of the quantum dot in the sequential tunneling regime. It is found that the noise Fano factor is a powerful tool to identify the asymmetry ratio of the coupling strengths in molecular devices. However, the noise Fano factor is always sub-Poissonian for this simple quantum dot. Later, several studies[13,15,16] have indicated that in order to observe the super-Poissonian noise, one may break the spin degeneracy by coupling the dot with spin-polarized electrodes. The dwell time of the electrons in the dot thus becomes spin dependent. In that way, the spin-dependent dwell time leads to a bunching of the tunneling electrons and might increase the shot noise above the Poisson value.

In most of the previous studies, much focus is attracted by the influence of the interaction effects localized on the dot. The tunneling processes are simply described by a constant coupling strength within the wideband approximation. In practical situations, the coupling may be sensitive to the Coulomb-interaction effect since the wave function on the dot can be modified by the many-body effects. Physically, one can expect that the presence of an electron on the dot will not only contribute an on-site charge energy but also make the dot-lead hybridization correlated. Meir *et al.*,[17] has proposed that the hybridization to the external leads may be sensitive to the charge number on the dot due to Coulomb effects. Intuitively, an electron occupying the quantum dot will decrease the tunneling rate of the second electron onto the dot due to the Coulomb interaction. Experiments have already demonstrated that the transparency of the coupling junction defined by gate voltage in semiconductor two-dimensional electron gas is sensitive to the Coulomb field established by an electron on a nearby quantum dot.[18] This sensitivity has made the quantum point contact an effective electrometer in many applications.[19,20] The mechanism of correlated hybridization has been proposed to explain the “0.7 anomaly” in quantum point contact.[17] However, the influence of this correlated coupling effect on the noise properties of quantum dots has not been reported.

It is the purpose of the present study to make a systematic investigation of the noise of a single level quantum dot with correlated hybridizations to the leads. Contrary to the previous findings that the repulsive on-site Coulomb interaction in a simple quantum dot can lead to a suppressed shot noise,[8,14] we show that the correlated hybridization due to the Coulomb interaction can enhance the shot noise. Analogous to the spin-dependent tunneling rates due to spin-polarized leads,[16] the correlated hybridization to the leads will make the tunneling rates or the dwell time of the electron depends strongly on whether the quantum dot is empty or not. The different dwell time for electrons tunneling through an empty dot or a singly occupied dot yields a bunching of the transferred electrons and enhances the shot noise. We show both analytically and numerically that an enhanced current noise or super-Poissonian noise may be possible if the coupling strength is sensitive to the number of electrons on the dot. The correlated hybridization induced super-Poissonian noise appears at high voltage where the dot may be doubly occupied. This should be in contrast to the previous studied mechanisms[3–10] for super-Poissonian noise where the energy level is considered as singly occupied. The nontrivial dependence of the Fano factor with the coupling strengths may be used to identify the correlated hybridization to the leads. In Sec. II, we first define our model system. Then we present the quantum master equation for sequential tunneling regime and the full counting statistics to obtain the current and noise properties. In Sec. III, we present both analytical and numerical results for the current noise Fano factor both for symmetric and asymmetric coupling schemes. Finally, a short conclusion is presented in Sec. IV.

II. MODEL AND THEORETICAL FORMALISM

We focus here on a dot containing only one energy level with spin degree of freedom. The quantum dot is coupled to the left (L) and right (R) leads. This quantum dot system can be well described by the single impurity Anderson model,

$$H = H_{\rm dot} + H_{\rm leads} + H_T, \tag{1}$$

where $H_{\rm dot}=\Sigma_\sigma \epsilon_\sigma d_\sigma^\dagger d_\sigma + U d_\uparrow^\dagger d_\uparrow d_\downarrow^\dagger d_\downarrow$ represents the single level quantum dot Hamiltonian with the Coulomb interaction strength U. d_σ ($d_\sigma^\dagger$) is the annihilation (creation) operator of the spin σ electron on the dot. The energy of the spin state ϵ_σ may be tuned by both the gate voltage and the Zeeman effect. $H_{\rm leads}=\Sigma_{l,k,\sigma}\epsilon_{l,k,\sigma}c_{l,k,\sigma}^\dagger c_{\alpha,k,\sigma}$ stands for the noninteracting leads at equilibrium. $c_{l,k,\sigma}$ is the annihilation operator of the electron with quantum number k and spin σ in the l=L,R lead. Due to the Pauli principle, the quantum dot can be classified into four possible states according to the electron number on the dot as $|0\rangle$ (empty), $|\sigma\rangle$ (one electron with spin $\sigma=\uparrow,\downarrow$), or $|\uparrow\downarrow\rangle$ (double occupancy). When the dot-lead hybridization is correlated,[17] the tunneling Hamiltonian may be given in terms of these number-resolved states as

$$H_T = \sum_{l,\sigma,k} (V_{l,k\sigma}^1 |\sigma\rangle\langle 0| c_{l,k,\sigma} + V_{l,k\sigma}^2 |\uparrow\downarrow\rangle\langle\bar{\sigma}| c_{l,k,\sigma}) + \text{H.c.}, \tag{2}$$

where the hybridization matrix element $V_{l,k\sigma}^1$ represents the transitions between 0 and 1 electron on the dot with an electron jumping between the dot and the l lead while $V_{l,k\sigma}^2$ represents the transition between 1 and 2 electron states. Without the correlated hybridization as discussed in most of the previous studies, the two transition rates are assumed to be constant and identical for simplicity, i.e., the transition does not discriminate the electron number on the dot. However, following Ref. 17, we physically expect $V^2 < V^1$ as the Coulomb potential of an electron already occupying the quantum dot will prevent the tunneling in of a second electron. The sensitivity of the transparency of a tunneling junction to an additional electron nearby has been experimentally verified in the quantum point contact.[21,22] This effect has made the quantum point contact an important tool to detect the charge states of a quantum dot. Our model seems to be familiar to that studied in Ref. 17 for the 0.7 anomaly in quantum point contact. However, we work in different transport regimes. In Ref. 17, the electrons in the leads are coherently scattered by a localized impurity to give rise to the Kondo physics at low temperature. As a consequence, the shot noise is suppressed due to the Kondo physics.[23] In the present study, the coupling between the leads and the dot is weak and we work in the sequential tunneling limit. Moreover, we will show that the correlated hybridization will enhance instead of reducing the shot noise Fano factor at high voltage bias.

In the sequential tunneling regime, it is appropriate to apply the quantum master equation with counting fields[24,25] to obtain the transport properties. To find out the current noise, we need the information of the operator $\mathcal{F}(\chi,t)=\text{Tr}_{\rm leads}\{e^{i\chi N_L}\rho(t)\}$ which is obtained by tracing out the lead degrees of freedom of the system density matrix ρ with a counting field χ which counts the number N_L of electrons in the left lead. The equation of motion for $\mathcal{F}$ is given by

$$\frac{d}{dt}\mathcal{F}(\chi,t) = [\mathcal{L} + (e^{i\chi}-1)\mathcal{J}_+ + (e^{-i\chi}-1)\mathcal{J}_-]\mathcal{F}(\chi,t), \tag{3}$$

where the superoperators after Fourier transform are given by

$$\begin{aligned}(\mathcal{L}\mathcal{F})_{\alpha\beta} = &-i(\epsilon_\alpha-\epsilon_\beta)\mathcal{F}_{\alpha\beta} + \frac{1}{2}\sum_{\gamma\delta}\sum_{l\sigma} \\ &\times\{-[f_l(\epsilon_{\gamma\delta})\Gamma^{l\sigma}_{\alpha\gamma;\gamma\delta} + \bar{f}_l(\epsilon_{\delta\gamma})\Gamma^{l\sigma}_{\gamma\delta;\alpha\gamma}]\mathcal{F}_{\delta\beta} \\ &+ [\bar{f}_l(\epsilon_{\delta\beta})\Gamma^{l\sigma}_{\alpha\gamma;\delta\beta} + f_l(\epsilon_{\beta\delta})\Gamma^{l\sigma}_{\delta\beta;\alpha\gamma}]\mathcal{F}_{\gamma\delta} \\ &+ [\bar{f}_l(\epsilon_{\delta\alpha})\Gamma^{l\sigma}_{\alpha\gamma;\delta\beta} + f_l(\epsilon_{\alpha\delta})\Gamma^{l\sigma}_{\delta\beta;\alpha\gamma}]\mathcal{F}_{\gamma\delta} \\ &- [\bar{f}_l(\epsilon_{\gamma\delta})\Gamma^{l\sigma}_{\delta\beta;\gamma\alpha} + f_l(\epsilon_{\delta\gamma})\Gamma^{l\sigma}_{\gamma\delta;\delta\beta}]\mathcal{F}_{\gamma\delta}\},\end{aligned} \tag{4}$$

$$(\mathcal{J}_+\mathcal{F})_{\alpha\beta} = \frac{1}{2}\sum_{\gamma\delta}\sum_{\sigma}[\bar{f}_L(\epsilon_{\delta\beta}) + \bar{f}_L(\epsilon_{\gamma\alpha})]\Gamma^{l\sigma}_{\alpha\gamma;\delta\beta}\mathcal{F}_{\gamma\delta}, \tag{5}$$

$$(\mathcal{J}_-\mathcal{F})_{\alpha\beta} = \frac{1}{2}\sum_{\gamma\delta}\sum_{\sigma}[f_L(\epsilon_{\beta\delta}) + f_L(\epsilon_{\alpha\gamma})]\Gamma^{l\sigma}_{\delta\beta;\alpha\gamma}\mathcal{F}_{\gamma\delta}. \tag{6}$$

Here, we have used the notation $\epsilon_{\alpha\beta}=\epsilon_\alpha-\epsilon_\beta$ and $\Gamma^{l\sigma}_{\alpha\beta;\gamma\delta}(\epsilon)=\frac{2\pi}{\hbar}\Sigma_k V^{\gamma\delta}_{l,k,\sigma}V^{\alpha\beta*}_{l,k\sigma}\delta(\epsilon-\epsilon_{lk\sigma})$. The hybridization matrix elements are given by $V^{0,\sigma*}_{l,k\sigma}=V^{\sigma,0}_{l,k\sigma}=V^1_{l,k\sigma}$ and $V^{\sigma,\uparrow\downarrow*}_{l,k\sigma}=V^{\uparrow\downarrow,\sigma}_{l,k\sigma}=V^2_{l,k\sigma}$. f_l is the Fermi function in the l lead and $\bar{f}_l=1-f_l$.

The importance of the operator $\mathcal{F}$ is that the moment generating function $\phi(\chi,t)$ of the counting statistics can be directly obtained by tracing out the dot degrees of freedom: $\phi(\chi,t)=\text{Tr}_{\rm dot}\,\mathcal{F}(\chi,t)$. By decomposing $\mathcal{F}$ into the Taylor series as $\mathcal{F}=\Sigma_{m=0}^{\infty}\frac{(i\chi)^m}{m!}\mathcal{F}_m$, where the coefficients $\mathcal{F}_m$ give direct access to the moments $\langle N_L^m\rangle=\text{Tr}_{\rm dot}\,\mathcal{F}_m$. Inserting the Taylor expansion of $\mathcal{F}$ into its equation of motion, one can arrive at the hierarchy

$$\frac{d}{dt}\mathcal{F}_0 = \mathcal{L}\mathcal{F}_0,$$

$$\frac{d}{dt}\mathcal{F}_1 = \mathcal{L}\mathcal{F}_1 + (\mathcal{J}_+ - \mathcal{J}_-)\mathcal{F}_0,$$

$$\frac{d}{dt}\mathcal{F}_2 = \mathcal{L}\mathcal{F}_2 + 2(\mathcal{J}_+ - \mathcal{J}_-)\mathcal{F}_1 + (\mathcal{J}_+ + \mathcal{J}_-)\mathcal{F}_0. \tag{7}$$

The transport information can be extracted by solving these equations. For example, the stationary solution of $\mathcal{F}_0$ gives the reduced density matrix of the quantum dot in the long-time limit. The current from the left lead is then simply given by

$$I = e\ \mathrm{Tr}_{\mathrm{dot}}\ \dot{\mathcal{F}}_1 = e(\mathrm{Tr}_{\mathrm{dot}}[(\mathcal{J}_+ - \mathcal{J}_-)\mathcal{F}_0]). \tag{8}$$

The above equations for the superoperators contains the off-diagonal elements of the operator $\mathcal{F}$. For the present model system, we have a single level quantum dot and do not include any spin flip. Therefore only the diagonal elements are relevant to the calculation of the transport properties. For more complex conductors such as multilevel systems with interlevel interaction, one need to consider the off-diagonal elements.

The zero-frequency current noise $S(0)$ is defined as

$$S(0) = \int dt \langle \delta\hat{I}(t)\delta\hat{I}(0) + \delta\hat{I}(0)\delta\hat{I}(t)\rangle, \tag{9}$$

where $\delta\hat{I}(t)=\hat{I}(t)-\langle I\rangle$, $\hat{I}$ is the current operator, and $\langle I\rangle$ is the expectation value of the current. With the information of the counting statistics, the zero-frequency current noise is given by[25]

$$S(0) = 2e^2\ \mathrm{Tr}_{\mathrm{dot}}[2(\mathcal{J}_+ - \mathcal{J}_-)\mathcal{F}_\perp + (\mathcal{J}_+ + \mathcal{J}_-)\mathcal{F}_0], \tag{10}$$

where a new function $\mathcal{F}_\perp$ is defined as $\mathcal{F}_\perp=\mathcal{F}_1 -\mathcal{F}_0\ \mathrm{Tr}_{\mathrm{dot}}\ F_1$ which obeys the equation of motion

$$\frac{d}{dt}\mathcal{F}_\perp = \mathcal{L}\mathcal{F}_\perp + (\mathcal{J}_+ - \mathcal{J}_- - I)\mathcal{F}_0. \tag{11}$$

In Eq. (10), the prefactor 2 has been used to make the definition of the Fano factor in consistent with the traditional way as $F=S(0)/2eI$.[1]

III. RESULTS

In the following, we discuss shot noise in the sequential tunneling regime where the tunneling rate depends on the electron number on the dot. The dot level may have a finite spin splitting due to Zeeman effect of an external magnetic field. Without loss of generality, we may assume the energy levels are arranged as $\epsilon_\uparrow+\epsilon_\downarrow+U \geq \epsilon_\uparrow \geq \epsilon_\downarrow$ in the following discussions. For the sake of simplicity, we neglect the energy dependence of the correlated hybridization matrix elements $V^i_{l,k\sigma}=V^i_{l\sigma}$ $(i=1,2)$ in the tunneling Hamiltonian. Usually, the bandwidth of the lead is much larger than the energy scale considered in the transport. We may therefore approximately take the density of states of the leads ρ_l to be an energy-independent constant and characterize the hybridization between the states on the dot and the leads by the coupling strengths $\Gamma_i^{l\sigma}=\frac{2\pi}{\hbar}|V^i_{l\sigma}|^2\rho_l$. In the present study, we consider the coupling strength to be spin independent since the lead is not spin polarized.

First, we consider symmetric coupling scheme, i.e., $\Gamma_1 =\Gamma_1^{\mathrm{L}}=\Gamma_1^{\mathrm{R}}$ and $\Gamma_2=\Gamma_2^{\mathrm{L}}=\Gamma_2^{\mathrm{R}}$ are independent of the lead label. A symmetric bias voltage is taken so that the chemical potentials of the left and right leads are give by $\mu_{\mathrm{L}}=-\mu_{\mathrm{R}} =\frac{eV_{\mathrm{dc}}}{2}$. We have set the density of state of the leads to be unit so that the coupling strength are given by $\Gamma_i=2\pi|V^i|^2$. We set the temperature $T=0.01$, the energy levels $\epsilon_\uparrow=0.5$ and $\epsilon_\downarrow =0.2$ are higher than the equilibrium Fermi energy of the system. The Coulomb strength $U=1.0$. We fix V^1 which characterize the transition between empty state and the singly occupied state to be 0.1. The corresponding tunneling strength is then given by $\Gamma_1=0.02\pi$. We vary V^2 which describes the transition between the singly occupied state and doubly occupied state to show the correlated hybridization effect on noise properties. In Fig. 1, numerical results of the current, noise power and noise Fano factor are displayed as a function of the bias voltage for different values $\Gamma_1/\Gamma_2=1$, 4, and 16. For $\Gamma_1=\Gamma_2$, our results reproduce the noise Fano factor for a single quantum dot known in previous literatures.[14] At very small voltage, the current noise is dominated by the thermal noise which is nonvanishing at zero bias and leads to the divergent behavior of the Fano factor. With increasing the voltage bias, the current noise power and the Fano factor curves show several plateaus. The edge between two adjacent plateaus indicates the voltage bias where a new energy level becomes energetically allowed with increasing the bias voltage. In Fig. 1, the edges are smoothed by the finite temperature. When the coupling strengths depend on the electron number on the dot, i.e., $\Gamma_1 \neq \Gamma_2$, from

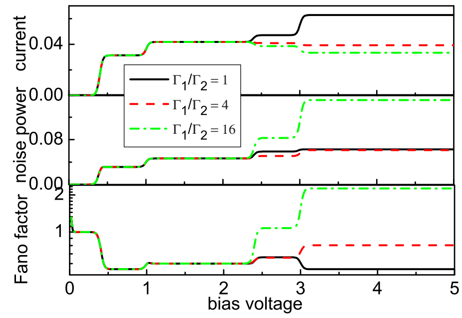

FIG. 1. (Color online) The current, noise power, and noise Fano factor of a quantum dot with symmetric coupling as a function of the bias voltage for different coupling strengths. The system parameters are $T=0.01$, $\epsilon_\downarrow=0.2$, $\epsilon_\uparrow=0.5$, and $U=1$. The coupling strength is given by $\Gamma_1=2\pi|V^1|^2$ for $V^1=0.1$. Different values of $\Gamma_2 =2\pi|V^2|^2$ are labeled in the figure. One can see that super-Poissonian noise appears when $\Gamma_1 \gg \Gamma_2$.

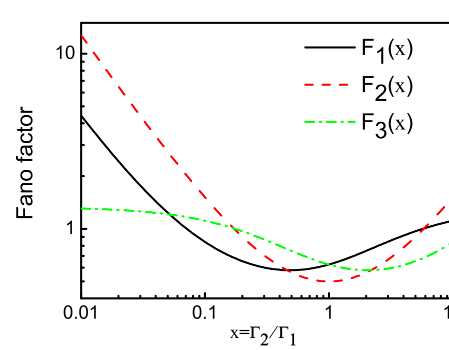

FIG. 2. (Color online) The noise Fano factor of a symmetric coupled quantum dot as a function of the parameter $x=\Gamma_2/\Gamma_1$ for the functions F_1, F_2, and F_3 displayed in Table I.

TABLE I. Noise Fano factor for the plateaus for different configuration of the energy levels of the dot and the chemical potentials in the leads. The coupling strengths of the two leads are symmetric. A minus (−) sign indicates that the thermal noise dominates since the dot energy levels are not in the transport window defined by the chemical potentials of the leads. The coupling strengths are Γ_1 and Γ_2. The parameter $x=\Gamma_2/\Gamma_1$.

	$\epsilon_\uparrow>\mu_L>\epsilon_\downarrow$	$\epsilon_\downarrow+U>\mu_L>\epsilon_\uparrow$	$\epsilon_\uparrow+U>\mu_L>\epsilon_\downarrow+U$	$\mu_L>\epsilon_\uparrow+U$
$\mu_R<\epsilon_\downarrow$	$\frac{1}{2}$	$\frac{5}{9}$	$F_1(x)=\frac{1+12x+15x^2+12x^3}{x(5+3x)^2}$	$F_2(x)=\frac{(1+x)^2}{8x}$
$\epsilon_\downarrow<\mu_R<\epsilon_\uparrow$	−	−	−	$F_3(x)=\frac{12+15x+12x^2+x^3}{(3+5x^2)^2}$
$\epsilon_\uparrow<\mu_R<\epsilon_\downarrow+U$	−	−	−	$\frac{5}{9}$
$\epsilon_\downarrow+U<\mu_R<\epsilon_\uparrow+U$	−	−	−	$\frac{1}{2}$

Fig. 2, one can see that the correlated hybridization can drastically change the transport properties at high voltages when electrons may be transferred via the doubly occupied state. This is due to the fact that at low bias voltage, the double occupancy is energetically forbidden. Electrons are transferred via the empty or the singly occupied state. No transition between the single occupancy and double occupancy is possible. When all the energy levels are available for the electron transport and $\Gamma_1 \gg \Gamma_2$, the tunneling rate of the transferred electron depends on the electron number on the dot. The doubly occupied dot can host the electrons much longer than a singly occupied dot before an electron tunnels out and contributes to the current. In this way, the competition of these two electron transfer rates gives rise to a bunching of the transferred electrons and leads to an enhanced noise. The mechanism presented in this study is different from the dynamical channel blockade discussed in Ref. 16 with spin-dependent couplings where the noise is enhanced when the voltage bias is not high enough to overcome the Coulomb-blockade effect. There, the noise is no longer sensitive to a lead polarization when the voltage is large enough to occupy the dot with two electrons. As a result, the super-Poissonian noise is suppressed to the sub-Poissonian in the high bias voltage regime.[16] This is in contrast to our results where the enhanced or super-Poissonian noise appears when the voltage is high enough to enable electron transfer via the doubly occupied state. Besides the noise Fano factor, Fig. 1 shows that the hybridized correlation can also modify the current and noise power behaviors. The current at high bias is reduced and a negative differential conductance (NDC) can be observed as shown in the upper panel of Fig. 1. We note that in the dynamical channel blockade regime, similar behaviors of NDC and super-Poissonian noise have also been discovered.[26] Such behavior may be helpful to identify the hybridized correlation by a direct measurement of the differential conductance.

In Fig. 1, we have used a set of specified parameters and the chemical potential of the right lead μ_R is always below the lowest energy level of the dot $\epsilon_\downarrow$. For more general situations, we present the analytical results for the Fano factor of a symmetric coupling dot in Table I. It contains all the possible Fano factor plateau values for the corresponding configurations of the energy levels relative to the chemical potential of the leads. For low bias without double occupancy on the dot, the Fano factor is always sub-Poissonian. For high bias voltage, the correlated hybridization plays a role in determining the noise properties. The Fano factor can be given as a function of the ratio $x=\Gamma_2/\Gamma_1$. These functions, F_1, F_2, and F_3 in Table I, are displayed in Fig. 2 where one can see that around $x=1$ or the coupling strength is not sensitive to the electron number on the dot, the Fano factor is sub-Poissonian. However, super-Poissonian noise is possible for $x \ll 1$. For the sake of comparison, although we physically expect $\Gamma_2<\Gamma_1$ or $x<1$ due to the Coulomb effect, we also displayed the Fano factor for $x>1$ which indicates that an electron on the dot can attract a second electron to the dot. For $x \gg 1$, the Fano factor can be enhanced to be larger than 1 since the competition of the two transfer processes can always lead to electron bunching. From Fig. 2, when both the singly and the doubly occupied states are available for electron transfer, one can see that the Fano factor F_1 and F_2 diverges with vanishing Γ_2, i.e., $x\to 0$. The physical picture of the giant Fano factor can be understood as following. After an electron jumps onto the dot, it spends a long time without electron transfer if the quantum dot is doubly occupied for $\Gamma_2 \ll \Gamma_1$. On the contrary, if the quantum dot is singly occupied, the electron spends a short time in the dot, jumps to the leads, and contributes to the current. Now, the dot is empty and ready for the next tunneling process. As a consequence, the giant Fano factor can be attributed to the switch between the fast and slow electron transfer processes in the transport.

In the above discussions, we focus on the symmetric coupling. However, for realistic devices, the coupling of the dot with the leads are not necessarily symmetric. The exact information on the coupling configuration between the dot and

TABLE II. Noise Fano factor of a quantum dot for different plateaus with asymmetric coupling for $\epsilon_\downarrow>\mu_R$. The parameters are defined as $x=\Gamma_L^2/\Gamma_L^1$, $y=\Gamma_R^2/\Gamma_R^1$, and $z=\Gamma_L^1/\Gamma_R^1$. The exact forms of F_4 and F_5 are presented in the text.

Transport regime	$\epsilon_\uparrow>\mu_L>\epsilon_\downarrow$	$\epsilon_\downarrow+U>\mu_L>\epsilon_\uparrow$	$\epsilon_\uparrow+U>\mu_L>\epsilon_\downarrow+U$	$\mu_L>\epsilon_\uparrow+U$
Fano factor	$\frac{1+z^2}{(1+z)^2}$	$\frac{1+4z^2}{(1+2z)^2}$	$F_4(x,y,z)$	$F_5(x,y,z)$

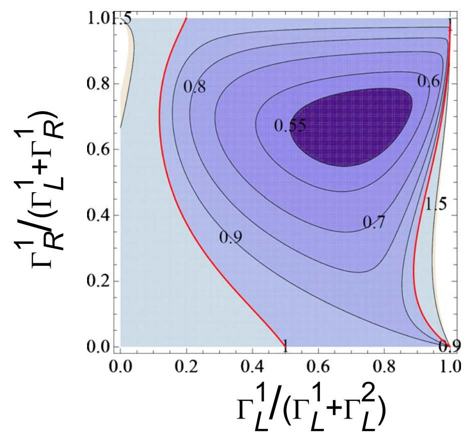

FIG. 3. (Color online) Contour plot of the noise Fano factor as a function of the ratios $(\Gamma_L^1/\Gamma_L^1+\Gamma_L^2)$ and $(\Gamma_R^1/\Gamma_L^1+\Gamma_R^1)$ for $\epsilon_\uparrow+U>\mu_L>\epsilon_\downarrow+U$ and $\epsilon_\downarrow>\mu_R$. We have assumed that $(\Gamma_L^1/\Gamma_L^1+\Gamma_L^2)=(\Gamma_R^1/\Gamma_R^1+\Gamma_R^2)$. The red lines (marked with 1) indicate that Fano factor is 1.

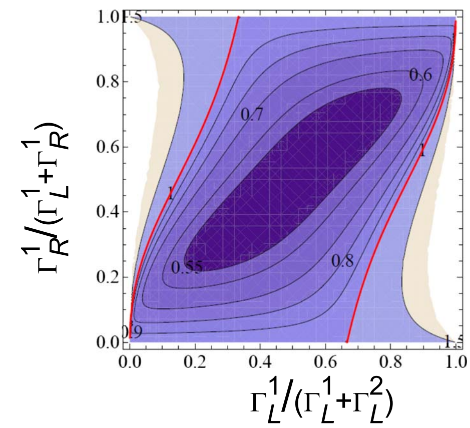

FIG. 4. (Color online) Contour plot of the noise Fano factor as a function of the ratios $(\Gamma_L^1/\Gamma_L^1+\Gamma_L^2)$ and $(\Gamma_R^1/\Gamma_L^1+\Gamma_R^1)$ for $\mu_L>\epsilon_\uparrow+U$ and $\epsilon_\downarrow>\mu_R$. We have assumed that $(\Gamma_L^1/\Gamma_L^1+\Gamma_L^2)=(\Gamma_R^1/\Gamma_R^1+\Gamma_R^2)$. The red lines (marked with 1) indicate that Fano factor is 1.

the leads remains a challenge in molecular electronics. Thielmann *et al.*[14] have proposed to determine the asymmetric coupling strengths by comparing the measured noise Fano factor and their analytical predications. In their studies, the hybridization is not correlated. Here, we focus on the noise behavior of a quantum dot with correlated hybridizations. In Table II, we present the analytical results for the noise Fano factor at different plateaus due to the chemical potential in the left lead μ_L while the chemical potential of the right lead is always below the lowest energy level of the dot, i.e., $\epsilon_\downarrow>\mu_R$. To characterize the asymmetric coupling, we introduce the following parameters as $x=\Gamma_L^2/\Gamma_L^1$, $y=\Gamma_R^2/\Gamma_R^1$, and $z=\Gamma_L^1/\Gamma_R^1$. In Table II, the functions F_4 and F_5 are given by

$$\begin{aligned} F_4(x,y,z) = 1 + 2z\{&xz^2[2+x(z-3)-2x^3z^2-x^2z(2z+5)] \\ &+xyz[-4(z+3)+x(1-14z-4z^2) \\ &+x^2z(1-2z+4z^2)]+y^2[x^2(z+4z^3) \\ &+x(2-8z)-8]\}/\{y(1+2z)(2+xz) \\ &+xz[1+z(x+3)+2xz^2]\}^2, \end{aligned}$$

$$F_5(x,y,z) = 1 + \frac{2z[(x-2)y^2+xz^2-2xyz(1+z)]}{(y+2yz+xz^2)^2}. \quad (12)$$

In Table II, we see that for low bias voltage ($\mu_L<\epsilon_\downarrow+U$), the noise Fano factor is always suppressed to be sub-Poissonian. The Fano factor is only determined by the ratio $z=\Gamma_L^1/\Gamma_R^1$ since the doubly occupied state is energetically forbidden. When the bias voltage is large enough to enable the doubly occupancy on the dot, the Fano factor becomes a nontrivial function of the ratios x, y, and z as defined above. As an example, we show the numerical results for the Fano factor F_4 and F_5 in Figs. 3 and 4, respectively, for the restriction $x=y$. In Figs. 3 and 4, we can see that for uncorrelated hybridization, $\Gamma_L^1/(\Gamma_L^1+\Gamma_L^2)=0.5$, the noise Fano factor is a function of $\Gamma_R^1/(\Gamma_L^1+\Gamma_R^1)$ which characterizes the asymmetric coupling strengths to the left and right leads. The Fano factor will not exceed 1, i.e., no super-Poissonian noise is possible for uncorrelated hybridization. However, for correlated hybridization, the super-Poissonian noise becomes possible. The two red lines indicate where the noise Fano factor can reach 1.

In general, the Fano factor is a nonmonotonic function of the three parameters x, y, and z due to the ratio of the coupling strengths as displayed in Table II. These analytical results combined with the experimental data of the current and noise may be used to identify the coupling configurations. More importantly, Table II indicates that the measured Fano factor can give an estimate of the correlated hybridization with $x\neq 1$ or $y\neq 1$ by comparing with the predications in Ref. 14.

IV. CONCLUSION

In conclusion, we have systematically investigated the noise properties of a single level quantum dot with correlated hybridization to the leads in the sequential tunneling regime. This correlated hybridization makes the electron tunneling become sensitive to the electron number on the dot. We present both analytical and numerical results indicating that the correlated coupling strengths can enhance the noise Fano factor at high bias voltage. In particular, when the coupling strengths depend strongly on the electron numbers on the dot, super-Poissonian noise can be expected due to the electron bunching of the transferred electrons when the quantum level may be doubly occupied. We also presented the analytical formulas for the Fano factor with correlated hybridization which can be used to make an estimate of the correlated hybridization effect on the coupling strengths in experiments.

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