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Noise characteristics of the Fano effect and the Fano–Kondo effect in triple quantum dots

T Tanamoto, Y Nishi and S Fujita

Advanced LSI laboratory, Corporate R&D Center, Toshiba Corporation, 1, Komukai Toshiba-cho, Saiwai-ku, Kawasaki 212-8582, Japan

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Abstract
We theoretically compare transport properties of the Fano–Kondo effect with those of the Fano effect, focusing on the effect of a two-level state in a triple quantum dot (QD) system. We analyze shot noise characteristics in the Fano–Kondo region at zero temperature, and discuss the effect of strong electronic correlation in QDs. We found that the modulation of the Fano dip is strongly affected by the on-site Coulomb interaction in QDs, and stronger Coulomb interaction (Fano–Kondo case) induces larger noise.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Quantum dot (QD) systems have attracted great interest for many years because they offer the possibility of controlling small numbers of electrons in various ways in order to understand many-body effects in electronic systems. Quantum correlation between localized states in QDs and free electrons in electrodes induces interesting phenomena such as the Fano effect and the Kondo effect. A number of important experiments have been carried out [1–9] and many theories have been proposed [10–14]. The Fano effect occurs as a result of quantum interference between a discrete energy state and a continuum state [1]. The Kondo effect is observed as a result of many-body correlations where internal spin degrees of freedom play an important role [2]. The Fano–Kondo effect, which is a combination of the Fano effect and the Kondo effect, can be observed when on-site Coulomb interaction in a QD is strong [4]. A T-shaped QD is considered to be suitable for facilitating discussion of the Fano–Kondo effect [4–6, 10–12].

Quantum and thermal fluctuations are the main obstacles to the observation of quantum correlations, and are estimated through current noise characteristics [15]. Shot noise is the zero frequency limit of the noise power spectrum and provides various items of information on correlation of electrons [12, 16–18]. For uncorrelated electrons, shot noise S_I shows the Schottky result $S_I = 2eI$, where e is an electronic charge and I is an average current. The ratio of shot noise S_I and full Poisson noise $2eI$, $\gamma \equiv S_I/(2eI)$, is called the Fano factor, and indicates important noise properties with regard to the quantum correlation.

Wu *et al* [12] calculated the noise properties of a T-shaped QD system and showed that shot noise strongly depends on the coupling strength between a side QD and a detector QD. As tunneling coupling between side QD and detector QD increases, γ quickly increases up to the Poisson value ($\gamma = 1$). López *et al* calculated shot noise of serially and laterally coupled double QD systems and showed that γ strongly depends on the coupling strength between QDs [16]. Thus, γ and shot noise reflect the coupling configuration of a QD system and provide important information about the electronic structure of the system.

In [14] we theoretically investigated conductance of the triple QD system depicted in figure 1, where QDs a and b are connected to electrodes through QD d. This triple QD system is considered to be in the same category as the T-shaped QD. When coupling between QD a and b is larger than that between QD b and d ($t_C > t_d$), this setup can be used as an apparatus for detecting a two-level system (QD a and QD b) by a QD d with electrodes. (We call QD d a detector QD.) In [14], we showed that the Fano dip in conductance is modulated for a slow detector (small tunneling rate of the detector) with no on-site Coulomb interaction in QD d. This is evidence of a bonding and antibonding state of the two-level system.

As mentioned above, noise properties strongly depend on the coupling strength and configurations of QDs. Thus, it is necessary to study the noise characteristics of the triple QD system. When the number of electrons is controlled, double QD a and b can be regarded as a charge qubit [19, 20] with a Fano interference detector QD. In the charge qubit system,

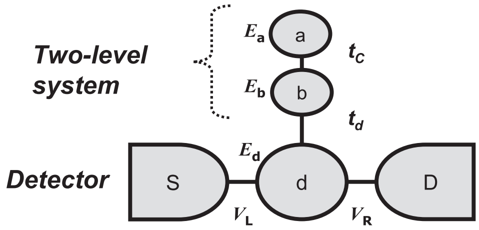

Figure 1. Schematic plot of a QD system. QDs a and b constitute a two-level system that is coupled to QD d only, which is connected to the electrodes.

noise characteristics are closely related to the decoherence mechanism. Therefore, the fundamental properties of the triple QD system should be clarified before investigating the more complicated charge qubit system.

Here we investigate the noise properties of the triple QD system from the viewpoint of electronic correlation in the QD system. In particular, we compare zero temperature shot noise properties of the Fano–Kondo effect with those of the Fano effect, in order to reveal the effect of strong on-site Coulomb interaction on the transport properties. We assume an infinite Coulomb interaction for QD a and b and no Coulomb interaction for QD d ($U_a = U_b = \infty$, $U_d = 0$) for the Fano–Kondo case. For the Fano case, we consider there is no on-site Coulomb interaction for all QDs ($U_a = U_b = U_d = 0$). This case of one degree of freedom [6, 21] is realized in large QDs. For simplicity, we assume there is a single energy level in each QD and that the two energy levels of QD a and QD b coincide and correspond to gate voltages applied to those QDs. We use the slave-boson mean-field theory (SBMFT) based on the Keldysh formalism in the nonequilibrium Green's function method. The formulation of the SBMFT is useful and is a good starting point for studying the transport properties of a strongly correlated QD system, although this method is usable in a region with a lower temperature (T) than the Kondo temperature T_K [22, 16].

2. Formulation

The Hamiltonian is constructed from electrode parts, QD parts, tunneling parts between QDs, and those between an electrode and a QD:

$$H = \sum_{\alpha=L,R}\sum_{k_\alpha,s} E_{k_\alpha} c^\dagger_{k_\alpha s} c_{k_\alpha s} + \sum_{\alpha_1=a,b,d}\sum_s E_{\alpha_1} f^\dagger_{\alpha_1 s} f_{\alpha_1 s} + \frac{t_C}{N}\sum_s (f^\dagger_{as} f_{bs} + f^\dagger_{bs} f_{as}) + \frac{t_d}{N}\sum_s (f^\dagger_{ds} f_{bs} + f^\dagger_{bs} f_{ds}) + \sum_{\alpha=L,R}\frac{V_\alpha}{\sqrt{N}}\sum_{k_\alpha,s}(c^\dagger_{k_\alpha s} f_{ds} + f^\dagger_{ds} c_{k_\alpha s}), \tag{1}$$

where E_{k_α} is the energy level for source ($\alpha = L$) and drain ($\alpha = R$) electrodes. E_a, E_b and E_d are energy levels for the three QDs, respectively. t_C, t_d and V_α are the tunneling coupling strength between QD a and QD b, that between QD b and QD d, and that between QD d and electrodes, respectively. $c_{k_\alpha s}$ and $f_{\alpha_1 s}$ are annihilation operators of the electrodes, and of the three QDs ($\alpha_1 = a, b, d$), respectively. s is the spin degree of freedom with spin degeneracy N; here we apply $N = 2$. In the slave-boson technique, a boson operator $b_{\alpha_1}(\alpha_1 = a, b)$ is introduced so that the fermion operator $f_{\alpha_1 s}$ is replaced by $f_{\alpha_1 s} \to b^\dagger_{\alpha_1} f_{\alpha_1 s}$ and $f^\dagger_{\alpha_1 s} \to f^\dagger_{\alpha_1 s} b_{\alpha_1}$. A constraint $\sum_s f^\dagger_{\alpha_1 s} f_{\alpha_1 s} + b^\dagger_{\alpha_1} b_{\alpha_1} = 1(\alpha_1 = a, b)$ is introduced in order to prohibit the double occupancy of electrons in QD a and QD b due to the infinite on-site Coulomb interaction. The mean-field Hamiltonian for the Fano–Kondo case is described by introducing a Lagrange multiplier λ_{α_1} as

$$H^{\mathrm{MF}} = \sum_{\alpha=L,R}\sum_{k_\alpha,s} E_{k_\alpha} c^\dagger_{k_\alpha s} c_{k_\alpha s} + \sum_{\alpha_1=a,b,d}\sum_s E_{\alpha_1} f^\dagger_{\alpha_1 s} f_{\alpha_1 s} + \frac{t_C}{N}\sum_s (f^\dagger_{as} b_a b^\dagger_b f_{bs} + f^\dagger_{bs} b_b b^\dagger_a f_{as}) + \frac{t_d}{N}\sum_s (f^\dagger_{ds} b^\dagger_b f_{bs} + f^\dagger_{bs} b_b f_{ds}) + \sum_{\alpha=L,R}\frac{V_\alpha}{\sqrt{N}}\sum_{k_\alpha,s}(c^\dagger_{k_\alpha s} f_{ds} + f^\dagger_{ds} c_{k_\alpha s}), + \sum_{\alpha_1=a,b}\lambda_{\alpha_1}\left(\sum_s f^\dagger_{\alpha_1 s} f_{\alpha_1 s} + b^\dagger_{\alpha_1} b_{\alpha_1} - 1\right). \tag{2}$$

Here, we take $z_{\alpha_1} \equiv b^\dagger_{\alpha_1} b_{\alpha_1}/2$ and $\tilde{E}_{\alpha_1} \equiv E_{\alpha_1} + \lambda_{\alpha_1}$ as mean-field parameters for QD a and QD b. The Hamiltonian for the Fano case is similar to H^{MF} except that $\lambda_a = \lambda_b = 0$ and $b_a = b_b = 1$ in equation (2).

In the Fano–Kondo effect, four self-consistent equations to determine mean-field parameters λ_{α_1} and b_{α_1} are derived by minimizing the free energy $\partial\langle H^{\mathrm{MF}}\rangle/\partial\lambda_{\alpha_1} = 0$ and $\partial\langle H^{\mathrm{MF}}\rangle/\partial b_{\alpha_1} = 0$ as

$$\tilde{t}_C \sum_s \langle f^\dagger_{bs} f_{as}\rangle + \lambda_a |b_a|^2 = 0, \tag{3}$$

$$\tilde{t}_C \sum_s \langle f^\dagger_{as} f_{bs}\rangle + \tilde{t}_d \sum_s \langle f^\dagger_{ds} f_{bs}\rangle + \lambda_b |b_b|^2 = 0, \tag{4}$$

$$\sum_s \langle f^\dagger_{\alpha_1 s} f_{\alpha_1 s}\rangle + |b_{\alpha_1}|^2 = 1, \qquad (\alpha_1 = a, b). \tag{5}$$

Current and noise formula are expressed by nonequilibrium Green's functions in the Keldysh formalism. In a nonequilibrium system, the state of the system at $t = +\infty$ is unknown and all quantities should be related to the state of the system at $t = -\infty$. This means that Green's functions depend not only on the times at which the operators act but also on the corresponding branch of the contour. Thus, we need types of Green's functions, such as $G^>$ and $G^<$, other than conventional time-ordered Green's function, and the relations between Green's functions are described as a matrix in the Keldysh formalism.

Equations (3)–(5) can be described by lesser Green's functions. For example, from definitions $G^<_{ab}(t, t') \equiv \mathrm{i}\langle f^\dagger_{bs}(t') f_{as}(t)\rangle$ and $G^<_{bd}(t, t') \equiv \mathrm{i}\langle f^\dagger_{ds}(t') f_{bs}(t)\rangle$, we have

$$\langle f^\dagger_{bs} f_{as}\rangle = -\mathrm{i}\int_{-\infty}^{\infty} G^<_{ab}(\omega)\,\mathrm{d}\omega/(2\pi), \tag{6}$$

$$\langle f^\dagger_{ds} f_{bs}\rangle = -\mathrm{i}\int_{-\infty}^{\infty} G^<_{bd}(\omega)\,\mathrm{d}\omega/(2\pi). \tag{7}$$

These lesser Green's functions can be derived from the retarded and advanced Green's functions by $G^< = (1 + G^r\Sigma^r)G_0^<(1 + G^a\Sigma^a) + G^r\Sigma^<G^a$, where $\Sigma^<$, Σ^r and Σ^a are the self-energy parts. The relations between the nonequilibrium Green's functions of different parts of the systems are obtained by applying analytic continuation rules to the equations of motion, which are derived from the above mean-field Hamiltonian [16]. For example, the retarded and advanced Green's functions for QDs are given as $G_{aa}^r(\omega) = [(\omega - \tilde{E}_b)B_r - |\tilde{t}_d|^2]/B_{00}$, $G_{bb}^r(\omega) = [(\omega - \tilde{E}_a)B_r]/B_{00}$ and $G_{dd}^r(\omega) = D_{ab}/B_{00}$ etc, where $D_{ab} \equiv (\omega - \tilde{E}_a)(\omega - \tilde{E}_b) - \tilde{t}_C^2$, $B_r \equiv \omega - \tilde{E}_d + \mathrm{i}\Gamma$ and $B_{00} \equiv D_{ab}B_r - (\omega - \tilde{E}_a)|\tilde{t}_d|^2$ with $\tilde{t}_C = t_C b_a b_b^\dagger/N$ and $\tilde{t}_d = t_d b_b^\dagger/N$. Here, $\Gamma_\alpha \equiv 2\pi\rho_\alpha(\mu_\alpha)|V_\alpha|^2$ is the tunneling rate between electrode α and QD d with a density of states (DOS) of $\rho_\alpha(\mu_\alpha)$ for each electrode at Fermi energy μ_α. $\Gamma \equiv (\Gamma_L + \Gamma_R)/2$, and we assume $\Gamma_L = \Gamma_R$. The lesser Green's function $G_{ba}^<(\omega)$ is given by

$$G_{ba}^<(\omega) = \frac{\mathrm{i}\tilde{t}_C^*|\tilde{t}_d|^2(\omega - \tilde{E}_a)}{B_{00}}[\Gamma_L f_L(\omega) + \Gamma_R f_R(\omega)]. \tag{8}$$

Here, $f_\alpha(\omega)$ is the Fermi distribution function expressed by $f_\alpha(\omega) \equiv [\exp((\omega - \mu_\alpha)/T) + 1]^{-1}$ where we set the symmetrical bias condition: $\mu_L = E_F - eV/2$ and $\mu_R = E_F + eV/2$.

Source current I_L is expressed as

$$I_L = (2e/h)\int_{-\infty}^{\infty} \mathrm{d}\omega T(\omega)(f_L(\omega) - f_R(\omega)), \tag{9}$$

where the transmission probability $T(\omega)$ is given as

$$T(\omega) = \frac{\Gamma_L\Gamma_R|D_{ab}|^2}{[D_{ab}(\omega - \tilde{E}_d) - (\omega - \tilde{E}_a)z_a t_d^2/2]^2 + \Gamma^2 D_{ab}^2/4} \tag{10}$$

(the denominator is B_{00}). Note that in the present case we can check that I_L and I_R are symmetric and satisfy current conservation. Conductance is given as $G = -\frac{2e}{h}\int \mathrm{d}\omega T(\omega)\frac{\partial f_L(\omega)}{\partial\omega}$. The transmission probability is related to a DOS of the detector QD $\rho_d(\omega) = -\mathrm{Im}G_{dd}^r(\omega)/\pi$ such as $T(\omega) = \frac{2\Gamma_L\Gamma_R}{\Gamma_L + \Gamma_R}\pi\rho_d(\omega)$, which means that we can discuss characteristics of a DOS similar to a transmission probability.

Current noise is calculated as a correlation function of current fluctuation as $S(t, t') = (1/2)[\langle\{\hat{I}_L(t), \hat{I}_L(t')\}\rangle - 2\langle\hat{I}_L(t)\rangle^2]$, where $\hat{I}_L(t) = (\mathrm{i}e/\hbar)\sum(V_L/\sqrt{N})[c_{k_L s}^\dagger(t)f_{ds}(t) -$ H.c.] is a current operator. The noise formula at $T = 0$ is derived similarly to that in [16], and we have

$$S(V) = \frac{4e^2}{h}\int_{-eV/2}^{eV/2} \mathrm{d}\omega T(\omega)(1 - T(\omega)). \tag{11}$$

The Fano factor γ at zero bias $V = 0$ is obtained by $\gamma = 1 - T(E_F)$, which indicates that shot noise is in the sub-Poissonian region ($\gamma \leqslant 1$). Similar to [14], we classify our triple QD system by the magnitude of t_C/t_d and Γ/t_d. The ratio t_C/t_d compares the internal coupling strength in a two-level system with that between the two-level system and the detector, and we regard the case where $t_C/t_d = 5$ as a strongly coupled two-level system and the case where $t_C/t_d = 1$ as a weakly coupled two-level system. If Γ/t_d is large, the electron that flows through QD d is so fast that the oscillation of an electron in the coupled QDs a and b cannot be detected. If Γ/t_d is small, the electron that flows through QD d makes it possible to observe evidence of bonding and antibonding states. We call a detector with large $\Gamma/t_d = 2$ a fast detector, and one with smaller $\Gamma/t_d = 0.4$ a slow detector. We assume that $D = 20t_d$, $|E_d| < 0.4t_d$, $\Gamma > 0.4t_d$ and $E_F = 0$ (D is a bandwidth). Then, we have the Kondo temperature $T_K \sim De^{-\pi|\tilde{E}_d - E_F|/\Gamma} \sim 1.6t_d$.

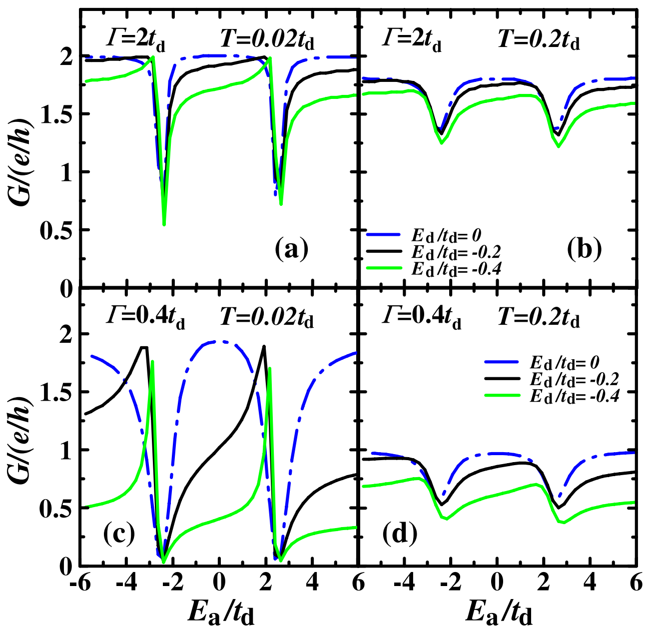

Figure 2. Conductance G as a function of an energy level of the two-level system $E_a(=E_b)$ with a strong coupling ($t_C/t_d = 5$) for the Fano case ($U_a = U_b = 0$): (a) $T/t_d = 0.02$ and (b) $T/t_d = 0.2$ for a fast detector ($\Gamma/t_d = 2$). (c) $T/t_d = 0.02$ and (d) $T/t_d = 0.2$ for a slow detector ($\Gamma/t_d = 0.4$). $E_F = 0$.

3. Numerical calculations

Here, we show numerical results of our triple QD system in terms of the Fano–Kondo effect and the Fano effect for a strong coupling case ($t_C/t_d = 5$). We have obtained similar results for a weak coupling case ($t_C/t_d = 1$), although the results for the weak coupling case show slightly complicated characteristics because the energy levels of weakly coupled triple QDs are closer to one another than those of strongly coupled QDs.

Before showing the results of the noise calculations, we show numerical results of the conductance and the current for the Fano case in figures 2 and 3. Figure 2 shows conductance of the Fano case as a function of E_a. A clear double-peak structure can be seen in every figure. This is in marked contrast to our previous results for the Fano–Kondo effects [14] where only a slow detector can detect modulation of a single Fano dip ($\Gamma = 0.4t_d$) at low temperature ($T = 0.02t_d$). The present clear double-peak structure is a direct result of the form of transmission probability $T(\omega)$, in particular, D_{ab} in the numerator of equation (10). These results show that the

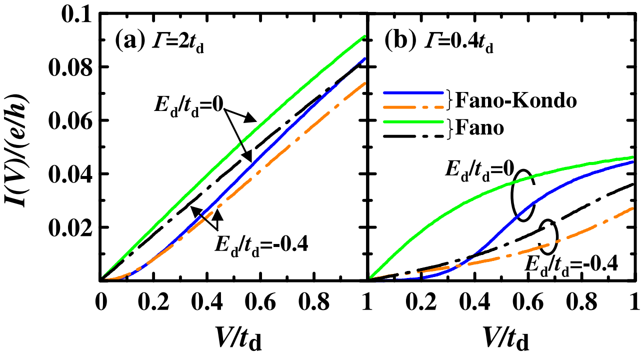

Figure 3. I–V characteristics for a strong coupling ($t_C/t_d = 5$) at $T = 0$: (a) Fast detector ($\Gamma/t_d = 2$) and (b) slow detector ($\Gamma/t_d = 0.4$). $E_a = E_b = 0 = E_{\mathrm{F}}$.

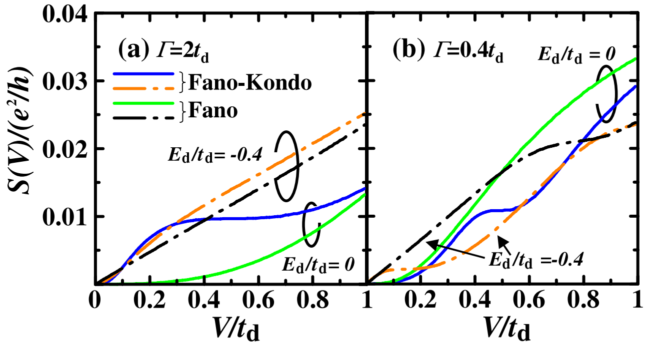

Figure 4. Shot noise as a function of bias voltage for a strong coupling ($t_C/t_d = 5$). (a) Fast detector ($\Gamma/t_d = 2$). (b) Slow detector ($\Gamma/t_d = 0.4$). $T = 0$. $E_a = E_b = 0 = E_{\mathrm{F}}$.

Kondo effect, a spin exchange effect, greatly changes the Fano effect. Dip structure is the largest for a slow detector at low temperature (figure 2 (c)). The asymmetry of the dip structure for $E_d \neq 0$ can also be understood from equation (10). Because $G \propto T(\omega \sim 0)$ at low temperature and we set $E_a = E_b$, we have $D_{ab}(\omega = 0) = \tilde{E}_a^2 - \tilde{t}_C^2$. Thus, for $E_d = 0$, both the numerator and the denominator of $T(\omega)$ are symmetric for E_a. However, when $E_d \neq 0$, the denominator deviates from symmetric form because of the $D_{ab}(\omega - E_d)$ in the expression. Since the resonant case ($E_d = E_a = E_b$) strongly reflects electronic correlations among QDs, a clearer difference between the Fano effect and the Fano–Kondo effect is evident, as shown in the following.

Figure 3 shows current–voltage (I–V) characteristics at $T = 0$. All currents look similar for a fast detector (a) in the case of both the Fano effect and the Fano–Kondo effect. This indicates that a fast detector is less sensitive to quantum states of a QD system than a slow detector. The current of the Fano–Kondo effect is always less than that of the Fano effect. This indicates that the current path from the source to the drain via the two-level system is suppressed by the Kondo effect because of the on-site Coulomb interaction.

Figure 4 shows shot noise characteristics as a function of bias voltage across the detector QD. E_d dependence is simpler for a fast detector (a). This is because a fast detector is more sensitive to the energy level of a detector QD d than to energy levels in two-level system. Shot noise of a slow detector reflects internal states of a two-level system.

Although the magnitude of current for a fast detector is larger than that for a slow detector (figure 3), the magnitude of shot noise for a fast detector is of the same order as that of a slow detector (figure 4). Thus, γ for a slow detector is relatively larger than that for a fast detector, as shown in figure 5. This is because of the stronger coupling of flowing electrons with two-level states in a slow detector. Strong nonlinearity around $V = 0$ is considered to reflect the resonant state of $E_d = 0$ ($= E_a = E_b = \mu_L = \mu_R$) and the dip of $E_d/t_d = -0.4$ in figure 5 (b) comes from the shift of resonant energy level. In both a fast detector and a slow detector, γ for the Fano–Kondo case is larger than that for the Fano case. This indicates that stronger electronic correlation induces more noise.

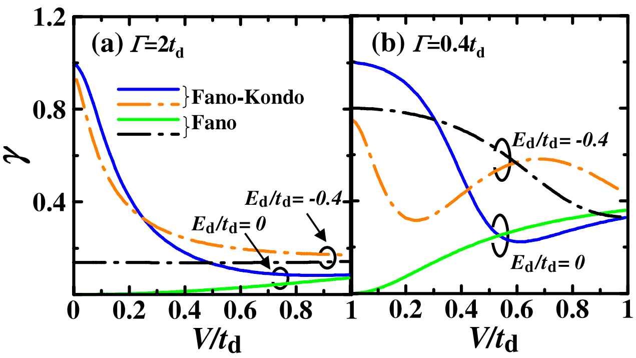

Figure 5. Fano factor γ as a function of bias voltage. $E_a = E_b = 0 = E_{\mathrm{F}}$ for a strong coupling ($t_C/t_d = 5$). (a) Fast detector ($\Gamma/t_d = 2$) and (b) slow detector ($\Gamma/t_d = 0.4$).

4. Discussion

We have shown that the slower detector, which is found to be preferable for detecting the electronic structure of a two-level state, induces more noise than a fast detector. This means that acquisition of detailed information about a two-level state induces more noise or a larger Fano factor. We also found that the Fano factor for strong on-site Coulomb interaction (the Fano–Kondo case) is larger than that for no Coulomb interaction (the Fano case). Thus, we can infer the relative strength of on-site Coulomb interactions in the two-level state by measuring the noise properties. As discussed in [14], when the number of electrons in the two-level state is controlled, a double QD a and b can be regarded as a charge qubit [19, 20]. This charge qubit condition would be realizable, for example, by forming smaller and closely coupled QDs, such that two electrons are not permitted into the QDs because of their mutually repulsive Coulomb interaction. Thus, if we consider the effect of other causes of noise such as phonons, more elaborate control of the measurement for a charge qubit system will be necessary.

Kobayashi *et al* [5] discussed the rapid smearing out of the dip structure with increasing temperature owing to the thermal broadening of the resonant level. Although we assume one energy level in each QD at $T = 0$, if we take more energy levels in each QD into consideration it is possible that the

Fano dip would smear out rapidly with increasing temperature because of the mixing of those energy levels, in addition to the thermal broadening.

We have used the SBMFT to describe quantum correlation between electrons in discrete energy levels and free electrons in electrodes. The essential part of the Kondo problem lies in the interaction between a discrete energy system (QD) that has finite degrees of freedom and a continuum energy system (electrode) that has infinite degrees of freedom. In general, the latter is more difficult to handle than the former. Read and Newns [23] confirmed the validity of the SBMFT for a single QD case. In our model, one extra QD that has finite degrees of freedom is simply added to the standard T-shaped QD system. This means that we add two additional spin degrees of freedom to the case of [23]. Thus, we think that the mean-field theory qualitatively remains valid for the triple QD system, although we should investigate the exact range of this validity in the future.

5. Conclusion

Focusing on the two-level state in a triple QD system, we intensively studied the transport properties through the Fano effect and the Fano–Kondo effect in the range of the SBMFT. The peak structure in the DOS of the Fano effect is greatly modulated from that of the Fano–Kondo effect. We analyzed the shot noise properties, and showed that, depending on the coupling strength among the triple QDs, modulation of noise and the Fano factor for a slower detector are larger than those for a faster detector. We also found that stronger Coulomb interaction (Fano–Kondo case) induces larger noise. These indicate that although a slower detector is better than a faster detector for reading out the quantum state of the two-level system, it is necessary to find optimal couplings of QDs and optimal operation parameters by paying attention to the trade-off that detailed reading out of a two-level state is inclined to enhance the noise of the system.

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