Fano resonance in electron transport through parallel double quantum dots in the Kondo regime

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Electron transport through parallel double quantum dot system with interdot tunneling and strong on-site Coulomb interaction is studied in the Kondo regime by using the finite-U slave boson technique. For a system of quantum dots with degenerate energy levels, the linear conductance reaches the unitary limit $(2e^2/h)$ due to the Kondo effect at low temperature when interdot tunneling is absent. As the interdot tunneling amplitude increases, the conductance decreases in the singly occupied regime and a conductance plateau structure appears. In the crossover to the doubly occupied regime, the conductance increases to reach a maximum value of $G=2e^2/h$. For parallel double dots with different energy levels, we show that the interference effect plays an important role in electron transport. The linear conductance is shown to have an asymmetric line shape of the Fano resonance as a function of gate voltage.

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I. INTRODUCTION

Due to the wave nature of electrons and the confined geometries in mesoscopic systems, the interplay between interference and interaction becomes one of the central issues in mesoscopic physics. Preservation of quantum coherence in electron transport through an interacting regime has been manifested in the observed Kondo effect in semiconductor quantum dot systems,[1] and more explicitly in the conductance Aharonov-Bohm (AB) oscillation in the interference experiment with a quantum dot embedded in one arm of an AB interferometer.[2] Recently, the Fano resonance has attracted much research interest as another important interference effect in mesoscopic systems. The Fano effect was first proposed as a result of the interference between resonant and nonresonant processes in the field of atomic physics.[3] It is found to be a ubiquitous phenomenon observed in a large variety of experiments, including neutron scattering, atomic photoionization, Raman scattering, and optical absorption. There has been recent progress in the observation of the Fano resonances in condensed matter systems, including an impurity atom on a metal surface,[4] single-electron transistors,[5,6] and quantum dots in an AB interferometer.[7,8]

In this paper we show that the Fano effect, which can be manifested by gate voltage dependence of the linear conductance, is also important for electron transport through double quantum dots (DQDs) in parallel configuration. For electron tunneling through quantum dots, it is well known that the strong on-site Coulomb interaction leads to the Kondo effect at low temperatures, so that the coexistence of the Fano resonance with the Kondo effect is expected to yield interesting transport phenomena. Electron transport through DQDs with series[9] and parallel[10] configurations has been realized in experiments, through which studies on the molecular states of the double dots and also the interference effect are carried out. Most of theoretical studies[11–14] are devoted to electron transport through DQDs connected in series, while relatively little attention is paid to the parallel configuration case, especially for the system in the Kondo regime.[13] For the DQD system with a parallel coupling, the interference effect should play an important role. Thus, in order to understand the role of the Fano effect, it is essential to take into account the coherence of the whole system. A model of the electron transport through a closed AB interferometer containing two single-level quantum dots, which assumes the electron transport through quantum dots is in full coherence, has been investigated in Ref. 15. Interesting phenomena, such as flux-dependent level attraction and interference-induced suppression of conductance, have been found. However, the effects of on-site Coulomb interaction and the interdot tunneling have not been considered. Ghost Fano resonance has also been observed in the study of electron transport through parallel DQDs with interdot tunneling but no on-site Coulomb interaction.[16]

In this paper we shall investigate electron transport through parallel DQDs (schematically plotted in Fig. 1) with interdot tunneling and on-site Coulomb interaction using the finite-U slave boson mean field theory (SBMFT) approach developed by Kotliar and Ruckenstein.[17] This formulation reproduces the results derived from the well known Gutzwiller variation wave function at zero temperature, and therefore is believed to be a powerful tool to study strong correlation effect of electron systems. The finite-U SBMFT has already been applied to investigate electron transport through a single quantum dot,[18], DQDs in series in the Kondo regime[19] and persistent current in a mesoscopic ring,[20] and was found to give good quantitative results for the Kondo effect on linear conductance.

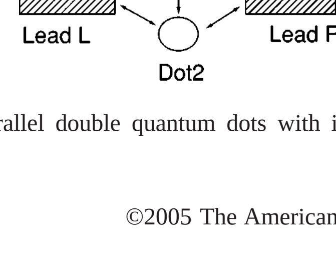

FIG. 1. Parallel double quantum dots with interdot tunneling t_c.

II. THE FINITE-*U* SLAVE BOSON MEAN FIELD THEORY OF PARALLEL COUPLED DQDS

Electron transport through parallel DQDs with interdot tunneling and on-site Coulomb interation can be described by the following Anderson impurity model:

$$H = \sum_{k\eta\sigma} \epsilon_{k\eta\sigma} c_{k\eta\sigma}^{\dagger} c_{k\eta\sigma} + \sum_{i\sigma} \epsilon_i d_{i\sigma}^{\dagger} d_{i\sigma} + \sum_i U n_{di\uparrow} n_{di\downarrow} + t_c \sum_{\sigma} (d_{1\sigma}^{\dagger} d_{2\sigma} + d_{2\sigma}^{\dagger} d_{1\sigma}) + \sum_{k\eta\sigma i} (v_{\eta i} d_{i\sigma}^{\dagger} c_{k\eta\sigma} + \text{H.c.}), \quad (1)$$

where $c_{k\eta\sigma}(c_{k\eta\sigma}^{\dagger})$ denote annihilation (creation) operators for electrons in the leads $(\eta = L, R)$, and $d_{i\sigma}(d_{i\sigma}^{\dagger})$ those of the single-level state in the ith dot $(i=1,2)$. U is the intradot Coulomb interaction between electrons, t_c is the interdot tunnel coupling, and $v_{\eta i}$ is the tunnel matrix element between lead η and dot i. We consider the symmetric coupling case with $\Gamma_i^L = \Gamma_i^R = \Gamma_i$, where $\Gamma_i^{\eta} = 2\pi \Sigma_k |v_{\eta i}|^2 \delta(\omega - \epsilon_{k\eta\sigma})$ is the hybridization strength between the ith dot and the lead η.

In the finite-U slave boson approach,[17,18] a set of auxiliary bosons e_i, $p_{i\sigma}$, d_i are introduced for each dot, which act as projection operators onto the empty, singly occupied (with spin up and spin down), and doubly occupied electron states on the quantum dot, respectively. The fermion operators $d_{i\sigma}$ are replaced by $d_{i\sigma} \to f_{i\sigma} z_{i\sigma}$, with $z_{i\sigma} = e_i^{\dagger} p_{i\sigma} + p_{i\bar{\sigma}}^{\dagger} d_i$. In order to eliminate unphysical states, the following constraint conditions are imposed: $\Sigma_{\sigma} p_{i\sigma}^{\dagger} p_{i\sigma} + e_i^{\dagger} e_i + d_i^{\dagger} d_i = 1$, and $f_{i\sigma}^{\dagger} f_{i\sigma} = p_{i\sigma}^{\dagger} p_{i\sigma} + d_i^{\dagger} d_i (\sigma = \uparrow, \downarrow)$. Therefore, the Hamiltonian (1) can be rewritten as the following effective Hamiltonian in terms of the auxiliary boson e_i, $p_{i\sigma}$, d_i, and the pesudo-fermion operators $f_{i\sigma}$:

$$H_{eff} = \sum_{k\eta\sigma} \epsilon_{k\eta\sigma} c_{k\eta\sigma}^{\dagger} c_{k\eta\sigma} + \sum_{i\sigma} \epsilon_i f_{i\sigma}^{\dagger} f_{i\sigma} + \sum_i U d_i^{\dagger} d_i + t_c \sum_{\sigma} (z_{1\sigma}^{\dagger} f_{1\sigma}^{\dagger} f_{2\sigma} z_{2\sigma} + \text{H.c.}) + \sum_{k\eta\sigma i} (v_{\eta i} z_{i\sigma}^{\dagger} f_{i\sigma}^{\dagger} c_{k\eta\sigma} + \text{H.c.}) + \sum_i \lambda_i^{(1)} \left(\sum_{\sigma} p_{i\sigma}^{\dagger} p_{i\sigma} + e_i^{\dagger} e_i + d_i^{\dagger} d_i - 1 \right) + \sum_{i\sigma} \lambda_{i\sigma}^{(2)} (f_{i\sigma}^{\dagger} f_{i\sigma} - p_{i\sigma}^{\dagger} p_{i\sigma} - d_i^{\dagger} d_i), \quad (2)$$

where the constraints are incorporated by the Lagrange multipliers $\lambda_i^{(1)}$ and $\lambda_{i\sigma}^{(2)}$. The first constraint can be interpreted as a completeness relation of the Hilbert space in each dot, and the second one equates the two ways of counting the fermion occupancy of a given spin.[17] In the framework of the finite-U SBMFT, the slave boson operators e_i, $p_{i\sigma}$, d_i, and the parameter z_{σ} are replaced by real c numbers. In this paper, we only consider the spin degenerate case without external magnetic field, so that all parameters are independent of the electron spin. We can neglect the spin index σ in the parameters hereafter. Thus in the mean field approximation, the effective Hamiltonian is given as

$$H_{eff}^{MF} = = \sum_{k\eta\sigma} \epsilon_{k\eta} c_{k\eta\sigma}^{\dagger} c_{k\eta\sigma} + \sum_{i\sigma} \tilde{\epsilon}_i f_{i\sigma}^{\dagger} f_{i\sigma} + \tilde{t}_c \sum_{\sigma} (f_{1\sigma}^{\dagger} f_{2\sigma} + \text{H.c.}) + \sum_{k\eta\sigma i} (\tilde{v}_{\eta i} f_{i\sigma}^{\dagger} c_{k\eta\sigma} + \text{H.c.}) + E_g, \quad (3)$$

where $\tilde{t}_c = t_c z_1 z_2$ and $\tilde{v}_{\eta i} = v_{\eta i} z_i$ represent the renormalized tunnel coupling between quantum dots and the renormalized tunnel amplitude between ith quantum dot and the lead η, respectively. z_1 and z_2 can be regarded as the wave function renormalization factors in the quantum dots. $\tilde{\epsilon}_i = \epsilon_i + \lambda_i^{(2)}$ is the renormalized dot energy level and $E_g = \Sigma_i [\lambda_i^{(1)} (2p_i^2 + e_i^2 + d_i^2 - 1) - 2\lambda_i^{(2)} (p_i^2 + d_i^2) + U d_i^2]$ is an energy constant.

Within this mean field effective Hamiltonian (3), the current formula through the DQDs is given as[15]

$$I = \frac{e}{h} \sum_{\sigma} \int d\omega [n_L(\omega) - n_R(\omega)] T(\omega), \quad (4)$$

where the transmission probability $T(\omega) = Tr[G^a(\omega) \tilde{\Gamma}^R G^r(\omega) \tilde{\Gamma}^L]$, and

$$\tilde{\Gamma}^L = \tilde{\Gamma}^R = \begin{pmatrix} \tilde{\Gamma}_1 & \sqrt{\tilde{\Gamma}_1 \tilde{\Gamma}_2} \\ \sqrt{\tilde{\Gamma}_1 \tilde{\Gamma}_2} & \tilde{\Gamma}_2 \end{pmatrix},$$

with $\tilde{\Gamma}_i = z_i^2 \Gamma_i$. The retarded/advanced Green's functions (GF) $G^{r/a}(\omega)$ have 2×2 matrix structures, which account for the double dot structure of the system. The matrix elements of the retarded GF are defined in time space as $G_{ij}^r(t-t') = -i\theta(t-t') \langle \{ f_{i\sigma}(t), f_{j\sigma}^{+}(t') \} \rangle$. By applying the equation of motion method,[21] one can obtain the retarded GF explicitly as

$$G^r(\omega) = \begin{pmatrix} \omega - \tilde{\epsilon}_1 + i\tilde{\Gamma}_1 & -\tilde{t}_c + i\sqrt{\tilde{\Gamma}_1 \tilde{\Gamma}_2} \\ -\tilde{t}_c + i\sqrt{\tilde{\Gamma}_1 \tilde{\Gamma}_2} & \omega - \tilde{\epsilon}_2 + i\tilde{\Gamma}_2 \end{pmatrix}^{-1}, \quad (5)$$

The advanced GF is given by $G^a(\omega) = [G^r(\omega)]^{\dagger}$. Substituting the retarded/advanced GF to the formula of transmission probability, one obtains

$$T(\omega) = \frac{[\tilde{\Gamma}_1(\omega - \tilde{\epsilon}_2) + \tilde{\Gamma}_2(\omega - \tilde{\epsilon}_1) + 2\tilde{t}_c \sqrt{\tilde{\Gamma}_1 \tilde{\Gamma}_2}]^2}{[(\omega - \tilde{\epsilon}_1)(\omega - \tilde{\epsilon}_2) - \tilde{t}_c^2]^2 + [\tilde{\Gamma}_1(\omega - \tilde{\epsilon}_2) + \tilde{\Gamma}_2(\omega - \tilde{\epsilon}_1) + 2\tilde{t}_c \sqrt{\tilde{\Gamma}_1 \tilde{\Gamma}_2}]^2}. \quad (6)$$

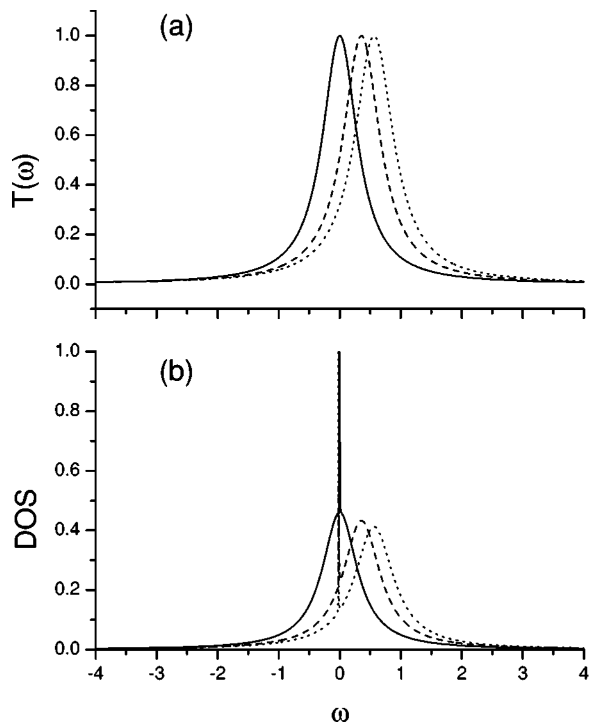

FIG. 2. (a) The transmission probability $T(\omega)$ and (b) the local density of state for the system with two identical quantum dots. Parameters used are $U=4.0$, $\Gamma^L=\Gamma^R=1.0$, and $\epsilon_d=-2.0$. The interdot tunnel coupling t_c are 0.0 (solid line), 0.5 (dashed line), and 1.0 (dotted line). (We take the energy unit as $\Gamma=1$, and $\omega=0$ corresponds to the Fermi energy of the leads.)

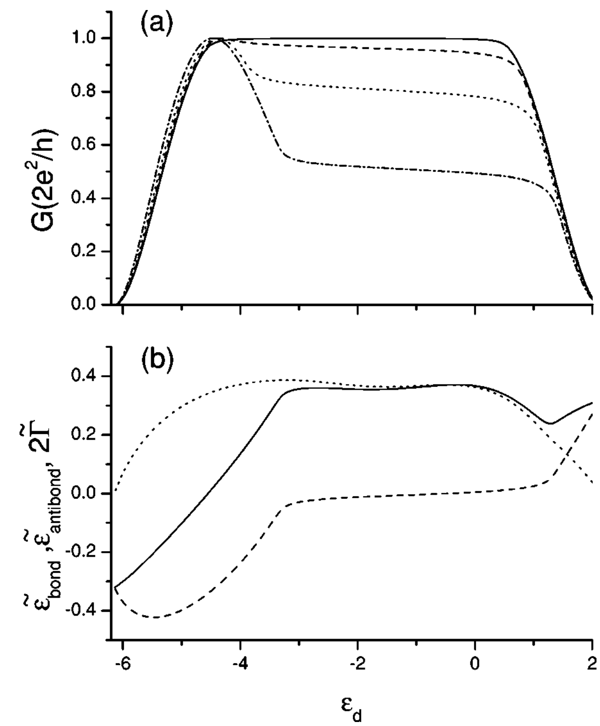

FIG. 3. (a)The linear conductance as a function of the dot level at zero temperature. Parameters used are $U=4.0$, and $\Gamma^L=\Gamma^R=1.0$, and the interdot tunneling $t_c=0.0$ (solid line), 0.2 (dashed line), 0.5 (dotted line), and 1.0 (dash-dotted line). (b) The bonding state energy $\tilde{\epsilon}_{bond}$ (solid line), the antibonding state energy $\tilde{\epsilon}_{antibond}$ (dashed line), and the level broadening $2\tilde{\Gamma}$ of the bonding state (dotted line) for $t_c=1.0$.

The conductance G at the absolute zero temperature in the limit of zero bias voltage is given by

$$G = \left.\frac{dI}{dV}\right|_{V=0} = \frac{2e^2}{h}T(\omega=0).$$

It is noticed that the formula for the transmission probability and conductance is equivalent to that of the transport through noninteracting DQD system, except that, in this case, the dot levels $\tilde{\epsilon}_i$, the coupling strength $\tilde{\Gamma}_i$, and $\tilde{t}_c$ are renormalized. Therefore, electron transport through DQDs is characterized by the parameters $\tilde{\epsilon}_i$, $\tilde{\Gamma}_i$, and $\tilde{t}_c$. However, it should be noted that $\tilde{\epsilon}_i$, $\tilde{\Gamma}_i$, and $\tilde{t}_c$ show strong dependence on the gate voltage applied to the quantum dots; hence, the result of linear conductance is quite different from the noninteracting model. In the spin degenerate case, we have ten unknown parameters e_i, p_i, d_i, $\lambda_i^{(1)}$, $\lambda_i^{(2)}(i=1,2)$ in total to determine. From the constraints and the equation of motion of the slave boson operators in the effective Hamiltonian, we obtain one set of self-consistent equations, which is a straightforward generalized form of the single dot case, as discussed in Ref. 18. In this set of equations, the distribution GF of the quantum dots $G_{ij}^<(t-t')=i\langle f_{j\sigma}^\dagger(t')f_{i\sigma}(t)\rangle$ is involved, and its Fourier transform is given by $G^<(\omega)=iG^r(\omega)[\tilde{\Gamma}^L n_L(\omega)+\tilde{\Gamma}^R n_R(\omega)]G^a(\omega)$. We have solved the self-consistent equations numerically.

In the following, we discuss the result of our calculation. First, we consider two identical QDs case: $\epsilon_1=\epsilon_2=\epsilon_d$ and $\Gamma_1=\Gamma_2=\Gamma$. Following Eq. (5), the transmission probability in this case has a Breit-Wigner resonance form, given by

$$T(\omega) = \frac{4\tilde{\Gamma}^2}{(\omega-\tilde{\epsilon}_d-\tilde{t}_c)^2+4\tilde{\Gamma}^2}. \tag{7}$$

The retarded GF on each dot is also explicitly given as

$$G_{ii}^r(\omega) = \frac{1}{2}\left[\frac{1}{\omega-(\tilde{\epsilon}_d-\tilde{t}_c)+0^+} + \frac{1}{\omega-(\tilde{\epsilon}_d+\tilde{t}_c)+2i\tilde{\Gamma}}\right]. \tag{8}$$

The spectral density in the ith QD follows from the relation $\rho_i(\omega)=-\mathrm{Im}\,G_{ii}^r(\omega+i0^+)/\pi$. It shows that the spectral density is the sum of one Lorentizan with the peak position located at $\tilde{\epsilon}_{bond}=\tilde{\epsilon}_d+\tilde{t}_c$ and one Dirac δ peak at $\tilde{\epsilon}_{antibond}=\tilde{\epsilon}_d-\tilde{t}_c$, where $\tilde{\epsilon}_{bond}$ and $\tilde{\epsilon}_{antibond}$ correspond to energy of the bonding and the antibonding state of quantum dots, respectively. The bonding state of DQDs has level broadening $2\tilde{\Gamma}$ due to its coupling with the leads. The δ peak structure indicates that the antibonding state is totally decoupled from the leads. Therefore, the electrons transport only through the channel of the bonding state, which gives a Breit-Wigner resonance form in the transmission.

In Fig. 2 we study the effect of interdot tunneling on the

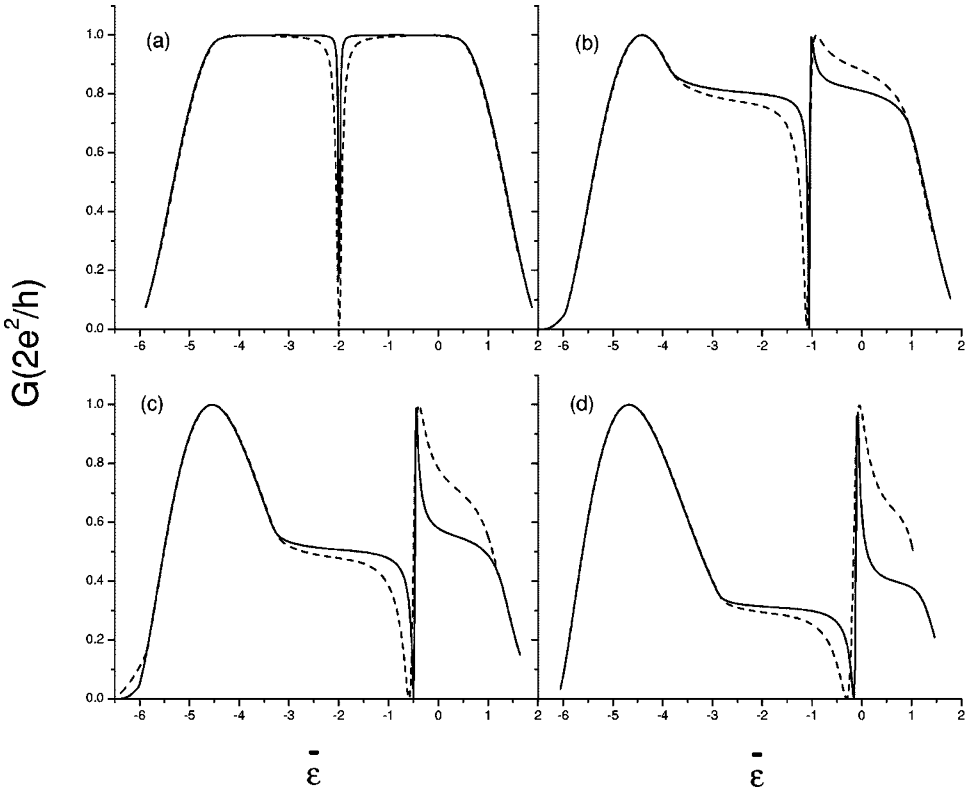

FIG. 4. The linear conductance at zero temperature for parallel double quantum dots with different energy levels. Here we define $\overline{\epsilon}=(\epsilon_1+\epsilon_2)/2$ and $\Delta\epsilon=\epsilon_1-\epsilon_2$. Parameters used are $U=4.0$, and $\Gamma^L=\Gamma^R=1.0$. The energy level differences are $\Delta\epsilon=0.5$ (solid line), 1.0 (dashed line). (a), (b), (c), and (d) correspond to the interdot tunneling $t_c=0.0,0.5,1.0,1.5$, respectively.

transmission probability and the local density of state of the QD in the singly occupied regime. Here we take the hybridization strength as the energy unit $\Gamma=1$, and $\epsilon_d=-2$. Figure 2(a) shows that with increasing the interdot coupling t_c, the line shape of Breit-Wigner resonance of transmission is preserved, while the center of the resonance shifts to higher energy. Thus, the value of transmission probability at zero frequency $T(\omega=0)$ decreases, which, in turn, results in suppression of the linear conductance at zero bias voltage. For the local density of state shown in Fig. 2(b), we see that the antibonding state energy is always nearby the Fermi energy of the lead, whereas the center of spectral density contributed from the bonding state shifts to higher energy along with increasing t_c.

The linear conductance G as a function of the energy level ϵ_d of the QD at zero temperature is plotted in Fig. 3(a) for several values of interdot tunneling t_c. When there is no direct tunneling between two dots ($t_c=0$), the conductance reaches the unitary limit ($G=2e^2/h$) in the Kondo regime, as expected. Upon increasing tunnel coupling t_c, the conductance becomes suppressed and forms a plateau structure in the regime of the singly occupied QD state. When QDs cross over to the doubly occupied state regime, the conductance increases to the maximum value $G=2e^2/h$. The line shape of the linear conductance can be explained from the gate voltage dependence of the spectral density and the zero frequency transmission of the QD. In Fig. 3(b) we plot the bonding state energy $\tilde{\epsilon}_{bond}$, the antibonding state energy $\tilde{\epsilon}_{antibond}$, and the level broadening $2\tilde{\Gamma}$ as functions of ϵ_d with $t_c=1$. One can see that in the singly occupied regime with decreasing ϵ_d, the antibonding state energy $\tilde{\epsilon}_{antibond}$, is fixed around the Fermi energy of the leads ($\epsilon_F=0$). This indicates that $\tilde{\epsilon}_d\approx\tilde{t}_c$, and the conductance $G/(2e^2/h)=4\tilde{\Gamma}^2/[(\tilde{\epsilon}_d+\tilde{t}_c)^2+4\tilde{\Gamma}^2]\approx 1/(\tilde{t}_c^2/\tilde{\Gamma}^2+1)$. For this identical quantum dot case, the value of $\tilde{t}_c^2/\tilde{\Gamma}^2$ is given by its bare value $\tilde{t}_c^2/\tilde{\Gamma}^2=t_c^2/\Gamma^2$. Consequently, the conductance shows a plateau structure and the ratio of t_c/Γ determines the height of the conductance plateau. This is in agreement with the value of conductance at the plateau structure for different t_c as shown in Fig. 3(a). With ϵ_d deceasing further, the QD state crosses over from the singly occupied to the doubly occupied regime, and $\tilde{\epsilon}_{bond}$ goes through from positive value to negative value. At the point $\tilde{\epsilon}_{bond}=\tilde{\epsilon}_d+\tilde{t}_c=0$, we obtain the maximum conductance $G=2e^2/h$. Further down, the level broadening $2\tilde{\Gamma}$ approaches zero and the DQD will be totally decoupled from the leads; thus, the conductance becomes zero.

Next, we consider DQD system with different dot levels, $\epsilon_1\neq\epsilon_2$, and define $\overline{\epsilon}=(\epsilon_1+\epsilon_2)/2$ and $\Delta\epsilon=\epsilon_1-\epsilon_2$. For the sake of simplicity, we still assume $\Gamma_1=\Gamma_2=\Gamma$. It is noted that in this case the renormalized hybridization strength $\tilde{\Gamma}_1\neq\tilde{\Gamma}_2$. In Fig. 4 we plot the linear conductance as a function of average energy of the dot levels. The parameters $\Delta\epsilon=0.5,1.0$ and $t_c=0.0,0.5,1.0,1.5$ are used. In the case of DQDs without direct tunnel coupling ($t_c=0$), Fig. 4(a) shows that the conductance curve has a narrow dip around the point $\overline{\epsilon}=-U/2$. From the formula for transmission [Eq. (6)], we note that the conductance vanishes when the condition $\tilde{\Gamma}_1\tilde{\epsilon}_2+\tilde{\Gamma}_2\tilde{\epsilon}_1$

$=2\tilde{t}_c\sqrt{\tilde{\Gamma}_1\tilde{\Gamma}_2}$ is satisfied. The strictly zero transmission is a consequence of destructive quantum interference for electron transport through the parallel DQDs, and it is absent for systems with DQDs connected in series. It is interesting to notice that only when the DQDs with different energy levels ($\Delta\epsilon \neq 0$), is this characteristic of interference revealed. This originates from the fact that, in this case, both the bonding and antibonding state channels are involved in the transmission. As the energy difference $\Delta\epsilon$ increases, the dip becomes more broadened. For nonzero interdot tunnel couplings as shown in Figs. 4(b)–4(d), the conductance curves have asymmetric line shapes, which are typical for the Fano resonance. This results from the constructive and destructive interference processes for electrons transmitted through the channels of bonding and antibonding states. It is noted that line broadening of the Fano dip or peak depends on the value of dot level difference $\Delta\epsilon$, which is similar to the noninteracting DQD case.[16] The effect of on-site interaction U is to introduce strong renormalization of the dot levels and the hybridization strength, hence, the center of the Fano resonance and line broadening have nonlinear dependence on the interdot tunneling t_c and the level difference $\Delta\epsilon$. It is interesting to notice the Fano resonances obtained in this study have some similarity with the experiment results in Ref. 5. Although their experiment is on electron transport through a single QD, the coupling strength between the quantum dot and the lead is strong and the Kondo effect and multilevels of the QD might be involved in the electron transport. Recently, Büsser *et al.*[22] have studied electron transport through multilevel quantum dots using exact-diagonalization techniques. It is interesting to notice that they have also found a conductance dip structure induced by an interference effect, as shown in Fig. 4(a). Actually, when $t_c=0$, the model studied in our paper is equivalent to considering two levels in a single quantum dot.

For a DQD system with an energy level difference, the local density of state in the ith QD $(i=1,2)$ is given by

$$\rho_i(\omega) = \frac{[\sqrt{\tilde{\Gamma}_i}(\omega - \tilde{\epsilon}_{\bar{i}}) + \sqrt{\tilde{\Gamma}_{\bar{i}}}\tilde{t}_c]^2}{[(\omega - \tilde{\epsilon}_1)(\omega - \tilde{\epsilon}_2) - \tilde{t}_c^2]^2 + [\tilde{\Gamma}_1(\omega - \tilde{\epsilon}_2) + \tilde{\Gamma}_2(\omega - \tilde{\epsilon}_1) + 2\tilde{t}_c\sqrt{\tilde{\Gamma}_1\tilde{\Gamma}_2}]^2}. \tag{9}$$

In Fig. 5, we plot the local density of state in each dot. The line shape of the density of the state can be regarded as a superposition of a Fano line shape close to the antibonding state energy and a Breit-Wigner resonance around the bonding state energy (see Ref. 16 for detailed discussion). The interference effect on the local density of state is manifested clearly as compared with that in Fig. 2(b).

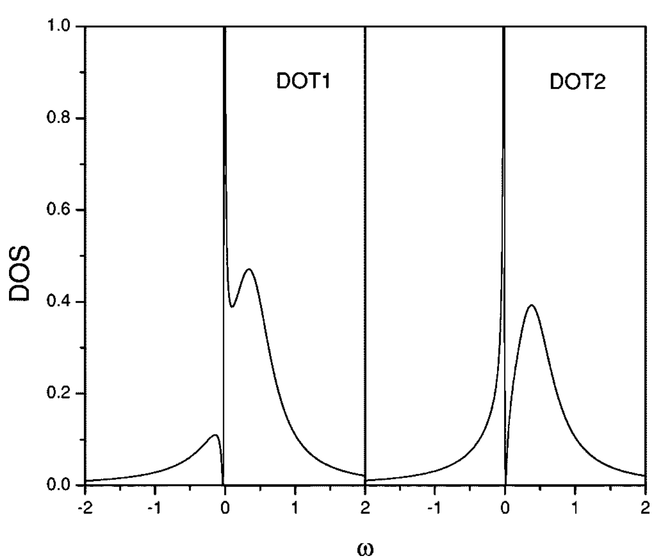

FIG. 5. The local density of state for each quantum dot. Parameters used are $U=4.0$, $\overline{\epsilon}=-2.0$, $\Delta\epsilon=1.0$, and $t_c=1.0$.

III. SUMMARY

In summary, we have studied the electron transport through DQDs in parallel configuration with interdot tunneling in the Kondo regime. The strong Coulomb repulsion in the dots is taken into account via the finite-U slave boson technique. The results of our calculation indicate several distinct features from the noninteracting model:[16] The conductance shows a plateau structure as a function of the dot level in the singly occupied regime; without interdot tunneling ($t_c=0$), there is a dip structure on the conductance plateau when the energy levels of two dots are different. When $t_c \neq 0$, the conductance has a Fano resonance line shape on the conductance plateau as a function of the average dot level; the energies of the bonding and antibonding states and the level broadening of the bonding state are strongly renormalized compared to the noninteracting model case. For instance, the antibonding state energy is almost fixed around the Fermi energy of the lead in the singly occupied region. The results are also different from those of the DQDs in series, in which the maximum conductance is achieved when the interdot tunneling $t_c=1.0$ and no Fano resonance is observed.[11–14,19] The Fano effect for parallel DQDs originates from the interference effect for electron transport through the two channels of bonding and antibonding states of parallel DQDs. In one recent experiment, Chen *et al.*[10]

studied the Kondo effect in parallel DQDs system. However, the maximum conductance obtained in their experiment is only about $0.1e^2/h$ by varying the gate voltage and interdot tunneling, so that we think the full coherent electron transport through DQDs was not achieved and the interference effect was not manifested. One may expect, in further experiments on the parallel DQDs system, to observe the conductance plateau structure and also the Fano resonance, as discussed above.

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