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ac field-induced Fano resonances in a parallel-coupled double quantum dot system

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Abstract

The effects of an ac electric field on the Fano resonance in a parallel-coupled double quantum dot system are investigated theoretically. The field can induce the photon-assisted Fano resonances for both symmetrical and asymmetrical parallel configurations. The magnitude and position of the photon-assisted Fano peak can be tuned by the ac field strength and frequency, respectively. Furthermore, the Fano resonance can appear with increasing the field frequency for both the symmetrical and asymmetrical configurations. This provides an efficient mechanism to control the Fano resonance. The photon–electron pumping effects for the symmetrical and asymmetrical cases are also studied in the weak- and strong-coupling regime.

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1. Introduction

The electron tunneling through quantum dot (QD) systems has been one of the interesting areas in recent years, in which the electron phase coherence can be sustained [1]. Interference experiments with an Aharonov–Bohm [2] (AB) ring containing one QD have been done to detect the quantum phase coherence [3–7]. The AB oscillations of the tunneling current as a function of the magnetic flux through the ring has been experimentally demonstrated, which reflects the fact that the phase coherence is maintained during the tunneling process through a QD. Fano effect [8], i.e., the asymmetric line shapes in conductance, is also a good tool to investigate the electron phase coherence in the QD system. The Fano-type line shapes in conductance stems from quantum interference between resonant and nonresonant processes [9–13]. It is known that a discrete level inside the QD can act as a Breit–Wigner-type scatter which is broadened by a factor of Γ due to couplings with the leads. When the phase of the tunneling electron smoothly changes by π on the resonance within Γ, the Fano effect in the conductance spectra can be realized [4].

More recently, an AB interferometer containing two QDs has been realized [14–17]. The open parallel-coupled double quantum dot (DQD) system makes the quantum transport phenomena rich and varied, in which the electron remains the coherence [18,19]. Inspired by these recent experiments, several groups have attempted to address this parallel DQD system theoretically and predicted the existence of the Fano resonance [20–25]. In the Fano effect of the conventional hybrid system [11–13], the nonresonant channel is served by a quantum point contact, which can detect the π phase shift around the resonant tunneling channel through the QD. In the Fano effect of the DQD system, however, the two molecular states play an important rule. The reference channel is the tunneling chan-

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nel through the state with a wide band, and the other channel through the state with a narrow band is accompanied with a π phase shift [26].

On the other hand, the time-dependent coherent transport of electrons through a mesoscopic system has received more and more attention. An essential feature is the well-known photon-assisted tunneling (PAT). The electron can tunnel through the system by emitting or absorbing multiple photons, and then the new inelastic tunneling channels are opened. The observations of PAT have been reported in systems of single QD experimentally [27–29]. Time-dependent tunneling through coupled QDs in series has received large attention both experimentally and theoretically. Experimentally, the PAT current through serially-coupled DQD has been observed, and the predicted extra resonance peaks under irradiation of microwave are clearly discovered [30,31]. Theoretically, since the studies about the microwave radiation effects in the early 1960's [32], different theoretical approaches have been developed. Based on the quantum rate equation approach, the studies of the PAT in serial DQD predicates that the photon response of the system exhibits satellite resonance peaks due to PAT processes [33,34]. Based on the nonequilibrium Green's function (NGF) method [35], the pumping current in two serially coupled quantum dots is studied [36].

So far, the photon-assisted Fano effects in a parallel-coupled DQD system are still less studied. Can we use an external ac electric field to tune the Fano effects? In this Letter, we propose an efficient mechanism for the operation of tuning the Fano resonance. The idea is based on the interference between the two molecular states caused by the photon-assisted tunneling. We assume that the electron tunneling through the DQD is coherent and that only one electronic state in each dot is involved, both facts consistent with the experiment. The ac field applied on the DQD system induces an adiabatic change for the energy of each dot [35–37]. Then the energy levels of each QD oscillate anti-symmetrically under the influence of the ac field. Our results show that the ac field can induce the photon-assisted Fano resonance which is absent without the field. While the original Fano resonance can be suppressed by the ac field. The magnitude and position of the Fano peak can be controlled by tuning the strength and frequency of the ac field, respectively.

The rest of this Letter is organized as follows. In Section 2 we present the model Hamiltonian and derive the formula of the photon-assisted current by using the NGF technique. In Section 3 we study the photon-assisted Fano resonance by tuning various parameters. Finally, a brief summary is given in Section 4.

2. Physical model and formula

The parallel coupled DQD system under an external time-varying field is described by the following Hamiltonian:

$$H = \sum_{\alpha=L,R} H_\alpha + H_D + H_T, \tag{1}$$

with

$$H_\alpha = \sum_k \epsilon_{\alpha,k} a^\dagger_{\alpha,k} a_{\alpha,k}, \tag{2}$$

$$H_D = \sum_{i=1,2} \varepsilon_i(t) d_i^\dagger d_i - \left(t_c d_1^\dagger d_2 + \text{H.c.}\right), \tag{3}$$

$$H_T = \sum_{\alpha,k,i=1,2} t_{\alpha i} d_i^\dagger a_{\alpha,k} + \text{H.c.} \tag{4}$$

H_α ($\alpha = L, R$) describes the left and right normal metal leads. H_D models the parallel-coupled DQD where $d_i^\dagger$ (d_i) represents the creation (annihilation) operator of the electron with energy ε_i in the dot i ($i = 1, 2$). The energy levels in the QDs are measured from the Fermi energy ($E_F = 0$) of the leads. The chemical potential of the leads are set as $\mu_L = eV/2$ and $\mu_R = -eV/2$ with eV the bias. t_c denotes the interdot coupling strength. Under the adiabatic approximation, the external ac electric field can be reflected in the single-electron energies which can be separated into two parts as $\varepsilon_1(t) = \varepsilon_1 + \Delta_0(t)$ and $\varepsilon_2(t) = \varepsilon_2 - \Delta_0(t)$ for the central conductor. ε_i is the time-independent single-electron energies without the ac field, and $\Delta_0(t)$ is a time-dependent part from the ac field, which can be written as $\Delta_0(t) = \Delta_0 \cos\omega_0 t$. H_T represents the tunneling coupling between the DQD and leads where $t_{\alpha i}$ is the hopping strength between the ith QD and the α lead. To capture the essential physics of photon-assisted Fano resonance, we consider the simplest case with noninteracting electrons in two single-level QDs.

The current $I_\alpha(t)$ from the α lead to the central region can be calculated from standard NGF techniques, and can be expressed in terms of the dot's Green function as [35–37]

$$I_\alpha(t) = \frac{2e}{\hbar} \text{Re} \int dt' \, \text{Tr}\big\{\big[\mathbf{G}^r(t,t')\mathbf{\Sigma}^<_\alpha(t',t) + \mathbf{G}^<(t,t')\mathbf{\Sigma}^a_\alpha(t',t)\big]\big\}. \tag{5}$$

Here, the Green's function $\mathbf{G}^{r,<}$ and the self-energy $\mathbf{\Sigma}^{a,<}$ are all two-dimensional matrices for the DQD system. The bold-faced letters are used to denote matrices. The retarded and lesser Green functions are defined as $\mathbf{G}^r(t,t') = -i\theta(t-t')\langle\{\Psi(t), \Psi^\dagger(t')\}\rangle$ and $\mathbf{G}^<(t,t') = i\langle\Psi^\dagger(t')\Psi(t)\rangle$, respectively, with the operator $\Psi^\dagger = (d_1^\dagger, d_2^\dagger)$. In order to obtain the expression of the current, we have to solve the Green's functions. The retarded Green's functions can be calculated by using Dyson equation $\mathbf{G}^r(t,t') = \mathbf{g}^r(t,t') + \int dt_1 \int dt_2 \, \mathbf{G}^r(t,t_1) \times \mathbf{\Sigma}^r(t_1,t_2)\mathbf{g}^r(t_2,t')$, where $\mathbf{g}^r(t,t')$ is the retarded Green's function for the uncoupled DQD without the coupling to the leads

$$\mathbf{g}^r(t,t') = -i\theta(t-t')\begin{pmatrix} e^{-i\int_{t'}^t \varepsilon_1(t_1)\,dt_1} & 0 \\ 0 & e^{-i\int_{t'}^t \varepsilon_2(t_2)\,dt_2} \end{pmatrix}. \tag{6}$$

The lesser Green's functions is related to the retarded Green's function through the Keldysh equation $\mathbf{G}^<(t,t') = \int dt_1 \int dt_2 \, \mathbf{G}^r(t,t_1)\mathbf{\Sigma}^<(t_1,t_2)\mathbf{G}^a(t_2,t')$. The advanced self-energy can be obtained from $\mathbf{\Sigma}^a_\alpha = (\mathbf{\Sigma}^r_\alpha)^\dagger$. The retarded self-energy is $\mathbf{\Sigma}^r = \sum_\alpha \mathbf{\Sigma}^r_\alpha + \mathbf{\Sigma}^r_c$, where $\mathbf{\Sigma}^r_\alpha$ and $\mathbf{\Sigma}^r_c$ are caused by the α lead and the interdot couplings, respectively. The lesser self-energy is $\mathbf{\Sigma}^< = \sum_\alpha \mathbf{\Sigma}^<_\alpha$.