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Quantum transport through two series Aharonov–Bohm interferometers with zero total magnetic flux*

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With the help of nonequilibrium Green's function technique, the electronic transport through series Aharonov–Bohm (AB) interferometers is investigated. We obtain the AB interference pattern of the transition probability characterized by the algebraic sum ϕ and the difference θ of two magnetic fluxes, and particularly a general rule of AB oscillation period depending on the ratio of integer quantum numbers of the fluxes. A parity effect is observed, showing the asymmetric AB oscillations with respect to the even and odd quantum numbers of the total flux in antiparallel AB interferometers. It is also shown that the AB flux can shift the Fano resonance peaks of the transmission spectrum.

Keywords: Aharonov–Bohm interferometer, difference of magnetic fluxes, Fano effect
PACC: 7210, 7320D, 7335

1. Introduction

Quantum dots (QDs) containing discrete energy levels, which can be tuned easily in experiments, have been attracting considerable attention continuously, and the study of quantum transport in QDs has become an interesting field which serves as a testing ground of physical phenomena, such as Kondo[1,2] and Fano effects.[3,4]

On the other hand, when the typical length scale is shorter than or comparable to the mean free path of electrons, the phase coherence of electrons passing through a QD system is retained[5] and the wave nature of electrons plays a decisive role. In the past decade, a widely adopted method for studying the phase coherence of traversing electrons in a QD system is to measure the Fano resonance in an Aharonov–Bohm (AB) interferometer by embedding the QD into one of its arms,[6] where a discrete level in the QD acts as a Breit–Wigner-type scatterer and is broadened by a factor of Γ due to couplings with the continua in leads. Unlike the conventional study,[7−10] the Fano resonance in the QD system has an advantage that its key parameters are readily tunable. The first observation of the Fano line-shape in the QD system was reported in Refs.[3, 11] in the single-electron-transistor experiments. Recently the Fano effect in a mesoscopic AB ring with an embedded QD[12,13] and in a quantum wire (QW) with a side-coupled QD[14] were investigated. The Coulomb-modified Fano resonances in a tunable Fano interferometer consisting of a QD have been observed.[15]

A parallel open double-quantum-dot (DQD)[16−18] threaded by a magnetic flux is regarded as an AB interferometer in which a part of the phase coherence of the electrons remains even in the presence of Coulomb repulsion.[1,19] The influence of the magnetic flux on quantum transport[20−22] and Fano lineshape in the DQD system has been investigated.[23] Tunable coupling strength between two parallel dots makes the transport properties more complicated and interesting.[24]

The quantum transport in a complex device of series AB interferometers possessing multi-path-channel may result in more rich quantum phase interference phenomena which, however, have not yet been revealed. We consider a device consisting of a coupled DQD with two magnetic fluxes as shown in Fig.1, which can be regarded as a double-AB-interferometer. Peculiar quantum phase interference phenomena are demonstrated.

The paper is organized as follows: in Section 2, we present the model Hamiltonian and the formulation of the transmission probability $T(\epsilon)$ and the current $I_{\rm L}$ with the help of nonequilibrium Green's function technique. The transmission probability and current as functions of the parameters ϕ and θ, namely the

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algebraic sum and difference of the two fluxes, are derived in Section 3, with which the AB oscillations of the transmission probability in both parallel and antiparallel interferometers are analysed. In Section 4, we study the effect of fluxes on the Fano resonance. Finally, a brief summary is given in Section 5.

2. Model and formulation

The system schematically shown in Fig.1 can be described by the following Hamiltonian:

$$H = \sum_{\alpha(\alpha=\mathrm{L,R})} H_\alpha + H_{\mathrm{DQD}} + H_{\mathrm{T}}, \tag{1}$$

where

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

represents the noninteracting electron gas in the left or right lead and $\epsilon_{\alpha k} = \epsilon^{(0)}_{\alpha k} + qv_\alpha$, with $\epsilon^{(0)}_{\alpha k}$ being the energy levels in the lead α and v_α the external voltage applied to it. The Hamiltonian of two parallel-coupled quantum dots is

$$H_{\mathrm{DQD}} = \sum_{i=1,2} \epsilon_i d^+_i d_i + (\Omega \mathrm{e}^{\mathrm{i}\theta} d^+_1 d_2 + \mathrm{h.c}), \tag{3}$$

with a single energy level ϵ_i in each quantum dot. Ω is the coupling strength between the two dots, and $\theta = 2\pi(\xi_{\mathrm{R}} - \xi_{\mathrm{L}})/2$ denotes a phase shift related to the algebraic difference between the two magnetic fluxes, $\Phi_\alpha = \xi_\alpha \Phi_0$ ($\alpha = \mathrm{L,R}$, $\Phi_0 = hc/e$ is the quantum unit of the magnetic flux), threading the left and right subrings. The tunnel coupling between quantum-dot and lead is described by

$$H_{\mathrm{T}} = \sum_{k\alpha i} (t_{\alpha i} \mathrm{e}^{\mathrm{i}\phi_{i\alpha}} a^+_{k\alpha} d_i + \mathrm{h.c}), \tag{4}$$

where $t_{\alpha i}$ is the coupling strength, and the phase shift $\phi_{i\alpha}$ of the electron wavefunction between the quantum dot i and lead α is seen to be

$$\phi_{\mathrm{L}1} = \phi_{1\mathrm{R}} = \phi_{\mathrm{R}2} = \phi_{2\mathrm{L}} = \frac{\phi}{4}, \tag{5}$$

where $\phi = 2\pi(\phi_{\mathrm{L}} + \phi_{\mathrm{R}})/\Phi_0 = 2\pi(\xi_{\mathrm{L}} + \xi_{\mathrm{R}})$ is the algebraic sum of the two magnetic fluxes in quantum unit Φ_0. The quantum flux number ξ_{L} in the left ring is set at a positive value while ξ_{R} is positive if the flux in the right ring is in the same direction as the left one, otherwise negative. We will derive in this paper a general formula of the quantum transport as a function of the parameters ϕ and θ, which give rise to arbitrary configurations of two AB interferometers. We call the special case of two fluxes of equal value in the same direction ($\xi_{\mathrm{R}} = \xi_{\mathrm{L}} = \xi$, and thus $\phi = 4\pi\xi$, $\theta = 0$) the parallel AB interferometers,[23] while the magnetic fluxes of opposite directions ($\xi_{\mathrm{R}} = -\xi_{\mathrm{L}} = \xi$, and thus $\theta = 2\pi\xi$, $\phi = 0$) the antiparallel interferometers. Although the total flux vanishes in antiparallel interferometers, we find that the AB oscillation remains due to the quantum phase interference of interdot paths.

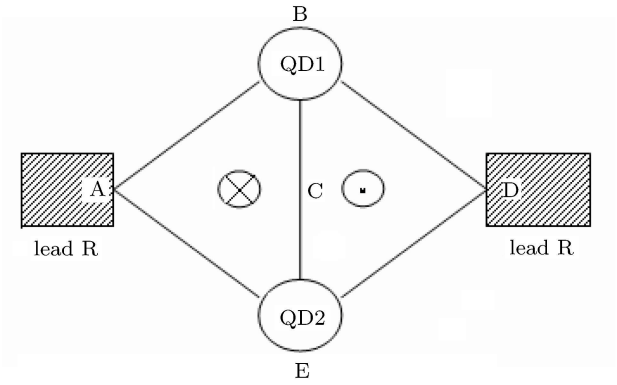


Fig.1. Schematic diagram of the double AB interferometer.

The linewidth matrices are defined as $\Gamma^\alpha_{ij} = \sum_k t_{\alpha i} t^*_{\alpha j} 2\pi\delta(\epsilon - \epsilon_{k\alpha})$ ($\alpha = \mathrm{L,R}$) and $\Gamma = \Gamma^{\mathrm{L}} + \Gamma^{\mathrm{R}}$, which can be represented as

$$\Gamma_{\mathrm{L}} = \begin{bmatrix} \Gamma^{\mathrm{L}}_1 & \sqrt{\Gamma^{\mathrm{L}}_1 \Gamma^{\mathrm{L}}_2}\mathrm{e}^{\mathrm{i}\phi/2} \\ \sqrt{\Gamma^{\mathrm{L}}_1 \Gamma^{\mathrm{L}}_2}\mathrm{e}^{-\mathrm{i}\phi/2} & \Gamma^{\mathrm{L}}_2 \end{bmatrix} \tag{6}$$

and

$$\Gamma_{\mathrm{R}} = \begin{bmatrix} \Gamma^{\mathrm{R}}_1 & \sqrt{\Gamma^{\mathrm{R}}_1 \Gamma^{\mathrm{R}}_2}\mathrm{e}^{-\mathrm{i}\phi/2} \\ \sqrt{\Gamma^{\mathrm{R}}_1 \Gamma^{\mathrm{R}}_2}\mathrm{e}^{\mathrm{i}\phi/2} & \Gamma^{\mathrm{R}}_2 \end{bmatrix}, \tag{7}$$

where Γ^α_{ii} is denoted by Γ^α_i for short.

We start from the Dyson equation for the evaluation of Green's function $G^{\mathrm{r}}(\epsilon)$,

$$G^{\mathrm{r}}(\epsilon) = g^{\mathrm{r}}(\epsilon) + g^{\mathrm{r}}(\epsilon)\Sigma^{\mathrm{r}}(\epsilon)G^{\mathrm{r}}(\epsilon), \tag{8}$$

where $g^{\mathrm{r}}(\epsilon)$ denotes the retarded Green's function of the isolated quantum dots, and can be easily obtained as

$$g^{\mathrm{r}}(\epsilon) = \begin{bmatrix} \dfrac{1}{\epsilon - \epsilon_1 + \mathrm{i}0^+} & 0 \\ 0 & \dfrac{1}{\epsilon - \epsilon_2 + \mathrm{i}0^+} \end{bmatrix}. \tag{9}$$

In our model, the self-energy $\Sigma^{\mathrm{r}}(\epsilon)$ consists of three parts

$$\Sigma^{\mathrm{r}}(\epsilon) = \Sigma^{\mathrm{r}}_{\mathrm{L}}(\epsilon) + \Sigma^{\mathrm{r}}_{\mathrm{R}}(\epsilon) + \Sigma^{\mathrm{r}}_{12}(\epsilon), \tag{10}$$

where $\Sigma^{\mathrm{r}}_\alpha(\epsilon)$ results from the tunnel coupling between QD and the lead, and $\Sigma^{\mathrm{r}}_{12}(\epsilon)$ is due to the interdot coupling. Under the wideband approximation (assume

that the self-energy is not sensitive to the energy), we have

$$\Sigma_\alpha^{\rm r} = -\frac{\rm i}{2}\Gamma_\alpha \tag{11}$$

and

$$\Sigma_{12}^{\rm r} = \begin{bmatrix} 0 & \Omega^* {\rm e}^{-{\rm i}\theta} \\ \Omega {\rm e}^{{\rm i}\theta} & 0 \end{bmatrix}. \tag{12}$$

Thus the Dyson equation becomes

$$G^{\rm r}(\epsilon) = g^{\rm r}(\epsilon) + g^{\rm r}(\epsilon)\Sigma_{12}G^{\rm r}(\epsilon) + g^{\rm r}(\epsilon)\sum_\alpha \Sigma_\alpha^{\rm r} G^{\rm r}(\epsilon), \tag{13}$$

which can be solved in energy representation, and then we obtain the retarded Green's function $G^{\rm r}$. The transmission probability $T(\epsilon)$ is defined as

$$T(\epsilon) = {\rm Tr}[\Gamma_{\rm L} G^{\rm r}(\epsilon)\Gamma_{\rm R} G^{\rm a}(\epsilon)], \tag{14}$$

where $G^{\rm a}(\epsilon) = [G^{\rm r}(\epsilon)]^+$.

Assume that the bias V is applied to the left lead and $\mu_{\rm R} = 0$, then the electric current can be found from following equation

$$J_{\rm L} = \frac{2e}{\hbar}\int \frac{{\rm d}\epsilon}{2\pi}[f_{\rm L}(\epsilon + eV) - f_{\rm R}(\epsilon)]T(\epsilon). \tag{15}$$

3. AB oscillation of transmission probability

Considering the symmetric case ($\Gamma_1^{\rm L} = \Gamma_2^{\rm L} = \Gamma_1^{\rm R} = \Gamma_2^{\rm R} = \Gamma$), and setting $\epsilon_1 = \epsilon_2 = \epsilon_0$, we obtain the retarded (advanced) Green's function as

$$G^{\rm r(a)} = \frac{1}{D^{\rm r(a)}} \begin{bmatrix} \epsilon - \epsilon_0 \pm {\rm i}\Gamma & \Omega {\rm e}^{-{\rm i}\theta} \mp {\rm i}\Gamma\cos\dfrac{\phi}{2} \\ \Omega {\rm e}^{{\rm i}\theta} \mp {\rm i}\Gamma\cos\dfrac{\phi}{2} & \epsilon - \epsilon_0 \pm {\rm i}\Gamma \end{bmatrix}, \tag{16}$$

where $D^{\rm r(a)} = (\epsilon - \epsilon_0)^2 \mp \Gamma^2 \pm 2{\rm i}(\epsilon - \epsilon_0)\Gamma - \Omega^2 \mp \Gamma^2\cos^2\frac{\phi}{2} \pm 2{\rm i}\Gamma\Omega\cos\frac{\phi}{2}\cos\theta$. Then the transmission probability with arbitrary flux configurations is given by

$$T(\epsilon) = \frac{{\rm e}^{-{\rm i}\phi}\eta_+\eta_-\Gamma^2}{D^{\rm r}D^{\rm a}}, \tag{17}$$

where

$$\eta_\pm = \Big[2\Omega\cos\theta \mp 2{\rm i}\Gamma\cos\frac{\phi}{2}\Big]{\rm e}^{{\rm i}\phi/2} + (\epsilon - \epsilon_0 \pm {\rm i}\Gamma)(1 + {\rm e}^{{\rm i}\phi}).$$

Now we analyse two special cases, namely, the parallel and antiparallel interferometers. For the parallel AB interferometers ($\xi_{\rm L} = \xi_{\rm R}$, $\theta = 0$) we have $\eta_\pm = 2(\epsilon - \epsilon_0 + \Omega)$ and the period of AB oscillation is 4π as can be seen from Fig.2(a) with non-vanishing minima located at the odd-integer number of the quantum flux unit Φ_0, while the maxima are located at the even-integer number of the quantum flux unit. In the antiparallel AB interferometers ($\xi_{\rm L} = -\xi_{\rm R}$, $\phi = 0$) the AB oscillation exists as can be seen from Fig.2(b) even though the total magnetic flux is zero in this case, in which the period of oscillation is also 4π. The maximum values at even-integer number of Φ_0 are higher than those at odd-integer. This asymmetric AB oscillation can be understood to be due to the multi-channel interference.

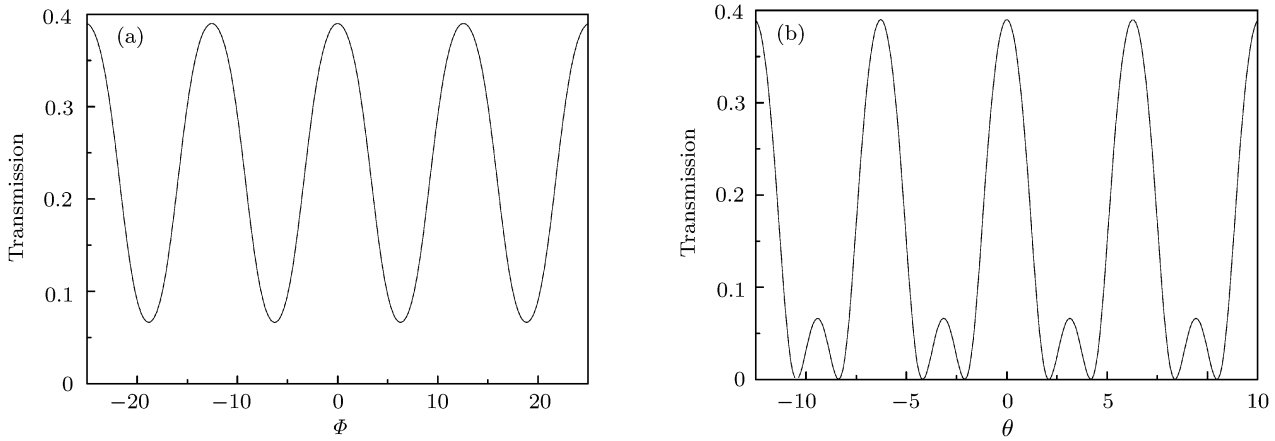


Fig.2. (a) The transmission probability T vs total magnetic flux ϕ in the parallel interferometers ($\theta = 0$), (b) θ-dependence of T in antiparallel interferometers ($\phi = 0$) with $\gamma = 1$, $\Omega = 0.2$, $\epsilon = 0.15$.

There are two kinds of paths along which the electrons can transport from left to the right lead: (1) left lead– QD1(QD2)– right lead; (2) left lead– QD1(QD2)– QD2(QD1)– right lead. For antiparallel interferometers ($\phi = 0$) the paths of kind-1 do not result in the AB interference but the paths of kind-2 do because of $\theta \neq 0$. This situation is just the opposite of the parallel case ($\theta = 0$, $\phi \neq 0$). From Eq.(18) we obtain $\eta_{\pm}^{\rm even} = 2(\epsilon - \epsilon_0 + \Omega)$ for the antiparallel case when $\theta = 2n\pi$ (thus total flux is even-integer of Φ_0), giving rise to a higher maximum value of transmission probability as compared with the odd-integer flux where $\theta = (2n+1)\pi$ and $\eta_{\pm}^{\rm odd} = 2(\epsilon - \epsilon_0 - \Omega)$, thus leading to a lower maximum value. The parity effect of AB-oscillation, depending on the even or odd quantum number of flux due to the multi-channel interference, is a new observation and has never been demonstrated yet. For arbitrary values of fluxes we find an interesting relation between the period P of AB-oscillation and the absolute ratio of the two-integer quantum number of fluxes as follows:

$$P = (n+1)\pi, \quad n = |\xi_{\rm R}|/|\xi_{\rm L}|, \tag{18}$$

as shown in Fig.3 with $n = 2$ (solid line), 3 (dashed line) and 4 (dotted line).

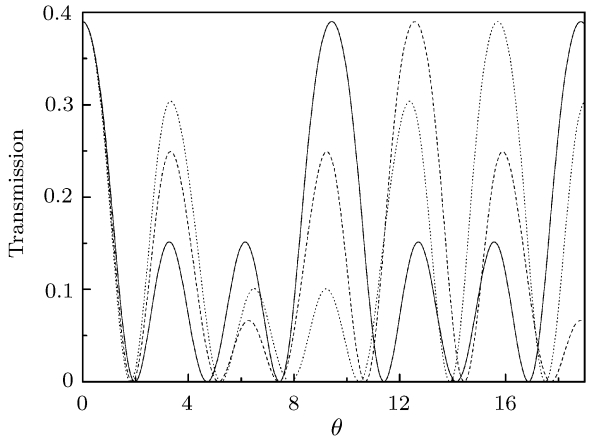


Fig.3. The AB oscillation with $n = 2$ (solid line), 3 (dashed line) and 4 (dotted line).

We can obtain the result in another way. The wavefunction for the whole system can be written as

$$\Psi = \Psi_{\rm o} + \Psi_{\rm i}, \tag{19}$$

where $\Psi_{\rm o}$ is the wavefunction which does not go through the point C, and $\Psi_{\rm i}$ is the wavefunction going through the point C, and thus we have

$$\Psi_{\rm o} = \Psi^0_{ABD} {\rm e}^{-{\rm i}e/c\hbar} \int_{ABD} \boldsymbol{A}_{\rm R} \cdot {\rm d}\boldsymbol{l} + \Psi^0_{AED} {\rm e}^{-{\rm i}e/c\hbar} \int_{AED} \boldsymbol{A}_{\rm R} \cdot {\rm d}\boldsymbol{l}, \tag{20}$$

$$\Psi_{\rm i} = \Psi^0_{ABCED} {\rm e}^{-{\rm i}e/c\hbar} \int_{ABCED} \boldsymbol{A}_{\rm R} \cdot {\rm d}\boldsymbol{l} + \Psi^0_{AECBD} {\rm e}^{-{\rm i}e/c\hbar} \int_{AECBD} \boldsymbol{A}_{\rm R} \cdot {\rm d}\boldsymbol{l}, \tag{21}$$

where Ψ^0_{ABD}, Ψ^0_{AED}, Ψ^0_{ABCED} and Ψ^0_{AECBD} are the wavefunctions in the absence of the magnetic flux. So the wavefunction for the whole system will be

$$\Psi = {\rm e}^{-{\rm i}e/c\hbar} \int_{ABD} \boldsymbol{A}_{\rm R} \cdot {\rm d}\boldsymbol{l} \{ \Psi^0_{ABD}[1 + {\rm e}^{-{\rm i}2\pi(\alpha_1+\alpha_2)}] + {\rm e}^{-{\rm i}2\pi\alpha_2} \Psi^0_{ABCED}[1 + {\rm e}^{{\rm i}2\pi(\alpha_2-\alpha_1)}] \}, \tag{22}$$

with $\Phi_1 = \alpha_1 \Phi_0$ and $\Phi_2 = \alpha_2 \Phi_0$. Then we have

$$\begin{aligned} |\Psi|^2 \approx{}& 2|\Psi^0_{ABD}|^2(1 + \cos 2\pi(\alpha_1 + \alpha_2)) \\ &+ 2|\Psi^0_{ABCED}|^2(1 + \cos 2\pi(\alpha_2 - \alpha_1)) \\ &+ 2(\Psi^0_{ABCED}(\Psi^0_{\rm ABD})^* + {\rm c.c}) \\ &\times (\cos(2\pi\alpha_1) + \cos(2\pi\alpha_2)). \end{aligned} \tag{23}$$

And when $\alpha_1 = \alpha_2 = \alpha/2$, where α is the total magnetic flux defined as $\alpha = \alpha_1 + \alpha_2$, we have

$$|\Psi|^2 \sim (1 + \cos(2\pi\alpha)) + 2\cos(\pi\alpha). \tag{24}$$

So, it is easy to find that the period is 4π, which is consistent with the result derived from the Green's function.

4. Fano resonance

We begin with bonding and antibonding dressed states of the QD using the following transformation:[20]

$$\begin{pmatrix} f_+ \\ f_- \end{pmatrix} = \begin{bmatrix} -\cos\beta {\rm e}^{{\rm i}\theta} & -\sin\beta \\ -\sin\beta & \cos\beta {\rm e}^{-{\rm i}\theta} \end{bmatrix} \begin{pmatrix} d_1 \\ d_2 \end{pmatrix}, \tag{25}$$

where f_- and f_+ denote the annihilation operators of the bonding and antibonding dressed states of the QD respectively, with the parameter β defined as $\beta = 1/2 \tan^{-1}[2\Omega/(\epsilon_1 - \epsilon_2)]$. For simplicity, in the following we only consider the symmetric case, i.e. $\epsilon_1 = \epsilon_2 = \epsilon_0$, and thus $\beta = \pi/4$. Then the Hamiltonian of the double-quantum-dot $H_{\rm DQD}$ can be diagonalized in terms of the new operators f_- and f_+,

$$\tilde{H}_{\rm DQD} = (\epsilon_0 - \Omega) f_+^+ f_+ + (\epsilon_0 + \Omega) f_-^+ f_-. \tag{26}$$

The retarded Green's function $G^{\rm r}_{\pm} = -{\rm i}\theta(t)\{f_{\pm}, f_{\pm}^+\}$ is found, using the equation of motion approach, to be

$$G^{\rm r}_{\pm}(\epsilon) = \frac{1}{\epsilon - (\epsilon_0 \mp \Omega) + {\rm i}\Gamma_{\pm}}, \tag{27}$$

where

$$\Gamma_{\pm} = \frac{1}{2}(\Gamma_{\pm}^{\rm L} + \Gamma_{\pm}^{\rm R}).$$

and

$$\Gamma_{\pm}^{\alpha} = \frac{1}{2}(\Gamma_1^{\alpha} + \Gamma_2^{\alpha}) \mp \sqrt{\Gamma_1^{\alpha}\Gamma_2^{\alpha}}\cos\Big(\frac{\phi}{2} + \theta\Big).$$

The local state density is defined as

$$\rho_{\pm}(\epsilon) = -\frac{1}{p\mathrm{i}}\mathrm{Im}G_{\pm}^{\rm r}(\epsilon) = \frac{1}{p\mathrm{i}}\frac{\Gamma_{\pm}}{[\epsilon - (\epsilon_0 \pm \Omega)]^2 + (\Gamma_{\pm})^2}. \qquad (28)$$

In the numerical evaluation of the parameter-θ dependence of the transmission probability as a function of the gate voltage ϵ, we set $\Gamma_1^{\rm L} = \Gamma_2^{\rm L} = \Gamma_1^{\rm R} = \Gamma_2^{\rm R} = 0.02\gamma$, where the parameter γ is taken as an energy unit. Figure 4(a) shows the transmission probability as a function of energy ϵ (spectrum) depending on the parameter Ω in the absence of the AB fluxes, where there is only a single peak (solid line) i.e. the Fano resonance if the two QDs are completely decoupled (i.e., $\Omega = 0$) while two peaks emerge at $\epsilon/\gamma = E_{\pm}$ (see Fig.4(b)) for non-vanishing Ω ($\theta \neq 0, \pi$) due to the existence of two discrete energy levels.

We now investigate the effect of the magnetic flux on the Fano resonance. For the antiparallel AB interferometers with $\theta = \pi/3$ the Fano resonance peak (see Fig.4(b)) is on the left side (solid line), while it shifts to the right side when θ increases to $2\pi/3$ (dotted line). When $\theta = \pi/2$ (dashed line), although we can observe two symmetric peaks, neither one is the Fano resonance. There exists at $\theta = 0$, π only a single peak located on the right and left sides respectively.

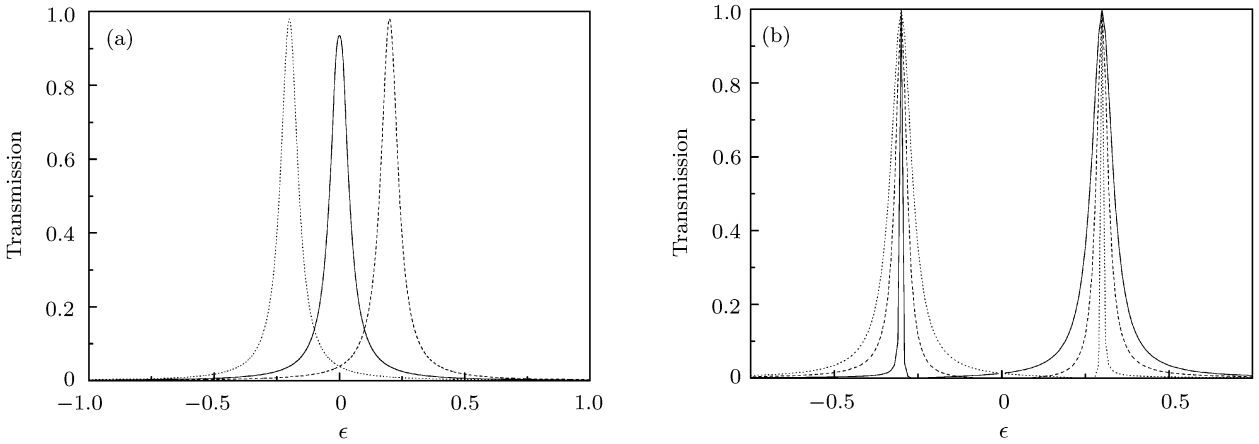


Fig.4. (a) The transmission probability T vs energy ϵ in the absence of the magnetic flux with $\Omega = 0$, $\theta = 0$ (solid line); $\Omega = 0.2$, $\theta = 0$ (dashed line); $\Omega = 0.2$, $\theta = \pi$ (dotted line). (b) T vs energy ϵ in the antiparallel interferometers: $\theta = \pi/3$ (solid line), $\theta = \pi/2$ (dashed line), $2\pi/3$ (dotted line).

5. Conclusion

Due to the multi-channel paths of transport the peculiar quantum interference phenomena are demonstrated. We find a general rule of the AB oscillation period of the transmission probability as a function of the integer quantum number ratio of two fluxes $\xi_{\rm R}/\xi_{\rm L} = n$. Particularly, a parity effect of the AB oscillations depending on the even and odd integer quantum numbers of the total flux is observed in the antiparallel interferometers. It is also shown that the magnetic flux can shift the Fano resonance peaks.

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