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Fano–Kondo effect in the T-shaped double quantum dots coupled to ferromagnetic leads*

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Using an equation-of-motion technique, we theoretically study the Fano–Kondo effect in the T-shaped double quantum dots coupled to two ferromagnetic leads by the Anderson Hamiltonian. We calculate the density of states in this system with both parallel and antiparallel lead-polarization alignments, and our results reveal that the interdot coupling, the spin-polarized strength and the energy level of the side coupled quantum dot greatly influence the density of states of the central quantum dot. This system is a possible candidate for spin valve transistors and may have potential applications in the spintronics.

Keywords: Fano–Kondo effect, density of states, quantum dots
PACC: 7520H, 7225, 7320D

1. Introduction

In recent years, there has been great interest in electronic transport through quantum dot (QD) systems because of their importance in physics and device applications. In particular, the observation of the Kondo effect[1−5] in QD systems opens a new path for the investigation of quantum correlation between the localized spin in QD and the conduction electrons in leads. The Fano effect,[6] which appears as a result of quantum interference between a discrete single energy level and a major electronic system, has also attracted much interest among researchers in microelectronic systems. The two-effect coexistence in one system has richer physics, and recent advance in nanofabrication technology has made it possible to investigate various aspects of these effects experimentally.[7] The T-shaped double quantum dot (DQD)[8−10] systems are a prototype of such correlated systems which are suited for investigating both the Fano effect and Kondo effect (Fano–Kondo effect). The Fano–Kondo interaction[11] is one of the particular effects caused by the interference between two distinct channels in the T-shaped DQD systems. There are a variety of parameter settings in the T-shaped DQD systems, which show somewhat different transport properties from the parallel or series DQD systems. The special arrangement of the two dots provides an additional path for the electron propagation. It is thus interesting to study how the Kondo versus Fano resonances affect the characteristic transport properties in the T-shaped DQD systems.

2. Model and solution

In this paper, we study the spin-polarized transport through the T-shaped DQD system where dot a operates in the Kondo regime and dot b is assumed to be non-interacting so that the energy level of dot b can be readily adjusted. The schematic diagram of our device is illustrated in Fig.1. In the following discussions, the interdot Coulomb interaction U on dot a is assumed to be sufficiently large ($U \to \infty$), so that the double occupancy of dot a is forbidden. Our model can be described by the following Anderson Hamiltonian:

$$H = \sum_{\sigma} \varepsilon_{d\sigma} d_{\sigma}^{\dagger} d_{\sigma} + \sum_{\sigma} \varepsilon_{d1} d_{1\sigma}^{\dagger} d_{1\sigma}$$

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$$+\sum_{k\sigma,\alpha=L,R}\varepsilon_{k\alpha\sigma}c^{\dagger}_{k\alpha\sigma}c_{k\alpha\sigma}$$
$$+\sum_{k\alpha\sigma}(V_{k\alpha\sigma}c^{\dagger}_{k\alpha\sigma}d_{\sigma}+\text{H.C})$$
$$+\sum_{\sigma}(t_{ab}d^{\dagger}_{1\sigma}d_{\sigma}+\text{H.C})+Un_{d\sigma}n_{d\bar{\sigma}}. \quad (1)$$

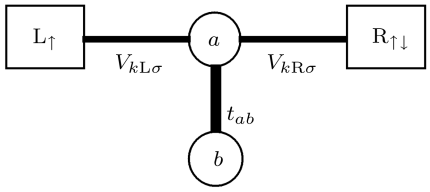


Fig.1. Schematic picture of the T-shaped DQD system. Dot a is connected with the ferromagnetic leads, dot b is side-coupled to dot a, t_{ab} is the interdot coupling strength and $V_{k\alpha\sigma}(\alpha=\mathrm{L},\mathrm{R},\sigma=\uparrow,\downarrow)$ represents the dot-lead tunnelling for dot a with spin σ.

The first three terms of the Hamiltonian correspond to the single electronic states of dot a, dot b, and the leads, respectively, where $c^{\dagger}_{k\alpha\sigma}(c_{k\alpha\sigma})$ is the creation (annihilation) operator of an electron with energy $\varepsilon_{k\alpha\sigma}$ and spin σ in the lead α ($\alpha=L,R$), the annihilation operator of the highest lying electron in dot a is represented by d_{σ}, and that is $d_{1\sigma}$ for dot b. The tunnelling coupling between the leads and dot a is given by the fourth term in the Hamiltonian. The fifth term describes the coupling between the two dots, and the last term gives the electron-electron Coulomb interaction in dot a, where $n_{d\sigma}(=d^{\dagger}_{\sigma}d_{\sigma})$ is the occupation number operator for spin σ.

It is assumed that the left and right leads are spin-polarized, where the relative orientations of magnetization between the two electrodes, namely, the parallel (P) and antiparallel (AP) configurations are considered. We can adopt the line width function $\Gamma_{\alpha\sigma}=2\pi\sum_{k\alpha}|V_{k\alpha\sigma}|^2\delta(\omega-\varepsilon_{k\alpha\sigma})$ and introduce the effective spin-polarization strength P_{α}, which is defined as $P_{\alpha}=\Gamma^{\alpha}_{\sigma}-\Gamma^{\alpha}_{\bar{\sigma}}/\Gamma^{\alpha}_{\sigma}+\Gamma^{\alpha}_{\bar{\sigma}}$ ($0\leq P_{\alpha}\leq 1$). Therefore the spin dependence of the coherent transport can be conveniently considered by introducing magnetic polarization factors P_{L} and P_{R} for the left and right leads, respectively. From the definition of P_{α}, $\Gamma_{\alpha\sigma}$ can be expressed as follows: $\Gamma^{\mathrm{L}}_{\uparrow(\downarrow)}=\Gamma_0(1\pm p_{\mathrm{L}})$, $\Gamma^{\mathrm{R}}_{\uparrow(\downarrow)}=\Gamma_0(1\pm p_{\mathrm{R}})$ for the P configuration and $\Gamma^{\mathrm{L}}_{\uparrow(\downarrow)}=\Gamma_0(1\pm p_{\mathrm{L}})$, $\Gamma^{\mathrm{R}}_{\uparrow(\downarrow)}=\Gamma_0(1\mp p_{\mathrm{R}})$ for the AP configuration, where Γ_0 describes the coupling between the QD and electrodes without internal magnetization. In this work, we adopt the symmetric leads, i.e. $p_{\mathrm{L}}=p_{\mathrm{R}}=p$.[12]

Within the Keldysh formalism the transport current $I=\Sigma_{\sigma}I_{\sigma}$ through the QD for $\Gamma_{\mathrm{R}\sigma}(\omega)=\lambda_{\sigma}\Gamma_{\mathrm{L}\sigma}(\omega)$ is[13]

$$I_{\sigma}=\frac{e}{h}\int \mathrm{d}\omega\frac{\Gamma_{\mathrm{L}\sigma}(\omega)\Gamma_{\mathrm{R}\sigma}(\omega)}{\Gamma_{\mathrm{L}\sigma}(\omega)+\Gamma_{\mathrm{R}\sigma}(\omega)}[f_{\mathrm{L}}(\omega)-f_{\mathrm{R}}(\omega)]\rho_{\sigma}(\omega). \quad (2)$$

What is more, the spectral density of states (DOS) in the QD is $\rho_{\sigma}(\omega)=-(1/\pi)\mathrm{Im}G^{r}_{d\sigma}(\omega)$, and $f_{\alpha}(\omega)=(\mathrm{e}^{\beta(\omega-\mu_{\alpha})}+1)^{-1}$ is the Fermi distribution function of lead α. From Eq.(2), it is obvious to see that the current is closely related to the DOS of the QD, so we can obtain something about the information of the current by means of the DOS in the QD.

In order to obtain the retarded Green function, we make use of the equation-of-motion method.[13] In the limit $U\to\infty$, Green's function at the dot a is determined to be

$$G^{r}_{d\sigma}=\frac{1-\langle n_{d\bar{\sigma}}\rangle}{\omega-\varepsilon_{d\sigma}-\Sigma^{r}_{0\sigma}(\omega)-\Sigma^{r}_{1_{\sigma}}(\omega)-\eta^{r}_{0\sigma}(\omega)-\eta^{r}_{1\sigma}(\omega)+\mathrm{i}0^{+}} \quad (3)$$

with

$$\Sigma^{r}_{0\sigma}(\omega)=\sum_{k\alpha}\frac{|V_{k\alpha\sigma}|^2}{\omega-\varepsilon_{k\alpha\sigma}+\mathrm{i}0^{+}},\quad \Sigma^{r}_{1\sigma}(\omega)=\sum_{k\alpha}\frac{|V_{k\alpha\bar{\sigma}}|^2 f_{\mathrm{L}/R}(\varepsilon_{k\bar{\sigma}})}{\omega-\tilde{\varepsilon}_{d\sigma}+\tilde{\varepsilon}_{d\bar{\sigma}}-\varepsilon_{k\alpha\bar{\sigma}}+\mathrm{i}0^{+}}, \quad (4)$$

and

$$\eta^{r}_{0\sigma}(\omega)=\frac{t^2_{ab}}{\omega-\varepsilon_{d1}+\mathrm{i}0^{+}},\qquad \eta^{r}_{1\sigma}(\omega)=\frac{t^2_{ab}f(\varepsilon_{d1\bar{\sigma}})}{\omega-\varepsilon_{d1}-\tilde{\varepsilon}_{d\sigma}+\tilde{\varepsilon}_{d\bar{\sigma}}+\mathrm{i}0^{+}}, \quad (5)$$

where $\tilde{\varepsilon}_{d\sigma}$ represents the renormalized spin levels which are found to satisfy the self-consistent equation $\tilde{\varepsilon}_{d\sigma} = \varepsilon_{d\sigma} + \mathrm{Re}[\Sigma^r_{1\sigma}(\tilde{\varepsilon}_{d\sigma}, \tilde{\varepsilon}_{d\bar{\sigma}}) + \eta^r_{0\sigma}(\tilde{\varepsilon}_{d\sigma}, \tilde{\varepsilon}_{d\bar{\sigma}}) + \eta^r_{1\sigma}(\tilde{\varepsilon}_{d\sigma}, \tilde{\varepsilon}_{d\bar{\sigma}})]$. The occupation number operator of the QD with spin σ must be calculated self-consistently from $\langle n_{d\sigma}\rangle = -\dfrac{\mathrm{i}}{2\pi}\displaystyle\int \mathrm{d}\omega G^<_{d\sigma}(\omega)$, and the lesser Green function $G^<_{d\sigma}(\omega)$ at the dot is calculated by the Keldysh equation $G^<_{d\sigma} = G^r_{d\sigma}\Sigma^<_\sigma G^a_{d\sigma}$ with $\Sigma^<_\sigma = \Sigma^<_{0\sigma}(\Sigma^{\mathrm{R}}_{0\sigma} - \Sigma^A_{0\sigma})(\Sigma^{\mathrm{R}}_\sigma - \Sigma^A_\sigma)$, where $\Sigma^<_{0\sigma} = \mathrm{i}(\Gamma_{\mathrm{L}\sigma} f_{\mathrm{L}\sigma} + \Gamma_{\mathrm{R}\sigma} f_{\mathrm{R}\sigma})$, while the self-energies $\Sigma^{\mathrm{R}(A)}_\sigma$ satisfy $G^{r(a)}_{d\sigma} = \left(\omega - \varepsilon_{d\sigma} - \Sigma^{\mathrm{R}(A)}_\sigma\right)^{-1}$.

For simplicity, the temperature is taken as $T = 0.005\Gamma_0$, $\varepsilon_{d\sigma}$ (the energy level of the dot a) is fixed at $-4.0\Gamma_0$, and the conduction band has a constant DOS with the bandwidth $D = 100\Gamma_0$. The interdot coupling t_{ab} and the energy levels of dot b are assumed to be readily adjustable. Here Γ_0 is used as the unit of energy and E_{F} at the equilibrium is set to be zero as energy reference.

3. Results and discussion

In Fig.2, we plot the DOS of dot a in the P lead-polarization alignment for different values of the interdot coupling. The DOS without Fano interference ($t_{ab} = 0$) is presented for comparison. For $t_{ab} = 0$, we can see that the DOS shows a Breit–Wigner line shape centred at the Fermi energy. This peak is fully determined by the Kondo effect. When it comes to $t_{ab} \neq 0$, the DQD leads are active, and electrons in the dot b are localized for DQD leads. Therefore, the Fano interference begins to play a major role in complicating the DOS of dot a. The DOS profile with Fano interference depicted in Fig.2 can be decomposed into a Breit–Wigner and a Fano line shape, which agrees well with that in Refs.[14,15]. We can easily see that the DOS splits into double peaks because of the Fano interference, and it is completely suppressed when $\omega = \varepsilon_{d1}$, which is the energy of the side-coupled dot. It is obviously seen that with the increase of the value of t_{ab}, the peaks move in opposite directions while the position of the zero DOS remains unchanged at the dot b energy level. What is more, the distance between the peaks gets smaller and the Fano peak becomes sharper when t_{ab} goes down. An extreme case is that as t_{ab} reaches zero, the width of the Fano resonance becomes zero, so the Fano dip vanishes and the DOS profile reduces to the simple Breit–Wigner function. Additionally, from Fig.2(a) and Fig.2(b), it is noticeable to find that the Kondo peak is greatly enhanced when the value of t_{ab} increases, which means that the Kondo resonance can be controlled effectively by the value of the interdot coupling strength between the two dots.

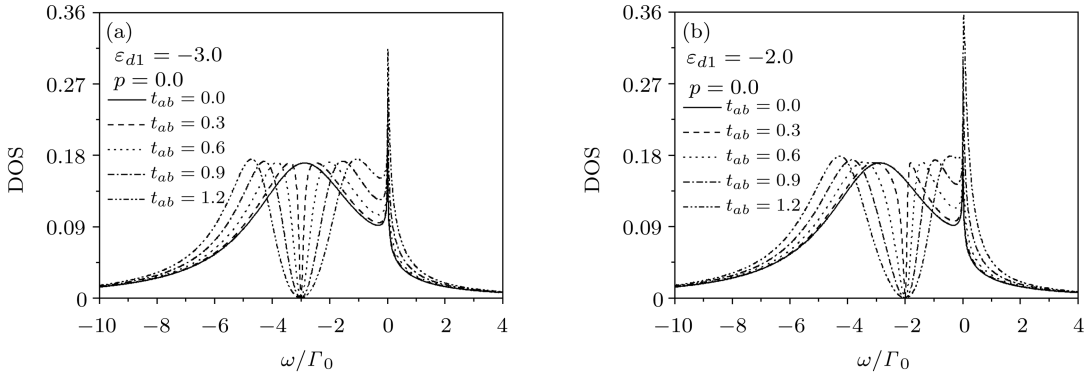


Fig.2. DOS of QD a in the P lead-polarization alignment for different values of the interdot coupling strength when the spin-polarization strength $p = 0$. (a) $\varepsilon_{d1} = -3.0\Gamma_0$, (b) $\varepsilon_{d1} = -2.0\Gamma_0$.

In Figs.3(a) and 3(b), the DOS of dot a for spin-up and spin-down configurations in the AP configuration are presented. In this case, there is a sharp Kondo peak at the Fermi energy and a Fano dip at the energy of the side-coupled dot b. Additionally, it is obviously seen that the DOS behaviour looks to be similar for spin-up and spin-down configurations, namely, the Kondo resonances for spin-up and spin-down configurations have the same position at the Fermi level. Even the Kondo peak is not influenced by the different values of the spin-polarization strength. In Figs.3(c) and 3(d), we plot the DOS of dot a for

spin-up (Fig.3(c)) and spin-down (Fig.3(d)) configurations in the P configuration. From the above figures, we can also easily find that the Kondo resonance is clearly manifested by a sharp peak at the Fermi energy in the DOS for the spin-up and spin-down configurations. But for the P configuration, the Kondo resonance splits, which is very different from the behaviour of the case for spins in the AP configuration. As shown in Fig.3, it can be easily seen that in the P configuration, the excitation characteristics of the DOS are remarkably different from the AP case in two prominent aspects: (i) The Kondo resonance for down-spin is enhanced with the increase of the value of the spin-polarization strength, while the up-spin resonance is suppressed; (ii) It is interesting that the broad single-particle resonances shift away from the Fermi level, but in opposite directions for different spins. The excitation for the down-spin shifts towards higher energy, while it shifts to lower energy for the up-spin. This result agrees well with that of Ref.[12], which is due to the splitting of the dot levels renormalized by the spin-dependent interacting self-energy $\tilde{\varepsilon}_{d\sigma}$ satisfying the self-consistent equation $\tilde{\varepsilon}_{d\sigma} = \varepsilon_{d\sigma} + \mathrm{Re}[\Sigma^{\mathrm{r}}_{1\sigma}(\tilde{\varepsilon}_{d\sigma}, \tilde{\varepsilon}_{d\bar{\sigma}}) + \eta^{\mathrm{r}}_{0\sigma}(\tilde{\varepsilon}_{d\sigma}, \tilde{\varepsilon}_{d\bar{\sigma}}) + \eta^{\mathrm{r}}_{1\sigma}(\tilde{\varepsilon}_{d\sigma}, \tilde{\varepsilon}_{d\bar{\sigma}})]$.[16] And this spin splitting of the dot levels in the interacting regime due to the magnetic properties of the electrodes leads to essential changes in the transport properties.[12]

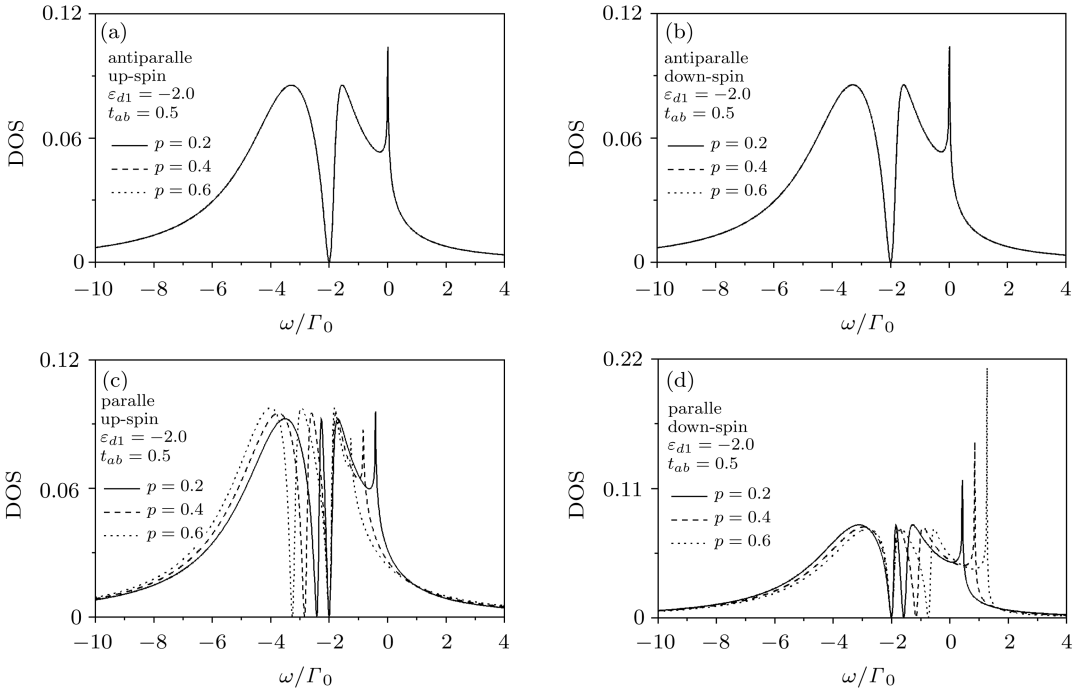


Fig.3. DOS of dot a with both AP and P lead-polarization alignments for spin-up and spin-down configurations, calculated for various values of the spin-polarization strength p. Here the energy level of dot a is set to be $-2.0\Gamma_0$ and the interdot coupling is equal to 0.5.

Figure 4 displays the DOS of dot a for spins in the AP lead-polarization alignment with the spin-polarization strength $p = 0.5$ in leads and the interdot coupling $t_{ab} = 0.5$. We can easily see that there is a sharp Kondo peak at the Fermi level. As shown in Figs.4(a), 4(b), 4(c), 4(d) and 4(e), the impact of the energy change of the side-coupled QD b on Kondo resonance is slight, and the DOS is completely suppressed when $\omega = \varepsilon_{d1}$, which is the same as the case in Fig.2. However, the Kondo resonance is enhanced dramatically when the energy is tuned at the Fermi energy (Fig.4(f)). From Fig.4, we can also find that in the AP configuration, a remarkable point is that the behaviour of the DOS seems to be similar for spin-up and spin-down configurations. This is because the Kondo resonances for up-spins and down-spins have the same position at the Fermi level as depicted in Fig.4. Even the DOS is not affected by the variance of magnetic polarization of the leads. In this case (AP configuration), the DOS for up- and down-spins in leads are the same, namely, $\rho_{\mathrm{L}\uparrow} + \rho_{\mathrm{R}\uparrow} = \rho_{\mathrm{L}\downarrow} + \rho_{\mathrm{R}\downarrow}$, and the spin current of electrons cannot be polarized.

Therefore, under the condition of AP configuration, the effect of the left lead on dot a counteracts that of the right lead on dot a. So, in addition to the influence of the spin-polarization strength, the rate of each spin (up-spin and down-spin) in the quantum dot remains the same, resulting in no net magnetic moment in dot a. This moment (i.e. the usual Fano and Kondo resonance) forms, which is the same as those for nonmagnetic electrodes, and up-spin electrons make the same contribution to the DOS as down-spin electrons behave. Therefore, these graphs are just the same as that in the condition of the P lead-polarization alignment with spin-polarized strength $p = 0$.

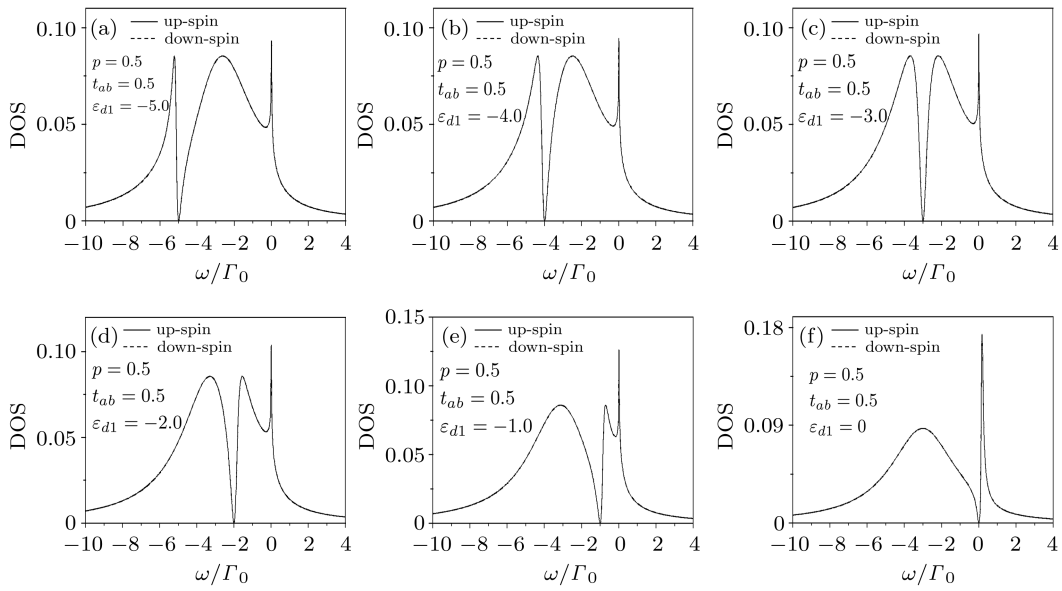


Fig.4. Spin-dependent DOS of QD a in the AP lead-polarization alignment for spin-up and spin-down configurations.

In order to clearly observe the characteristic spin-dependence in the DOS, let us consider the contribution of up- and down-spin electrons in the P lead-polarization alignment with the spin-polarization strength $p = 0.5$ in the leads and the interdot coupling $t_{ab} = 0.5$, too. As shown in Fig.5, we can see that the contribution of up-spin electrons is dramatically different from that of down-spin electrons. This happens because in the P configuration and when $p \neq 0$, there is an overall asymmetry for up- and down-spins, namely, $\rho_{\mathrm{L}\uparrow} + \rho_{\mathrm{R}\uparrow} > \rho_{\mathrm{L}\downarrow} + \rho_{\mathrm{R}\downarrow}$, so the hybridization for up-spins is larger than that for down-spins ($\Gamma_{\alpha\uparrow} > \Gamma_{\alpha\downarrow}$) because of the spin-dependent DOS in leads. Additionally, the bare level $\varepsilon_{d\sigma}$ is renormalized and the up-spin (down-spin) electron lowers (raises) its energy. Thus, the average occupation of the QD with up-spins is larger than those with down-spins ($n_{d\uparrow} > n_{d\downarrow}$). What is more, it can be easily seen from the Fig.5 that the Kondo resonance splits, which is very different from the behaviour of the case for spins in the AP lead-polarization alignment. This is mainly caused by the splitting of the dot levels renormalized by the spin-dependent interacting self-energy $\tilde{\varepsilon}_{d\sigma}$. From Fig.5, we can easily find that for up-spin electrons, the Kondo resonance is suppressed, while it is enhanced greatly for down-spins and it is very much stronger than that of up-spins. Moreover, it is obviously seen that the Kondo peak shifts away from the Fermi level and moves in opposite directions for different spins. For up-spin electrons, it moves left, while it moves right for down-spin electrons. And we can obtain that the distance of the shift for the up-spin is $\tilde{\varepsilon}_{d\uparrow} - \tilde{\varepsilon}_{d\downarrow}$, while it is $\tilde{\varepsilon}_{d\downarrow} - \tilde{\varepsilon}_{d\uparrow}$ for the down-spin. The reason is that there is the antiferromagnetic coupling in the electrons of electrodes and quantum dot, resulting in a higher rate of down-spin than up-spin, and the net magnetic moment of the QD which is related to the magnetic strength of electrodes is not zero. On the other hand, we found that due to the energy split caused by the polarization, the DOS splits again compared with that in the condition of the AP configuration. The energy level ε_{d1} of the side-coupled QD

for up-spin electrons becomes ε_{d1} and $\varepsilon_{d1}+\tilde{\varepsilon}_{d\uparrow}-\tilde{\varepsilon}_{d\downarrow}$, and the energy level ε_{d1} of down-spin electrons ε_{d1} and $\varepsilon_{d1}+\tilde{\varepsilon}_{d\downarrow}-\tilde{\varepsilon}_{d\uparrow}$. As discussed above, the DOS is completely suppressed when ω is equal to the energy level of side-coupled dot b, so two dips in the DOS graphs occur. Meanwhile, in Fig.5(f), the Kondo resonance is also enhanced greatly when the energy is tuned at the Fermi energy, as mentioned in the condition of the AP configuration.

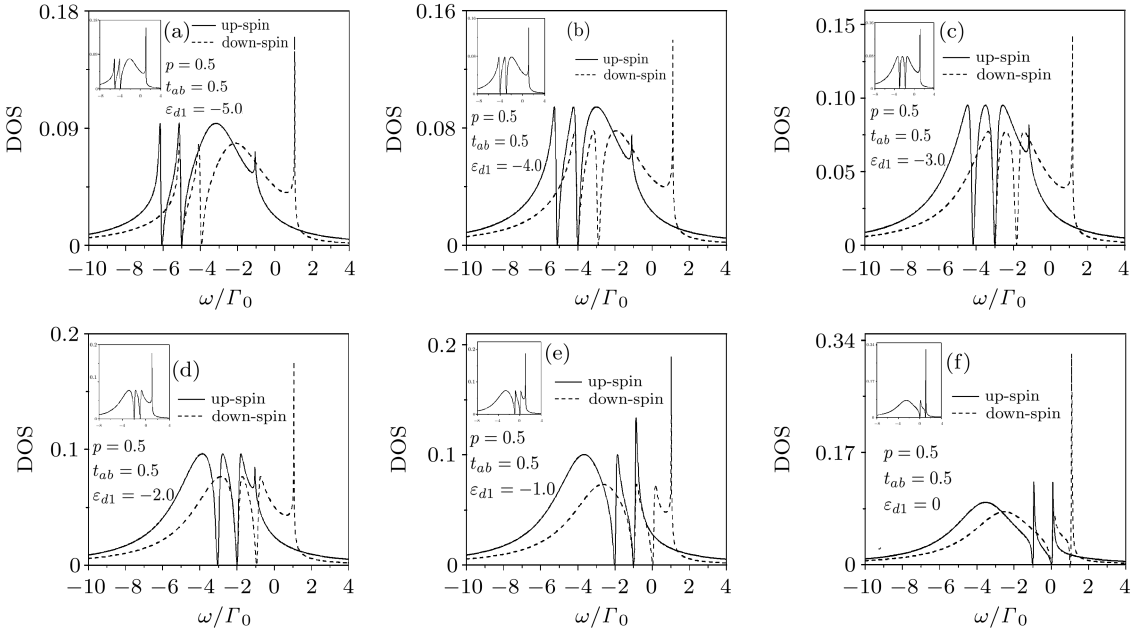


Fig.5. Spin-dependent DOS of QD a in the P lead-polarization alignment for spin-up and spin-down configurations. Insets are the graphs for down-spin configuration.

4. Conclusion

In summary, by applying the equation-of-motion technique, we have presented a qualitative study of spin-polarized transport properties of the T-shaped DQD system in the Kondo regime. It is shown that the interdot coupling, the spin-polarized strength and the energy level of the side couple QD play an essential role in the DOS of dot a: either the increase of the interdot coupling strength or that of the energy level of the side coupled QD enhances the Kondo resonance. Especially, the Kondo resonance is strengthened greatly when the side dot energy is tuned at the Fermi energy. Meanwhile, the Kondo resonance splits for the spin-up and spin-down configurations due to polarization: the down-spin resonance is enhanced, while the up-spin resonance is suppressed. The behaviours of them provide more information about the properties in the T-shaped DQD system, and the rich physical characteristics can be attributed to the coexistence of the Fano–Kondo effect and provide more information about the properties in the T-shaped DQD system. We expect these novel results are helpful in exploiting the role of electronic correlation in spintronics, such as exploiting the spin-filter devices.

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