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Spin-polarized transport through the T-shaped double quantum dots*

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Using the Keldysh nonequilibrium Green function and equation-of-motion technique, this paper investigates the spin-polarized transport properties of the T-shaped double quantum dots (DQD) coupled to two ferromagnetic leads. There are both Fano effect and Kondo effect in the system, and due to their mutual interaction, the density of states, the current, and the differential conductance of the system depend sensitively on the spin-polarized strength. Thus the obtained results show that this system is provided with excellent spin filtering property, which indicates that this system may be a candidate for spin valve transistors in the spintronics.

Keywords: spin polarized transport, Fano–Kondo effect, quantum dots
PACC: 7225, 7520H, 7320D

1. Introduction

Recent intensive investigations of electron transport through quantum dot (QD) systems have uncovered correlation effects in nanoscale systems. In particular, the observation of the Kondo effect[1−5] in QD systems opened a new path for the investigation of quantum correlation between localized spin in QD and the free lead. 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 interests among researches in microelectronic systems. The T-shaped double quantum dots (DQD)[7−9] system is a prototype of such correlated systems which is suited for investigating both the Fano effect and Kondo effect (Fano–Kondo effect). There are a variety of parameter settings in the T-shaped DQD system, which show somewhat different transport properties from the parallel or series DQD system. 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 effect affects the characteristic transport properties in the T-shaped DQD system. Meanwhile, since the Kondo effect stems from many body effects relating to intrinsic spin degrees of freedom, magnetic fields have a great influence on transport properties, which has resulted in intensive study of the spin-dependent[10] transport through various resonant tunnelling QD structures due to their importance in physics.

Our work has been concentrated on the Keldysh nonequilibrium Green function technique[11] to study the spin polarized transport properties with Fano–Kondo interaction in the T-shaped DQD system shown schematically in Fig.1. The paper is organized as follows. In Sec.2 we give a description about the theoretical model for this system. Section 3 gives a detailed discussion of our calculated results. The last section sums up our conclusions.

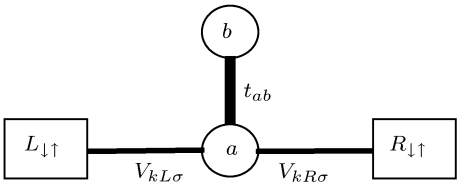


Fig.1. Schematic picture of the T-shaped DQD system. Dot a is connected with the ferromagnetic (FM) leads, dot b is side coupled to dot a, t_{ab} is the interdot coupling and $V_{k\alpha\sigma}$ ($\alpha = L, R\sigma = \uparrow, \downarrow$) represents the dot-lead tunnelling for dot a with spin σ.

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2. Model and solution

In this paper, we use a $N(=2)$ fold degenerate Anderson Hamiltonian to investigate the transport properties of the T-shaped DQD system. In the following discussions, the intradot Coulomb interaction U ($U\rightarrow\infty$) on each dot is assumed to be sufficiently large to prevent the double occupancy. This assumption allows us to use a slave-boson representation[12] of correlated electrons in the dots. In this representation, the Hamiltonian can be written as

$$H=\sum_{k\alpha\sigma}\varepsilon_{k\alpha\sigma}c^{+}_{k\alpha\sigma}c^{+}_{k\alpha\sigma}\sum_{\sigma;m=a,b}\varepsilon_m f^{+}_{m\sigma}f_{m\sigma}+\frac{1}{\sqrt{N}}\sum_{k\alpha\sigma}V_{k\alpha\sigma}(c^{+}_{k\alpha\sigma}b^{+}_{a}f_{a\sigma}+\mathrm{H.C})$$
$$+\frac{t_{ab}}{\sqrt{N}}\sum_{\sigma}(f^{+}_{a\sigma}b_a b^{+}_{b}f_{b\sigma}+\mathrm{H.C})+\sum_{m=a,b}\lambda_m\Big(b^{+}_{m}b_m+\sum_{\sigma}f^{+}_{m\sigma}f_{m\sigma}-1\Big). \quad (1)$$

The first and second term in the Hamiltonian represent the electronic states in the leads and the dots, where $c^{+}_{k\alpha\sigma}(c_{k\alpha\sigma})$ is the creation (annihilation) operator of an electron with energy $\varepsilon_{k\alpha\sigma}$ and spin σ in the lead α (α=L, R). The coupling between the lead and dot a (between the two dots) is given by the third (fourth) term in the Hamiltonian. The last term with the Lagrange multiplier λ_m is introduced so as to incorporate the constraint imposed on the slave particles $\sum_{\sigma=\uparrow\downarrow}f^{+}_{m\sigma}f_{m\sigma}+b^{+}_{m}b_m$=1, where $b_m(f_{m\sigma})$ is the slave-boson (pseudofermion) annihilation operator for an empty state (singly occupied state). The mixing term in the Hamiltonian $V_{k\alpha\sigma}$ leads to the line width function $\Gamma^{\alpha}_{\sigma}(\varepsilon)=\pi\sum_{k\alpha\sigma}V^{2}_{k\ \alpha\sigma}\delta(\varepsilon-\varepsilon_{k\alpha\sigma})$. Here, we introduce the effective spin polarization strength p following the definition given in Ref.[13] $p=\Gamma^{\alpha}_{\sigma}-\Gamma^{\alpha}_{\bar{\sigma}}/\Gamma^{\alpha}_{\sigma}+\Gamma^{\alpha}_{\bar{\sigma}}$ ($0\leq p\leq 1$) and this definition of p is equivalent to the condition imposed on $\Gamma^{L(R)}_{\uparrow}=(1+p)\Gamma^{L(R)}|_{P=0}$, $\Gamma^{L(R)}_{\downarrow}=(1-p)\Gamma^{L(R)}|_{P=0}$ for up-spin (majority-spin) electrons and down-spin (minority-spin) electrons respectively.

To analyse the model, we apply the mean field approximation to the slave-boson treatment. We introduce the renormalized quantities $\tilde{V}_{k\alpha\sigma}=V_{k\alpha\sigma}\tilde{b}_a$, $\tilde{t}_{ab}=t_{ab}\tilde{b}_a\tilde{b}_b$, $\tilde{\varepsilon}_m$=ε_m+λ_m. The mean-field values of $\tilde{b}_a,\tilde{b}_b,\lambda_a$, and λ_b are determined by the following self-consistent equations, which are derived by the equation of motion method for the nonequilibrium Keldysh functions,[14]

$$\tilde{b}^{2}_{a(b)}-\mathrm{i}\sum_{\sigma}\int\frac{\mathrm{d}\varepsilon}{4\pi}G^{<}_{a,a(b,b)\sigma}(\varepsilon)=\frac{1}{2}, \quad (2)$$

$$\lambda_{a(b)}\tilde{b}^{2}_{a(b)}=\mathrm{i}\sum_{\sigma}\int\frac{\mathrm{d}\varepsilon}{4\pi}(\varepsilon-\tilde{\varepsilon}_{a(b)\sigma})G^{<}_{a,a(b,b)\sigma}(\varepsilon). \quad (3)$$

In the above equations, $G^{<}_{a,a(b,b)\sigma}(\varepsilon)$ is the Fourier transform of the Keldysh Green function $G^{<}_{a,a(b,b)\sigma}(t-t')=\mathrm{i}<f^{+}_{a(b)\sigma}(t'),\ f_{a(b)\sigma}(t)>$. From the equation of the operator $f_{m\sigma}$,[15] we have the explicit form of the Green function,

$$G^{<}_{a,a\sigma}(\varepsilon)=2\mathrm{i}(\tilde{\Gamma}^{L}_{\sigma}f_L(\varepsilon)+\tilde{\Gamma}^{R}_{\sigma}f_R(\varepsilon))(\varepsilon-\tilde{\varepsilon}_b)^2/|D_\sigma(\varepsilon)|^2, \quad (4)$$

$$G^{<}_{b,b\sigma}(\varepsilon)=2\mathrm{i}(\tilde{\Gamma}^{L}_{\sigma}f_L(\varepsilon)+\tilde{\Gamma}^{R}_{\sigma}f_R(\varepsilon))\tilde{t}^{2}_{ab}/|D_\sigma(\varepsilon)|^2, \quad (5)$$

with $\tilde{\Gamma}^{\alpha}_{\sigma}=\tilde{b}^{2}_{a}\Gamma^{\alpha}_{\sigma}$ and $\tilde{\Gamma}_{\sigma}=\tilde{\Gamma}^{L}_{\sigma}+\tilde{\Gamma}^{R}_{\sigma}$ ($m=a,b$ and α=L, R), where the denominator of Eqs.(4) and (5) is $D_\sigma(\varepsilon)$=$(\varepsilon-\tilde{\varepsilon}_a+\mathrm{i}\tilde{\Gamma}_\sigma)(\varepsilon-\tilde{\varepsilon}_b)-\tilde{t}^{2}_{ab}$. From the renormalized parameter determined self-consistently in Eqs.(2) and (3), we obtain the density of states (DOS) of the two dots as $\rho_a(\varepsilon)=-\sum_\sigma\frac{\tilde{b}^{2}_{a}}{\pi}\mathrm{Im}((\varepsilon-\tilde{\varepsilon}_b)/D_\sigma(\varepsilon))$ and $\rho_b(\varepsilon)$ =$-\sum_\sigma\frac{\tilde{b}^{2}_{b}}{\pi}\mathrm{Im}((\varepsilon-\tilde{\varepsilon}_a+\mathrm{i}\tilde{\Gamma}_\sigma)/D_\sigma(\varepsilon))$.

Applying the Landauer formula in steady state, we can derive the current through the two dots,[16]

$$I=\frac{2e}{h}\sum_{\sigma}\int\mathrm{d}\varepsilon(f_L(\varepsilon)-f_R(\varepsilon))T_\sigma(\varepsilon), \quad (6)$$

where the transmission probability is given by

$$T_\sigma(\varepsilon)=2\tilde{\Gamma}^{L}_{\sigma}\tilde{\Gamma}^{R}_{\sigma}(\varepsilon-\tilde{\varepsilon}_b)^2/|D_\sigma(\varepsilon)|^2. \quad (7)$$

We can thus compute the differential conductance $G=\mathrm{d}I/\mathrm{d}V$ from the current I in Eq.(6).

For simplicity, the band width of the leads is taken as $D=60\Gamma_0$ and the energy level of the two dots is fixed at ε_a=$\varepsilon_b=-3.0\Gamma_0$ (Kondo regime with $T^{0}_{k}=10^{-3}\Gamma_0$). we choose two typical values: $t_{ab}=0.3$ for the weak inter-dot coupling and $t_{ab}=2.0$ for the strong interdot coupling. In the following calculation we assume $\Gamma^{L}_{\sigma}=\Gamma^{R}_{\sigma}$ and take $\Gamma_0=\Gamma^{L}_{\sigma}|_{P=0}+\Gamma^{R}_{\sigma}|_{P=0}$ as the unit of energy.

3. Results and discussion

In Fig.2, we plot the total DOS of the two dots in the equilibrium case. For $t_{ab} = 0.3$ (Figs.2(a) and 2(b)), the Kondo resonance is formed around the Fermi energy for the two dots, but $\rho_b(\varepsilon)$ yields a much smaller value than $\rho_a(\varepsilon)$ with increasing p (Fig.2(b)). However, for $t_{ab} = 2.0$ (Fig.2(c)) the width of the Kondo resonance for dot a (with a sharp dip) is changed with the variance of the spin polarization of the leads and the Kondo resonance splits into double peaks with an invariable $\rho_a(0)$ around the Fermi energy. While the DOS of dot b (Fig.2(d)) does not change much as that in the weak interdot coupling strength when $p < 0.5$, however the down spin DOS of dot b splits into double peaks when $p > 0.5$, which can be seen form the inset of Fig.2(d). Such differences can be interpreted as follows: in the weak interdot coupling, the moments of the Kondo states of the DQD do not combine into two molecular states, and the molecular state is suppressed by the presence of a pseudogap in the effective DOS. The weak exchange J can be neglected and this DQD system is similar to $t_{ab} = 0.0$ situation (inset of Fig.2(a)), which is accordant with Ref.[17] that the Kondo resonance is also formed in the Fermi energy. At the same time, dot b seems to be an isolated dot, which can contribute to the small value of the DOS of dot b. In the strong coupling regime, a quantum critical point on the boundary between the bonding and antibonding Kondo states can be reached, the two dots are coupled coherently and form an artificial molecule, the energy levels of the bonding and antibonding orbits are formed by the coherent superposition of the Kondo states of each dot, the energy levels of the bonding and antibonding states split clearly, so the Kondo resonance peak splits into two peaks. We also mention that when the two leads are not polarized ($p = 0.0$), we can get the same results as that in the Ref.[18]. When we come to the dot b, according to the definition of p, the width of Kondo resonance of dot b for down-spin electrons becomes broad as p increases, therefore, the corresponding peak in $\rho_b(\varepsilon)$ splits into two sub-peaks as p increases, which is what we see from the inset of Fig.2(d).

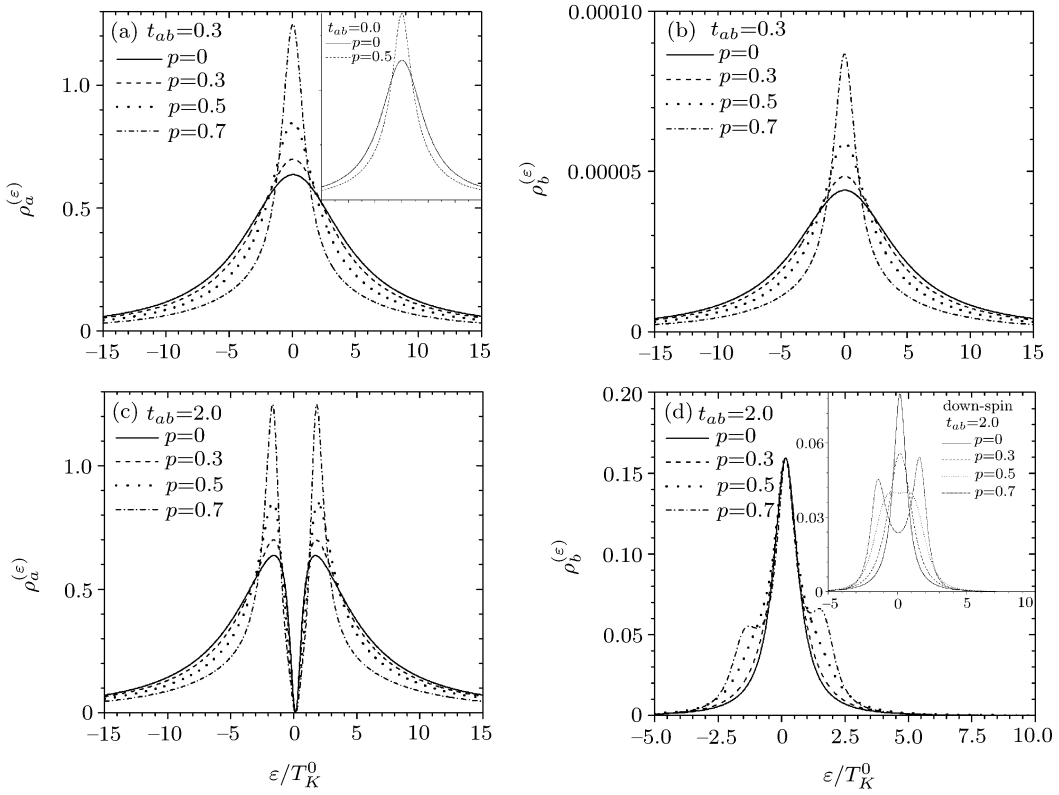


Fig.2. DOS for dot a and dot b in the equilibrium case.

Figure 3 shows the DOS of the two dots in the nonequilibrium case. We find that the DOS of dot a changes slightly with the increasing V in both the weak and strong interdot coupling, for that the interdot coupling between the two dots is much larger than the applied bias. While the DOS of dot b changes slightly by the chemical potential in the strong interdot coupling case, namely, the Kondo resonance of the down-spin electrons becomes narrow with the increase of chemical potential, which can be seen from the inset of Fig.3(d). Furthermore, we owe such a fact that $\varepsilon_a = \varepsilon_b$ and $\Gamma_\sigma^L = \Gamma_\sigma^R$, the symmetric structure of the system makes the electrons transport the device systematically. We can figure out from Figs.2 and 3 that the transport properties of the system are intensively controlled by the spin-polarized strength of the leads, namely, the width of the Kondo resonance is broadened (sharpened) for the up (down) spin electrons under the control of spin-polarized strength p. We may know that the system provides an example of a controlled setting in which to investigate quantum-critical behaviour in a strongly correlated system in both the equilibrium and nonequilibrium case. Besides the chemical potential can also influence the transport properties of the system which can be known from the differential conductance and the current of the system in Fig.4.

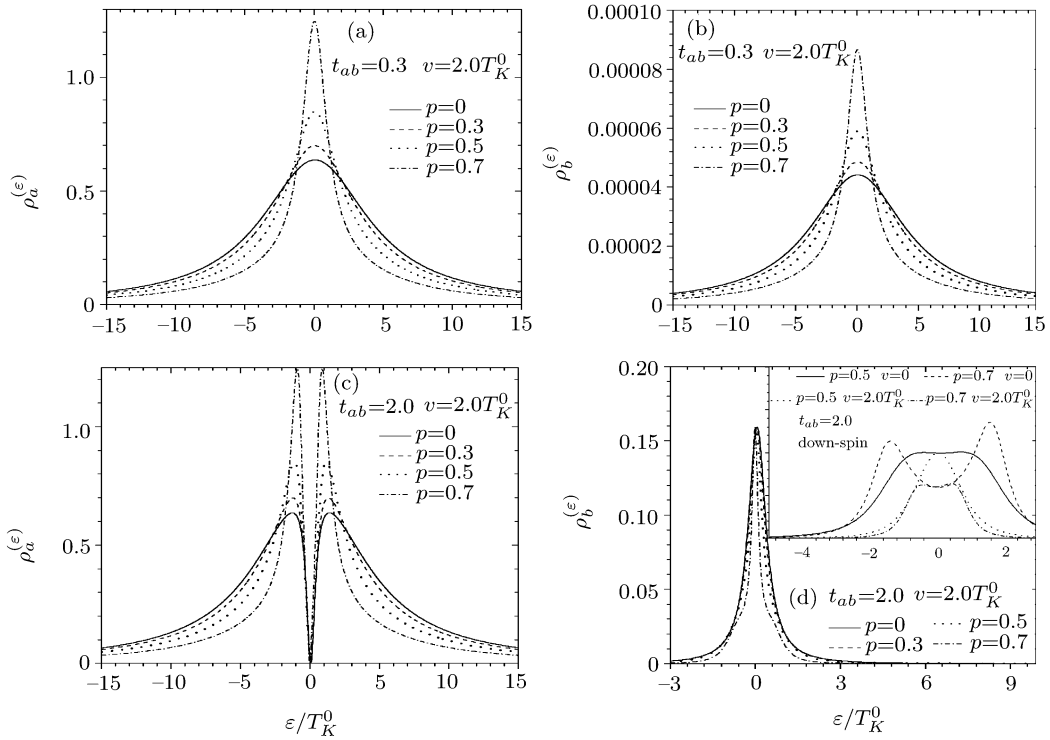


Fig.3. DOS for dot a and dot b in the nonequilibrium case.

As shown in Fig.4, the differential conductance and the current are plotted. Since we fixed $\varepsilon_a = \varepsilon_b$, the differential conductance (the current) must be symmetric (asymmetric) across the zero bias which is what we found in Fig.4. In the weak interdot coupling (Figs.4(a) and 4(c)), only dot a is active, the unitary limit of the differential conductance (Fig.4(a)) at zero bias is reached. Note that, the DOS of the two dots in the weak interdot coupling is almost flat in the vicinity of the Fermi energy, so the current I is approximately linear in the bias voltage as p increases (Fig.4(c)). Besides, the electrons are localized on the individual dot, two dots are nearly decoupled and act just like an one dot system which is what we find in the DOS from Figs.2 and 3. While for $t_{ab} = 2.0$ the conductance (Fig.4(b)) shows a concave shape in the zero bias voltage and the current (Fig.4(d)) is getting smooth from Fano-like shape as p increases, which is attributed to the quantum Fano-interference effect by the two dots as a finite-size quantum cavity, and the down-spin DOS of dot b is obviously affected by the chemical potential, the energy level of dot b crosses over the Fermi

energy when interdot coupling gets strong, adding a new path for the electrons to go through, so the conductance (Fig.4(b)) is governed by both the Kondo and Fano effect. In the next place, owing to that the coupling between the two dots is much larger than the applied bias voltage, the current is very weak in the low bias voltage. What is more, electrons in the quantum dot will experience various interactions and the occurrence of a nontrivial suppression of the conductance is associated with a Fano–Kondo effect between two distinct channels: one is the Kondo scattering off the effective spin in the side-connected dot, and the other is the Fano interference between two paths (a direct path of left electrode-active dot a- right electrode ($L-a-R$) and an indirect path of left electrode-active dot a-side dot b-active dot a-right electrode (L–a–b–a–R)). According to principle of conservation of energy, the higher the voltage, the stronger the current, so we find that the current rises sharply with a positive value for $V \leq 0.5$. Although the current flows mainly through the dot-a in the system, dot b still plays an important role in controlling the current in the system. We may realize that the spin filtering effect is fully caused not only by the interplay of Fano–Kondo effect, but also the special quantum dot arrangement of the system.

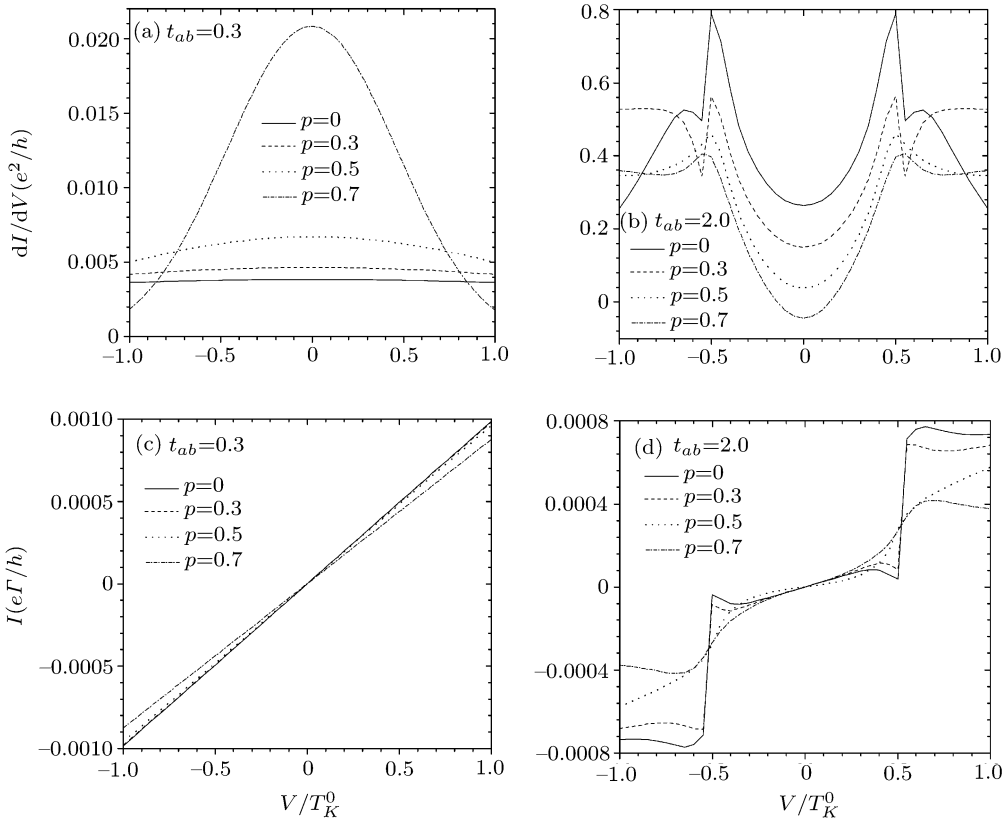


Fig.4. Differential conductance and the current of the system as a function of V.

4. Conclusion

In summary, we have presented the spin-polarized transport properties of the T-shaped DQD system by using the Keldysh equation of motion (EOM) method. Our results show that the DOS of the two dots depends sensitively on the spin-polarized strength for the weak and strong interdot coupling strength in both the equilibrium and nonequilibrium case. We also pay attention to the influence of the spin-polarized strength p on the differential conductance and the current of the system. The behaviours of them provide more information about the transport properties in the T-shaped DQD system, as well as that the rich physical behaviour can be attributed to the coexistence of both the Fano effect and Kondo effect. The T-shaped DQD system is also a very promising quantum dot configuration, it may provide the optimal environment for

the study of the Kondo effect and Fano effect. Such system involving single or multiple quantum dots may provide many opportunities for strong interaction effects, which stimulate further experimental and theoretical studies in the spintronics.

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