Vol 17 No 1, January 2008
1674-1056/2008/17(01)/0296-07

Chinese Physics B

© 2008 Chin. Phys. Soc.
and IOP Publishing Ltd

Spin-flip process through double quantum dots coupled to two half-metallic ferromagnetic leads*

Yan Cong-Hua(闫从华)[a)†], Wu Shao-Quan(吴绍全)[a)],
Huang Rui(黄 睿)[b)], and Sun Wei-Li(孙威立)[a)]

[a)] *College of Physics and Electronic Engineering, Sichuan Normal University, Chengdu* 610068, *China*
[b)] *College of Sciences of Southwest Petroleum University, Chengdu* 610500, *China*

(Received 26 December 2006; revised manuscript received 2 April 2007)

We investigate the spin-flip process through double quantum dots coupled to two half-metallic ferromagnetic leads in series. By means of the slave-boson mean-field approximation, we calculate the density of states in the Kondo regime for two different configurations of the leads. It is found that the transport shows some remarkable properties depending on the spin-flip strength. These effects may be useful in exploiting the role of electronic correlation in spintronics.

Keywords: spin-flip, double quantum dots, half-metallic ferromagnetic leads
PACC: 7335, 7335C, 7215Q

1. Introduction

In recent years, the double-quantum-dot (DQD) systems have attracted much attention because of their importance in physics and device applications.[1−10] In contrast to the single quantum dot (QD), the DQD systems have richer physics. On the one hand, with recent advances in nanofabrication technology, the related experiments can be preformed under controlled circumstances, and the DQD systems provide an ideal model system for the study of the two-impurity effect,[10] which has long been the highlight in condensed-matter physics.[11] On the other hand, a series-coupled DQD can cross over from the weak tunnelling regime to the strong tunnelling regime by varying the dot-dot coupling strength. In the weak tunnelling coupling regime, when the temperature is below the Kondo temperature, the Kondo resonance is formed in each dot and lead, and the tunnelling is dominated by hopping between the two Kondo states. On the contrary, in the strong tunnelling regime, the electrons are delocalized over both dots, and two dots are coupled coherently and form an artificial molecule. Therefore, the DQD systems have been suggested as possible candidates for building blocks of a quantum computer[12] and other possible device applications.[13] Recent theoretical and experiment studies have shown that coherent couplings between dots can be fulfilled by adjusting relevant parameters properly when the DQD systems are coupled to the electrodes,[14−16] where the Kondo resonance peak splits into two peaks as a result of the energy difference between the bonding and antibonding states in the Kondo regime.

Half-metallic ferromagnets (HMF) are ferromagnetic metallic compounds showing a spin polarization of $P = 100\%$ at the Fermi level $E_{\rm F}$ in the ideal case and at zero temperature. This means that the spin-resolved density of states (DOS) presents a metallic character only for one spin direction (usually majority-spin), with energy bands crossing $E_{\rm F}$; contrary to this, the other spin direction (minority-spin) behaves like an insulator with $E_{\rm F}$ inside a band gap. This exotic behaviour has inspired research not only in the field of basic science, but also for applications in spintronics, since the extreme spin polarization suggests that the HMF are ideal for inducing and manipulating the transport of spin-polarized electrons. In principle, HMF are ideal spin injectors and detectors, because under moderate voltage they can carry current in only one spin direction.

Since HMF were originally introduced in 1983,[17] the properties have been explored extensively.[18,19] Recently, it has been pointed out that we can con-

*Project supported by Scientific Research Fund of Sichuan Provincial Education Department of China (Grant No 2006A069) and Funds for Major Basic Research Project of Sichuan Province, China (Grant No 2006J13-155).
†E-mail: yanconghua99@yahoo.com.cn

trol the spin-state of a single electron spin trapped in a semiconductor quantum dot by laser cooling and the fidelity can reach as high as 99.8%.[20] But the properties of QD coupled to two HMF leads were seldom mentioned.[21] Therefore, we theoretically study spin-flip process through double quantum dots coupled to HMF leads in series. It is assumed that the left and right leads are fully polarized, where the relative orientation of magnetization between the two electrodes, namely, the parallel (P) and antiparallel (AP) configurations are considered. When the magnetic electrodes are in P configuration, we assume that the spin-majority electrons are up and the spin-minority electrons are down. We further assume that in the AP configuration the magnetization of the right electrode is reversed.

2. Formulation of the models

In Fig.1, the DQD system is described by an $N(=2)$-fold degenerate two-impurity Anderson Hamiltonian with the inter-dot tunnelling. In the limit $U \to \infty$ (U is the Coulomb repulsion in the QD), the Hamiltonian can be written in terms of auxiliary slave-boson operators plus constraints and spin-flip process:[14−16]

$$H = \sum_{k\alpha,\sigma} \varepsilon_{k\alpha\sigma} c^+_{k\alpha\sigma} c_{k\alpha\sigma} + \sum_{\alpha,\sigma} \varepsilon_{\alpha\sigma} f^+_{\alpha\sigma} f_{\alpha\sigma} + \frac{t_c}{N} \sum_{\sigma} (f^+_{L\sigma} b_L b^+_R f_{R\sigma} + f^+_{R\sigma} b_R b^+_L f_{L\sigma}) + r \sum_{\alpha,\sigma} (f^+_{\alpha\sigma} f^+_{\alpha\bar{\sigma}} + f^+_{\alpha\bar{\sigma}} f_{\alpha\sigma}) + \frac{1}{\sqrt{N}} \sum_{k\alpha,\sigma} V_{\alpha\sigma} (c^+_{k\alpha\sigma} b^+_\alpha f_{\alpha\sigma} + f^+_{\alpha\sigma} b_\alpha c_{k\alpha\sigma}) + \sum_\alpha \lambda_\alpha \left(\sum_\sigma f^+_{\alpha\sigma} f_{\alpha\sigma} + b^+_\alpha b_\alpha - 1 \right), \quad (1)$$

where $c^+_{k\alpha\sigma}(c_{k\alpha\sigma})$ is the creation (annihilation) operator of an electron with spin σ in the lead α ($\alpha = L, R$), and the fourth term is used to describe potential spin–orbit coupling, which may cause the spin rotation of an electron in the DQD. According to the slave-boson of electrons in the left or right dot, $d^+_{\alpha\sigma}(d_{\alpha\sigma})$ is replaced by $d^+_{\alpha\sigma} \to f^+_{\alpha\sigma} b_\alpha (d_{\alpha\sigma} \to f_{\alpha\sigma} b^+_{\alpha\sigma})$ where $b_\alpha(f_{\alpha\sigma})$ is the slave-boson (pseudo-fermion) annihilation operator of an empty state (singly occupied state). The last term with the Lagrange multiplier λ_α is introduced to incorporate the constraint imposed on the slave particles $\sum_{\sigma=\uparrow\downarrow} f^+_{\alpha\sigma} f_{\alpha\sigma} + b^+_\alpha b_\alpha = 1$. Here we only consider the symmetric dots with $\varepsilon_{L\sigma} = \varepsilon_{R\sigma} = \varepsilon_0$ and the line width function is $\Gamma^\alpha_\sigma(\varepsilon) = \pi \sum_{\alpha,\sigma} |V_{\alpha\sigma}|^2 \delta(\varepsilon - \varepsilon_{k\alpha\sigma})$. By introducing the effective spin-polarization strength $p = (\Gamma^\alpha_\sigma - \Gamma^\alpha_{\bar{\sigma}})/(\Gamma^\alpha_\sigma + \Gamma^\alpha_{\bar{\sigma}})$ $(0 \le p \le 1)$, $\Gamma^L_\uparrow = \Gamma^R_\uparrow = (1+p)\Gamma_0$, $\Gamma^L_\downarrow = \Gamma^R_\downarrow = (1-p)\Gamma_0$ are for the P configuration, and $\Gamma^L_\uparrow = \Gamma^R_\downarrow = (1+p)\Gamma_0$, $\Gamma^L_\downarrow = \Gamma^R_\uparrow = (1-p)\Gamma_0$ are for the AP configuration, where Γ_0 is the value at $p = 0$. To analyse our model, we use the slave-boson mean-field approximation,[4] in which boson fields are approximated by their mean values, $b_\alpha(t)/\sqrt{N} \to \langle b_\alpha(t) \rangle / \sqrt{N} = \tilde{b}_\alpha$, $\tilde{V}_{\alpha\sigma} = V_{\alpha\sigma}\tilde{b}_\alpha$, $\tilde{t}_c = t_c \tilde{b}_L \tilde{b}_R$, and $\tilde{\varepsilon}_\alpha = \varepsilon_0 + \lambda_\alpha$.

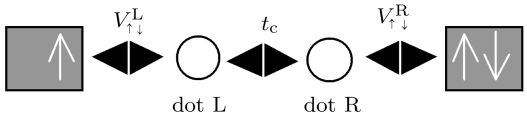


Fig.1. Schematic of the DQD system coupled to HFM leads, t_c is the inter-dot coupling and $V_{\alpha\sigma}(\alpha = L, R \;\; \sigma = \uparrow, \downarrow)$ represents the dot-lead tunnelling for an electron with spin σ.

To determine the mean-field values of ($\tilde{b}_L$, $\tilde{b}_R$, λ_L, λ_R), we employ the equation of motion method with the non-equilibrium Keldysh Green functions. This educes the following set of self-consistent equations,

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

$$(\tilde{\varepsilon}_{L(R)} - \varepsilon_0)\tilde{b}^2_{L(R)} - i \sum_\sigma \int \frac{d\varepsilon}{4\pi} (\varepsilon - \tilde{\varepsilon}_{L(R)}) G^<_{LL(RR)\sigma\sigma}(\varepsilon) = 0, \quad (3)$$

where $G^{<}_{\mathrm{LL(RR)}\sigma\sigma}(\varepsilon)$ is the Fourier transform of the Keldysh Green function $G^{<}_{\alpha\alpha'\sigma\sigma'}(t-t') = \mathrm{i}\langle f^{+}_{\alpha'\sigma'}(t')f_{\alpha\sigma}(t)\rangle$. From the equation of motion of the operator $f_{\alpha\sigma}$,[2,4] we have the explicit form of the Green function,

$$\begin{pmatrix} G^{<}_{\mathrm{LL(RR)}\sigma\sigma'} \\ G^{<}_{\mathrm{LL(RR)}\bar{\sigma}\sigma'} \\ G^{<}_{\mathrm{RL(LR)}\sigma\sigma'} \\ G^{<}_{\mathrm{RL(LR)}\bar{\sigma}\sigma'} \end{pmatrix} = \begin{pmatrix} \omega-\tilde{\varepsilon}_{\mathrm{L(R)}}+\mathrm{i}\tilde{\Gamma}_{\mathrm{L(R)}\sigma} & -r & -\tilde{t}_{\mathrm{c}} & 0 \\ -r & \omega-\tilde{\varepsilon}_{\mathrm{L(R)}}+\mathrm{i}\tilde{\Gamma}_{\mathrm{L(R)}\bar{\sigma}} & 0 & -\tilde{t}_{\mathrm{c}} \\ -\tilde{t}_{\mathrm{c}} & 0 & \omega-\tilde{\varepsilon}_{\mathrm{R(L)}}+\mathrm{i}\tilde{\Gamma}_{\mathrm{R(L)}\sigma} & -r \\ 0 & -\tilde{t}_{\mathrm{c}} & -r & \omega-\tilde{\varepsilon}_{\mathrm{R(L)}}+\mathrm{i}\tilde{\Gamma}_{\mathrm{R(L)}\bar{\sigma}} \end{pmatrix}^{-1} \times \begin{pmatrix} \tilde{\Gamma}_{\mathrm{L(R)}\sigma}f_{\mathrm{L(R)}}G^{a}_{\mathrm{LL(RR)}\sigma\sigma'} \\ \tilde{\Gamma}_{\mathrm{L(R)}\bar{\sigma}}f_{\mathrm{L(R)}}G^{a}_{\mathrm{LL(RR)}\bar{\sigma}\sigma'} \\ \tilde{\Gamma}_{\mathrm{R(L)}\sigma}f_{\mathrm{R(L)}}G^{a}_{\mathrm{RL(LR)}\sigma\sigma'} \\ \tilde{\Gamma}_{\mathrm{R(L)}\bar{\sigma}}f_{\mathrm{R(L)}}G^{a}_{\mathrm{RL(LR)}\bar{\sigma}\sigma'} \end{pmatrix}. \tag{4}$$

With $\tilde{\Gamma}^{\alpha}_{\sigma} = \tilde{b}^{2}_{\alpha}\Gamma^{\alpha}_{\sigma}$, $G^{a}_{\alpha\alpha'\sigma\sigma'} = (G^{\mathrm{r}}_{\alpha\alpha'\sigma\sigma'})^{*}$, where the representation of $G^{\mathrm{r}}_{\alpha\alpha'\sigma\sigma'}$ is

$$\begin{pmatrix} G^{\mathrm{r}}_{\mathrm{LL(RR)}\sigma\sigma'} \\ G^{\mathrm{r}}_{\mathrm{LL(RR)}\bar{\sigma}\sigma'} \\ G^{\mathrm{r}}_{\mathrm{RL(LR)}\sigma\sigma'} \\ G^{\mathrm{r}}_{\mathrm{RL(LR)}\bar{\sigma}\sigma'} \end{pmatrix} = \begin{pmatrix} \omega-\tilde{\varepsilon}_{\mathrm{L(R)}}+\mathrm{i}\tilde{\Gamma}_{\mathrm{L(R)}\sigma} & -r & -\tilde{t}_{\mathrm{c}} & 0 \\ -r & \omega-\tilde{\varepsilon}_{\mathrm{L(R)}}+\mathrm{i}\tilde{\Gamma}_{\mathrm{L(R)}\bar{\sigma}} & 0 & -\tilde{t}_{\mathrm{c}} \\ -\tilde{t}_{\mathrm{c}} & 0 & \omega-\tilde{\varepsilon}_{\mathrm{R(L)}}+\mathrm{i}\tilde{\Gamma}_{\mathrm{R(L)}\sigma} & -r \\ 0 & -\tilde{t}_{\mathrm{c}} & -r & \omega-\tilde{\varepsilon}_{\mathrm{R(L)}}+\mathrm{i}\tilde{\Gamma}_{\mathrm{R(L)}\bar{\sigma}} \end{pmatrix}^{-1} \times \begin{pmatrix} 1 \\ 0 \\ 0 \\ 0 \end{pmatrix}. \tag{5}$$

Moreover, we obtain the density of states for the dot $\alpha(\alpha = \mathrm{L,R})$ as $\rho_{\alpha\sigma}(\varepsilon) = -1/\pi\tilde{b}^{2}_{\alpha}\mathrm{Im}G^{\mathrm{r}}_{\alpha\alpha\sigma\sigma}(\varepsilon)$, in which $G^{\mathrm{r}}_{\alpha\alpha\sigma\sigma}(\varepsilon)$ is the Fourier transform of the Keldysh Green function $G^{\mathrm{r}}_{\alpha\alpha'\sigma\sigma'}(t-t') = -\mathrm{i}\theta(t-t')\left\langle\left\{f_{\alpha\sigma}(t), f^{+}_{\alpha'\sigma'}(t')\right\}\right\rangle$.

3. Results

Next, we discuss the results computed at absolute zero in the equilibrium and non-equilibrium cases separately with the DQD coupled to HMF or ferromagnetic (FM) leads. To be simple, the bandwidth of the leads is taken as $D = 60\ \Gamma_0$ and the bare level for two dots is fixed as $\varepsilon_0 = -3.5\ \Gamma_0$ (Kondo regime with $T^{0}_{\mathrm{K}} = 10^{-3}\Gamma_0$). Γ_0 is used as the unit of the energy and the Fermi level at $V = 0$ as the origin of the energy. We choose two typical values: $t_{\mathrm{c}} = 0.3$ for the weak inter-dot coupling and $t_{\mathrm{c}} = 3.0$ for the strong inter-dot coupling.

The transport properties in the equilibrium ($V = 0$) case are studied first. We denote the DOS for the left and right dots as $\rho_{\sigma}(\varepsilon) = \rho_{\mathrm{L}\sigma}(\varepsilon) = \rho_{\mathrm{R}\sigma}(\varepsilon)$ in the P configuration and $\rho_{\mathrm{L}\sigma}(\varepsilon) = \rho_{\mathrm{R}\bar{\sigma}}(\varepsilon)$ in the AP configuration.

As shown in Fig.2, when $r = 0$, for $t_{\mathrm{c}} = 0.3$ (Fig.2(a) and 2(b)), the Kondo resonance is formed in each dot and lead, and the tunnelling is dominated by hopping between the two Kondo states. But for $t_{\mathrm{c}} = 3.0$ (Fig.2(c) and 2(d)), the two dots are coupled coherently and form an artificial molecule, the energy levels of the bonding and antibonding states split clearly, the bonding and anti bonding orbits are formed by the coherent superposition of the Kondo states of each dot, so the Kondo resonance peak splits into two peaks. Remarkably, by increasing the value of the spin-flip transition r, we find some exotic phenomena. For relatively small values of $r(r < T^{0}_{\mathrm{K}})$,

the height of the Kondo peaks decreases but the DOS does not split. The appearance of a splitting occurs at $r \sim T_{\rm K}^0$. Importantly, due to the coexistence of the Kondo state and the intradot spin-flips, the positions of the peaks in the DOS are renormalized by Kondo correlations. For large values of r ($r > T_{\rm K}^0$), the splitting becomes more obvious. When the leads are 100% polarized, as shown in Fig.3, we find that both the spin-up and spin-down cases are the same as the FM case when $t_{\rm c} = 0.3$. However, when DQD are strongly coupled $t_{\rm c} = 3.0$ (Figs.3(c) and 3(d)), the spin-up peaks are split into four from three and the spin-down ones change from two sharp Kondo peaks into three that are not obvious. These phenomena are different from those in the FM case, caused by the increasing magnitude of the polarization. The splitting is due to the coupling of spin-flip transition process between the dot and the magnetic electrodes and can be expressed by the high order self-energy.

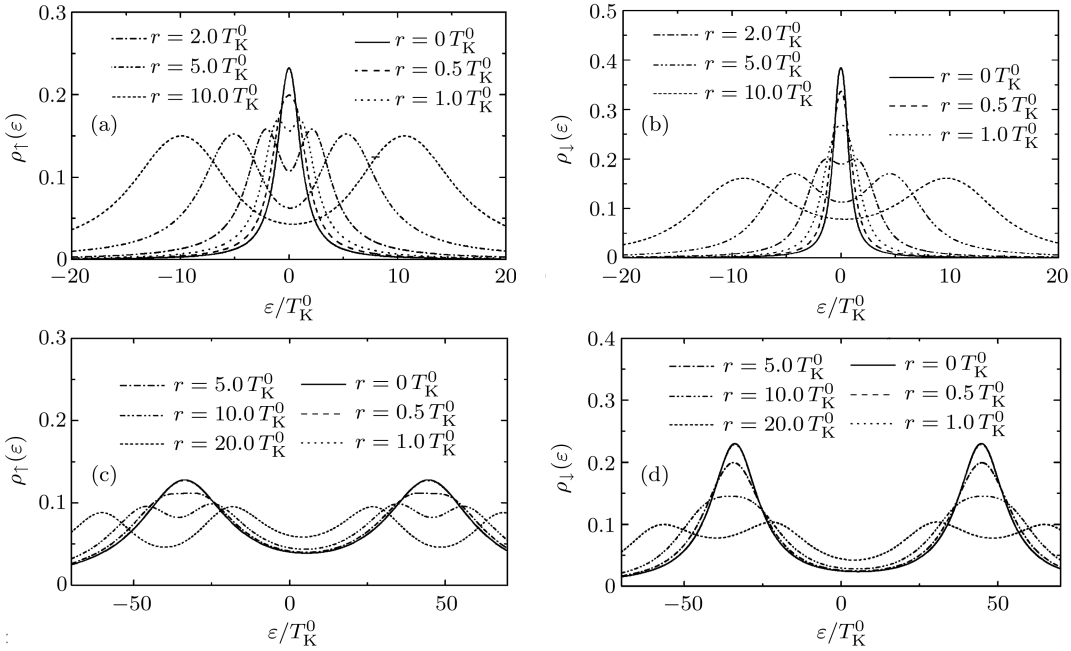


Fig.2. DOS of the left and the fight dots coupled to FM leads $p = 0.3$: (a)(b) $t_{\rm c} = 0.3$ and (c)(d) $t_{\rm c} = 3.0$ with the P configuration in the equilibrium case.

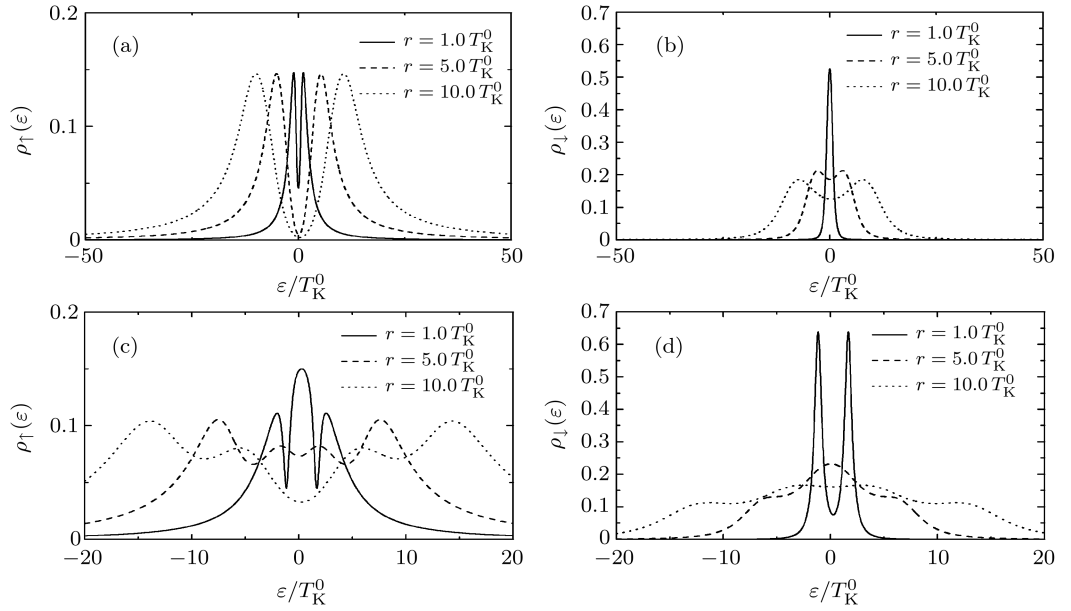


Fig.3. DOS of the left and the right dots coupled to HFM leads: (a)(b) $t_{\rm c} = 0.3$ and (c)(d) $t_{\rm c} = 3.0$ with the P configuration in the equilibrium case.

In the AP configuration, as shown in Fig.4 and Fig.5, $\rho_{\mathrm{L}\sigma}(\varepsilon) = \rho_{\mathrm{R}\bar{\sigma}}(\varepsilon)$, for simplicity, we only focus on the left dot. By increasing the value of the spin-flip transition r of the HF leads, both the original spin-up and spin-down Kondo peaks are split into two well-defined peaks (Figs.4(a) and 4(b)) or four peaks (Figs.4(c) and 4(d)). When the leads are fully polarized as shown in Fig.5, when $t_{\mathrm{c}} = 0.3$, the spin-up DOS have two well-defined peaks, and increasing r makes the Kondo resonance become wider. In the spin-down case, the height of Kondo peak is suppressed sharply and the width of it becomes broader with the increasing of r. For $r > T_{\mathrm{K}}^0$, the original spin-down Kondo peak is split into tow peaks. But when $t_{\mathrm{c}} = 3.0$, for $r > T_{\mathrm{K}}^0$, the original two spin-up peaks are split into four from two and the spin-down ones are changed from two into one with rather high apex at $\varepsilon = 0$.

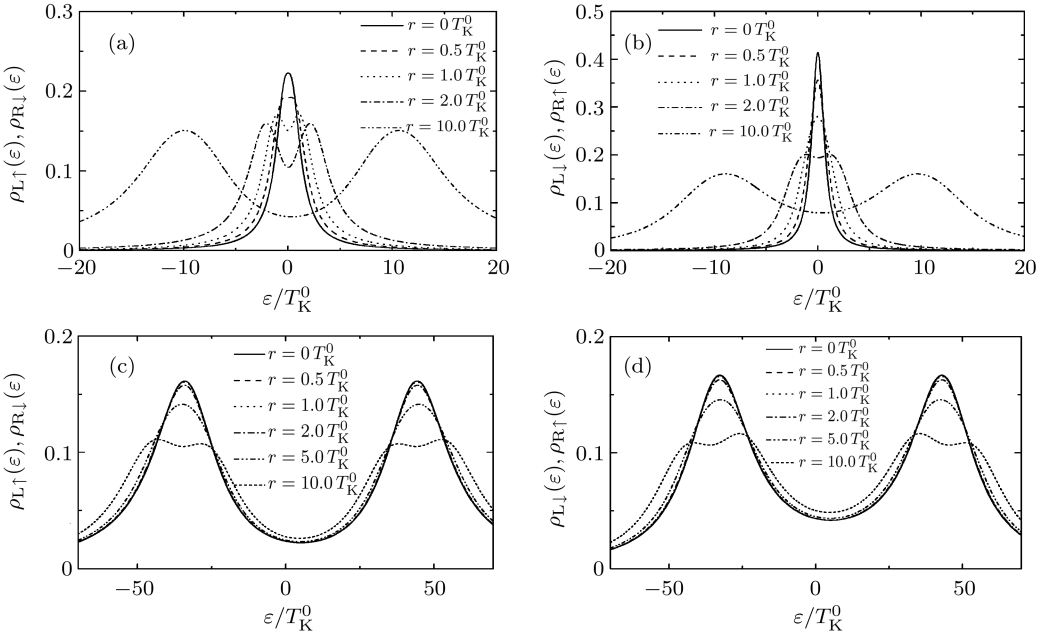


Fig.4. DOS of the left and the right dot coupled to FM leads $p = 0.3$: (a)(b) $t_{\mathrm{c}} = 0.3$ and (c)(d) $t_{\mathrm{c}} = 3.0$ with the AP configuration in the equilibrium case.

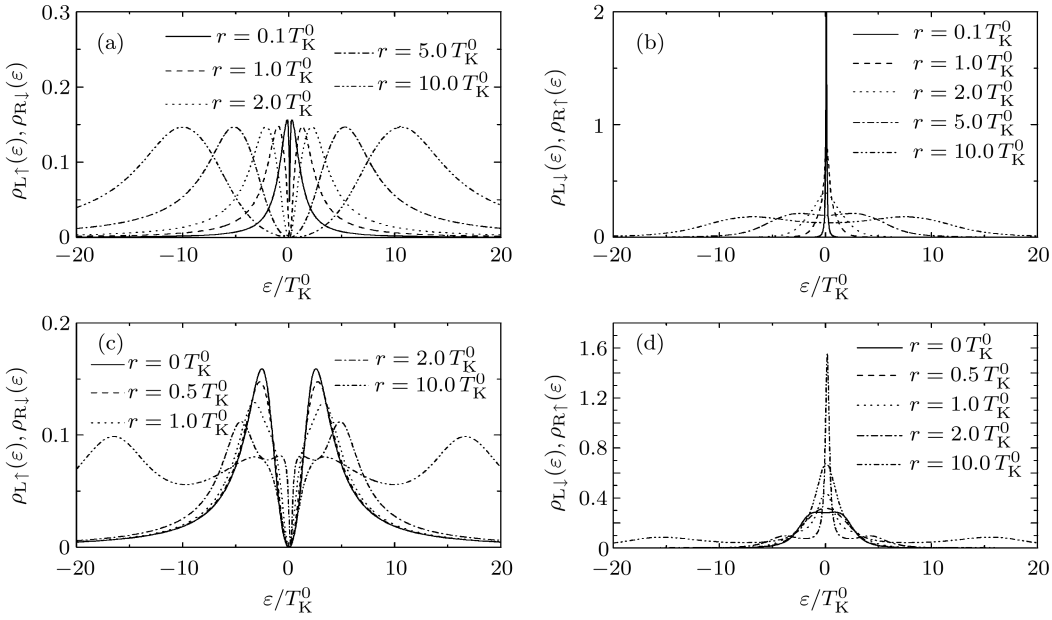


Fig.5. DOS of the left and the right dot coupled to HFM leads: (a)(b) $t_{\mathrm{c}} = 0.3$ and (c)(d) $t_{\mathrm{c}} = 3.0$ with the AP configuration in the equilibrium case.

We next show the results in the non-equilibrium ($V \neq 0$) case with the P and AP configurations of the polarized leads. We set the chemical potentials $u_{\rm L} = V/2$ and $u_{\rm R} = -V/2$.

Let us first look at the Kondo resonance at $t_{\rm c}$=0.3 in Fig.6. At small V, the DOS for up-spin electrons has sharp splitting peaks due to the 100% polarization of the leads. With increasing V, the Kondo resonance of the left (right) dot is shifted, following the change in the chemical potential of the left (right) HFM leads. There is no more splitting caused by different value of V, so we investigate the transport properties with $V = 0.3\,T_{\rm K}^0$ or $V = 3.0\,T_{\rm K}^0$.

As shown in Fig.7, the DOS for up-spin electrons has two obvious peaks with small splitting at small r. In addition, for large value of r, the splitting becomes wider. Especially, when $r = 0.0$, for the down-spin electrons, there is no Kondo resonance. The reason is that, with the spin polarization of $P = 100\%$ at the Fermi level, the spin-resolved DOS presents a metallic character only for the up direction, but the down direction behaves like an insulator with $E_{\rm F}$ inside a band gap. When $r > 0.0$, the Kondo resonance appearance. Moreover, in Fig.8, with AP configuration, both the spin-up and spin-down Kondo peaks of the DQD are split into four peaks for large value of r. These exotic phenomena are caused by the spin-flip which will open one more path in the tunnelling of an electron out of the QD: an electron with a spin-up (down) can tunnel into the QD, but due to the spin-flip, it can tunnel out of the QD as an electron with spin-down (up). An electron spending more time in QD due to polarization now has more probability to tunnel out from the dot. Besides, the spin-flip not only shifts the level position of QD, but also changes the spin-up and spin-down distribution of DOS for the split levels.

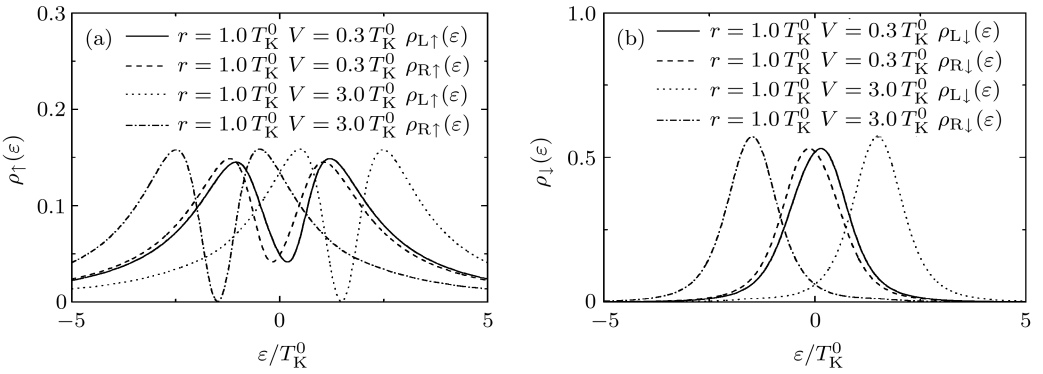


Fig.6. DOS of the left and the right dot coupled to HFM leads with the P configuration in the non-equilibrium case of $V = 0.3\,T_{\rm K}^0$ or $V = 3.0\,T_{\rm K}^0$ for $t_{\rm c} = 0.3$.

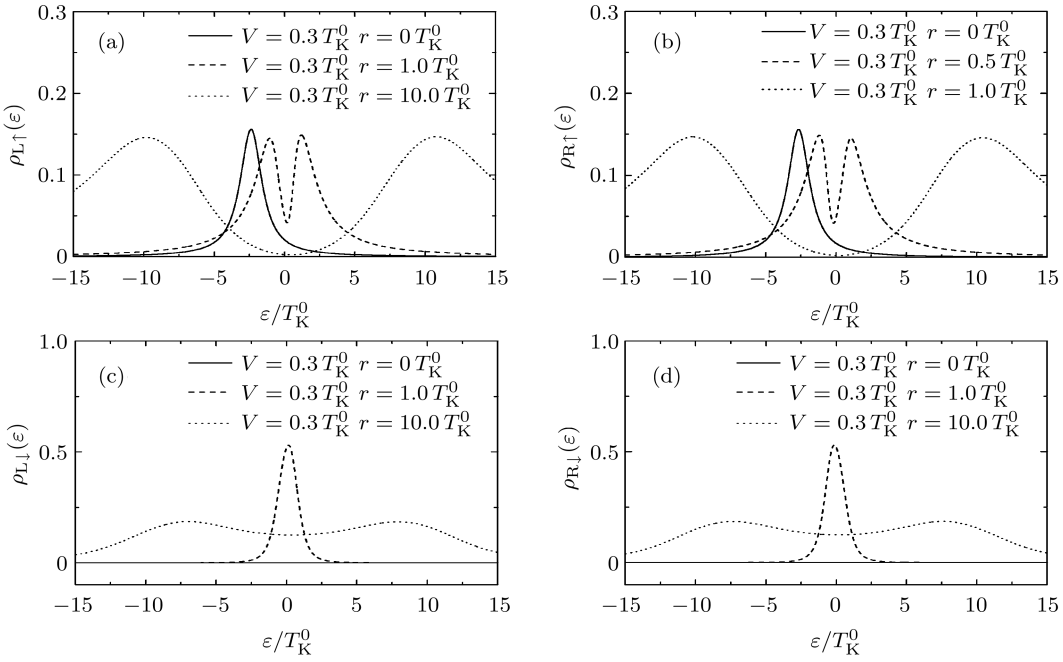


Fig.7. DOS of the left and the right dots coupled to HFM leads with the P configuration in the non-equilibrium case of $t_{\rm c} = 0.3$, $V = 0.3\,T_{\rm K}^0$.

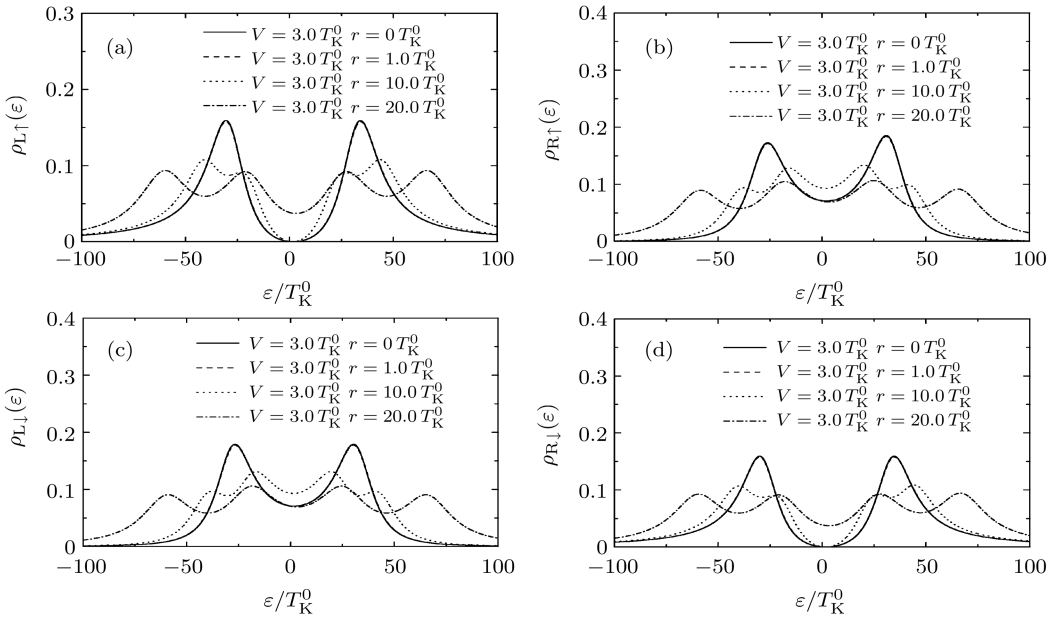


Fig.8. DOS of the left and the right dots coupled to HFM leads with the AP configuration in the non-equilibrium case of $t_{\rm c} = 3.0,\ V = 3.0\,T_{\rm K}^0$.

4. Conclusion

By applying the slave-boson mean-field approximation to highly correlation Anderson model, we find that the strength of the spin-flip process is one of the key parameters to control transport phenomena via the modified Kondo resonances, when the DQD are coupled to the FM or HFM leads in both the equilibrium and the non-equilibrium cases. When the DQD are coupled to FM leads in series and $r = 0$, the above results are consistent with other author's work.[15] But when the spin-flip scatting strength is comparable with the Kondo temperature, the original single Kondo peak in the DOS is split into a structure with more than one peak. We expect these novel results are useful in exploiting the role of electronic correlation in spintronics, such as exploiting the spin-filter devices.

References

[1] Cronenwett S M, Oosterkamp T H and Kouwenhoven L P 1998 *Science* **282** 932

[2] Georges A and Meir Y 1999 *Phys. Rev. Lett.* **82** 3508

[3] Wu S Q, Sun W L, Yu W L and Wang S J 2005 *Acta Phys. Sin.* **54** 2910 (in Chinese)

[4] Aguado R and Langreth D C 2000 *Phys. Rev. Lett.* **85** 1946

[5] Wu S Q and Wang S J 2003 *Chin. Phys. Lett.* **20** 1574
Zhou B, Wu S Q, Sun W L and Zhou X L 2004 *Chin. Phys.* **13** 225
Chen X W, He D J, Wu S Q and Song K H 2006 *Acta Phys. Sin.* **55** 4287 (in Chinese)

[6] Aono T and Eto M 2001 *Phys. Rev.* B **63** 125327

[7] Lopez R, Aguado R and Platero G 2002 *Phys. Rev. Lett.* **89** 136802

[8] Sergueev N, Sun Q F, Guo H, Wang B G and Wang J 2002 *Phys. Rev.* B **65** 165303

[9] Wu S Q, Chen X W, Sun W L and Wang S J 2004 *Acta Phys. Sin.* **53** 2336 (in Chinese)
Song H Z, Zhang P, Duan S Q and Zhao X G 2006 *Chin. Phys.* **15** 2130

[10] Izumida W and Sakai O 2000 *Phys. Rev.* B **62** 10260

[11] Jones B A, Varma C M and Wilkins J W 1998 *Phys. Rev. Lett.* **61** 125

[12] Loss D and Divincenzo D P 1998 *Phys. Rev.* A **57** 120

[13] Yoffe A D 2001 *Adv. Phys.* **50** 1

[14] Zhang P, Xue Q K, Wang Y and Xie X C 2002 *Phys. Rev. Lett.* **89** 286803

[15] Tanaka Y and Kawakami N 2004 *J. Phys. Soc. Jpn.* **73** 2795

[16] Hewson A C 1993 *The Kondo Problem to Heavy Fermions* (Cambridge: Cambridge University Press)

[17] Groot R A, Mueller F M, Engen P G and Buschow K H J 1983 *Phys. Rev. Lett.* **50** 2024

[18] Zutic I, Fabian J and Das S S 2004 *Rev. Mod. Phys.* **76** 323

[19] Lezaic M, Mavropoulos P, Enkovaara J, Bihlmayer G and Blügel S 2005 cond-mat/0512277

[20] Atature M, Dreiser J, Badolato A, Hogele A, Karrai K and Imamoglu A 2006 *Nature* **312** 551

[21] Krawiec M 2005 cond-mat/0504604