Physica B 464 (2015) 77–82

Contents lists available at ScienceDirect

Physica B

journal homepage: www.elsevier.com/locate/physb

Effect of spin-flip scattering on the electron transport through double quantum dots

Fu-Bin Yang [a,b,*], Rui Huang [c], Yan Cheng [d,**]

[a] Department of Physics, College of Computer, Civil Aviation Flight University of China, Guanghan 618307, China
[b] Department of Mathematics, Sichuan Normal University Chengdu College, Chengdu 611745, China
[c] College of Sciences, Southwest Petroleum University, Chengdu 610500, China
[d] Institute of Atomic and Molecular Physics, College of Physical Science and Technology, Sichuan University, Chengdu 610065, China

ARTICLE INFO

Article history:
Received 19 January 2015
Received in revised form
8 February 2015
Accepted 9 February 2015
Available online 10 February 2015

Keywords:
Quantum transport
Kondo effect
Spin-flip
Quantum dot

ABSTRACT

We systematically investigate the electron transport through double quantum dots (DQD) with particular emphasis on the spin-flip scattering of an electron in the DQD. By means of the slave-boson mean-field approximation, we calculate the linear conductance and the transmission in the Kondo regime at zero temperature. The obtained results show that both the linear conductance and transmission probability are quite sensitive to the spin-flip strength when the DQD structure is changed among the serial, parallel and T-shaped. It is suggested that such a theoretical model can be used to study the physical phenomenon related to the spin manipulation transport.

1. Introduction

Recently, many efforts have been made to investigate theoretically coupled quantum dots (QDs) [1,2]. With respect to coupled QDs, the wave functions of each quantum dot state can penetrate into the tunneling barrier and overlap each other. As well as being a model for studying the physics of strongly correlated electrons, the coupled QDs are utilized in controllable quantum coherent systems for spintronic [3] and quantum information processing devices [4]. In real spin systems, it is difficult to manipulate the spin-up state and the spin-down state individually. In contrast, since the coupled DQD system is separated, it is much easier to control the spin freedom of each dot. As a result, the physical phenomenon related to the spin-flip which is induced by the spin–orbit electrons have suggested that it can potentially offer a gate controllable approach to manipulate the spin [5,6]. Researchers have detected the spin-flip process in a single proton, a first step toward precision measurements of the antiproton's spin magnetic moment [7]. The observed photoelectron spin-flip process in Bi_2Se_3 also enables a precision measurement of the spin detection [8]. All of which indicate the importance of the intrinsic spin-flip effect in the mesecopical systems.

Due to that the electrons in the QD can flip its spin, a very sharp Kondo peak emerges in the density of states (DOS) of the QD. The parameters in the coupled QDs can be modulated experimentally in a continuous and reproducible manner, offering an appropriate platform to study the Kondo problem [9]. In particular, the observation of the Kondo effect in strongly correlated systems has opened a path for the investigation of the spin-flip effect, which stimulates further experimental [10] and theoretical studies [11]. When electron–electron correlations due to the Kondo effect are affected by such spin-flip effect, the transport properties exhibit remarkable properties [12]. There have been a number of theoretical works in the DQD systems. For example, it was pointed out that the spin-flip shows a splitting effect on the Kondo resonance in the single quantum dot system [13], whereas such effects do not appear in the DQD system. The T-shaped DQD is another prototype for the special arrangement of the DQD which provides an additional path of electron propagation, but the detailed analysis about the spin-flip effect has not been done. Thus it is interesting to systematically study how the spin-flip interference together with the Kondo effect affects characteristic transport properties in a variety of DQD systems, including the serial DQD, parallel DQD, and T-shaped DQD systems.

2. The model and method

In this work, we mainly focus on the effect of spin-flip scattering on the electron transport through a DQD system, which is

* Corresponding author at: Department of Physics, College of Computer, Civil Aviation Flight University of China, Guanghan 618307, China.
** Corresponding author.
E-mail addresses: fbinyang@qq.com (F.-B. Yang), ycheng66@qq.com (Y. Cheng).

http://dx.doi.org/10.1016/j.physb.2015.02.009
0921-4526/

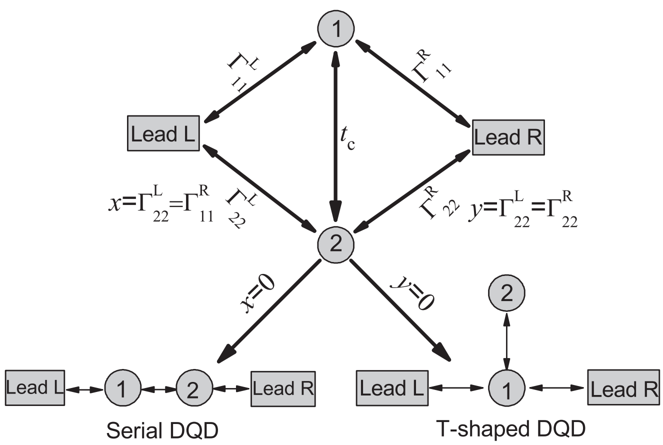

Fig. 1. A schematic illustration of DQD system connected by the interdot tunneling strength t_c. $\Gamma^{\alpha}_{mm}(\alpha = L, R;\ m = 1, 2)$ represents the resonance width due to transfer between the m-th dot and the α-th lead. By changing the ratio of tunneling amplitudes, we can change the system among the serial DQD (x=0), parallel DQD and T-shaped DQD (y=0).

shown schematically in Fig.1. The Hamiltonian of the original d levels of the two dots can be described as follows:

$$H = H_{DQD} + H_{\alpha} + H_T, \tag{1}$$

where

$$H_{DQD} = \sum_{m,\sigma} \varepsilon_{m\sigma} d^{+}_{m\sigma} d_{m\sigma} + U n_{d_{m\sigma}} n_{d_{m\bar{\sigma}}} + \frac{t_c}{N} \sum_{\sigma} (d^{+}_{1\sigma} d_{2\sigma} + h.\ c.\ ) + \frac{r}{N} \sum_{m,\sigma} (d^{+}_{m\sigma} d_{m\bar{\sigma}} + h.\ c.\ ) H_{\alpha} = \sum_{k\alpha,\sigma} \varepsilon_{k\alpha\sigma} c^{+}_{k\alpha\sigma} c_{k\alpha\sigma} H_T = \frac{1}{\sqrt{N}} \sum_{k\alpha,m,\sigma} (V_{m\alpha\sigma} c^{+}_{k\alpha\sigma} d^{+}_{m\sigma} + h.\ c.\ )$$

Here H_{DQD} is the Hamiltonian of the DQD and $d^{+}_{m\sigma}(d_{m\sigma})$ is the creation (annihilation) operator of the electron in the QDs with m=1,2. t_c describes the interdot coupling strength and r is the spin-flip strength that may cause the spin rotation of an electron in the QDs. Since the spin quantization axes in the electrodes are fixed by the internal magnetization of the magnets, an electron is in a superposition of spin-up (spin-down) states as it tunnels into (out of) the dot. As a result, the physical phenomenon related to the spin-flip may be realized in a DQD system. H_{α} describes the non-interacting leads with $c^{+}_{k\alpha\sigma}(c_{k\alpha\sigma})$ the creation (annihilation) operator of an electron in the lead. H_T denotes the tunneling between the DQD and the lead $\alpha(\alpha = L, R)$. The tunneling between the lead and the QDs can be rewritten by an effective strength $\Gamma^{\alpha}_{mm\sigma} = \pi \sum_{k,\alpha,\sigma} V_{m\alpha\sigma} V^{*}_{m\alpha\sigma} \delta(\varepsilon - \varepsilon_{k\alpha\sigma})$. We first interpolate the serial DQD and parallel DQD by continuously changing $x = \Gamma^{L}_{22\sigma} = \Gamma^{R}_{11\sigma}$ while keeping $\Gamma_0 = \Gamma^{L}_{11\sigma} = \Gamma^{R}_{22\sigma}$ as the unity. For example, at x=0 the model is reduced to the serial DQD and x=1 the parallel DQD. We next change $y = \Gamma^{L}_{22\sigma} = \Gamma^{R}_{22\sigma}$ with the resonance width $\Gamma_0 = \Gamma^{L}_{11\sigma} + \Gamma^{R}_{11\sigma}$ fixed as unity. At y=0, the system is equal to the T-shaped DQD and y=1 the parallel DQD.

In the following discussions, the intradot Coulomb interaction U ($U \to \infty$) on each dot is assumed to be sufficiently large, so that the double occupancy is forbidden. An alternative way to represent the infinite Coulomb interaction is the conventional slave-boson mean field approximation [14], where the creation (annihilation) operator of electrons in the dots, $d^{+}_{m\sigma}(d_{m\sigma})$ is replaced by $d^{+}_{m\sigma} \to f^{+}_{m\sigma} b_m$. $b_m(f_{m\sigma})$ is the slave-boson (pseudo-fermion) annihilation operator for an empty (singly occupied) state. We can thus model the DQD Hamiltonian as follows:

$$H_{DQD} = \sum_{m,\sigma} \varepsilon_{m\sigma} f^{+}_{m\sigma} f_{m\sigma} + \frac{t_c}{N} \sum_{\sigma} (f^{+}_{1\sigma} b_1 b^{+}_2 f_{2\sigma} + h.\ c.\ ) + \frac{r}{N} \sum_{m,\sigma} b_m b^{+}_m (f^{+}_{m\sigma} f_{m\bar{\sigma}} + h.\ c.\ ) + \sum_m \lambda_m \left(\sum_{\sigma} f^{+}_{m\sigma} f_{m\sigma} + b^{+}_m b_m - 1 \right) \tag{2}$$

The last term with the Lagrange multiplier λ_m is introduced so as to incorporate the constraint imposed on the slave particles$\sum_{\sigma=\uparrow\downarrow} f^{+}_{m\sigma} f_{m\sigma} + b^{+}_m b_m = 1$. In the numerical calculations, we replace the boson operator by their expectation values $b^{+}_m(b_m) \to < b^{+}_m > = \tilde{b}_m$, which results in the renormalized quantities $\tilde{V}_{m\alpha\sigma} = V_{m\alpha\sigma} \tilde{b}_m, \tilde{t}_c = t_c \tilde{b}_1 \tilde{b}_2$, $\tilde{r}_m = r \tilde{b}^{2}_m$ and $\tilde{\varepsilon}_{m\sigma} = \varepsilon_{m\sigma} + \lambda_m$ in the slave-boson mean-field approximation. The mean-field values of $\tilde{b}_m$, λ_m are determined by minimization of the free energy due to the Hamiltonian of the system. We can derive the set of self-consistent equations according to the equation of motion method for the nonequilibrium Keldysh Green functions [15]:

$$\tilde{b}^{2}_m - i \sum_{\sigma} \int \frac{d\varepsilon}{4\pi} G^{<}_{mm,\sigma}(\varepsilon) = \frac{1}{2} \tag{3}$$

$$\lambda_m \tilde{b}^{2}_m = i \sum_{\sigma} \int \frac{d\varepsilon}{4\pi} (\varepsilon - \tilde{\varepsilon}_{m\sigma}) G^{<}_{mm,\sigma}(\varepsilon) \tag{4}$$

Eq. (3) represents the constraint imposed on the slave particles, while Eq. (4) is obtained from the stationary condition that the boson field is time independent at the mean-field level. From the equation of motion of the operator $f_{m\sigma}$ [15], we have the explicit matrix form of the Green function:

$$[G^{r}_{\sigma}]^{-1} = \begin{pmatrix} \varepsilon - \tilde{\varepsilon}_{1\sigma} + i\tilde{\Gamma}_{11\sigma} & -(\tilde{t}_c - i\tilde{\Gamma}_{21\sigma}) & -\tilde{r}_1 & 0 \\ -(\tilde{t}_c - i\tilde{\Gamma}_{12\sigma}) & \varepsilon - \tilde{\varepsilon}_{2\sigma} + i\tilde{\Gamma}_{22\sigma} & 0 & -\tilde{r}_2 \\ -\tilde{r}_1 & 0 & \varepsilon - \tilde{\varepsilon}_{1\sigma} + i\tilde{\Gamma}_{11\bar{\sigma}} & -(\tilde{t}_c - i\tilde{\Gamma}_{21\bar{\sigma}}) \\ 0 & -\tilde{r}_2 & -(\tilde{t}_c - i\tilde{\Gamma}_{12\bar{\sigma}}) & \varepsilon - \tilde{\varepsilon}_{2\bar{\sigma}} + i\tilde{\Gamma}_{22\bar{\sigma}} \end{pmatrix} \tag{5}$$

$$G^{<} = G^{r}_{\sigma} \begin{pmatrix} \sum_{\alpha} \tilde{\Gamma}^{\alpha}_{11\sigma} f_{\alpha} & \sum_{\alpha} \tilde{\Gamma}^{\alpha}_{21\sigma} f_{\alpha} & 0 & 0 \\ \sum_{\alpha} \tilde{\Gamma}^{\alpha}_{12\sigma} f_{\alpha} & \sum_{\alpha} \tilde{\Gamma}^{\alpha}_{22\sigma} f_{\alpha} & 0 & 0 \\ 0 & 0 & \sum_{\alpha} \tilde{\Gamma}^{\alpha}_{11\bar{\sigma}} f_{\alpha} & \sum_{\alpha} \tilde{\Gamma}^{\alpha}_{21\bar{\sigma}} f_{\alpha} \\ 0 & 0 & \sum_{\alpha} \tilde{\Gamma}^{\alpha}_{12\bar{\sigma}} f_{\alpha} & \sum_{\alpha} \tilde{\Gamma}^{\alpha}_{22\bar{\sigma}} f_{\alpha} \end{pmatrix} G^{a}_{\sigma} \tag{6}$$

with $\tilde{\Gamma}^{\alpha}_{mn\sigma} = \tilde{b}_m \tilde{b}_n \Gamma^{\alpha}_{mn\sigma}$ and $\tilde{\Gamma}_{mn\sigma} = \tilde{\Gamma}^{L}_{mn\sigma} + \tilde{\Gamma}^{R}_{mn\sigma}$ $(n = 1, 2)$.

By the Keldysh non-equilibrium Green's function (NEGF) method, we can further derive the Landauer current formula of this system

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

where $f_{L(R)}(\varepsilon)$ is the Fermi distribution function of the left (Right) lead and $T_{\sigma}(\varepsilon)$ is the transmission probability per spin given by $T_{\sigma}(\varepsilon) = Tr[\Gamma^{L} G^{r}_{\sigma} \Gamma^{R} G^{a}_{\sigma}]$.

3. Numerical results

In this section, we will present the numerical results of linear conductance and transmission probability for the DQD systems with the serial, parallel, and T-shaped geometries. For simplicity, we assume the energy levels for the spin up and spin down are degenerate ($\tilde{\Gamma}^{\alpha}_{mn\sigma} = \tilde{\Gamma}^{\alpha}_{mn\bar{\sigma}}$). We deal with the symmetric dots in the