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Tunable spin selective transport and quantum phase transition in parallel double dot system

Yong-Chen Xiong [a,*], Wei-Zhong Wang [b], Shi-Jun Luo [a], Jun-Tao Yang [a]

[a] School of Science, Hubei University of Automotive Technology, Hubei, 442002, PR China
[b] Department of Physics, and Key Laboratory of Artificial Micro- and Nano-structures of Ministry of Education, Wuhan University, Wuhan, 430072, PR China

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ABSTRACT

We study theoretically the spin selective transport and the quantum phase transition (QPT) in a double dot device by means of the numerical renormalization group technique. When the gate voltage ε is in the Kondo regime and the interdot hopping t is large enough, a first order QPT between local spin singlet and S_z=1 of the triplet is observed as the magnetic field B increases. Beyond the Kondo regime, the QPTs depend closely on ε and t, and perfect spin filter is found, where the effect of spin filtering could easily be manipulated by tuning external parameters. We show that the interplay between the Zeeman effect and the antiferromagnetic interdot hopping, and occupancy switching are responsible for the QPT and the spin selective transport.

1. Introduction

When magnetic impurities were embedded in metallic hosts, anomalous scattering of conduction band electrons could be observed, and the localized magnetic moments are screened at low temperature. This is the so-called Kondo effect [1], which has been revived in mesoscopic physics for the last several years [2]. Ever since then, the Kondo effect in artificial magnetic impurities, i.e., semiconductor quantum dots, has attracted much attention both experimentally and theoretically [3–16]. The remarkable advantage of these systems is the fine manipulation of the parameter space, e.g., the hybridization couplings and the impurity levels, which is a hard task in bulk solids. Recently, research attention has tended to the fascinating physics in coupled double quantum dot (DQD) system, where quantum phase transition (QPT) has been predicted [5,17–22]. Basically, there are two kinds of spin configurations for the localized parallel dots, i.e., the triplet and the singlet, which could be tuned by adjusting the interdot hopping [19], level spacing [20], antiferromagnetic spin–spin interaction [21], or interdot Coulomb repulsion [23]. The QPT between triplet and singlet could be first order or Kosterlitz-Thouless (KT) type depending on the symmetric and/or asymmetric Kondo coupling [20,22]. Experimentally, these QPTs have also been possibly observed [8,24–27]. Another theme that has gained considerable attention is the quantum interference between different paths, which will certainly affect the linear conductance through the DQD [14,28–31].

Recently, due to rapid progress in quantum computation [32] and spintronics [33–36], it is more desirable to gain spin-polarized currents, where quantum dot device has been considered as an alternative candidate. For example, a single dot in the Coulomb blockade regime weakly coupled to current leads acts as an efficient spin filter in the presence of a magnetic field

* Corresponding author.
E-mail address: xiongyc_lx@huat.edu.cn (Y.-C. Xiong).

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[37], and spin valves composed of an interacting quantum dot coupled to two ferromagnetic leads are realized when the relative angle of the leads' magnetization directions are tuned [38]. For a quantum wire with a single ballistic channel side coupled to a quantum dot in the magnetic field also reveals spin filtering [39]. These works are limited to a single dot system, it is necessary to know how could DQD systems be considered as spin filter, and what are the advantages? Although less studied, DQD system as a spin filter also attracted some attention. For instance, for a serial DQD system containing the Rashba spin–orbit interaction, the spin-polarized Andreev reflection is revealed [40]. For DQD connected to two channels, a spin-orbital SU(2) Kondo state can be achieved and the device acts as a spin filter, which links to the spatial separation effect [41]. For a DQD ring with the Rashba spin–orbit interaction, the spin-dependent interdot tunneling coupling and the magnetic flux, a 100% spin-polarized conductance can be obtained [42]. For DQD attached to spin polarized leads, perfect spin filtering with large conductance is revealed by tuning the level spacing [43].

In this paper, we consider a parallel DQD system with interdot hopping t and magnetic field B (see Fig. 1), and study the transport properties and the QPTs by using the Wilson's numerical renormalization group (NRG) technique. We find that by sweeping the gate voltage ε across different regimes (i.e., the Kondo, the mixed-valence and the frozen impurity regimes), the linear conductance G reveals perfect spin filtering when t and B are chosen in appropriate regimes, and the effect of this spin selective transport could easily be manipulated by tuning ε, t and/or B. For instance, when ε is chosen in the Kondo regime, e.g., the particle-hole (p-h) symmetric point (i.e., $\varepsilon=-U/2$ with U being the on-site Coulomb repulsion), and t is large enough, we find the reappearance and splitting of the Kondo peak as B increases, and a first order QPT between local spin singlet and $S_z=1$ of the triplet is observed. In this case, the spin filtering is difficult to occur. When ε is in the mixed-valence regime, the results are complicated and fascinating. With fixed small (or zero) t, a first order QPT between magnetic frustration phase and $S_z=1$ of the triplet is found at a critical point B_c, and in the regime $B<B_c$, $G_{down}\geq G_{up}$, with G_{up} (G_{down}) being the conductance of up-spin (down-spin) electron. While in the regime $B>B_c$, one finds $G_{up}\geq G_{down}$. For fixed large t, a crossover and a first order QPT are found, and a perfect spin filter is realized, where only the electrons with down spin could transmit. If ε is in the frozen impurity regime, spin selective transport could also be found, however, the effect of spin filtering are different, where only the electrons with up spin could transmit the DQD, while those with down spin are completely suppressed. Compare with the results presented in previous works, our work does not rely on spin-polarized leads or Rashba spin–orbit interaction, and the effect of spin filtering could easily be manipulated by external parameters, e.g., the gate voltage, the magnetic field, and the distance between impurity atoms. It should be noted that similar system was also investigated in a two-impurity Anderson model containing an antiferromagnetic Ruderman-Kittel-Kasuya-Yosida (RKKY) interaction [21], however, their work only limited at p-h symmetric case, thus the spin selective transport is difficult to occur.

The rest of the paper is organized as follows. In Sec. 2, we define the model Hamiltonian of the DQD system, and present the calculation algorithms. In Sec. 3, we discuss the quantum phase transition and the transport properties of the system. Finally a summary is given in Sec. 4.

2. Model and method

To study the spin selective transport and the QPT of the parallel DQD setup in Fig. 1, we consider the following Andersonian model:

$$H = H_{leads} + H_{hyb} + H_{dots}, \tag{1}$$

where $H_{leads} = \sum_{\nu k\sigma} \varepsilon_k c^{\dagger}_{\nu k\sigma} c_{\nu k\sigma}$ is the Hamiltonian of the non-interacting leads, and $H_{hyb} = \sum_{\nu ki\sigma} V_k (c^{\dagger}_{\nu k\sigma} d_{i\sigma} + H.c.)$ describes the coupling interaction energy between the leads and the dots. Here, $c_{\nu k\sigma}$ annihilates a spin-σ electron of wave vector k and energy ε_k in lead ν (ν=L,R), and $d_{i\sigma}$ annihilates a spin-σ electron of energy ε_i in dot i (i=1,2). V_k is the tunnel matrix between conduction leads and quantum dots, and we assume two dots are coupled symmetrically to the same conduction band. For the strongly-correlated DQD,

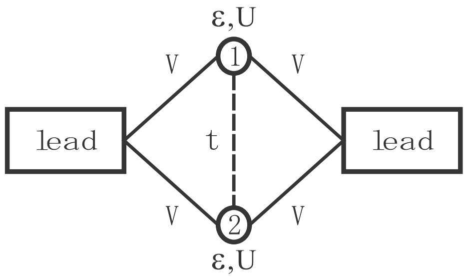

Fig. 1. Schematic view of the parallel DQD device attached to conduction leads.