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# Effect of spin exchange interaction on shot noise and tunnel magnetoresistance in double quantum dots

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## HIGHLIGHTS

- The electron correlation is a highly focused topic of research in mesoscopic transport-systems.
- This paper demonstrates how the giant negative differential conductance can be generated by the spin exchange interaction (SEI) of two electrons.
- Moreover the SEI has great influences on the tunnel magnetoresistance and shot noise.
- It also leads to enhancement or suppression of the super-Poissonian statistics of transport electrons depending on the type of exchange couplings.

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## ABSTRACT

By means of the Rate equation approach in sequential tunneling regime, we study spin-polarized transport through series double quantum dots (DQD) weakly coupled to collinear ferromagnetic leads with particular attention on the effect of interdot spin exchange interaction (SEI). For the asymmetric DQD giant negative differential conductance is realized, which depends on the energy-level spacing between two dots. It is demonstrated that the voltage dependencies of the tunnel magnetoresistance (TMR) and the shot noise are sensitive to the SEI, which leads to the additional imbalance between spin-polarized currents. The super-Poissonian statistics is enhanced in the parallel leads' configuration by the ferromagnetic SEI, which favorites the spin bunching, while it is suppressed by stronger antiferromagnetic SEI in antiparallel configuration for a symmetric DQD. The voltage dependencies of the TMR and shot noise may be used to probe the SEI.



## 1. Introduction

The spin-polarized electron transport through a DQD system has attracted considerable attention in recent years because of its potential applications in nanoelectronics, spintronics, and some quantum computation and storage [1–8]. The DQD, which is often called an artificial molecule, is considered as an ideal system to study the fundamental many-body interactions in the quantum transports [9,10]. Numerous fascinating phenomena have been found such as Kondo effect [11,12], Coulomb blockade [1,13,14], Pauli spin blockade [9,15–18], negative differential conductance (NDC) [14,19,20], the TMR effect [19,21,22], spin-orbital coupling [12,17], and thermoelectric effect [23]. Various transport characteristics are obtained from the different geometries of the DQD connections (such as parallel, series and T-shape) [10]. For the series DQD system, the competition between the tunnel coupling $t$ and the level spacing $\Delta$ (which is defined as the energy-level difference between two dots) may greatly affect the dynamics of electron transport [9]. Particularly the spin-polarized transport through a DQD system is analyzed showing the strong dependence of the TMR on the number of electrons occupying the QD and the super-Poissonian shot noise [10]. Moreover the SEI, which generates singlet and triplet states, may cause different transport properties [21,24]. On the other hand, the shot noise, from which the transport mechanism can be well understood, is more suitable to serve as a characterization of the quantum transport device than the current and thus has been extensively investigated in recent years [10,25–27]. Particularly the super-Poissonian noise is caused by many mechanisms, such as dynamic Coulomb blockade, Pauli spin blockade, spin accumulation, competition between fast and slow channels, and asymmetric tunnel couplings as well [10,25,26].The TMR, which depends on the relative orientations of the lead magnetization, plays a critical role in the development of magnetic sensors and storage devices [21,24,28,29]. Various aspects have been studied in relation with the TMR effect such as spin accumulation, spin-flip, asymmetric couplings, and non-collinear configurations of electrode-magnetization [5,21,30–32].

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Negative TMR is also realized in the DQD and two-level single quantum dot (QD) systems [19,21,22]. Although the SEI dependence of spin-polarized transport was observed in DQDs [8,9], the effect of SEI on shot noise and TMR has not yet been studied respectively with and without the interdot level spacing.

The interdot SEI results in the singlet and triplet electron states with the exchange-coupling ($J$) dependent energies, which are different from the one-electron states. Moreover the level spacing $\Delta$ between two QDs may also lead to some new phenomena. So, we in this paper study spin-polarized transport through both the symmetric ($\Delta=0$) and asymmetric ($\Delta\neq 0$) DQDs and pay special attention to the SEI induced effects on the shot noise and TMR as well. The general mechanism to generate the super-Poissonian statistics is discussed and, moreover, additional super-Poissonian region is also predicted for stronger ferromagnetic (FM) SEI with FM leads.

## 2. Model and method

We consider a series DQD weakly coupled to two colinear FM leads. Fig. 1 is the schematic diagram of the series DQD transport model with interdot spin exchange interaction. The Hamiltonian of the system includes three parts $H=\sum_{\alpha=L,R}H_\alpha+H_{DQD}+H_T$. The Hamiltonian of DQD is given by Refs. [9,33]

$$H_{DQD}=\sum_{i=1,2}\left[\varepsilon_i n_i+\frac{1}{2}n_i(n_i-1)U\right]+t\sum_\sigma(d^\dagger_{1\sigma}d_{2\sigma}+h.c.)$$
$$+\left(U'-\frac{J}{2}\right)n_1n_2-2J\mathbf{S_1}\cdot\mathbf{S_2}, \quad (1)$$

where $\varepsilon_i$ denotes the noninteracting electron energy of QD-i and $n_i$ is the number of electrons. $U$ and $U'$ denote the onsite and interdot Coulomb potentials respectively. $d^\dagger_{i\sigma}$ ($d_{i\sigma}$) is the creation (annihilation) operator for an electron with spin-$\sigma$ in QD-$i$ with $t$ being the tunnel coupling constant. The SEI is FM if $J>0$, and is antiferromagnetic (AFM) if $J<0$. $\mathbf{S}_i=\frac{1}{2}\sum_{\sigma\sigma'}d^\dagger_{i\sigma}\boldsymbol{\sigma}_{\sigma\sigma'}d_{i\sigma'}$ denotes the electron spin-operator of the second-quantization in QD-$i$, where $\boldsymbol{\sigma}=(\sigma_x,\sigma_y,\sigma_z)$ is the usual Pauli matrix [8,9,21,33,34]. Noninteracting electrons in the electrode-$\alpha$ ($\alpha=L,R$) are described by $H_\alpha=\sum_{k,\sigma}\varepsilon_{\alpha k\sigma}c^\dagger_{\alpha k\sigma}c_{\alpha k\sigma}$ with $\varepsilon_{\alpha k\sigma}$ being the corresponding electron energy, where $c^\dagger_{\alpha k\sigma}$ ($c_{\alpha k\sigma}$) denotes the creation (annihilation) operator for an electron with spin-$\sigma$ and momentum $k$. $H_T=\sum_{k\sigma}(t_{L1}c^\dagger_{Lk\sigma}d_{1\sigma}+t_{R2}c^\dagger_{Rk\sigma}d_{2\sigma}+h.c.)$ is the coupling term, where $t_{L1}$ ($t_{R2}$) denotes the tunnel matrix-element between lead-$L$ (lead-$R$) and the QD-1 (QD-2). We introduce the coupling strength between the lead and DQD defined by $\Gamma_{\alpha i\sigma}=2\pi\rho_{\alpha\sigma}|t_{\alpha i}|^2$ with $\rho_{\alpha\sigma}$ denoting the density of electrons of spin-$\sigma$ in the lead-$\alpha$.

For the large intradot Coulomb repulsions $U$, the double-occupancy of electrons in each QD can be neglected for moderate bias voltages [21]. The states of DQD are direct product of single-QD states such as $|n_1\rangle|n_2\rangle$ with $n_1$, $n_2=0,\uparrow,\downarrow$ respectively. Then we can obtain from Eq. (1) the analytic eigenvalues and eigenstates of

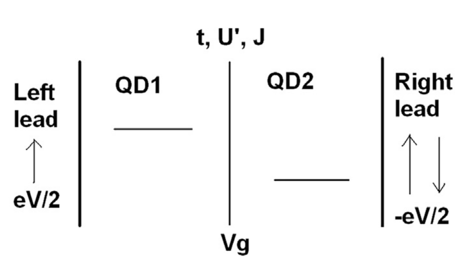


**Fig. 1.** Schematic diagram of the series DQD transport model with interdot spin exchange interaction.

**Table 1**
Eigenstates and Eigenenergies of the model.

| Eigenstate | Eigenenergy |
|---|---|
| $\|0\rangle=\|0\rangle\|0\rangle$ | 0 |
| $\|\sigma\rangle_\pm=a_\pm\|\sigma\rangle\|0\rangle+b_\pm\|0\rangle\|\sigma\rangle$ | $\varepsilon\pm\sqrt{\Delta^2+4t^2}/2$ |
| $\|S\rangle=(\|\uparrow\rangle\|\downarrow\rangle-\|\downarrow\rangle\|\uparrow\rangle)/\sqrt{2}$ | $2\varepsilon+U'+J$ |
| $\|T\rangle_0=(\|\uparrow\rangle\|\downarrow\rangle+\|\downarrow\rangle\|\uparrow\rangle)/\sqrt{2}$ | $2\varepsilon+U'-J$ |
| $\|T\rangle_{+1}=\|\uparrow\rangle\|\uparrow\rangle$ | $2\varepsilon+U'-J$ |
| $\|T\rangle_{-1}=\|\downarrow\rangle\|\downarrow\rangle$ | $2\varepsilon+U'-J$ |

the coupled DQD shown in Table 1, where

$$\Delta=\varepsilon_1-\varepsilon_2,\quad \varepsilon=(\varepsilon_1+\varepsilon_2)/2,$$
$$a_\pm=\frac{\Delta\pm\sqrt{\Delta^2+4t^2}}{\sqrt{(\Delta\pm\sqrt{\Delta^2+4t^2})^2+4t^2}},\quad b_\pm=\frac{2t}{\sqrt{(\Delta\pm\sqrt{\Delta^2+4t^2})^2+4t^2}}.|S\rangle$$

denotes the singlet state, while $|T\rangle_0$, $|T\rangle_{+1}$ and $|T\rangle_{-1}$ are the triplet states, the energies of which are $J$-dependent.

In terms of the eigenenergies and eigenstates of the coupled DQD, we can calculate the stationary transition probability-vector $\mathbf{P}$ (with the normalization condition $\mathrm{Tr}(\mathbf{P})=1$) by Rate Equation approach in the sequential tunneling regime:

$$\frac{d}{dt}\mathbf{P}=\mathbf{MP}=\mathbf{0}, \quad (2)$$

where $M_{nn'}=\sum_{\alpha\sigma}W^{nn'}_{\alpha i\sigma}$ and $M_{nn}=-\sum_{\alpha\sigma}\sum_{n'}W^{n'n}_{\alpha i\sigma}$ are the nondiagonal and diagonal elements respectively with the tunneling matrix elements defined by $W^{nn'}_{\alpha i\sigma}=(\Gamma_{\alpha i\sigma}/\hbar)[f_\alpha(\varepsilon_{n'}-\varepsilon_n)|C^\sigma_{nn'}|^2+(1-f_\alpha(\varepsilon_n-\varepsilon_{n'}))|C^\sigma_{n'n}|^2]$. $f_\alpha(\varepsilon)=(1+e^{(\varepsilon-\mu_\alpha)})^{-1}$ is the Fermi distribution function and $C^\sigma_{n'n}=\langle n'|d_{i\sigma}|n\rangle$ is the transition amplitude between two states of the DQD. In the weak symmetric coupling between DQD and leads we have $\Gamma=\Gamma_{L1}=\Gamma_{R2}=\sum_\sigma\Gamma_{\alpha i\sigma}\ll k_BT$. The spin polarization of FM lead-$\alpha$ is defined as $P_\alpha=(\rho_{\alpha\uparrow}-\rho_{\alpha\downarrow})/(\rho_{\alpha\uparrow}+\rho_{\alpha\downarrow})$, where $\rho_{\alpha\uparrow}$ ($\rho_{\alpha\downarrow}$) denotes the density of states for the spin-up (spin-down) electrons. So we have the relations $\Gamma_{\alpha i\uparrow}=\Gamma(1+P_\alpha)/2$, $\Gamma_{\alpha i\downarrow}=\Gamma(1-P_\alpha)/2$, and assume $P_L=P_R=p$ for parallel (P) configuration of the lead magnetization, $P_L=-P_R=p$ for the antiparallel (AP) configuration. The corresponding stationary currents are obtained as

$$I=\langle I_L\rangle=-e\sum_{n,n',\sigma}(n'-n)W^{nn'}_{L\sigma}P(n)=\mathrm{Tr}(\mathbf{W}_{IL}\mathbf{P}) \quad (3)$$

in both configurations respectively [11,21], where $P(n)$ is the population probability of state $|n\rangle$. The spin-dependent shot noise is defined by the current–current correlation

$$S^{\sigma,\sigma'}_{\alpha,\alpha'}(\omega)=2\int_{-\infty}^{+\infty}[\langle I^\sigma_\alpha(t)I^{\sigma'}_{\alpha'}(0)\rangle-\langle I^\sigma_\alpha\rangle\langle I^{\sigma'}_{\alpha'}\rangle]e^{i\omega t}\,dt. \quad (4)$$

For the stationary current the zero-frequency shot noise can be calculated as

$$S=\sum_{\sigma,\sigma'}S^{\sigma,\sigma'}_{L,L}=2e^2\mathrm{Tr}[(|\mathbf{W}_{IL}|+\mathbf{W}_{IL}\mathbf{G}\mathbf{W}_{IL}+\mathbf{W}_{IL}\mathbf{G}^*\mathbf{W}_{IL})\mathbf{P}], \quad (5)$$

where $\mathbf{G}=-(\mathbf{M}+i\omega\mathbf{E})^{-1}+(i\omega)^{-1}\mathbf{Q}$ is the Green function with $\omega=0$ being a singular point. $\mathbf{E}$ denotes a unit matrix and $\mathbf{Q}$ is a matrix with elements $Q_{nn'}=P(n)$. Thus we can obtain the Fano factor [26]

$$F=\frac{S}{2e|I|}, \quad (6)$$

which characterizes the type of shot noise such that it is called the sub-Poissonian if $F<1$ and super-Poissonian if $F>1$. The super-Poissonian statistics resulted from the bunching of electrons provides the information to probe the correlation and entanglement of