Non-equilibrium Kondo effect in double quantum dot

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Abstract

We investigate theoretically a non-equilibrium transport through a double quantum dot (DQD) in a parallel geometry. It is shown that the resonance Kondo tunneling through a parallel DQD with even occupation and singlet ground state may arise at a strong bias, which compensates the energy of singlet/triplet excitation. Using the renormalization group technique we derive scaling equations and calculate the differential conductance as a function of an auxiliary DC-bias for parallel DQD being in a regime described by SO(4) symmetry.

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PACS: 72.10.–d; 72.10.Fk; 72.15.Qm; 05.10.Cc

Keywords: Quantum dots; Kondo effect; Nonequilibrium

Kondo effect (KE) is a collective phenomenon which manifests itself in strongly correlated electron systems, such as heavy fermion compounds, and in artificial nanosize structures (quantum dots, nanotubes, etc). Moreover, fabricated nanoscale devices provide a possibility to adjust practically any interaction parameter and create a unique condition for observation of many-particle phenomena. It has been predicted theoretically \cite{1} and observed experimentally \cite{2}, that the differential conductance of a dot with odd number of electrons increases with decreasing temperature, being a universal function of single scaling parameter $T/T_K$. The resonance tunneling is attributed to KE and corresponding universal energy scale $T_K$ is a Kondo temperature. It is known, that the KE usually exists when the spin of nano object is half-integer (the number of electrons is odd) whereas external magnetic field and external DC(AC) bias results in strong suppression of this collective phenomenon. However, it has been recently shown \cite{3}, that the KE may arise also in the absence of both these premises. In this paper, we report yet another possibility to induce resonance Kondo tunneling in a double dot with even number of electrons by applying external DC-bias $eV$.

The double quantum dot (DQD) in parallel geometry (see Fig. 1) was realized experimentally in Ref. \cite{4}. It has been shown in Ref. \cite{5}, that if the number of electrons is even, DQD possesses the dynamical SO(4) symmetry of spin rotator. The low energy part of its spectrum is formed by singlet/triplet pair with a ground state singlet $|S\rangle$ having the energy $E_S$ and a triplet excitation $|T\rangle$ with the energy $E_T$. The Hamiltonian of DQD is

\begin{equation}
H_d = E_S|S\rangle \langle S| + \sum E_T|T_\eta\rangle \langle T_\eta|. \tag{1}
\end{equation}

The KE is absent as a zero-bias anomaly in differential conductance provided $\delta = E_T - E_S \gg T_K^\text{eq}$ where $T_K^\text{eq}$ is a Kondo temperature characterizing KE for $S = 1$ in equilibrium. However, under the resonance condition $|eV - \delta| \ll T$ the new channel of resonance co-tunneling arises, because the non-diagonal matrix element of exchange interaction $\langle S|J|T\rangle \neq 0$. It is shown in Ref. \cite{5}, that the Hamiltonian of DQD in parallel geometry coupled with leads satisfy this
with bandwidth $D$, conductance $G$ and temperature $T$ through a triplet channel. The differential energy scale determines a non-equilibrium Kondo condition: 

$$H_{\text{int}} = \sum_{(2\sigma)} J_{\sigma\sigma} J_{\sigma\sigma} + \sum_{(3\sigma)} (J_{\sigma\sigma} S_{\sigma\sigma} + J_{\sigma\sigma} S_{\sigma\sigma})$$ \[J_{\sigma\sigma} = \alpha \delta_{\sigma}\] 

Here $c_{\sigma\sigma}$ denotes conduction electrons in leads $z = L, R$ with bandwidth $D$, fermions $f_{\sigma}$ stand for two-electron singlet/triplet states in a dot $A = s, \pm 1, 0$, the coupling constants $J_{s}, J_{T}, J_{ST} \sim W/\epsilon_{F}$ denote singlet, triplet and singlet–triplet constants, respectively. The $4 \times 4$ matrices $S^d$ and $P^d$ define 6 generators of SO(4) group (see details in [6]). $\alpha_d$ are the Pauli matrices.

Following the poor man's scaling approach, we derive the system of coupled renormalization group (RG) equations for (2). The equations for $L_{\sigma}$ co-tunneling ($\sigma = L, R$) are as follows:

$$\frac{dJ_{\sigma}^T}{d \ln D} = -\nu J_{\sigma}^T J_{\sigma}^T, \quad \frac{dJ_{\sigma}^{ST}}{d \ln D} = -\nu J_{\sigma}^{ST} J_{\sigma}^{ST}, \quad \frac{dJ_{\sigma}^{LR}}{d \ln D} = \frac{1}{2} J_{\sigma}^{ST} J_{\sigma}^{ST} + \frac{1}{2} J_{\sigma}^{LR} J_{\sigma}^{LR},$$ \[\alpha_d = \mu \delta_{\sigma}\] 

where $\nu$ is a DoS on a Fermi level in the leads.

As a result, the effective exchange couplings are strongly renormalized at $T \rightarrow T_K^\text{eq} \sim (T_K^2)^2/D$. This energy scale determines a non-equilibrium Kondo temperature through a triplet channel. The differential conductance $G(eV, T)/G_0 \sim |J_{\sigma\sigma}^{ST}|^2$ [7] is the universal function of two parameters $T/T_K$ and $eV/T_K$ (see Fig. 2). $G_0 = e^2/\pi \hbar$:

$$G/G_0 \sim \ln^{-2}(\max(|eV - \delta|, T)/T_K).$$ \[\alpha_d = \mu \delta_{\sigma}\] 

The analysis of decoherence effects associated with singlet/triplet transition leads to the following limitations for the external parameters of the real dot:

$$\hat{\delta}(\hat{\delta}/D)^2 \ll T_K^\text{eq}, \hat{\delta} \ll \delta \sim eV \ll D.$$ \[\alpha_d = \mu \delta_{\sigma}\] 

The decoherence rate $\hbar/\tau_d$ out of this domain is not negligible as compared to $T_K$ and cuts off the strong-coupling physics at low temperatures. The contribution to $\hbar/\tau_d$ from the virtual transitions between different degenerate triplet states has a threshold character and is responsible for asymmetry of the conductance peak. Thus, we predict an existence of non-equilibrium resonance Kondo tunneling robust to the spin-decoherence effects. It can be observed in DC-biased DQD in parallel geometry.

References