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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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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 [1] and observed experimentally [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 [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. [4]. It has been shown in Ref. [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 $|T\eta\rangle$ with the energy E_T. The Hamiltonian of DQD is

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

The KE is absent as a zero-bias anomaly in differential conductance provided $\delta = E_T - E_S \gg T_K^{eq}$ where T_K^{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. [5], that the Hamiltonian of DQD in parallel geometry coupled with leads satisfy this

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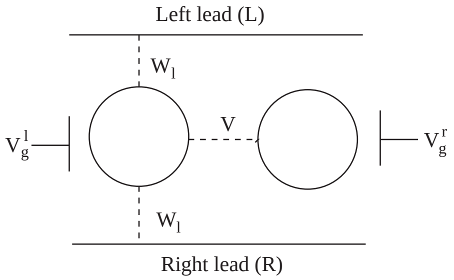

Fig. 1. Double quantum dot in parallel geometry.

condition:

$$
\begin{aligned}
H_{\text{int}} = & \sum_{\{\alpha\sigma\}} J^{S}_{\alpha\alpha'} f_s^{\dagger} f_s c^{\dagger}_{k\alpha\sigma} c_{k'\alpha'\sigma} \\
& + \sum_{\{\alpha\sigma\}} \left(J^{T}_{\alpha\alpha'} \hat{S}^{d}_{\Lambda\Lambda'} + J^{ST}_{\alpha\alpha'} \hat{P}^{d}_{\Lambda\Lambda'} \right) \\
& \times \tau^{d}_{\sigma\sigma'} c^{\dagger}_{k\alpha\sigma} c_{k'\alpha'\sigma'} f^{\dagger}_{\Lambda} f_{\Lambda'}.
\end{aligned}
\tag{2}
$$

Here $c_{k\alpha\sigma}$ denotes conduction electrons in leads $\alpha = L, R$ with bandwidth D, fermions f_Λ stand for two-electron singlet/triplet states in a dot $\Lambda = s, \pm 1, 0$, the coupling constants J^S, J^T, $J^{ST} \sim W^2/\varepsilon_F$ denote singlet, triplet and singlet–triplet constants, respectively. The 4×4 matrices S^d and P^d define 6 generators of SO(4) group (see details in [6]), τ^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 $L\alpha$ co-tunneling ($\alpha = L, R$) are as follows:

$$
\begin{aligned}
& \frac{dJ^{T}_{L\alpha}}{d\ln D} = -\nu J^{T}_{LL} J^{T}_{L\alpha}, \quad \frac{dJ^{ST}_{L\alpha}}{d\ln D} = -\nu J^{ST}_{LL} J^{T}_{L\alpha}, \\
& \frac{dJ^{S}_{LR}}{d\ln D} = \frac{1}{2}\nu \left(J^{ST}_{LL,+} J^{TS}_{LR,-} + \frac{1}{2} J^{ST}_{LL,z} J^{TS}_{LR,z} \right),
\end{aligned}
\tag{3}
$$

where ν is a DoS on a Fermi level in the leads.

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

$$
G/G_0 \sim \ln^{-2}(\max[(eV - \delta), T]/T_K). \tag{4}
$$

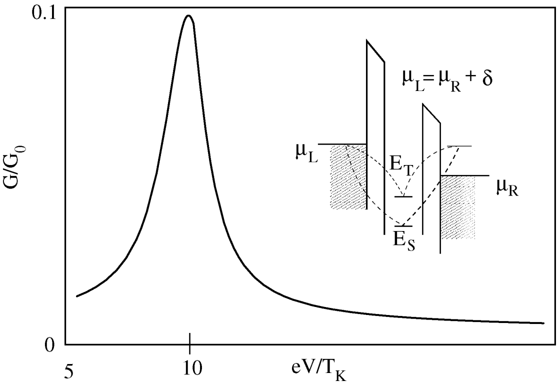

Fig. 2. Differential conductance as a function of DC-bias eV/T_K ($\delta/T_K = 10$, $\hbar/\tau T_K = 0.1$). Inset shows co-tunneling processes responsible for Kondo tunneling.

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

$$
\delta(\delta/D)^2 \ll T_K^{\text{neq}} \ll T_K^{\text{eq}} \ll \delta \sim eV \ll D. \tag{5}
$$

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.

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