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Spin-Dependent Transport through SU(4) Kondo Dot in the Presence of Spin-Flip Processes

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The spin-resolved current of carbon nanotube quantum dot coupled to ferromagnetic electrodes and influenced by spin-flip scattering is studied in the Kondo regime by the equation of motion method.

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1. Introduction

Carbon nanotube quantum dot (CNT-QD) is a unique system exhibiting exotic many-body spin–orbital Kondo effect [1].The long spin lifetimes of carbon nanotubes, well elaborated technology of their coupling to ferromagnetic electrodes [2] and relatively high Kondo temperatures [1] offer the prospect for using Kondo effect in spintronics.The aim of the present paper is to discuss the combined influence of ferromagnetic leads and spin-flip processes on spin-resolved transport in these systems.

2. Model

The low energy band structure of semiconducting carbon nanotubes is orbitally doubly degenerate. This degeneracy corresponds to clockwise and counterclockwise symmetry of the wrapping modes in CNTs [3]. In the present considerations we restrict to the single shell and the dot is modeled by double orbital Anderson Hamiltonian with equal intraorbital and the interorbital Coulomb interaction ($\mathcal{U}$) and spin flip scattering in the dot parameterized by $\mathcal{R}$:

$$\mathcal{H} = \sum_{k\alpha m\sigma} \epsilon_{k\alpha m\sigma} c^{+}_{k\alpha m\sigma} c_{k\alpha m\sigma} + \sum_{m\sigma} \epsilon_{m\sigma} d^{+}_{m\sigma} d_{m\sigma} + \sum_{k\alpha m\sigma} t_\alpha \left(c^{+}_{k\alpha m\sigma} d_{m\sigma} + \mathrm{H.c.} \right) + \sum_{m} \mathcal{U} n_{m+} n_{m-} + \sum_{\sigma\sigma'} \mathcal{U} n_{1\sigma} n_{-1\sigma'} + \sum_{m} \mathcal{R} \left(d^{+}_{m+} d_{m-} + \mathrm{H.c.} \right), \quad (1)$$

where $m = \pm 1$ numbers the orbitals, the leads channels are labeled by (m, α), $\alpha = \mathrm{L}, \mathrm{R}$, $\epsilon_{m\sigma} = \epsilon_0 - eV_{\mathrm{g}}$ and V_{g} denotes gate voltage. We set $|e| = |g| = |\mu_{\mathrm{B}}| = |k_{\mathrm{B}}| = |h| = 1$. The spin polarization of the leads $\mathcal{P} = \mathcal{P}_\alpha$ is defined by spin-dependent densities of states ($\varrho_{\alpha\sigma}$), $\mathcal{P}_\alpha = (\varrho_{\alpha+} - \varrho_{\alpha-})/(\varrho_{\alpha+} + \varrho_{\alpha-})$. Current flowing through CNT-QD in the $|m\sigma\rangle$ channel $\mathcal{I}_{m\sigma} = (\mathcal{I}_{\mathrm{L}m\sigma} - \mathcal{I}_{\mathrm{R}m\sigma})/2$ can be expressed in term of the lesser Green functions as follows [4]:

$$\mathcal{I}_{\alpha m\sigma} = \sum_k t_\alpha \left[G^{<}_{m\sigma,k\alpha m\sigma}(t) - G^{<}_{k\alpha m\sigma,m\sigma}(t) \right]. \quad (2)$$

The corresponding conductances are defined as $\mathcal{G}_{m\sigma} = \mathrm{d}\mathcal{I}_{m\sigma}/\mathrm{d}V$, $\mathcal{G}_\sigma = \mathcal{G}_{1\sigma} + \mathcal{G}_{-1\sigma}$ and polarization of conductance $\mathrm{PC} = (\mathcal{G}_+ - \mathcal{G}_-)/(\mathcal{G}_+ + \mathcal{G}_-)$. The Green functions are found by the equation of motion method using the Lacroix decoupling, which preserves the Kondo correlations [5] and the lesser Green functions $G^<$ are determined using the Ng ansatz [6], according to which the lesser self-energy $\Sigma^<$ is proportional to the self-energy of the corresponding noninteracting system $\Sigma^<(\omega) = \Lambda\Sigma^{0<}(\omega)$, and Λ can be found by the Keldysh requirement $\Sigma^> - \Sigma^< = \Sigma^{\mathrm{R}} - \Sigma^{\mathrm{A}}$, where $\Sigma^{\mathrm{R(A)}}$ are retarded (advanced) self-energies. The role of polarization of electrodes is twofold: it makes the tunneling induced broadenings spin dependent $\Gamma_{\alpha m\sigma} = 2\pi t_\alpha^2 \varrho_{\alpha m\sigma}$, and it induces an effective exchange splitting (Δ_{exch}) via spin-dependent charge fluctuations. For brevity we do not cite here the explicit formula for Δ_{exch}, this can be found e.g. in [7].

3. Results and discussion

We present numerical results for $\epsilon_0 = -6$ and $\mathcal{U} = 15$ ($\Gamma = \sum_{\alpha m\sigma} \Gamma_{\alpha m\sigma}$ is taken as the energy unit). Figures 1a,b present polarization of conductance of CNT-QD in the Kondo regime versus gate and bias voltages for different values of spin-flip scattering amplitudes. Figures 1c,d show generalized transmissions $\mathcal{T}^{\sigma\sigma} = 4(\Gamma_{\mathrm{L}} G^{\mathrm{R}} \Lambda \Gamma_{\mathrm{R}} G^{\mathrm{A}})$ [8, 9], which incorporate part of the nonequilibrium effects of the Coulomb interaction. Polarization of electrodes breaks the spin degeneracy leading to a crossover from spin–orbital SU(4) to coupled orbital SU(2) Kondo effect. For $\mathcal{R} = 0$ the three peak structure of transmission is observed ($E \approx T_{\mathrm{K}}$, $E \approx T_{\mathrm{K}} \pm \Delta_{\mathrm{exch}}$) and for $\mathcal{R} \neq 0$ the satellites reflecting spin and spin–orbital fluctuations further split and locate around $E \approx T_{\mathrm{K}} \pm (\Delta_{\mathrm{exch}} \pm 2\mathcal{R})$, where T_{K} denotes polarization and spin-flip perturbed Kondo temperature. For small values of exchange splitting all the peaks are

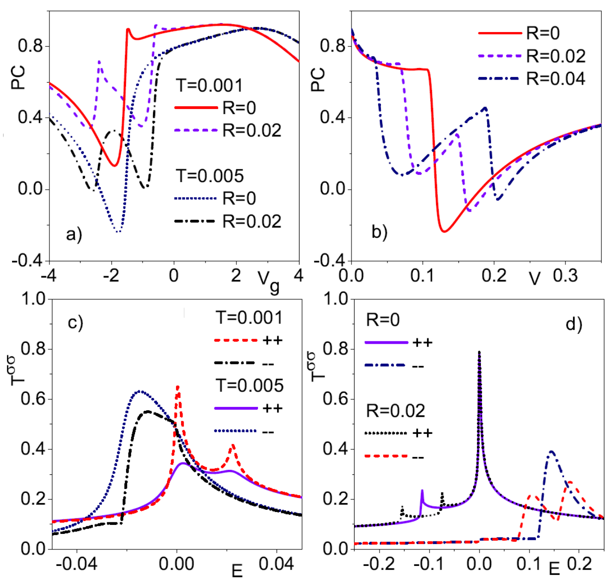

Fig. 1. Polarization of conductance of CNT-QD coupled to ferromagnetic electrodes ($\mathcal{P} = 0.6$) in the Kondo regime for different values of spin-flip amplitude (a) vs. gate voltage, (b) vs. bias voltage ($V_g = 1$, $T = 0.001$). Generalized spin resolved transmissions of CNT-QD for gate voltage (c) $V_g = -2$ ($\mathcal{R} = 0$), (d) $V_g = 1$ ($T = 0.001$).

located close to E_F (Fig. 1c, $V_g \approx -2$, $\Delta_{exch} \approx 0.02$). Location near E_F explains strong impact of spin-flip scattering or temperature on linear PC in this region. The ratio of spin resolved linear transmissions is easily disturbed in this case. As it is seen in Fig. 1a in this range suppression ($T = 0.001$) or even a change of sign of linear PC ($T = 0.005$) can result. For gate voltages away from $V_g = -2$ ($|\Delta_{exch}| > T_K$) linear PC reaches high values and is more robust against spin flips, which is especially visible for positive V_g (Fig. 1a). This is a consequence of strong dominance of majority spin linear transmission around the Fermi energy in this range (Fig. 1d, $V_g = -1$, $\Delta_{exch} = -0.12$). Figure 1b shows bias dependence of PC. Local minima of PC(V) are observed when bias voltage V sweeps across new resonances (Fig. 1d).

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