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COHERENT TRANSPORT THROUGH DOUBLE DOT SYSTEM

S. LIPIŃSKI AND B. R. BUŁKA

Institute of Molecular Physics, Polish Academy of Sciences
M. Smoluchowskiego 17, 60-179 Poznań, Poland

Abstract: The coherent spin dependent transport through a set of two capacitively coupled quantum dots (DQD) is considered in the limit of infinite intra and interdot coulomb interactions. The Kondo effect in DQD has two possible sources: the spin and the "orbital" degeneracies. For the vanishing magnetic field and equal site energies of the dots, currents flowing through each of the four channels are equal and the linear conduction reaches the unitary limit at zero temperature. To calculate the densities of states we use the expression for the Green's function derived by Meier *et al*. [1] for the single dot by the equation of motion method (EOM) and generalized by us to the DQD system in approximation which favors separate fluctuations of spin, orbital isospin and the simultaneous fluctuations of both of them. Apart from the Kondo peak, also the satellite many-body peaks located above and below the Fermi level are found in the densities of states. The positions of the peaks are determined by the strength of the magnetic field. Whereas the states of both spin orientations contribute almost equally to the central Kondo resonance, the satellite peaks are characterized by different spin orientations.

1. INTRODUCTION

Spin dependent tunneling through nanostructures has became a very active area of research due to its possible applications in field sensors [2], conventional computer hardware (*e.g.* magnetic random access memories (MRAMs) [2]) and in quantum computers [3]. In commonly used magnetoresistive devices the ferromagnetic electrodes are used. To control the transport its dependence on the relative orientation of magnetic moments of the leads is exploited. The problem of attaching ferromagnetic electrodes to a QD is far from trivial and therefore it is of importance to examine the field control of current also for the structures coupled to nonmagnetic leads. For the resonant tunneling a separation of the spin channels is possible, but extremely high magnetic fields are required (the Zeeman splitting should be of the order of the coupling to the leads). For typical values of 0.1-0.5 meV [4] the corresponding fields lie in the range 2-10 T. For special cases of systems characterized by an enhanced g factor the necessary fields are slightly smaller. Magnetic field also influences transport in the coherent regime. The natural scale of the field in this case is determined by a typical width of the many-body resonance. This is much smaller than the coupling strength Γ. For the single dot the field induced splitting of the Kondo resonance is now experimentally well documented [5]. For the deep dot level the Kondo peaks corresponding to the opposite spin directions move with the field almost symmetrically with respect to the Fermi level and consequently the linear conductance does not exhibit significant spin polarization. This is a consequence of the fact that h = 0 Kondo resonance lies just above the Fermi level. The relative increase of the difference between the spin-resolved conductances is expected with the increase of temperature or by a shift of the dots energy towards the mixed valence regime. The unperturbed resonance moves then on the right from the Fermi level introducing, for the finite field, spin asymmetry. The spin-filtering effect for the single dot in the coherent regime is described in [6]. Recently Kondo effect has been also observed in double dot structures [7]. The large number of tunable parameters (*e.g.* gate voltages, tunneling strengths) allows the delicate manipulation of the Kondo physics.

The aim of the present paper is to discuss the influence of magnetic field on the structure of the many-body resonances of DQD and to examine the field dependence of the conductance. The occurrence of the satellite peaks in DOS reflects in the apperance of the corresponding peaks in the nonlinear conductance. Their position is determined by the field. This property can be used in measuring the field. The side peaks above and below the Fermi level are characterized by the opposite spin polarization and we predict that this should be observed in the strong spin dependence of boson assisted tunneling.

2. CAPACITIVELY COUPLED DOUBLE QUANTUM DOT IN THE KONDO REGIME

We discuss the system of two capacitively coupled quantum dots placed in a magnetic field. Each of the dots is coupled to its own pair of the leads. The corresponding Hamiltonian reads:

$$H = \sum_{kri\sigma} \varepsilon_{kri\sigma} c^+_{kri\sigma} c_{kri\sigma} + \sum_{i\sigma} \varepsilon_{i\sigma} c^+_{i\sigma} c_{i\sigma} + \sum_{i} U_i n_{i+} n_{i-} + U \sum_{\sigma\sigma'} n_{1\sigma} n_{2\sigma'} + \sum_{kri\sigma} t_{ri} (c^+_{kri\sigma} c_{i\sigma} + h.c), \quad (1)$$

where i numbers the dots (i = 1, 2) and leads are labeled by (i, r) ($r = L, R$). $\varepsilon_{i\sigma} = \varepsilon_i + \sigma h$, $\sigma = \pm 1$ (we set $|e| = g = \mu_B = k_B = 1$). The first term describes electrons in the electrodes, the second represents the field dependent site energies, the third and fourth accounts for intra and intercoulomb interactions and the last one describes the tunneling.

For strong inter and intradot interactions the Kondo effect has two possible sources, the spin and orbital degeneracies. In the following we restrict to the case, where the spin degeneracy is removed by an external magnetic field ($\varepsilon_{1\sigma} = \varepsilon_{2\sigma}$, $\varepsilon_{1\uparrow} \neq \varepsilon_{2\downarrow}$).

Assuming quasi-elastic transport, for which the current conservation rule is fulfilled for any ω, one can express the current $I = \sum_{i\sigma} I_{i\sigma}$ [1] in the form:

$$I_{i\sigma} = \frac{e}{\hbar} \int d\omega \frac{\Gamma_{iL\sigma}(\omega)\Gamma_{iR\sigma}(\omega)}{\Gamma_{iL\sigma}(\omega) + \Gamma_{iR\sigma}(\omega)} [f_{iL}(\omega) - f_{iR}(\omega)] \, \rho_{i\sigma}(\omega) \quad (2)$$

where $\rho_{i\sigma}(\omega) = (1/\pi)\ \mathrm{Im}\, G^r_{i\sigma}(\omega)$ and f_{ir} are Fermi distribution functions of the electrodes. The current, the distribution functions and the Green's functions are also the functions of temperature, field and bias voltage. For simplicity of considerations we restrict here to the case of identical dots ($\varepsilon_i \equiv \varepsilon_0$), identical electrodes and to the equal couplings to the dots *i.e.* $t_{ri} \equiv t$. The bare Green's functions of the electrodes $g_{r\sigma} = \sum_k g_{kr\sigma} = \sum_k 1/(\omega - \varepsilon_{kr\sigma}) \approx g$ are taken in the form $g = -i\pi\rho_0$, where $\rho_0 = 1/2D$ is the assumed constant density of states for $|\varepsilon| < D$ and D is the half of the bandwidth of electrons in the electrodes. Consequently the elastic couplings to the electrodes are energy independent $\Gamma_{ir\sigma}(\omega) = 2\pi t^2\rho_0 \equiv \Gamma$ (we set $\Gamma = 1$). The spin-resolved nonlinear conductance can be calculated form (2) by numerical derivative $\breve{G}_\sigma$(V) $\equiv \partial I_\sigma / \partial V$, $I_\sigma = I_{1\sigma} + I_{2\sigma}$.

For strong interactions $(U_1, U_2, U) \to \infty$ and deep dot level ($\varepsilon_{i\sigma} >> \Gamma$) the retarded Green's function can be approximated by the following multipole expression:

$$G^r_{i\sigma}(\omega) = \frac{1-n_\Omega}{3}\sum_{l\in\Omega}\frac{1}{\omega-\varepsilon_{i\sigma}-\Sigma_0-\Sigma^1_{i\sigma,l}(\omega)}, \tag{3}$$

where $\Sigma_0 = i\Gamma$ is the self-energy for the noninteracting QD due to tunneling of the $i\sigma$ electron, Ω is a set of the quantum numbers labeling the virtual intermediate states in the tunneling and n_Ω denotes the average total occupation of these states. $\Omega = \{(\bar{i},\sigma),(i,\bar{\sigma}),(\bar{i},\bar{\sigma})\}$, $n_\Omega = \sum_{l\in\Omega}\langle n_l\rangle$ and $\{\Sigma^1_{is,l}\}$ denote the correlation parts of the self-energy ($\bar{1} = 2$, $\bar{2} = 1$). Expression (3) is a simple generalization to the DQD system case of the single dot formula of Meier *et al*. [1] derived by the EOM technique with the decoupling procedure for higher order Green's functions which neglects correlations in the leads. Formulas (3) and (4) correspond to the approximation, which separately takes into account the isospin fluctuations, spin fluctuations and fluctuations of strongly coupled spin and isospin.

$$\Sigma^1_{i\sigma,i'\sigma'} = t^2\sum_{k\in L,R}\frac{f_{L,R}(\varepsilon_{ki'\sigma'})}{\omega-\varepsilon_{i\sigma}+\varepsilon_{i'\sigma'}-\varepsilon_{ki'\sigma'}+i\delta_{i\sigma'}}, \tag{4}$$

$\delta_{i\sigma}$ describes decoherence due to a finite bias voltage or field induced level splitting. An estimate of the lifetime can be obtained from perturbation theory [1].

The first sequence of correlated tunneling represented by $\Sigma^1_{i\sigma,\bar{i}\sigma}$ occurs through the intermediate virtual states of the same spin but from different dot. They induce the fluctuations of the single dot occupations (the orbital isospin flips). As a result the orbital Kondo resonances for each spin channel is built up. The second type of tunneling processes ($\Sigma^1_{i\sigma,i-\sigma} = \Sigma^1_{i\sigma,\bar{i}-\sigma}$) link the nondegenerate states and cause the singularity of self-energy in the regions separated from Fermi level by Zeeman splitting. In the limit of the vanishing magnetic field they correspond to the spin Kondo effect and to the simultaneous fluctuations of spin and isospin. The neglected processes, which mix the above mentioned three types of fluctuations are of special importance for systems, close to the full fourfold spin-orbital degeneracy. Their role is under investigation by more careful treatment of EOM equations and the results will be published elsewhere. Let us only comment here on the spurious effect, which occurs in the Meyer approach for finite bias, also in the case of the single dot. The imaginary part of the self energy exhibits two steps, one for each chemical potential (their heights for $\delta_{i\sigma} \to 0$ are equal $\Gamma/2$). Consequently the shifted Kondo peaks dramatically differ in their widths. This effect has not been observed in more rigorous approximations [8] and therefore we believe that it is only an artifact of the method. In the following we approximate $\mathrm{Im}\,\Sigma^1_{i\sigma,l}(V)$ by $\mathrm{Im}\,\Sigma^1_{i\sigma,l}(V=0)$, what removes this unphysical difficulty.

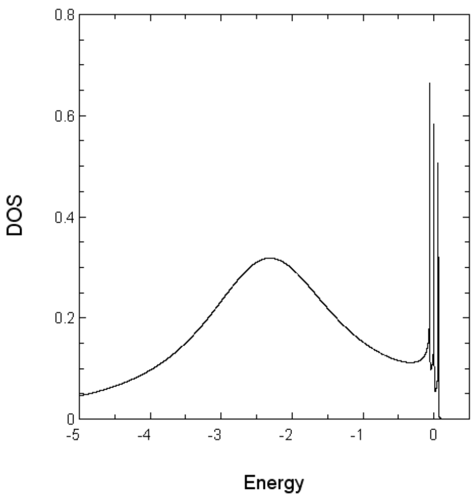

Fig. 1. Total density of states of the capacitively coupled double quantum dot in magnetic field $h = 0.03$ calculated for the bare dot energy $\varepsilon_0 = -3.3$ (Γ is the energy unit)

Figure 1 presents the total density of states (DOS) of the DQD system for finite magnetic field and vanishing bias voltage $V \rightarrow 0$ in the case of the deep dots levels. We do not discuss here any decoherence effects and the calculations were performed for $\delta = \delta_{i\sigma} = 0.001$. The shift of the broad charge fluctuation peak from the bare positions $\varepsilon_{i\sigma}$ reflects the renormalization of the dots levels by spin and orbital isospin fluctuations.

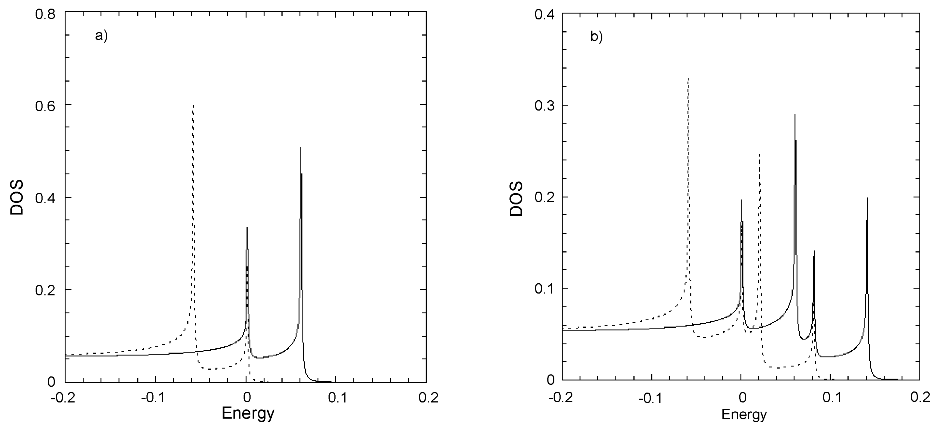

Fig. 2. Spin dependent DOS of DQD in magnetic field $h = 0.03$ for spin up (solid line) and spin down (dashed line), $\varepsilon_0 = -3.3$. a) zero bias voltage $V = 0$, b) $V = 0.08$

The spin-projected densities of states plotted in the narrow energy region around E_F are shown on Fig. 2a. The similar triple peak structure around E_F in the DOS of double dot system b)

was earlier found by Pohjola *et al.* within the resonant-tunneling approximation [8]. The peak at the Fermi level corresponds to the orbital isospin fluctuations and the satellite peaks located roughly in the positions $\pm 2h$ are due to the tunneling processes involving levels split by the field. The satellite peaks are characterized by different spin orientations. A small spin asymmetry is also visible for the central Kondo resonance, what for the deep dots level case, is mainly due to the occurrence of other (spin-dependent) many-body resonances in its vicinity. The spin asymmetry of the Kondo peak manifests also in the slave boson calculations [9]. Obviously more rigorous calculations are desired for the definite conclusion. This question is important for the spin-filtering problem. The different spin polarization of the lower and upper satellite peaks should reflect in the strong spin dependence of inelastic tunneling. The effect can be masked however by strong decoherence. For stationary transport, discussed here, different polarizations of the satellite peaks have only small influence. The reason for that is explained on Fig. 2b, where the spin-projected DOS is plotted for finite bias voltage. The potential of the left electrode is assumed to be zero. A voltage between the left and right leads causes the Kondo peaks to split, leaving a peak in DOS at the chemical potential of each lead. The satellite peaks also split by V. For $V \approx \pm 2h$ the satellite peaks of opposite spin polarization enter from the opposite sides the energy region between the Fermi levels of the leads and consequently the peaks in the differential conductance build up.

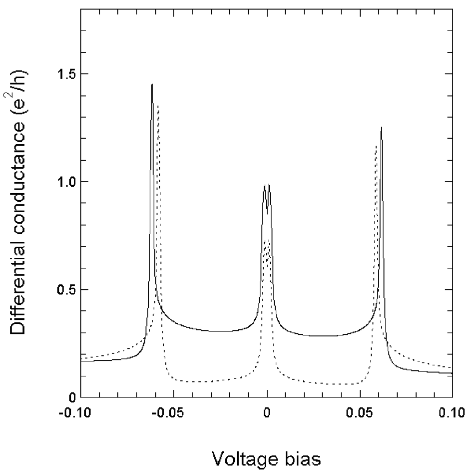

Fig. 3. Differential conductance *vs*. applied bias for spin up (solid line) and spin down (dashed line). Magnetic field h = 0.03 and dot energy $\varepsilon_0 = 3.3$

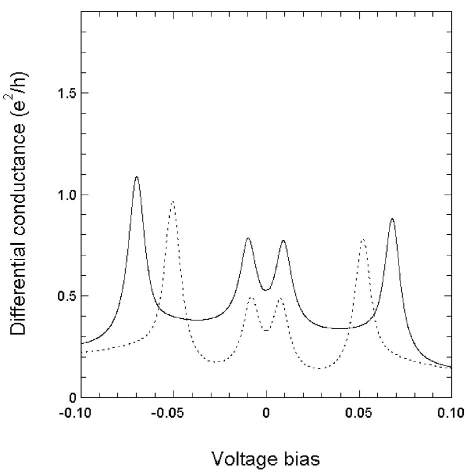

Fig. 4. Differential conductance *vs*. applied bias for spin up (solid line) and spin down (dashed line). Magnetic field h = 0.03 and dot energy $\varepsilon_0 = 2.75$

This is presented on Fig. 3. The fact that the positions of the nonlinear conductance peaks are determined by the strength of the field can be used in measuring the fields. The peaks for the opposite spin orientations are slightly shifted and this effect increases moving with the energies of the dots closer to E_F (*e.g.* by changing the gate voltages) (Fig. 4). Such an effect is expected due to the increasing difference between the centers of up and down spin Kondo resonances with moving towards mixed valence regime. It has to be emphasized that because of the crudeness of our approach the presented preliminary results can only be trusted qualitatively. The more rigorous calculations on this problem, which also include the spin asymmetry between the junctions, are under the way.

In conclusion, we studied transport through a capacitiviely coupled double quantum dot placed in a magnetic field. The system exhibits the Kondo effect due to fluctuations of the "orbital" isospin. In addition, the satellite peaks above and below the Fermi level are found. They are characterized by different spin polarization. Both the linear and nonlinear conductances are spin dependent and this dependence increases when moving towards the mixed valence regime.

Acknowledgments

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