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Boson-Induced Orbital Kondo Effect

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The single dot in magnetic field and double quantum dot with broken spin-orbital symmetry are discussed in the boson field environment. It is shown that the time dependent potential induces the Kondo effect, provided that the single boson energy compensates the spin or orbital splitting. The photon induced recovery of orbital degeneracy can occur within the same spin channel or with the spin mixing. In the former case the spin polarized photocurrent is expected.

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1. Introduction

The influence of time-dependent external fields on quantum transport through nanoscopic devices has attracted a lot of interest in recent years [1]. One of the controversial issues is how the Kondo effect is affected by irradiation. Application of a microwave ac voltage at a frequency ω higher than $k_{\mathrm{B}}T_{\mathrm{K}}/\hbar$ (T_{K} — Kondo temperature) is expected to create new peaks in the density of states displaced by energies $n\hbar\omega$ from the main Kondo resonance [2]. In contrast to these predictions some theoretical papers [3] argue that decoherence of the Kondo coupling by the microwave excitations might be so strong that it destroys the Kondo effect before the satellites can emerge. On the other hand, quite recently single photon satellite peaks in the differential conductance have been observed for photon energy somewhat greater than the Kondo scale and carefully chosen microwave voltage [4]. This stimulates further research in the field of photon assisted Kondo effect. Motivated by these experiments we address the following question: can the Kondo effect be recovered under boson assistance for the originally nondegenerate states?

2. Model and formalism

We first discuss the single quantum dot (QD) placed in a magnetic field (broken spin degeneracy SU(2)) and next generalize the considerations into the system of two capacitively coupled dots (DQD) with broken spin-orbital degeneracy (SU(4)). It is assumed that the levels of the dots are time-dependent, which experimentally can be achieved by means of time-dependent gate voltages. We focus our study on the transport in the Kondo regime. The systems are modeled by single dot (H_1) or two-dot ($H_1 + H_2 + H_{1-2}$) time-dependent Anderson Hamiltonians with additional interdot interaction in the latter case.

$$H_1(t) = \sum_{k\in[\mathrm{L,R}],\sigma} \varepsilon_{k1\sigma} c^+_{k1\sigma} c_{k1\sigma} + \sum_{\sigma} (E_{1\sigma} + V_{ac}\cos\omega_0 t) d^+_{1\sigma} d_{1\sigma} + \sum_{k\in[\mathrm{L,R}],\sigma} (t c^+_{k1\sigma} d_{1\sigma} + \mathrm{h.c.}) + U n_{1+} n_{1-}, \tag{1}$$

$$H_{1-2} = U_{12} n_{1\sigma} n_{2\sigma}. \tag{2}$$

$E_{i\sigma} = E_i + \sigma h$, $\sigma = \pm 1$ (we set $g = |e| = \mu_{\mathrm{B}} = k_{\mathrm{B}} = 1$). The ac voltage with intensity V_{ac} and frequency ω_0 modulates in time the position of QD levels. For brevity all the formal expressions given below refer to the single dot only, a generalization for DQD is straightforward.

Since in the present paper we are interested only in qualitative features of ac current response we use, following [5], a very crude ansatz for quantum dot Green's function in the presence of an ac potential

$$G_{d\sigma}(t, t_1) = \exp\left(-\mathrm{i}\frac{V_{ac}}{\omega_0}(\sin\omega_0 t - \sin\omega_0 t_1)\right) \overline{G_{d\sigma}(t - t_1)}, \tag{3}$$

where $\overline{G_{d\sigma}(t, t_1}$ is the static quantum dot Green function. The simplifying assumption (3), which introduces the time breaking global phase means that the effect of ac potential is included by considering only spin or orbital isospin fluctuations which happen in a coherent way.

The linear conductance g deduced from a non-equilibrium Keldysh technique [6] is related to the time-averaged Green function $\langle G\rangle$ by

$$g = \sum_{\sigma} g_{\sigma} = \frac{e^2}{\hbar}\frac{\Gamma}{2}\sum_{\sigma}\int \mathrm{d}\omega \frac{\partial f(\omega)}{\partial\omega} \mathrm{Im}\langle G_{d\sigma}(\omega)\rangle, \tag{4}$$

where $f(\omega)$ is the Fermi function and Γ, chosen as the energy unit, denotes level broadening produced by the attached leads ($\Gamma = \pi t^2 \rho_0$, ρ_0 — density of states of the leads). Using (3) one gets the time averaged Green function in a form

$$\langle G_{d\sigma}(\omega)\rangle = \sum_{n=-\infty}^{\infty} J_n^2(\beta) \overline{G_{d\sigma}(\omega + n\omega_0)}. \tag{5}$$

One only accounts in this approach for coherent tunneling processes involving the absorption or emission of photons. J_n is the Bessel function of n-th order and $\beta = V_{ac}/\omega_0$.

3. Results and discussion

First we present results for the strongly interacting ($U \to \infty$) single QD in the Kondo limit $E_0 = -4$ ($T_{\mathrm{K}} \approx 0.0075$) placed in a magnetic field $h \sim 1.5 T_{\mathrm{K}}$ in the presence of ac gate potential. In Fig. 1 the linear conductance is plotted as a function of the ac frequency for constant value of argument β. The two visible peaks are fingerprints of zero bias photon assisted Kondo effect. The higher peak ($\omega_0 = 2h$) corresponds to many coherent subsequent single photon assisted tunnelling processes ($n = 1$) and the lower ($\omega_0 = h$) reflects Kondo tunneling associated with two photon processes ($n = 2$, probability given by $J_2^2(\beta)$). It has to be emphasized that because of the crudeness of our approach and neglect of decoherence effects our results can be only trusted qualitatively.

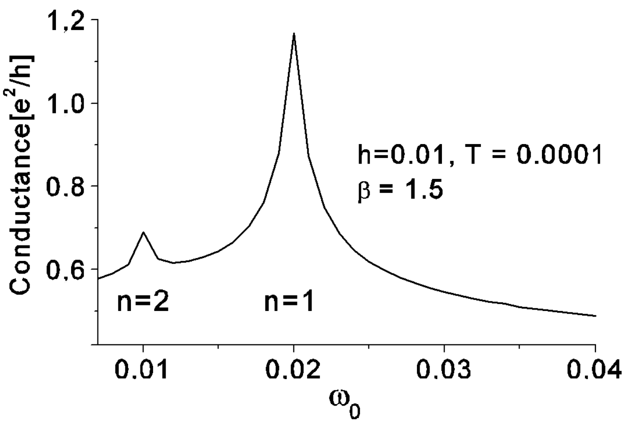

Fig. 1. (a) Linear conductances of QD placed in a magnetic field drawn as a function of microwave frequency. The ratio $\beta = V_{ac}/\omega_0$ is fixed.

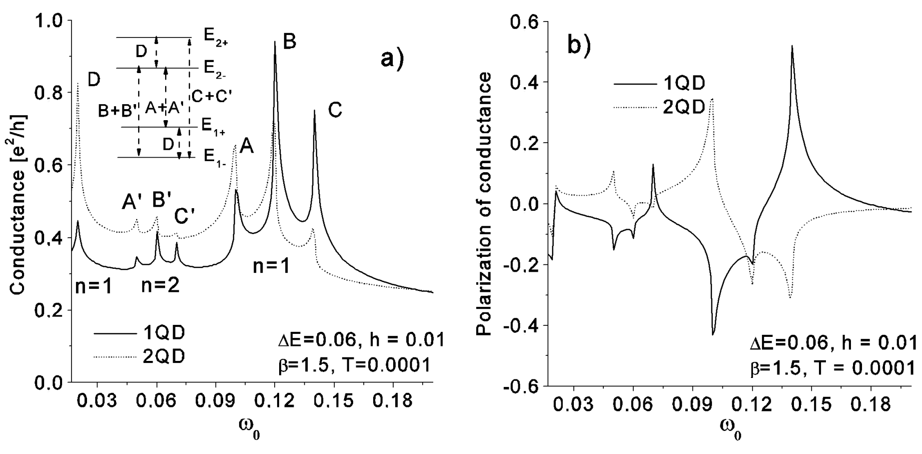

Fig. 2. (a) Linear conductances of capacitively coupled dots as a function of microwave frequency. Inset shows the energy scheme of the dot levels and the corresponding photon transitions. (b) Corresponding polarizations of conductances of DQD vs. frequency.

To verify the hypothesis on the photon induced Kondo tunneling more rigorous calculations are required, which are under way and the results will be published elsewhere. Now let us discuss the system of two capacitively coupled dots. For vanishing magnetic field and symmetric dots ($E_1 = E_2$) the Kondo effect appears simultaneously in spin and orbital sectors (SU(4)). Magnetic field breaks spin degeneracy and the difference of the gate voltages applied to the dots breaks orbital degeneracy ($E_2 - E_1 = \Delta E \neq 0$). In consequence, the Kondo resonance is destroyed and no zero bias maximum of conductance is observed. The situation changes in the presence of ac potentials. Figure 2a presents conductance vs. ac frequency. The observed series of peaks suggest that again under photon assistance the Kondo effect recovers. The scheme of energy levels and corresponding photon transitions shown in the inset helps in ascribing the peaks to the corresponding photon absorption and emission processes. Figure 2b presents the corresponding polarization of conductance defined as $\mathrm{PC} = (g_+ - g_-)/(g_+ + g_-)$. The observed high values of polarizations of photon assisted Kondo peaks suggest a possibility of generation of spin polarized current in the Kondo DQD.

Acknowledgments

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