Transmittance through an Aharonov-Bohm ring with embedded quantum dot described by Kondo Hamiltonian

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Abstract

Kondo physics of quantum dots together with the transmittance phase behavior are of considerable current interest, both experimentally [1] and theoretically [2].

The presence of magnetic impurities in the Q.D. produces new effects (like the spin- flip scattering) due to the exchange interaction between the spin of the conducting electrons and the localized spins.

We numerically find the complex transmittance of a Q.D. directly connected to leads or embedded in an A-B ring, as in recent experimental devices used to calculate the phase (whose behavior has not been fully understood). The magnetic flux through the ring and gate potential applied on the dot are varied. We use a tight-binding model for the Kondo Hamiltonian and the Landauer-Büttiker transport formalism [3] for the ring-dot system (and the results can be seen as predictions of such a model).

1.Introduction

There are several ways of approaching spin transport in mesoscopic systems such as: numerical renormalization group [4], slave boson method [5] or equation of motion method [6]. Generally, an approximate solution of the Anderson Hamiltonian is searched.

However, a solution of the (more simple) Kondo Hamiltonian is also interesting, although experimental results on transport through Quantum Dots with magnetic impurities are lacking. Kondo Hamiltonian can also be seen as an approximation of Anderson Hamiltonian for systems with odd number of electrons.

In section 2. we shall present the Formalism proposed for calculateing transmittances (module and phase) through mesoscopic devices with localized spins. The generalization of Landauer-Büttiker single-channel transport formalism represents the main result of this work.

The next sections will present some graphics numerically obtained and their interpretations, together with the conclusions.

2. The FORMALISM

The model Hamiltonian we use for the description of the Quantum Ring with embeded quantum dot is a 2D tight-binding Hamiltonian with Pierls phases included in the hopping term.

The dot spinless Hamiltonian reads:

$$H^D = \sum_{i \in QD} V_g c_i^+ c_i + t^D \sum_{\langle i,i' \rangle} e^{i2\pi\Phi_{ii'}} c_i^+ c_i' \tag{1}$$

Here $c_i^+(c_i)$ are creation (annihilation) operators in localized states indexed by $i \in QD$ and $t^D$is the nearest neighbour hopping integral in the dot. The phase $\Phi_{ii'}$ comes from Peierls substitution and accounts for the magnetic flux through the unit cell of the lattice measured in quantum flux units Φ/Φ_0.

The ring is single-channel and is coupled to the dot by the hopping parameter τ.

The next step is to build the spin non-Hermitian Hamiltonian.

$$\begin{pmatrix} H_{\uparrow\uparrow}^{eff} & H_{\uparrow\downarrow} \\ H_{\downarrow\uparrow} & H_{\downarrow\downarrow}^{eff} \end{pmatrix} \tag{2}$$

Where we used the notations:

$$H_{\uparrow\uparrow}^{eff} = H_{spinless}^{R+D} - JS_n^z |n \uparrow\rangle\langle n \uparrow| + t_{RL}^2 t_L \sum_\alpha e^{-ik} |\alpha \uparrow\rangle\langle\alpha \uparrow| \tag{3}$$

$$H_{\downarrow\downarrow}^{eff} = H_{spinless}^{R+D} + JS_n^z |n \downarrow\rangle\langle n \downarrow| + t_{RL}^2 t_L \sum_\alpha e^{-ik} |\alpha \downarrow\rangle\langle\alpha \downarrow| \tag{4}$$

$$H_{\uparrow\downarrow} = -JS_n^-|n\uparrow\rangle\langle n\downarrow| \tag{5}$$

$$H_{\downarrow\uparrow} = -JS_n^+|n\downarrow\rangle\langle n\uparrow| \tag{6}$$

We note that H^{eff} depends on the energy $E = 2cosk$ of the incident electron.

The arrow indicates the spin of the conduction electron.

"n" is the site of the localized spin addressed by S_n operators.

J is the exchange integral as in Kondo Hamiltonian and describes the strengh of spin-spin interaction.

Finally, one has to calculate the retarded green function

$$G^+(E) = (E - H^{eff} + i0)^{-1}$$

which is to be used in the Landauer-Buttiker formula in order to obtain the conductance $g_{\alpha,\beta}$.

From the matrix equation we have:

$$G_{\uparrow\uparrow}(z) = (z - H_{\uparrow\uparrow}^{eff} - H_{\uparrow\downarrow}(z - H_{\downarrow\downarrow}^{eff})^{-1}H_{\downarrow\uparrow})^{-1} \tag{7}$$

$$G_{\uparrow\downarrow}(z) = G_{\uparrow\uparrow}(z)H_{\uparrow\downarrow}^{eff}(z - H_{\downarrow\downarrow}^{eff})^{-1} \tag{8}$$

3. Numerical results

The previously described Formalism is applied on mesoscopic devices such as Quantum dots (placed on a branch of an Aharonov-Bohm interferometer). This aims to imitate (regardless of the spin degree of freedom) the conditions of the Yacoby phase-measureing experiment [6].

As a rule (and as previously mentioned) three transmittances are calculated: spin-conserving (with the localized spin in one of the two directions) and spin-flip (only when localized spin and the spin of the conducting electron have opposite projections on the z-axis).

The magnetic flux through the ring (interferometer) and the gate potential on the dot are varied. When the magnetic flux is varied, typical Aharonov-Bohm oscillations (period Φ_0- the flux cuantum) are observed both in the presence and in the absence of the localized spin. It is because the Hamiltonian has (and therefor all observables) the Φ_0 periodicity. In the presence of the localized spin, the shape of these oscillations becomes more complex. The spin conserving transmittance (with localized spin down) has a local maxim (for aproximatly integer fluxes) where the spin-flip transmittance has a minim. One can notice the period to slightly differ from Φ_0, that is because of the dot's finite area.

In Figures 3 and 4 we show predictions for gate dependence of the module and phase of transmittance for the dot (module transmittance only for the interferometer). We notice certain phase lapses between resonances (not always) and that certain resonances (those in-phase with the central one - at fermi level) appear appproximately the same in the ring+dot picture. So the interferometer may give, in spite of the phase-locking effect [8], information about phase of transmittances.

Figure 5 simulates the module and phase of the Spin-Flip transmittance.

We want to mention that a three dimensional can be regarded as an alternative (and the only one experimentally available)way of telling the phase of the transmittance (seen as depending on gate). When a peak is approached as a "hill" and the goes down as a "valley" it means that somewhere near the resonance there has been a phase lapse by π. Of course, for comparation with phase lapses in Figure 3, an opened geometry (one act of interference) is required (we do not give the picture here).

Parameters used for figures: dot-ring coupling $\tau = 0.25$, exchange parameter and J=-1 (except for Figure 1 where J=0). The dot is a 5X3 lattice with a localized Spin placed on the ring (the region common for both ring and dot).

CONCLUSIONS

The generalized single-channel Landauer-Buttiker formalism that we have developed is suitable for adressing transport phenomena in quantum dots with magnetic impurities.

Due to the presence of spin degree of freedom, the problem under study, although being one dimensional, becomes a multi-channel one. Therefor, one may say that some enquiring experimental results appear because of single-channel interpretation of a multi-channel problem.

Etanglement between electron and spin-flipper states leads to reduction of Aharonov-Bohm oscillations in spite of the absence of any inelastic scattering.

The transmittance phase of the spin-flipped component exhibits less π lapses (Fano zeroes) then the spin-conserving one.

In the present there is no experimental work to be compared with our results, but is expected in near future.

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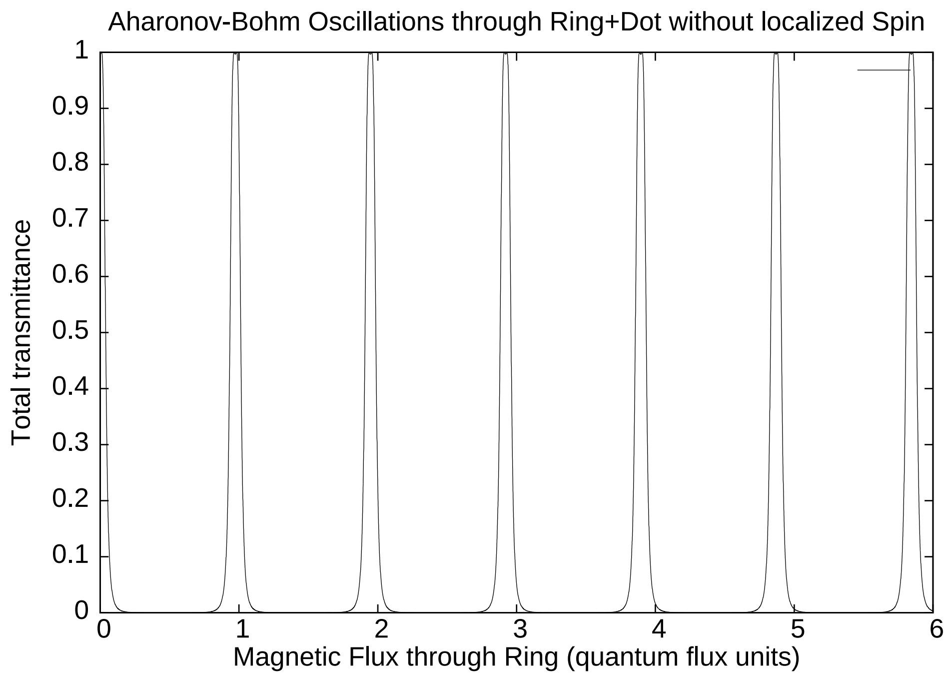

Figure 1: Typical Aharonov-Bohm oscillations

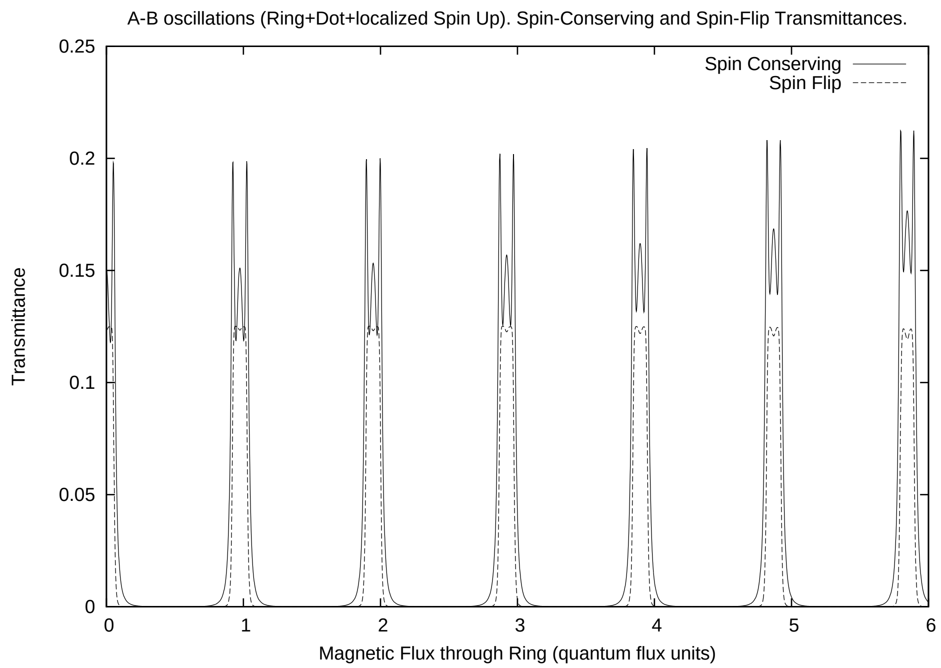

Figure 2: Possible Spin signature on A-B oscillations shape

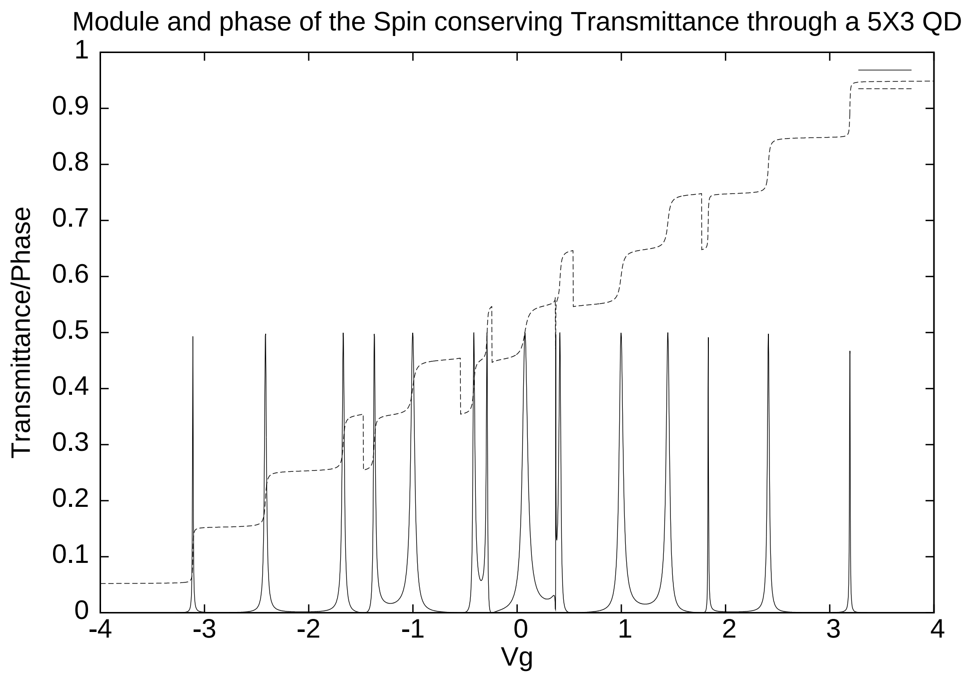

Figure 3: Dot

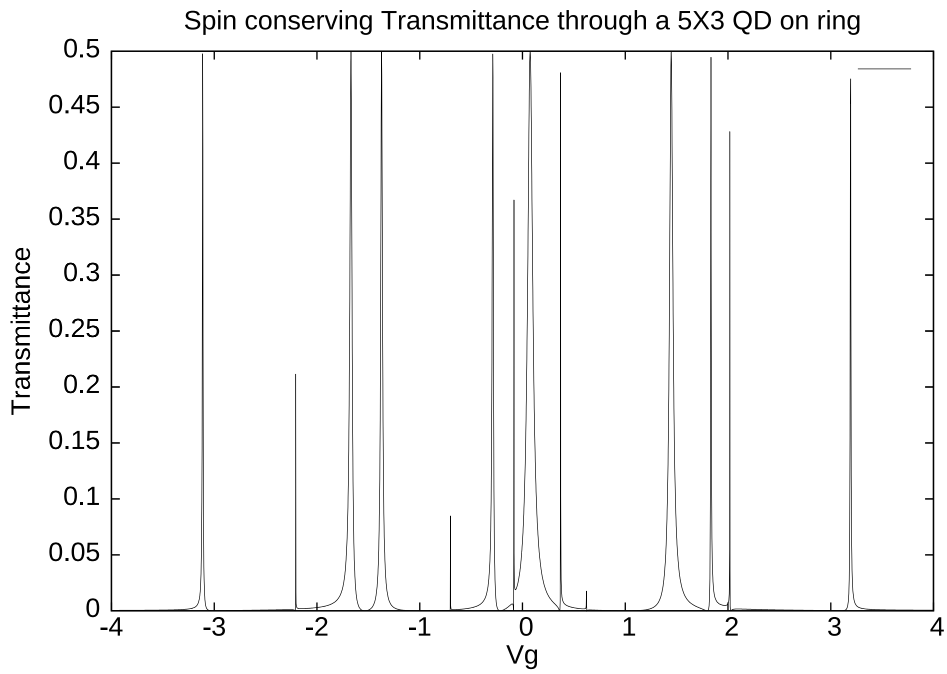

Figure 4: Ring+Dot

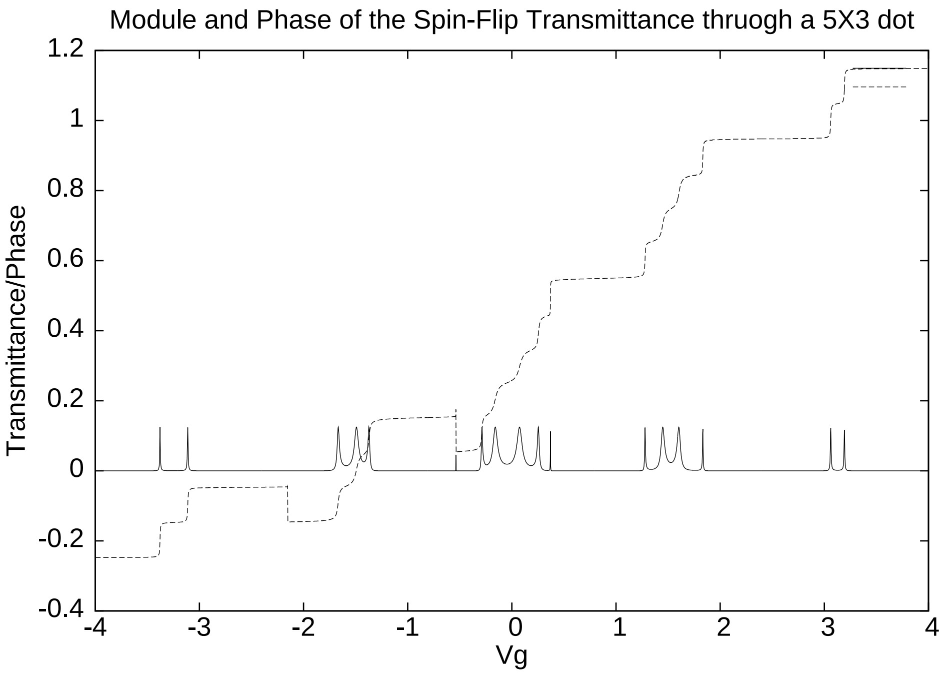

Figure 5: Dot with localized Spin