STRONG ELECTRON CORRELATIONS AND QUANTUM INTERFERENCE EFFECTS IN ELECTRONIC TRANSPORT THROUGH A WIRE WITH SIDE-ATTACHED KONDO QUANTUM DOTS*

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(Received July 10, 2002)

Conductance through a system consisting of a wire with two side-attached quantum dots is calculated. Both the quantum dots take part in destructive interference with ballistic channel through the wire. Such geometry of the device allows to control the strength of the quantum interference and suppression of the conductance through the system. The minimum present in the gate voltage characteristics of the conductance can be turned into plateau. We propose an experimental setup where the strength of the quantum interference can be smoothly controlled by changing the level positions inside quantum dots by appropriate gate voltages.

PACS numbers: 72.15.Qm, 73.63.–b

Kondo effect, a fascinating phenomenon investigated intensively for last three decades, has been observed in resonant electronic transport through nanodevices [1] recently. In geometry where a quantum dot (QD) is side-coupled to the quantum wire, it acts as Kondo scattering centre. There appear two transmission channels for traveling electronic waves: ballistic channel through a wire and a channel formed by the QD Kondo resonance at the Fermi level. Destructive interference of both channels causes suppression of the transmission. This geometry is conceptually analogous to the Fano model [2] consisting of a continuous spectrum and a discrete level.

A single quantum dot side-attached to a perfect wire was investigated in resonant regime in [3–5]. Quantum interference in a QD bridged by a direct channel was also investigated by us [6]. In this paper we study a double-side-QD arrangement (see the diagram inset in Fig. 1).

* Presented at the International Conference on Strongly Correlated Electron Systems, (SCES 02), Cracow, Poland, July 10–13, 2002.

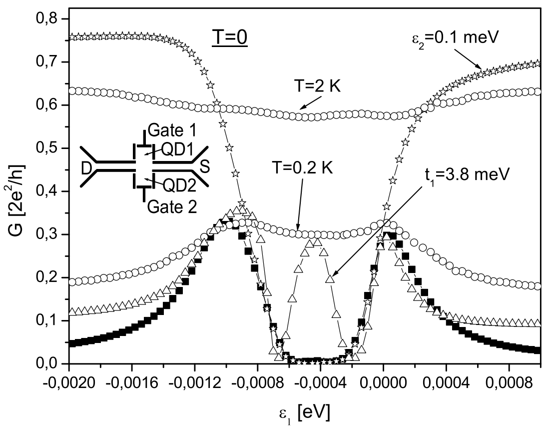

Fig. 1. Conductance *vs* QD_1 spatial level position for the system depicted in the inset. Curves are calculated for $T = 0$, $U = 1$ meV $\varepsilon_2 = -U/2$ and coupling to the wire $t_\gamma = 5.3$ meV ($\gamma = 1,\ 2$). Two curves for finite temperatures (circles) are also included. Curve with stars corresponds to $T = 0$ and $\varepsilon_2 = 0.1$ meV. Curve for $t_1 = 3.8$ meV (triangles) depicts QD_1 in Coulomb blockade regime.

Hamiltonian of the nanodevice is taken in the form:

$$H = \sum_{\gamma=1,2} \sum_{\sigma} \varepsilon_\gamma d^+_{\gamma,\sigma} d_{\gamma,\sigma} + \sum_{\gamma=1,2} U_\gamma n_{\gamma\uparrow} n_{\gamma\downarrow}$$
$$+ \sum_{\substack{\gamma=1,2\\ \sigma,k}} t_\gamma [d^+_{\gamma\sigma} c_{k\sigma} + \text{h.c.}] + \sum_{\substack{\alpha=L,R\\ k,k',\sigma}} t_\alpha [c^+_{k\sigma,\alpha} c_{k'\sigma} + \text{h.c.}] + H_{\text{wire}} + H_{\text{el}} \,, \quad (1)$$

where γ-index numbers quantum dots. We assume spin-only degeneracy of the discrete QD's levels. t_γ represents hopping between the wire and the quantum dots and t_α- hopping between the wire and the electrode α. The last two terms in Eq. (1) represent the perfect single-mode quantum wire and the electrodes. Density of states in the wire and in the electrodes have been assumed to have Lorentzian shape with a halfwidth much larger than Kondo temperature of each QD.

To calculate conductance through the considered nanodevice, total density of states should be known at the point where both quantum dots are attached to the wire. It has been calculated with the use of Dyson equation written in the form of scattering T-matrix for interacting case. At the first stage the calculation has been performed for electron $G_{0,\sigma}$ propagating through the wire in the presence of one quantum dot only (Eq. (2)). Then Dyson equation (Eq. (3)) has been written in the presence of the second QD, but with a Green function already dressed in the first step $G_{1,\sigma}$. As a result we have:

$$G_{1,\sigma}(\omega) = G_{0,\sigma}(\omega) + G_{0,\sigma}(\omega)T_{1,\sigma}(\omega)G_{0,\sigma}(\omega)\,, \tag{2}$$

$$G_{2,\sigma}(\omega) = G_{1,\sigma}(\omega) + G_{1,\sigma}(\omega)T_{2,\sigma}(\omega)G_{1,\sigma}(\omega)\,, \tag{3}$$

with the scattering matrix $T_{\gamma,\sigma}(\omega) = t_\gamma^2 G_{d\gamma,\sigma}(\omega)$ which contains electronic correlations causing Kondo effect. A bare conduction electron retarded propagator is taken in the form $G_{0,\sigma}(\omega) = -i\pi\rho_{\rm wire}(\omega)$. $G_{d\gamma,\sigma}(\omega)$ is a dressed propagator of the electron localized in QD_γ. The *interference* effects between $G_{0,\sigma}$ ($G_{1,\sigma}$) and $G_{d1,\sigma}$ ($G_{d2,\sigma}$) are comprised in the terms $[G_{0,\sigma}]^2T_{1,\sigma}$ ($[G_{1,\sigma}]^2T_{2,\sigma}$).

In Eq. (3) apart from terms of the type $G_{0,\sigma}(\omega)T_{\gamma,\sigma}(\omega)G_{0,\sigma}(\omega)$, ($\gamma = 1, 2$), which describe scattering of the electronic wave in a particular dot γ, also terms of the form $G_{0,\sigma}(\omega)T_{1,\sigma}(\omega)G_{0,\sigma}(\omega)T_{2,\sigma}(\omega)G_{0,\sigma}(\omega)$ appear, describing processes of *multiple scattering*, when *both* DQs are involved. We have analyzed the influence on the conductance of each term separately.

Calculations of dressed propagators $G_{d1}(\omega)$ and $G_{d2}(\omega)$ including many-body effects have been performed within interpolative perturbative scheme (IPS) [7] which is an extension of the selfconsistent second order perturbation in Coulomb repulsion U [8] to the atomic limit. This method fulfills Friedel–Langreth sum rule [9] and allows to calculate density of states of quantum dot coupled to electrodes and conductance for various temperatures and coupling to electrodes. Spectral density of the nanodevice has been calculated from the relation $\rho_{\mathrm{nano},\sigma}(\omega) = -(1/\pi)\mathrm{Im}\mathrm{G}_{2,\sigma}(\omega + \mathrm{i}\delta)$.

Linear-response zero bias conductance has been calculated [10] for the symmetric coupling to the leads $\Gamma(\omega) = 2\pi t^2\rho_{el}(\omega)$ ($t_{\mathrm{L}} = t_{\mathrm{R}} = t$):

$$G(V_{g1}, V_{g2}) = \frac{2\pi e^2}{h}\sum_\sigma \int_{-\infty}^{\infty} \Gamma(\varepsilon)\left(-\frac{\partial f(\varepsilon)}{\partial\varepsilon}\right)\rho_{\mathrm{nano},\sigma}(\varepsilon, V_{g1}, V_{g2})d\varepsilon\,, \tag{4}$$

where $f(\varepsilon)$ is the Fermi distribution function, and gate voltage dependence on the quantum dots level positions has been written explicitly.

Conductance through the nanodevice *vs* level position of QD_1 and representative values of QD_2 level position is plotted in Fig. 1. A perfect resonance at $T = 0$ for the Anderson impurity takes place when $\varepsilon_\gamma = -U/2$, *i.e.* for the symmetric Anderson model. In the considered symmetry it corresponds to a full strength of destructive interference and total extinction of the transmission. When the dot level is empty ($\varepsilon_\gamma > 0$) or fully occupied ($\varepsilon_\gamma + U < 0$) the dot very weakly disturbs the transport through the wire. Thus, by setting $\varepsilon_2 = 0.1$ meV (see Fig. 1) QD_2 is driven far from resonance. In this case conductance *vs* level position ε_1 resembles the curve for one side-coupled quantum dot [3–5]. When the level ε_1 is shifted towards the Fermi level, $\varepsilon_{\mathrm{F}} = 0$, by an appropriate gate voltage, the QD_1 is gradually tuned to a maximum resonance. In the range of $\varepsilon_1 < 0$ and $\varepsilon_1 + U > 0$ (*i.e.* when level ε_1 is singly occupied) the electronic transport is completely blocked at $T = 0$. Picture drastically changes when QD_2 is driven to a perfect resonance by setting $\varepsilon_2 = -0.5$ meV (see the curve with black squares). In this case, when ε_1 is doubly occupied or empty, the conductance is destroyed in turn by perfect Kondo resonance of QD_2 (it is seen that conductance goes to zero when $\mid \varepsilon_1 \mid \to \infty$). When ε_1 is shifted towards Fermi level, the *multiple scattering* increases and *enhances* the conductance to the unitary limit when ε_1 reaches the value $-U/2$. These terms exactly compensate destructive influence of QD_2 in this region. Thus, the conductance is fully blocked by resonant scattering of QD_1. When ε_1 crosses Fermi level *multiple scattering* decreases and conductance is diminished by destructive interference of QD_2 again.

At finite temperatures, neither QD_1 nor QD_2 are able to fully block the conductance because Kondo effect is partially diminished. In this case, an intermediate situation takes place when both QDs have comparable destructive influence on electronic wave propagating through the wire and a plateau of conductance is observed (see the curves for finite temperatures).

For weaker coupling of the QD_1 to the wire ($t_1 = 3.8$ meV) the dot enters Coulomb blockade regime and two peaks with a separation of the order of U become visible in conductance.

This work was supported by the Polish State Committee for Scientific Research (KBN) under Grant No. 2 P03B 087 19.

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