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# Diagnostics of many-particle electronic states: non-stationary currents and residual charge dynamics

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The control and diagnostics of electronic states in semiconductor nanostructures attracts a great deal of attention now a days. One of the key problems in this area is a development of efficient methods of detection of electronic states with different spin orientation as spin degrees of freedom are considered to play an important role in realizing new functions in modern nanoelectronic devices such as spin pumps [1–3] and turnstiles [4, 5], spin interference devices [6], quantum dot spin cellular automata [7–9], and devices for the qubit information [10, 11].

Double QDs are recently an attractive objects for spin-dependent transport analysis [12, 13]. Electronic transport through the coupled QDs was considered both in the case of coupling to spin-polarized magnetic and non-magnetic [13] leads. Coupled QDs can be applied for modern nanoelectronic devices creation due to the particular properties of charge and spin kinetics of individual localized states [14, 15]. The possibility of QDs integration in a small size quantum circuits deals with careful analysis of relaxation processes and non-stationary effects influence on the electron transport through the dots system [16]. Electronic transport in such systems is strongly governed by the presence of Coulomb correlations and by the ratio between the QDs coupling and interaction with the reservoir [17]. Moreover, electron transport properties through nanoscale systems and the results of STM/STS measurements are very sensitive to the geometry of the experiment and to the type of switching to reservoir. As it was shown in [18, 19] spatial symmetry of investigated system strongly affects the current properties both in stationary and non-stationary cases. Correct interpretation of quantum effects in nanoscale systems provides an opportunity to use them as a basis for high speed electronic and logic devices creation [20]. Consequently, the problem of charge kinetics in correlated low-dimensional systems due to the coupling with reservoir is really vital. Moreover, non-stationary characteristics provide more information about the properties of nanoscale systems comparing to the stationary ones. Current noise characteristics in a metallic diffusive conductor have been proposed as a measure of spin imbalance in [21].

In the present paper we propose the way of different many-particle electronic states characterization in the system of two interacting quantum dots (impurity atoms) with Coulomb correlations by means of non-stationary current analysis and investigation of the charge trapping effects. Initial charge time evolution is analyzed in terms of pseudo particle technique with additional constraint on possible states [22].

The Hamiltonian of the system

$$\hat{H} = \hat{H}_{\rm dot} + \hat{H}_{\rm res} + \hat{H}_{\rm tun} \tag{1}$$

is written as a sum of the QDs Hamiltonian

$$\hat{H}_{\rm dot} = \sum_{l,\sigma} \varepsilon_l \hat{n}_{l\sigma} + \sum_{l,\sigma} U_l \hat{n}_{l\sigma}\hat{n}_{l-\sigma} + T(\hat{c}^+_{1\sigma}\hat{c}_{2\sigma} + \hat{c}^+_{2\sigma}\hat{c}_{1\sigma}), \tag{2}$$

electronic reservoir Hamiltonian

$$\hat{H}_{\rm res} = \sum_{k\sigma} \varepsilon_k \hat{c}^+_{k\sigma}\hat{c}_{k\sigma}, \tag{3}$$

and the tunneling part, which describes transitions between the dots and reservoir

$$\hat{H}_{\rm tun} = \sum_{k\sigma} t_{k1}(\hat{c}^+_{k\sigma}\hat{c}_{1\sigma} + \hat{c}^+_{1\sigma}\hat{c}_{k\sigma}) + \\ + \sum_{p\sigma} t_{k2}(\hat{c}^+_{k\sigma}\hat{c}_{2\sigma} + \hat{c}^+_{2\sigma}\hat{c}_{k\sigma}). \tag{4}$$

Here index $k$ labels continuous spectrum states in the reservoir. We'll consider the symmetric coupling to reservoir and assume hopping amplitudes between the

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reservoir and QD with the energy $\varepsilon_l$ to be independent on the momentum and spin, so further $t_{k1} = t_{k2} = t$. Tunneling transfer amplitude between the dots $T$ is also considered to be independent on the momentum and spin. Operators $\hat{c}_k^+/\hat{c}_k$ are the creation/annihilation operators for the electrons in the continuous spectrum states $k$. $\hat{n}_{l\sigma(-\sigma)} = \hat{c}^+_{l\sigma(-\sigma)}\hat{c}_{l\sigma(-\sigma)}$-localized state electron occupation numbers. $U_l$ is the on-site Coulomb repulsion for the double occupation of the localized state. For rather large values of Coulomb interaction $U_l$ and low temperatures only single electron and low energy two-electron states can be considered, as all other states are separated by the Coulomb gap. So, one can obtain non-stationary system of equations for the pseudo-particle filling numbers, which for the single and two-electron states can be solved both numerically and analytically. Electron occupation numbers $N_{\rm el}$ can be obtained from the pseudo-particle occupation numbers considering spin degrees of freedom.

We'll consider charge time evolution from the singlet and triplet initial states. Non-stationary behavior of the system occupation numbers depends on the initial conditions. When relaxation starts from the singlet state charge trapping effects are not present in the system even for identical QDs ($\varepsilon_1 = \varepsilon_2$ and $U_1 = U_2$). Charge trapping is present for identical QDs ($\varepsilon_1 = \varepsilon_2$ and $U_1 = U_2$) when relaxation starts from the triplet state. This is the direct manifestation of selections rules influence on the electrons transitions between QDs states and reservoir, which are determined by the matrix elements. For different QDs, when conditions $\varepsilon_1 \neq \varepsilon_2$ and $\Delta\varepsilon/T << 1$ are fulfilled, two different timescales for charge relaxation from the one-particle states with the energies $\varepsilon_a$ and $\varepsilon_s$ exist in the system. For identical QDs time evolution of initial triplet state leads to charge trapping. For slightly different QDs the second relaxation time scale $\gamma_a$ appears in the system. It reveals in the slow charge relaxation instead of charge trapping obtained in the absence of energy levels detuning. For initially singlet state the presence of Coulomb interaction slightly changes relaxation dynamics and do not influence the relaxation processes if initial state is a triplet one.

Obtained significant difference in non-stationary behavior of localized charge for singlet and triplet states gives us possibility to propose experimental scheme, which allows to distinguish different two-electronic states.

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