Diagnostics of many-particle electronic states from non-stationary currents and residual charge

N. S. Maslova\textsuperscript{1}, P. I. Arseyev\textsuperscript{2}, and V. N. Mantsevich\textsuperscript{1}
\textsuperscript{1}Moscow State University, 119991 Moscow, Russia.
\textsuperscript{2}P. N. Lebedev Physical Institute RAS, 119991 Moscow, Russia
(Dated: February 20, 2022)

We propose the method for identifying many particle electronic states in the system of coupled quantum dots (impurities) with Coulomb correlations. We demonstrate that different electronic states can be distinguished by the complex analysis of localized charge dynamics and non-stationary characteristics. We show that localized charge time evolution strongly depends on the properties of initial state and analyze different time scales in charge kinetics for initially prepared singlet and triplet states. We reveal the conditions for existence of charge trapping effects governed by the selection rules for electron transitions between the states with different occupation numbers.

I. INTRODUCTION

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\textsuperscript{[1,2,3,4,5]} and turnstiles\textsuperscript{[6,7]}, spin interference devices\textsuperscript{[8,9]}, quantum dot spin cellular automata\textsuperscript{[10,11]}, and devices for the qubit\textsuperscript{[12,13]}. Double QDs are recently an attractive objects for spin-dependent transport analysis\textsuperscript{[14,15,16,17]}. Electronic transport through the coupled QDs was considered both in the case of coupling to spin-polarized magnet\textsuperscript{[18]} and non-magnetic\textsuperscript{[19]} 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\textsuperscript{[20,21]}. 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\textsuperscript{[22,23,24,25,26]}. 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\textsuperscript{[27,28]}. 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\textsuperscript{[29,30,31,32]}. 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 one.

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\textsuperscript{[29,30,31,32]}

II. THEORETICAL MODEL

We consider the problem of different many particle electronic states resolution in the system of two interacting correlated quantum dots (impurities) by analyzing its non-stationary characteristics. Coupled quantum dots are weakly connected to the substrate, so there is no charge transfer from the dots to the substrate. Charge transfer in the system is allowed only between the dots and due to the QDs coupling to the reservoir, switched to the system at $t = 0$ (see Fig. 1).

![FIG. 1. Sketch of two interacting quantum dots on the substrate coupled to reservoir.](image)

The Hamiltonian of the system

$$\hat{H} = \hat{H}_{\text{dot}} + \hat{H}_{\text{res}} + \hat{H}_{\text{tun}}$$

is written as a sum of the QDs Hamiltonian

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

(2)
and the tunneling part, which describes transitions between the dots and reservoir

\[ H_{\text{tun}} = \sum_{k\sigma} t_{k1}(\hat{c}_{k\sigma}^+ \hat{c}_{1\sigma}) + \sum_{p\sigma} t_{k2}(\hat{c}_{k\sigma}^+ \hat{c}_{2\sigma} + \hat{c}_{2\sigma}^+ \hat{c}_{k\sigma}). \]  

(4)

Here index \( k \) labels continuous spectrum states in the reservoir. Localized charge time evolution depends on the way of coupling to reservoir as it was shown in [21]. We’ll consider the symmetric coupling to reservoir and assume hopping amplitudes between the reservoir and QD with the energy \( \varepsilon_1 \) 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 \( \hat{c}_{k\sigma}^+, \hat{c}_{k\sigma} \) are the creation/annihilation operators for the electrons in the continuous spectrum states \( k \). \( \hat{n}_{\sigma\sigma} = \hat{c}_{\sigma\sigma}^+ \hat{c}_{\sigma\sigma} \) are the localized state electron occupation numbers, where operator \( \hat{c}_{\sigma\sigma}^+ \) destroys electron with the spin \( \sigma(-\sigma) \) on the single particle energy level \( \varepsilon_1 \). \( U_{\text{t}} \) is the on-site Coulomb repulsion for the double occupation of the localized state. We consider low temperature regime when Fermi level is well defined and temperature is much lower than all the typical energy scales in the system. Let us further consider \( \hbar = 1 \) and \( e = 1 \) elsewhere. As we consider the strong coupling between the QDs, the basis of exact eigenfunctions and eigenvalues of coupled QDs without interaction with the reservoir should be applied. Wave functions for the single- and multi-electronic states are well known:

Two single electron states with the wave function

\[ \Psi_{m\sigma} = \mu_{\sigma} \cdot |0\uparrow\rangle|0\downarrow\rangle + \nu_{\sigma} \cdot |0\downarrow\rangle|0\uparrow\rangle. \]  

(5)

and energies

\[ \varepsilon_{a(s)} = \frac{\varepsilon_1 + \varepsilon_2}{2} \pm \sqrt{\frac{(\varepsilon_1 + \varepsilon_2)^2}{4} + T^2}. \]  

(6)

exist in the system. Coefficients \( \mu_\sigma \) and \( \nu_\sigma \) are determined by the eigenvector of matrix:

\[ \begin{pmatrix} \varepsilon_1 & -T \\ -T & \varepsilon_2 \end{pmatrix}. \]  

(7)

Six two electronic states exist in the system: two states with the same spin direction \( T^+ |\uparrow\rangle, T^- |\downarrow\rangle \) and four states with the opposite spins and wave function:

\[ \Psi_{\sigma} = \alpha_j \cdot |\uparrow\rangle|0\downarrow\rangle + \beta_k \cdot |\downarrow\rangle|0\uparrow\rangle + \gamma_j \cdot |0\uparrow\rangle|\downarrow\rangle + \delta_j \cdot |0\downarrow\rangle|\uparrow\rangle. \]  

(8)

Two electron energies and coefficients \( \alpha_j, \beta_j, \gamma_j \) and \( \delta_j \) are determined by the eigenvalues and eigenvectors of matrix:

\[ \begin{pmatrix} 2\varepsilon_1 + U_1 & -T & -T & 0 \\ -T & \varepsilon_1 + \varepsilon_2 & 0 & -T \\ -T & 0 & \varepsilon_1 + \varepsilon_2 & 0 \\ 0 & -T & -T & 2\varepsilon_2 + U_2 \end{pmatrix}. \]  

(9)

These are low energy singlet \( S^0 \) and triplet \( T^0 \) states and excited singlet and triplet states \( S^{0*} \) and \( T^{0*} \). Low energy triplet state \( T^0 \) with energy \( \varepsilon_1 + \varepsilon_2 \) exists for any values of QDs energy levels \( \varepsilon_1 \) and Coulomb interaction \( U_1 \). Corresponding coefficients in Eq.(8) are \( \alpha = \delta = 0 \) and \( \beta = -\gamma = \sqrt{\frac{1}{2}} \).

Two three electron states with the wave function

\[ \Psi_{m\sigma} = p_m |\uparrow\rangle|\downarrow\rangle|\uparrow\rangle + q_m |\uparrow\rangle|\downarrow\rangle|\uparrow\rangle \]  

(10)

with \( m = \pm 1 \) exist in the system. Coefficients \( p_m \) and \( q_m \) and energies are determined by the eigenvectors and eigenvalues of matrix:

\[ \begin{pmatrix} 2\varepsilon_1 + \varepsilon_2 & U_1 & -T \\ -T & 2\varepsilon_2 + U_2 & -T \\ -T & -T & 2\varepsilon_2 + U_2 \end{pmatrix}. \]  

(11)

Finally, single four-electronic state exists in the system with the wave function

\[ \Psi_n = |\downarrow\rangle|\downarrow\rangle. \]  

(12)

Coupling to reservoir leads to the changing of electrons number in the dots due to the tunneling processes. Kinetic properties are governed by the selection rules, which are determined by the matrix elements between the states with different number of electrons. Transitions between the states with different number of electrons can be analyzed in terms of pseudo-particle operators with constraint on the physical states (the number of pseudo-particles). Consequently, the electron operator \( \hat{c}_{\sigma l}^+ (l = 1, 2) \) can be written in terms of pseudo-particle operators:

\[ \begin{align*}
\hat{c}_{\sigma l}^+ &= \sum_i X_i X_i^\sigma d_{\sigma l}^+ f_{\sigma l}^+ + \sum_j Y_{ji} Y_{ji}^\sigma d_{\sigma l}^+ \psi_{\sigma l}^+ f_{\sigma l}^+ + \sum_{m,j} Z_{mij} Z_{mij}^\sigma d_{\sigma l}^+ \psi_{\sigma l}^+ f_{\sigma l}^+ \\
&+ \sum_{m,j} Z_{mj} Z_{mj}^\sigma d_{\sigma l}^+ \psi_{\sigma l}^+ f_{\sigma l}^+ + \sum m W_m W_m^\sigma d_{\sigma l}^+ \psi_{\sigma l}^+ f_{\sigma l}^+.
\end{align*} \]  

(13)
where \( f^+_σ (f^−_σ) \) and \( ψ^+_σ (ψ^−_σ) \) are pseudo-fermion creation (annihilation) operators for the electronic states with one and three electrons correspondingly. \( b^+ (b) \), \( d^+ (d) \) and \( ϕ^+ (ϕ) \) are slave boson operators, which correspond to the states without any electrons, with two electrons or four electrons. Operators \( ψ^+_m−σ \) describe system configuration with two spin up electrons \( σ \) and one spin down electron \( −σ \) in the symmetric and asymmetric states.

Matrix elements \( X^σ_i, Y^σ−σ_j, Y^σ+σ_j, Z^σ−σ_m, Z^σ+σ_m \) and \( W^σ−σ_m \) can be defined as:

\[
X^σ_i = ⟨Ψ^+σ | c^+σ_i | 0⟩ \\
Y^σ−σ_j = ⟨Ψ^σ−σ | c^+σ_i | Ψ^−σ⟩ \\
Y^σ+σ_j = ⟨Ψ^σ+σ | c^−σ_j | Ψ^σ⟩ \\
Z^σ−σ_m = ⟨Ψ^σ−σ | c^+σ_i | Ψ^−σ⟩ \\
Z^σ+σ_m = ⟨Ψ^σ+σ | c^−σ_j | Ψ^σ⟩ \\
W^σ−σ_m = ⟨Ψ^σ−σ | c^+σ_i | Ψ^σ−σ⟩
\]

Finally one can easily express matrix elements through the matrices (7), (9), (11) eigenvectors elements:

\[
X^σ_i = ρ_i; X^σ−σ_j = ν_i \\
Y^σ−σ_j = α_j ρ_i + β_i ν_i \\
Y^σ+σ_j = δ_j ν_i + γ_j ρ_i \\
Y^σ+σ_j = ν_i Y^σ−σ_j = ρ_i \\
Z^σ−σ_m = p_m χ_j + q_m δ_j \\
Z^σ+σ_m = p_m α_j + q_m β_j \\
Z^σ−σ_m = p_m Z^σ+σ_m = q_m \\
W^σ−σ_m = q_m W^σ+σ_m = p_m
\]

For identical QDs and arbitrary values of Coulomb correlations charge trapping can occur due to the presence of one particle "dark state" with the energy \( ε + T \). Matrix element, which corresponds to transitions between this state and empty states is equal to zero. This transition is forbidden by the symmetry of the tunneling Hamiltonian [4]. If there is the way of allowed transitions from initial state to the "dark state" during relaxation processes, the residual charge is trapped in this one-particle state.

Conditions, which determine allowed and restricted transitions between the states with different number of electrons can be easily found:

I. Transitions between the state with zero electrons and single electron state:

\[
X^σ_i = ∑_{l=1,2} X^σ_i = ∑_{l=1,2} ⟨ψ^σ | c^+σ_i | 0⟩ = ρ_i + ν_i = \{ 0 \ \text{allowed} \}
\]

II. Transitions between single electron state and two electron state with:

\[
Y^σ−σ_j = ∑_{l=1,2} Y^σ−σ_j = ∑_{l=1,2} ⟨ψ^σ−σ | c^+σ_i | ψ^−σ⟩ = α_j ρ_i + δ_j ν_i + γ_j ρ_i + \gamma_j ρ_i = \{ 0 \ \text{allowed} \}
\]

III. Transitions between two electron state and three electron state:

\[
Z^σ−σ_m = ∑_{l=1,2} Z^σ−σ_m = ∑_{l=1,2} ⟨ψ^σ−σ | c^+σ_i | ψ^−σ⟩ = p_m χ_j + q_m δ_j = \{ 0 \ \text{allowed} \}
\]

IV. Transitions between three electron state and four electron state:

\[
W^σ−σ_m = ∑_{l=1,2} W^σ−σ_m = ∑_{l=1,2} ⟨ψ^σ−σ | c^+σ_i | ψ^σ−σ⟩ = p_m + q_m = \{ 0 \ \text{allowed} \}
\]

For slightly different QDs (\( ε_1 \neq ε_2 \)) these matrix elements determine different time scales of the system dynamics. For rather large values of Coulomb interaction \( U_t \) 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, the following non-stationary system of equations can be obtained for the pseudo particle filling numbers \( N_i, N_{dj−σ}, N_{dj+σ} \) and \( N_k \):
\[
\frac{\partial N_{\delta j}^{\sigma - \sigma}}{\partial t} = -2\gamma \sum_{i,\sigma} |Y_{ji}^{\sigma - \sigma}|^2 \cdot N_{\delta j}^{\sigma - \sigma}
\]
\[
\frac{\partial N_{\sigma}}{\partial t} = 2\gamma \sum_{j,\sigma} |Y_{ji}^{\sigma - \sigma}|^2 N_{\delta j}^{\sigma - \sigma} - |X_{i}^{\sigma}|^2 N_{\delta}^{\sigma} + \sum_{j} |Y_{ji}^{\sigma}|^2 \cdot N_{\delta j}^{\sigma}
\]
\[
\frac{\partial N_{\delta j}^{\sigma \sigma}}{\partial t} = -2\gamma \sum_{i,\sigma} |Y_{ji}^{\sigma \sigma}|^2 \cdot N_{\delta j}^{\sigma \sigma}
\]

where

\[
|X_{i}^{\sigma}|^2 = |\nu_{i} + \mu_{i}|^2,
\]
\[
|Y_{ji}^{\sigma - \sigma}|^2 = |\alpha_{j} \mu_{i} + \beta_{j} \nu_{i} + \gamma_{j} \mu_{i} + \delta_{j} \nu_{i}|^2,
\]
\[
|Y_{ji}^{\sigma \sigma}|^2 = |\nu_{i} + \mu_{i}|^2
\]

and \(\gamma = \nu_{i}\mu_{i}^{2}\), \(\nu_{i}\) - is the unperturbed density of states in the reservoir. Depending on the tunneling barrier width and height typical tunneling coupling strength \(\gamma\) can vary from \(10 \mu eV\) to \(1 \div 5 meV\).

System of Eqs. (22) for the single and two-electron states can be solved both numerically and analytically with initial conditions \(N_{\delta j}^{\sigma - \sigma}(0) = 1\), \(N_{\sigma}(0) = 0\), \(N_{\delta}(0) = 0\) and \(N_{\delta}(0) = 0\). Analytical expressions, which determine charge relaxation, have the following form:

\[
N_{\delta j}^{\sigma - \sigma}(t) = e^{-2\lambda t},
\]
\[
N_{\sigma}(t) = \frac{\lambda_{j}}{\lambda_{a} - \lambda_{s}} \cdot (e^{-\lambda_{s}t} - e^{-2\lambda_{s}t}),
\]
\[
N_{\delta}(t) = \frac{\lambda_{j}s}{\lambda_{a} - \lambda_{s}} \cdot (e^{-\lambda_{s}t} - e^{-2\lambda_{s}t}),
\]
\[
N_{b}(t) = 1 - N_{\delta j}^{\sigma - \sigma}(t) - \sum_{\sigma} N_{\sigma}(t) - \sum_{s} N_{s}(t)
\]

where

\[
\lambda = 2\gamma \sum_{i} |\alpha_{j} \mu_{i} + \beta_{j} \nu_{i} + \delta_{j} \nu_{i} + \gamma_{j} \mu_{i}|^2,
\]
\[
\lambda_{a} = 2\gamma \cdot |\mu_{a} + \nu_{a}|^2,
\]
\[
\lambda_{s} = 2\gamma \cdot |\mu_{s} + \nu_{s}|^2,
\]
\[
\lambda_{j} = 2\gamma \cdot |\alpha_{j} \mu_{a} + \beta_{j} \nu_{a} + \gamma_{j} \mu_{a} + \delta_{j} \nu_{a}|^2,
\]
\[
\lambda_{j} = 2\gamma \cdot |\alpha_{j} \mu_{s} + \beta_{j} \nu_{s} + \delta_{j} \mu_{s} + \gamma_{j} \nu_{s}|^2.
\]

Index \(a\) corresponds to the state with energy:

\[
\varepsilon_{a} = \frac{\varepsilon_{1} + \varepsilon_{2}}{2} + \sqrt{\left(\frac{\varepsilon_{1} + \varepsilon_{2}}{2}\right)^2 + \lambda^2}
\]

and index \(s\) - to the state with energy:

\[
\varepsilon_{s} = \frac{\varepsilon_{1} + \varepsilon_{2}}{2} - \sqrt{\left(\frac{\varepsilon_{1} + \varepsilon_{2}}{2}\right)^2 + \lambda^2}
\]

Electron occupation numbers \(N_{\epsilon}(\epsilon)\) can be obtained from the pseudo particle occupation numbers considering spin degrees of freedom by the following expression:

\[
N_{\epsilon}(t) = 2 \cdot N_{\delta j}^{\sigma - \sigma}(t) + \sum_{\sigma} N_{\sigma}(t) + \sum_{s} N_{s}(t)
\]

We’ll consider charge time evolution from the singlet and triplet initial states. For singlet initial state coefficients \(\alpha, \beta, \gamma\) and \(\delta\) are determined as an eigenvector of matrix (9) corresponding to its minimal eigenvalue. For the triplet initial state coefficients \(\alpha = \delta = 0\) and \(\beta = -\gamma = -\frac{\sqrt{\lambda}}{\gamma}\).

Non-stationary behavior of the system occupation numbers depends on the initial conditions. Fig demonstrates charge relaxation from initially occupied singlet (see solid lines in Fig) and triplet (see dashed lines in Fig) states for different system parameters.

FIG. 2. (Color online) Electron occupation numbers time evolution from initial singlet state - solid lines and triplet state - dashed line. Black solid and dashed lines: \(\varepsilon_{1}/\gamma = \varepsilon_{2}/\gamma = 7\) and \(U_{1}/\gamma = U_{2}/\gamma = 20\); red solid and dashed lines: \(\varepsilon_{1}/\gamma = 7.4\), \(\varepsilon_{2}/\gamma = 7\) and \(U_{1}/\gamma = U_{2}/\gamma = 20\); blue solid and dashed lines: \(\varepsilon_{1}/\gamma = \varepsilon_{2}/\gamma = 7\) and \(U_{1}/\gamma = 21\), \(U_{2}/\gamma = 20\). Parameters \(T/\gamma = 2\) and \(\gamma = 1\) are the same for all the figures.

When relaxation starts from the singlet state charge trapping effects are not present in the system even for identical QDs \((\varepsilon_{1} = \varepsilon_{2} \text{ and } U_{1} = U_{2})\). Charge trapping is present for identical QDS \((\varepsilon_{1} = \varepsilon_{2} \text{ and } U_{1} = U_{2})\) when relaxation starts from the triplet state (see black dashed line in the Fig). 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.
FIG. 3. (Color online) Sketch of the measurement scheme, applicable for distinguishing two-electronic states with different spin orientation.

For different QDs, when conditions $\varepsilon_1 \neq \varepsilon_2$ and $\Delta \varepsilon/T \ll 1$ are fulfilled, two different timescales for charge relaxation from the states with the energies $\varepsilon_a$ and $\varepsilon_s$ exist in the system. The presence of initial energy levels detuning $\Delta \varepsilon$ leads to the appearance of two timescales $\gamma_s$ and $\gamma_a$, related by the ratio:

$$
\gamma_a = \frac{\Delta \varepsilon^2}{T^2} \cdot \gamma_s.
$$

(29)

All other relaxation rates, present in the system can be expressed through $\gamma_s$ and $\gamma_a$:

$$
\gamma_{T^0_s} = \frac{1}{2} \cdot \gamma_a,
\gamma_{T^0_a} = \frac{1}{2} \cdot \gamma_s,
\gamma_{S^0_s} = |\alpha + \beta|^2 \cdot \gamma_s,
\gamma_{S^0_a} = |\alpha + \beta|^2 \cdot \gamma_a.
$$

(30)

Charge relaxation from the triplet state to the single electron states does not depend on the value of Coulomb interaction $U_d$. Moreover, relaxation rates from the single electron states also do not depend on the value of Coulomb correlations (see Fig.2). 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 (see red dashed line in the Fig.2) 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 (see Fig.3). Let us consider the situation, when unknown initial two-electronic state is prepared. There exists four different configurations $S^0, T^0, T^+ \text{ or } T^-$. To define the particular initial state one has to analyze non-stationary system characteristics and to control the value of residual charge $Q$. To measure non-stationary current (see $I_I$ and $I_{II}$ in the Fig.3), one has to use the system of two consecutive spin-polarized leads (see lead1 and lead2 in the Fig.3) with opposite directions of applied external magnetic field (see $B_+$ and $B_-$ in the Fig.3).

Proposed experimental scheme allows to distinguish different two-electronic states in the system of two interacting quantum dots with Coulomb correlations by means of the logic diagram shown in Fig.4.

FIG. 4. (Color online) Sketch of the logic diagram, which enables to resolve initial many particle electronic states with different spin orientation.

States $S^0$ and $T^0$ can be resolved by means of residual charge $Q$ control just after non-stationary current pulse $I_{II} \neq 0$ has been registered after both leads. If measured charge is equal to zero $Q = 0$, then initial state was $S^0$. In the case of non-zero charge $Q \neq 0$ initial state was $T^0$ (see logic diagram in the Fig.4a). Initial states $T^+$ and $T^-$ can be resolved only by the measurements of non-stationary currents. If measured charge after both leads is absent $I_{II} = 0$ but non-stationary current between the leads $I_I$ has non-zero value, then initial state was $T^+$. Contrary, the absence of current registered between the leads $I_I = 0$ means that initial state was $T^-$ (see logic diagram in the Fig.4b).

III. CONCLUSION

We have proposed the method of how to distinguish different two-particle electronic states in the system of two interacting quantum dots (impurity atoms) with Coulomb correlations. This method is based both on the
analysis of the system non-stationary current characteristics and on the control under the residual charge value. The resolution of two-particle electronic states becomes possible due to appearance of significantly different time scales in dynamics of initially singlet and triplet states. We also demonstrated the possibility of charge trapping in the proposed system due to the selection rules presence, which govern electron transitions between different electronic states. The method discussed in the paper can be used for the control under many-particle electronic states in modern nanoelectronic devices such as electronic pumps, turnstiles, logic and quantum information devices and new types of electronic devices based on non-equilibrium non-stationary currents.

This work was supported by RSF grant 16−12−00072.

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