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Current correlations for the transport of interacting electrons through parallel quantum dots in a photon cavity

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ABSTRACT

We calculate the current correlations for the steady-state electron transport through multi-level parallel quantum dots embedded in a short quantum wire, that is placed in a non-perfect photon cavity. We account for the electron–electron Coulomb interaction, and the para- and diamagnetic electron–photon interactions with a stepwise scheme of configuration interactions and truncation of the many-body Fock spaces. In the spectral density of the temporal current–current correlations we identify all the transitions, radiative and non-radiative, active in the system in order to maintain the steady state. We observe strong signs of two types of Rabi oscillations.

1. Introduction

Experiments [1–6] in which the electron transport through nanoscale electronic systems placed in photon cavities, and model calculations [7–11] thereof, are gaining attention in the last years.

Due to small size of the electronic systems the constant average current through the system in the steady state does not convey much information about the underlying processes, and one might expect information about radiative transitions to be lost at that time scale, or not detectable [12]. In order to remedy this situation researchers have realized that the noise power spectrum, or the noise power spectral density of a system calculated through the Fourier transform of the current–current two-time correlation function can be measured experimentally [13]. Many theoretical researchers have used this to calculate the noise spectral density for electron transport through model systems in different situations using, for example, non-equilibrium Green functions [14], Markovian master equation in the steady state [15], or non-Markovian master equations in the transient regime [16], just to mention very few.

Complementary to the calculation of the noise power spectral densities of the charge current transport through electron systems on the nanoscale, the calculation of the power spectral properties of photon emission statistics of cavities with embedded electron systems has been undertaken by many more theoretical groups [17–19,7]. Recently, we have investigated the photon correlations in the emission radiation from a photon cavity containing a short quantum wire with embedded two parallel quantum dots through which a steady state current is driven with a bias difference between two external leads [20]. There, the spectral density of the fluctuations in the radiation can be used to differentiate between the conventional and the ground state electroluminescence in the strong electron–photon coupling regime [7,20]. Here, we will demonstrate that in this complex interacting many-state system, the power spectral density of the temporal current–current correlations can be used to identify the underlying processes, the transitions between interacting many-body states of cavity-photon dressed electron states, that contribute to maintaining the system in its steady state.

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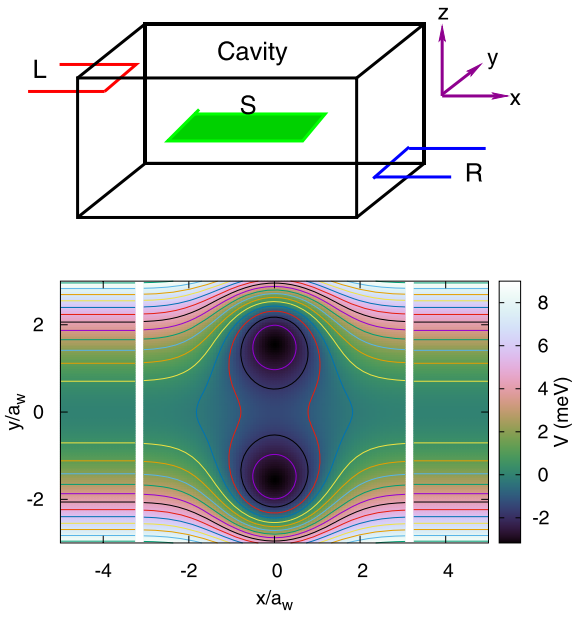

Fig. 1. (Upper) Schematic short quantum wire with the embedded parallel quantum dots, the central system (S), in a 3D photon cavity coupled to the left (L) and right (R) leads. The color and the height of the leads represents their chemical potentials. (Lower) The potential energy landscape defining the parallel quantum dots embedded in a short quantum wire of length 150 nm $\approx 6.3a_w$, where $a_w = 23.8$ nm is the effective magnetic length for magnetic field $B = 0.1$ T and parabolic confinement energy $\hbar\Omega_0 = 2.0$ meV of the short wire and leads in the y-direction. The gaps at $x \approx \pm 3.15a_w$ indicate the onset of the semi-infinite leads. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

2. Model

We consider a short two-dimensional GaAs quantum wire with length $L = 150$ nm placed in a photon cavity. We use the 36 lowest in energy single-electron states of the wire, $|i\rangle$, to build a many-electron Fock space of 0–3 Coulomb interacting electrons, $|\mu\rangle$. The potential defining the short quantum wire with two parallel quantum dots displayed in Fig. 1 is

$$V(x,y) = \left[\frac{1}{2}m^*\Omega_0^2 y^2 + eV_g + V_d\sum_{i=1}^{2}\exp\left\{-(\beta x)^2 - \beta^2(y-d_i)^2\right\}\right] \times\theta\left(\frac{L_x}{2} - |x|\right) \quad (1)$$

with $\hbar\Omega_0 = 2.0$ meV, $V_d = -6.5$ meV, $\beta = 0.03$ nm^{-1}, $d_1 = -50$ nm, $d_2 = +50$ nm, $L_x = 150$ nm, and θ is the Heaviside step function. The plunger gate voltage V_g is used to move the states of the system up or down with respect to the bias window defined by the external leads to be describe below.

We use as a kernel for the mutual electron–electron Coulomb interaction

$$V_{\rm Coul}(\mathbf{r}-\mathbf{r}') = \frac{e^2}{\kappa_e\sqrt{|\mathbf{r}-\mathbf{r}'|^2+\eta_c^2}}, \quad (2)$$

with a small regularizing parameter $\eta_c/a_w = 3\times10^{-7}$ (a_w being defined below), and for GaAs parameters we assume $\kappa_e = 12.4$, $m^* = 0.067m_e$, and $g^* = -0.44$. In terms of field operators the Hamitonian of the central system is

$$H_{\rm S} = \int d^2r\,\psi^\dagger(\mathbf{r})\left\{\frac{\pi^2}{2m^*} + V(\mathbf{r})\right\}\psi(\mathbf{r}) + H_{\rm EM} + H_{\rm Coul} - \frac{1}{c}\int d^2r\,\mathbf{j}(\mathbf{r})\cdot\mathbf{A}_\gamma - \frac{e}{2m^*c^2}\int d^2r\,\rho(\mathbf{r})A_\gamma^2, \quad (3)$$

with

$$\boldsymbol{\pi} = \left(\mathbf{p} + \frac{e}{c}\mathbf{A}_{\rm ext}\right), \quad (4)$$

where $\mathbf{A}_{\rm ext}$ is a classical vector potential producing an external homogeneous small magnetic field $B = 0.1$ T along the z-axis, perpendicular to the plane of the two-dimensional quantum wire, inserted to break the spin and the orbital degeneracies of the states in order to enhance the stability of the results. The first term in the second line of Eq. (3) is the paramagnetic, and the second term the diamagnetic, electron–photon interaction. The external magnetic field, B, and the parabolic confinement energy of the leads and the central system $\hbar\Omega_0 = 2.0$ meV, together with the cyclotron frequency $\omega_c = (eB)/(m^*c)$ lead to an effective characteristic confinement energy $\hbar\Omega_w = \hbar(\omega_c^2 + \Omega_0^2)^{1/2}$, and an effective magnetic length $a_w = (\hbar/(m^*\Omega_w))^{1/2}$. This characteristic length scale assumes approximately the value 23.8 nm for the parameters selected here. In terms of the cavity photon creation and annihilation operators, $a^\dagger$ and a, the Hamiltonian for the single cavity photon mode is $H_{\rm EM} = \hbar\omega a^\dagger a$, with energy $\hbar\omega$.

We assume a rectangular photon cavity $(x,y,z) \in \{[-a_c/2, a_c/2]\times[-a_c/2, a_c/2]\times[-d_c/2, d_c/2]\}$ with the short quantum wire centered in the $z = 0$ plane. In the Coulomb gauge the polarization of the electric field parallel to the transport in the x-direction (with the unit vector $\mathbf{e}_x$) is accomplished in the TE$_{011}$ mode, or perpendicular (defined by the unit vector $\mathbf{e}_y$) in the TE$_{101}$ mode. The two versions of the quantized vector potential for the cavity field are in a stacked notation expressed as

$$\mathbf{A}_\gamma(\mathbf{r}) = \begin{pmatrix}\hat{\mathbf{e}}_x\\ \hat{\mathbf{e}}_y\end{pmatrix}\mathcal{A}\left\{a + a^\dagger\right\}\begin{pmatrix}\cos\left(\frac{\pi y}{a_c}\right)\\ \cos\left(\frac{\pi x}{a_c}\right)\end{pmatrix}\cos\left(\frac{\pi z}{d_c}\right), \quad (5)$$

for the TE$_{011}$ and TE$_{101}$ modes, respectively. The strength of the vector potential, $\mathcal{A}$, determines the coupling constant $g_{\rm EM} = e\mathcal{A}\Omega_w a_w/c$, here set to 0.05 meV, or 0.10 meV, leaving a dimensionless polarization tensor

$$g_{ij}^k = \frac{a_w}{2\hbar}\left\{\langle i|\hat{\mathbf{e}}_k\cdot\boldsymbol{\pi}|j\rangle + \text{h.c.}\right\}. \quad (6)$$

In order to maintain high numerical accuracy the cavity-photon dressed electron states have to be constructed in a step wise manner [21]. First, the Fock space of non-interacting electrons is constructed from 36 accurate single-electron states keeping enough one-, two-, and three-electron states such that the energy of the highest states for each electron number surpasses the bias window defined by the chemical potential in each lead by much. For the selected parameters the total number of states is 1228. This basis is then used to diagonalize the Coulomb interacting (2) electron system. Next, a basis is constructed as a tensor product of the 120 lowest in energy Coulomb interacting electron states and the 16 lowest eigenstates of the photon number operator. These are used to diagonalize the electron–photon interacting system. Finally, 120 lowest of these cavity-photon dressed electron states are used for the transport calculation. The step wise construction is reminiscent of the step wise construction of a Green function for an interacting electron–photon system.

The coupling of the central system to the leads is described by the Hamiltonian

$$H_T = \theta(t)\sum_{il}\int d\mathbf{q}\left(T_{\mathbf{q}i}^l c_{\mathbf{q}l}^\dagger d_i + (T_{\mathbf{q}i}^l)^* d_i^\dagger c_{\mathbf{q}l}\right), \quad (7)$$

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