Modeling two different nonlinear aspects in quantum dot systems

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Excitation of radial collective modes in a quantum dot

Beyond linear response - hard test of Coulomb implementation - Raman

Two Coulomb interacting electrons in a quantum dot
Short electric pulse $W(t)$ for $t \in [0, \pi]$ ps

Parabolic confinement

$$V_{\mathrm{conf}}(\mathbf{r}) = \tfrac{1}{2} m^* \omega_0^2 r^2$$

parabolic + "central hill"

$$V_{\mathrm{conf}}(\mathbf{r}) = \tfrac{1}{2} m^* \omega_0^2 r^2 + V_0 \exp\left(-\gamma r^2\right)$$

Exact CI

$$i\hbar \partial_t \rho(t) = [H + W(t), \rho(t)]$$

$$i\hbar \partial_t \rho(t) = [H, \rho(t)]$$

Mean field

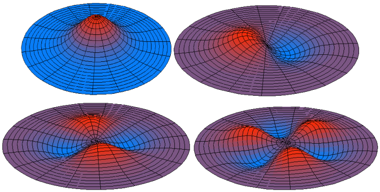
$$i\hbar \partial_t \rho(t) = [H(t) + W(t), \rho(t)]$$

$$i\hbar \partial_t \rho(t) = [H(t), \rho(t)]$$

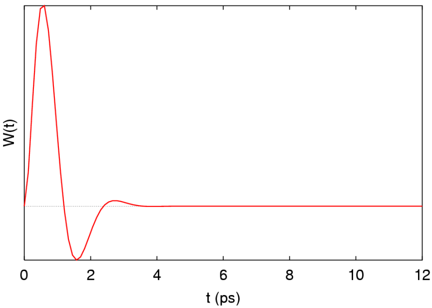
Electric pulse

At $t = 0$: $H(t) \rightarrow H + W(t)$

$$W(t) = V_t r^{|N_p|} \cos(N_p\phi) \exp(-sr^2 - \Gamma t) \sin(\omega_1 t) \sin(\omega t) \theta(\pi - \omega_1 t)$$



- $N_p = 0, \pm 1, \pm 2, \pm 3$
- $s = 0$, $\Gamma = 2$ THz
- $\omega = 4$ THz, $\omega_1 = 1$ THz

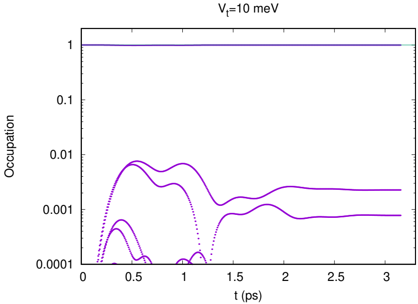


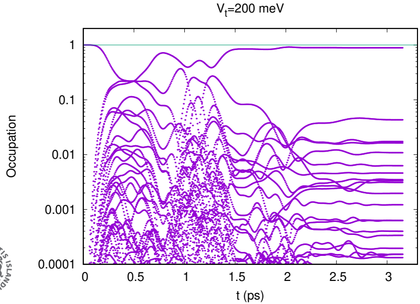
Many paths to solution, here we use

$$\rho(t) = T(t)\rho(0)T^\dagger(t) \quad \leftarrow \quad i\hbar\partial_t T(t) = H(t)T(t)$$

- GaAs parameters, $\langle r^2 \rangle = \mathrm{Tr}\{r^2 \rho(t)\}$
- DFT: Linear single-electron base, grid-free, LSDA, Phys. Rev. B 68, 165343 (2003)
- Two-electron Fock space, static 16836 states, dynamic 2415 states, Annalen der Physik 526, 235 (2014)
- FORTRAN 2008, MKL, OpenMP, CUDA, CuBLAS, MAGMA

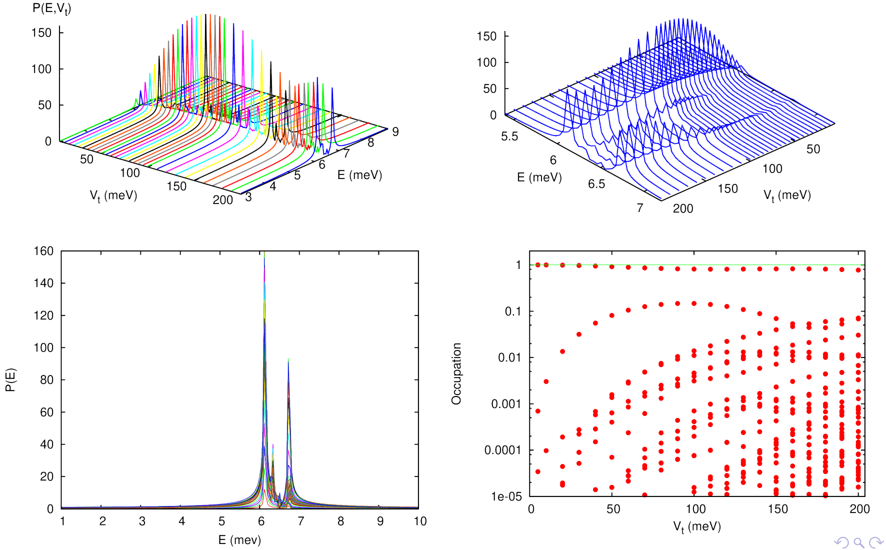
Exact, no hill, Occupation



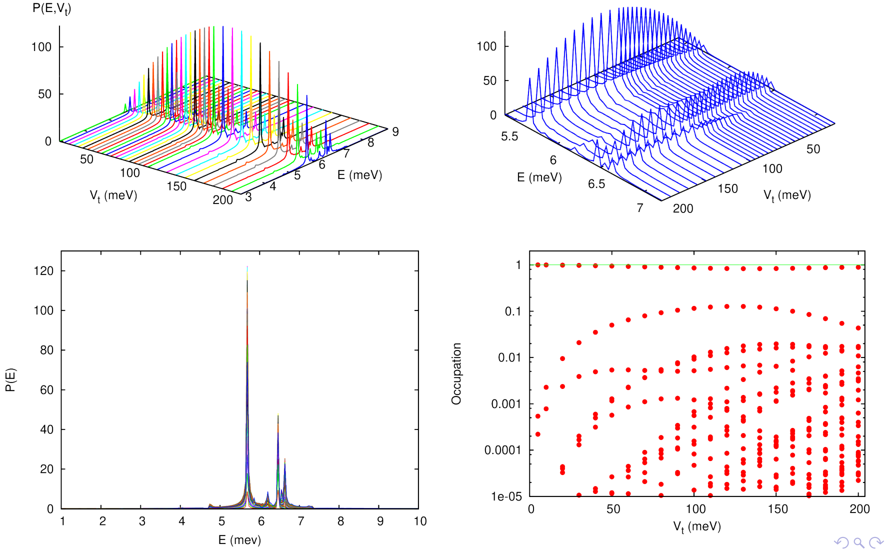


Occupation **only changes** during the external pulse W(t)

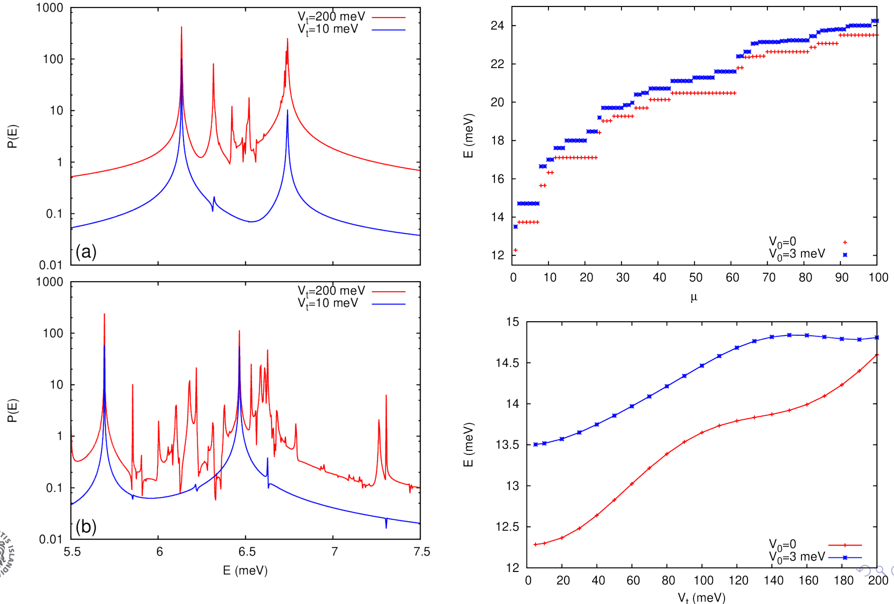
Exact, no hill



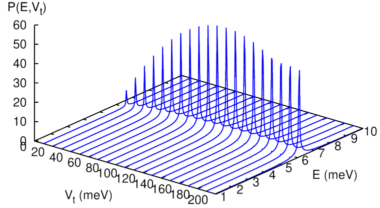
Exact, central hill, $V_0 = 3.0$ meV

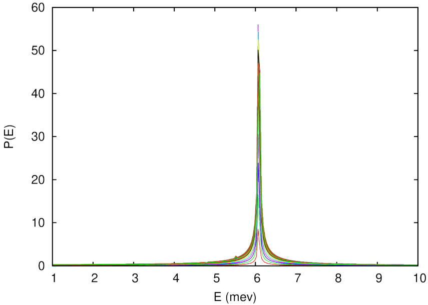


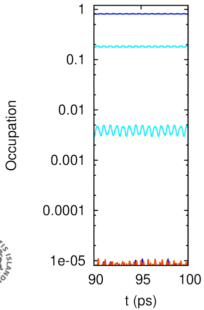
Exact, Fourier power spectrum $\langle r^2 \rangle$, spectrum and $\langle E \rangle$

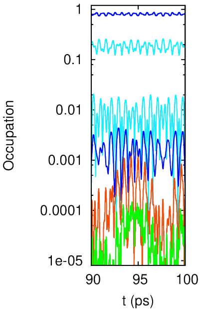


Hartree, central hill, $V_0 = 3.0$ meV



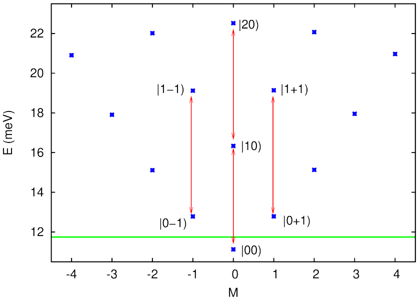


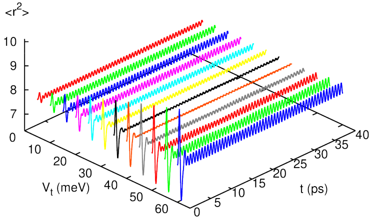


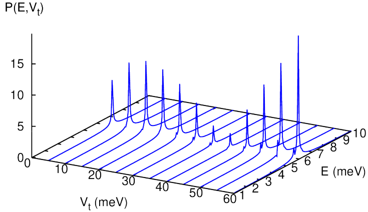


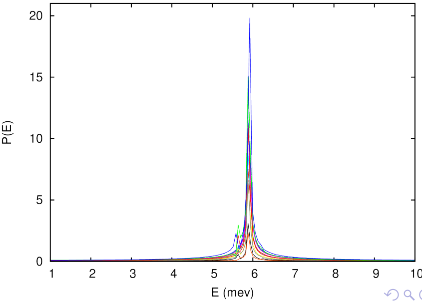
No side-peak
Missing correlations
$\Delta\mathcal{M} = 0$, $\Delta M = 0$
t-dependent occupation

LSDA, central hill, $V_0 = 3.0$ meV

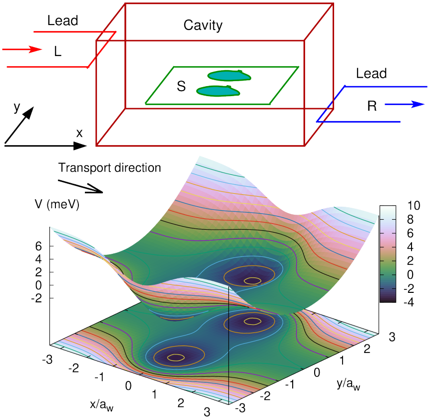








Electron transport through photon cavity



- Exact Coulomb interaction, 1-3 electrons
- One photon mode, x- or y-polarized
- Exact electron - photon interactions, paramagnetic $\sim \mathbf{p} \cdot \mathbf{A}$, diamagnetic $\sim \rho A^2$
- Weak coupling to leads
- Photon reservoir
- Geometry, anisotropy

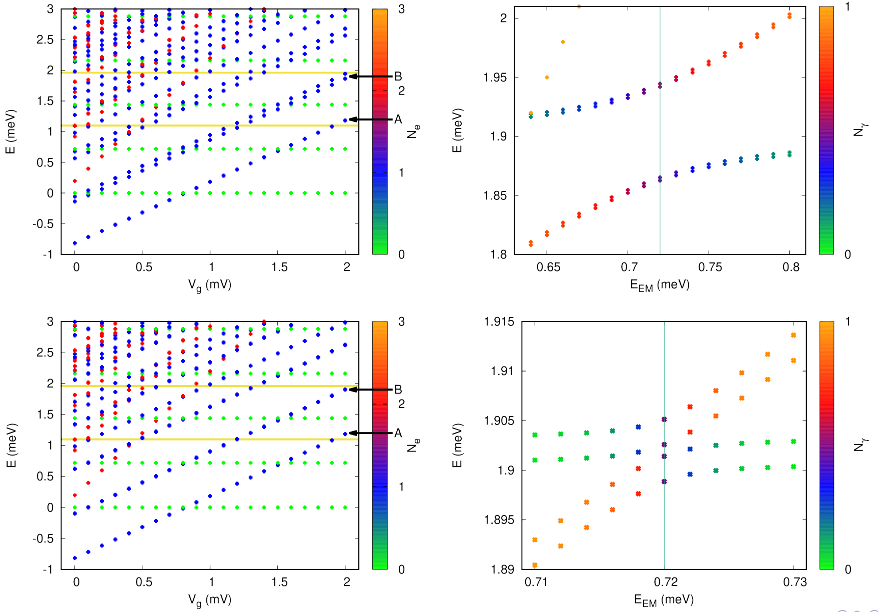
Transient regime

- Fock space of photon dressed many-electron states
- Projection on central system
- Non-Markovian master equation
- Integral kernel of second order in lead-system coupling
- 120 many-body states in transport
- parallelized calculations
- Stepwise truncations
- Fortschritte der Physik **61**, 305 (2013)

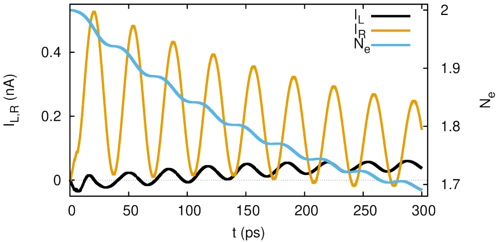
Long time - steady state

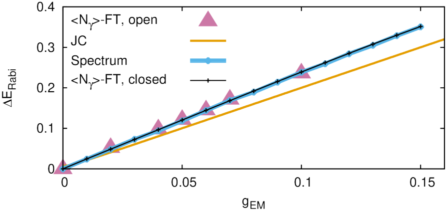
- Mapping into Liouville space of transitions, vectorization and tensor products
- Markovian master equation
- Exact matrix solution
- 14400 transitions in transport
- Computer Physics Communications **220**, 81 (2017)

Two types of Rabi-oscillations, geometry → selection rules



Transient regime, Rabi-oscillations in current

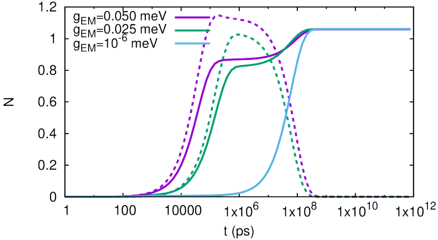


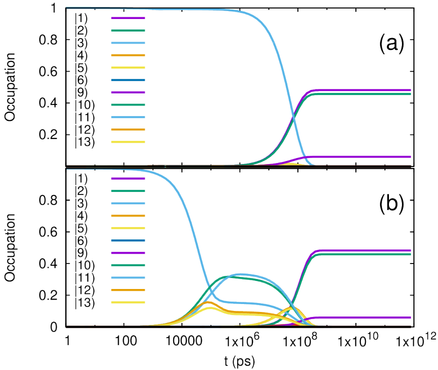


$\hbar\omega = 2.0$ meV, y-polarization, Initial Rabi-split 2e-state, $g_{\mathrm{EM}} = 0.05$ meV

ACS Photonics **2**, 930 (2015)

Radiative and non-radiative transitions

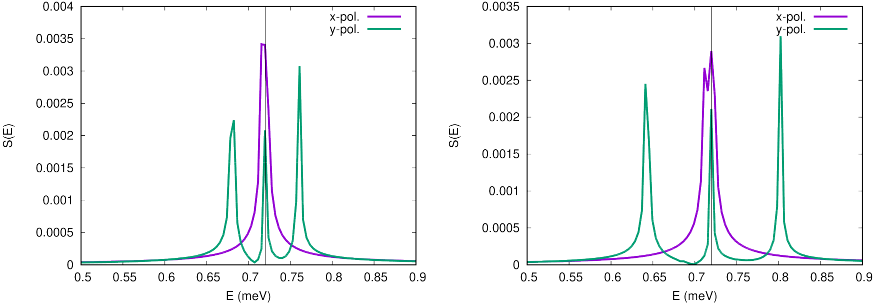




$\hbar\omega = 0.8$ meV, x-polarization, $g_{\rm EM} = 0.05$ meV

Annalen der Physik **529**, 1600177 (2017)

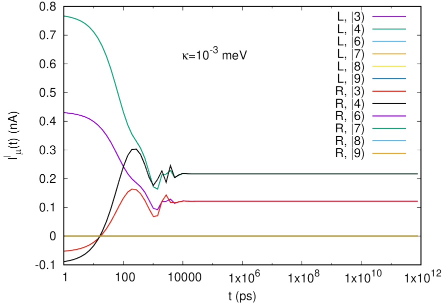
Steady-state photon-correlations

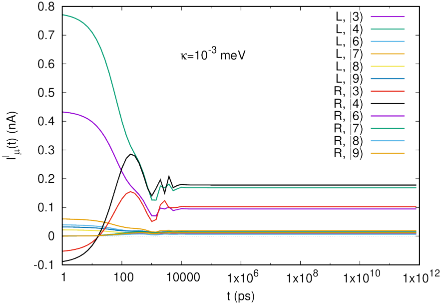


$\hbar\omega = 0.72$ meV, $V_g = 2.0$ mV, x-polarization, $g_{\rm EM} = 0.05$ and 0.10 meV
Ground state and conventional electroluminescence

Annalen der Physik **530**, 1700334 (2018)

Partial current

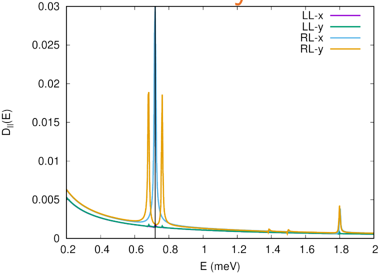


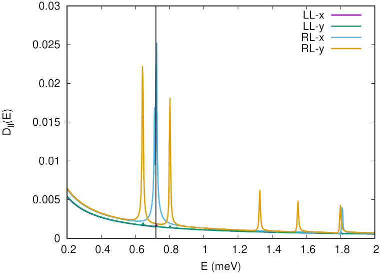


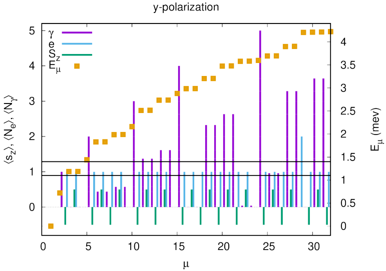
$\hbar\omega = 0.72$ meV, $V_g = 2.0$ mV, x-polarization, $g_{\mathrm{EM}} = 0.05$
$\Delta\mu = 0.3$ and 0.86 meV

Annalen der Physik **530**, 1700334 (2018)

Steady-state current correlations







Peak (meV)	Transitions
0.642	$\lvert\breve{03}) \leftrightarrow \lvert\breve{06}), \lvert\breve{04}) \leftrightarrow \lvert\breve{07})$
0.801	$\lvert\breve{03}) \leftrightarrow \lvert\breve{08}), \lvert\breve{04}) \leftrightarrow \lvert\breve{09})$
1.33	$\lvert\breve{03}) \leftrightarrow \lvert\breve{11}), \lvert\breve{04}) \leftrightarrow \lvert\breve{12})$
1.55	$\lvert\breve{03}) \leftrightarrow \lvert\breve{13}), \lvert\breve{04}) \leftrightarrow \lvert\breve{14})$
1.80	$\lvert\breve{03}) \leftrightarrow \lvert\breve{16}), \lvert\breve{04}) \leftrightarrow \lvert\breve{17})$

$\hbar\omega = 0.72$ meV, $V_g = 2.0$ mV, x-polarization, $g_{\mathrm{EM}} = 0.05$ and 0.10 meV
$\Delta\mu = 0.3$ meV, (arXiv:1707.08295)

Conclusions - questions

- In a system of 2 parallel QD polarization of cavity field can select the type of the dominant $e-\gamma$-interaction
- Two different types of Rabi oscillations
- Current correlations reveal all underlying transitions in the steady state
- Geometry brings in huge variation in lead system coupling
- Rabi-oscillations can be observed in current or current correlations
- Two types of ground state electroluminescence
- Non-linear $e-\gamma$ effects? $\cdots$
- Weak excitation in a closed $e-\gamma$ system Journal of Optics **17**, 015201 (2015)

Collaboration and support

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