Photon-statistics and entanglement in quantum light emission from semiconductor quantum dots

A. Carmele, M.-R. Dachner, M. Richter, and A. Knorr

Outline

Strong coupling limit:

- ❑ The Jaynes-Cummings model (JCM)
- ❑ Photon-probability cluster expansion (PPCE)
- ❑ Electron-LO-phonon interaction: temperature dependent T1-times
- ❑ Electron-electron interaction: Electrically driven single-photon source

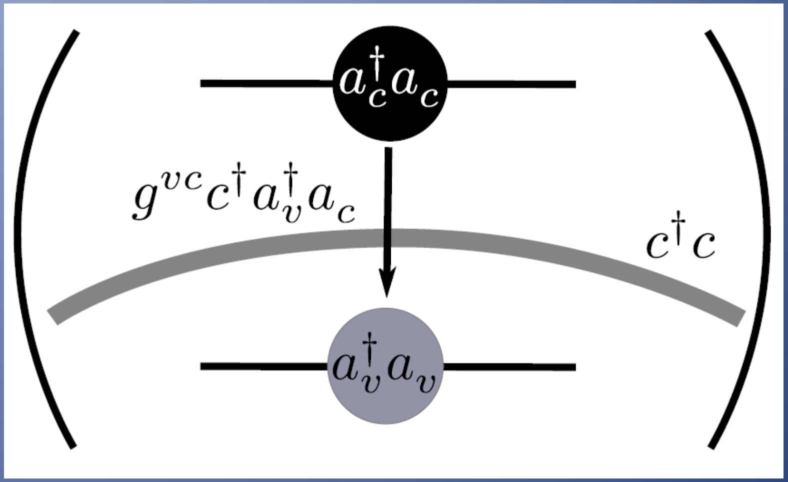
Weak coupling limit:

- ❑ Polarization entangled photon pairs: temperature dependent concurrrence

Brief notes about Atom-Cavity QED

The Jaynes-Cummings model: [1]

- ❑ One-electron assumption
- ❑ One interaction: electron-light
- ❑ Closed system



„The simplest fully quantized model of interest“ (J.H. Eberly)

[1]E. Jaynes and F. Cummings, Proc.IEEE 51, 89 (1963)

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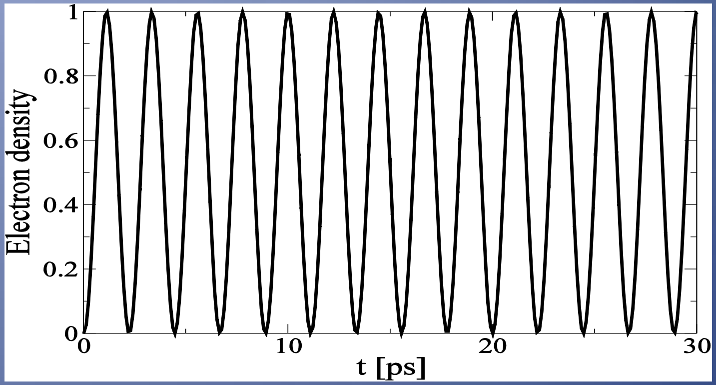

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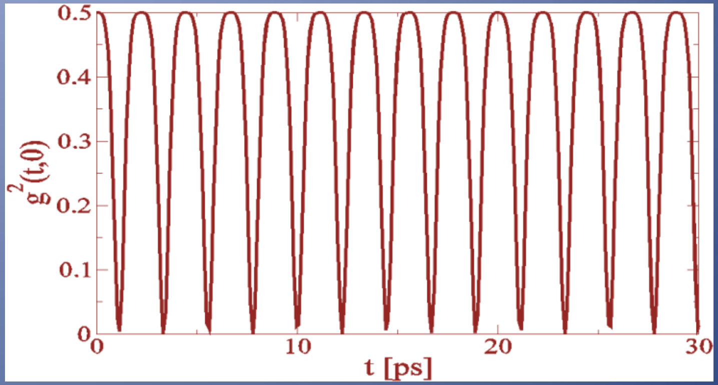

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Heisenberg equation of motion approach to treat more interactions

$$-i\hbar\partial_t\langle O\rangle = \langle[H_0 + H_{el-pt}, O]\rangle$$

To reproduce the Jaynes-Cummings model,
we introduce a factorization approach for strongly correlated systems:
the photon probability cluster expansion (PPCE).[1]

$$p_n = \langle |n\rangle\langle n| \rangle \qquad f_n^h = p_n - \langle |n\rangle\langle n| a_v^\dagger a_v\rangle$$

$$\langle c^\dagger c\rangle = \sum_{n=1}^{\infty} n\, p_n \qquad f_n^e = \langle |n\rangle\langle n| a_c^\dagger a_c\rangle$$

[1]M. Richter, et al., PRL, 103, 087407 (2009)

Heisenberg equation of motion approach to treat more interactions

$$-i\hbar\partial_t\langle O\rangle = \langle[H_0 + H_{el-pt}, O]\rangle$$

For given initial conditions, the analytical solution of the JCM is reproduced, e.g.:

$$f_0^e = f_0^h = 1, p_0 = 1, p_n = 0 \quad (n > 0)$$

Solution via differentiating with respect to time:

$$\partial_t^2(f_0^e - p_1) = -4(g^{vc})^2(f_0^e - p_1)$$

↓

$$f_0^e(t) - p_1(t) = \cos(2g^{vc}t) = \cos^2(g^{vc}t) - \sin^2(g^{vc}t)$$

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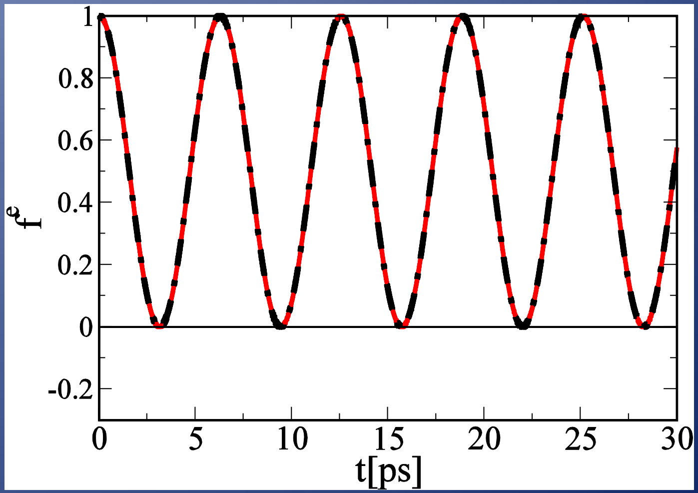
Solution of the Jaynes-Cummings model for the case of vacuum Rabi oscillation:

$$f_0^e(t) = \cos^2(g^{vc}t)$$

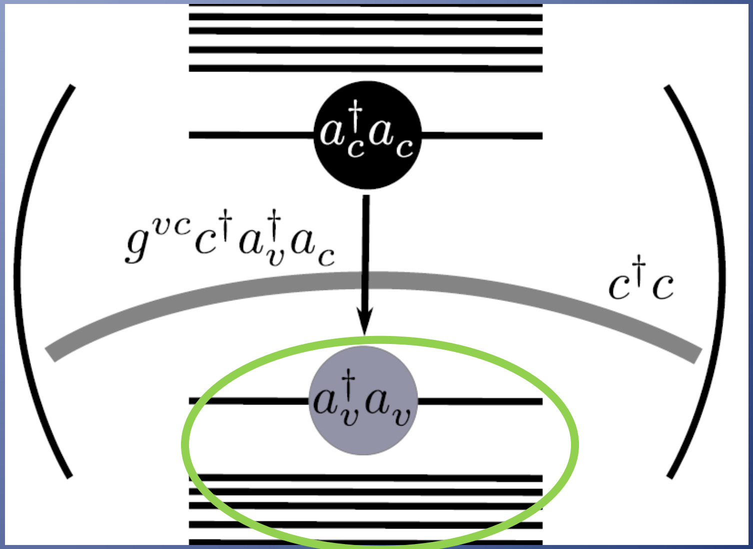


[1]PSSB, accepted (2009)

Quantum optics in the semiconductor

Due to the quantum dot-wetting layer interaction, the one-electron assumption not valid anymore.

$$\langle |n\rangle\langle n| a_1^\dagger a_2^\dagger a_3 a_4 \rangle \neq 0$$



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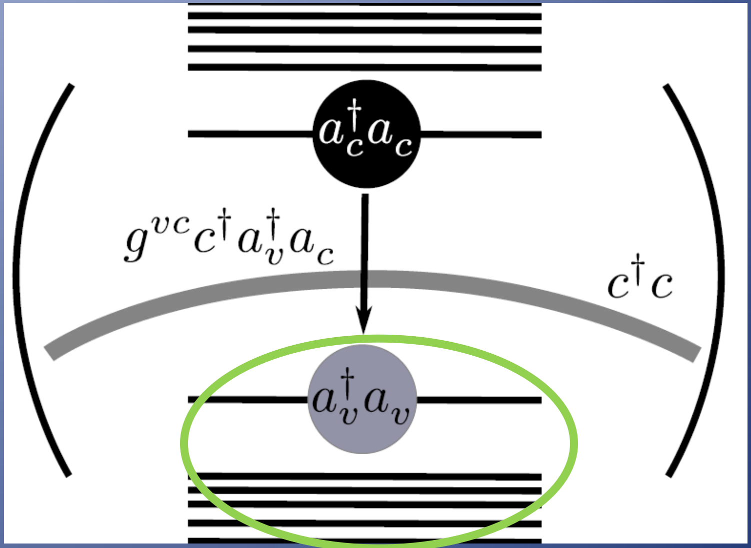

$$\langle |n\rangle\langle n| a_1^\dagger a_2^\dagger a_3 a_4 \rangle \neq 0$$

This many-particle contribution is taken into account via the Hartree – Fock approximation

$$\langle a_1^\dagger a_2^\dagger a_3 a_4 \rangle \approx \langle a_1^\dagger a_4 \rangle \langle a_2^\dagger a_3 \rangle - \langle a_1^\dagger a_3 \rangle \langle a_2^\dagger a_4 \rangle$$

Here, we introduce a modified the Hartree – Fock approximation [1]

$$\langle |n\rangle\langle n| a_1^\dagger a_2^\dagger a_3 a_4\rangle = p_n \langle \frac{|n\rangle\langle n|}{p_n} a_1^\dagger a_2^\dagger a_3 a_4\rangle$$

[1]PRL, 103, 087407 (2009)

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↓

$$\begin{aligned}\langle |n\rangle\langle n| a_1^\dagger a_2^\dagger a_3 a_4 \rangle &\approx p_n \Big\{ \langle \frac{|n\rangle\langle n|}{p_n} a_1^\dagger a_4 \rangle \langle \frac{|n\rangle\langle n|}{p_n} a_2^\dagger a_3 \rangle - \langle \frac{|n\rangle\langle n|}{p_n} a_1^\dagger a_3 \rangle \langle \frac{|n\rangle\langle n|}{p_n} a_2^\dagger a_4 \rangle \Big\} \\ &\approx \frac{1}{p_n} \Big\{ \langle |n\rangle\langle n| a_1^\dagger a_4 \rangle \langle |n\rangle\langle n| a_2^\dagger a_3 \rangle - \langle |n\rangle\langle n| a_1^\dagger a_3 \rangle \langle |n\rangle\langle n| a_2^\dagger a_4 \rangle \Big\}\end{aligned}$$

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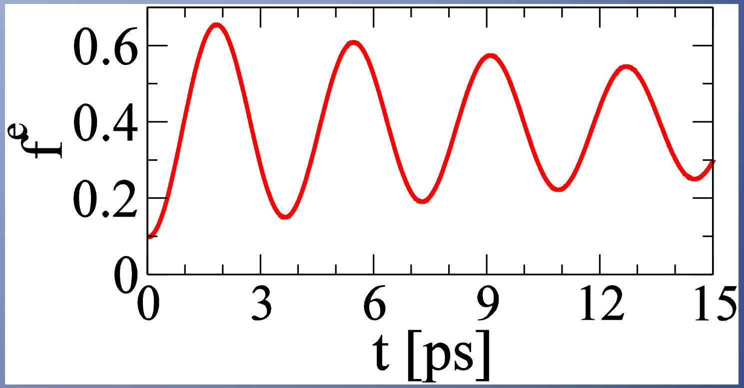
Few photon limit,
the anti-bunching regime is simulated:



Amplitude of Rabi flops depends on the deviation from the one-electron assumption of electron and hole densities.

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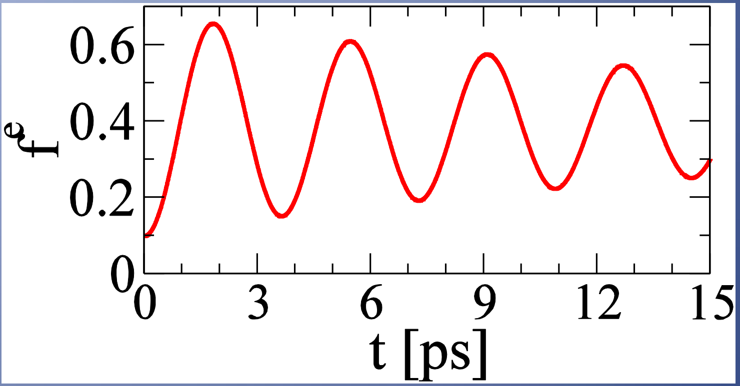

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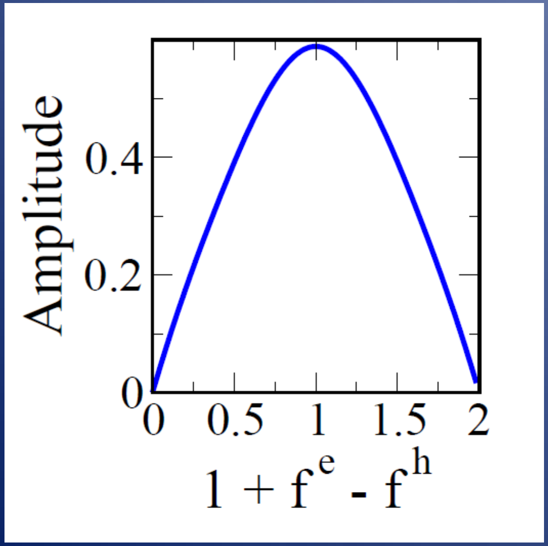
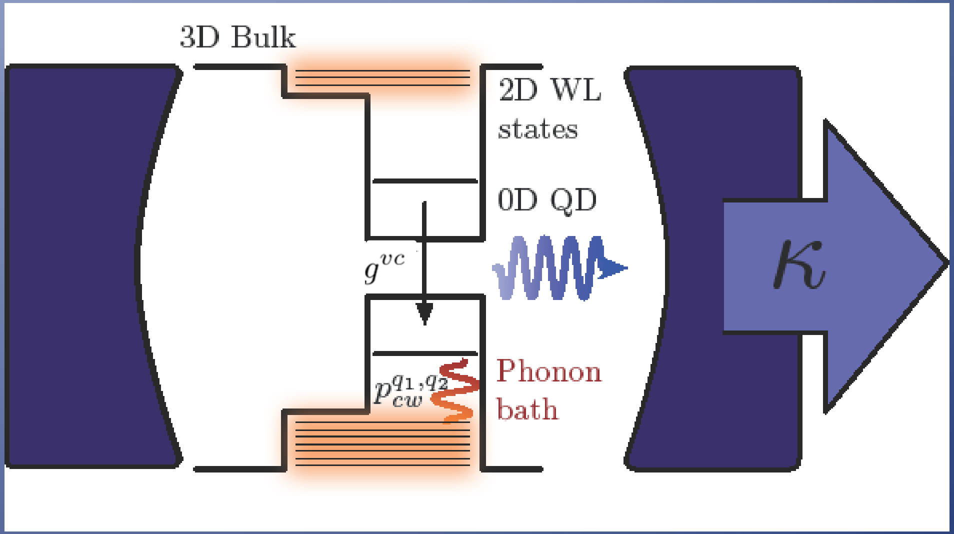


The amplitude of the Rabi flops might be used as a measure for the number of electrons in the actual quantum dot

Quantum optics in the semiconductor

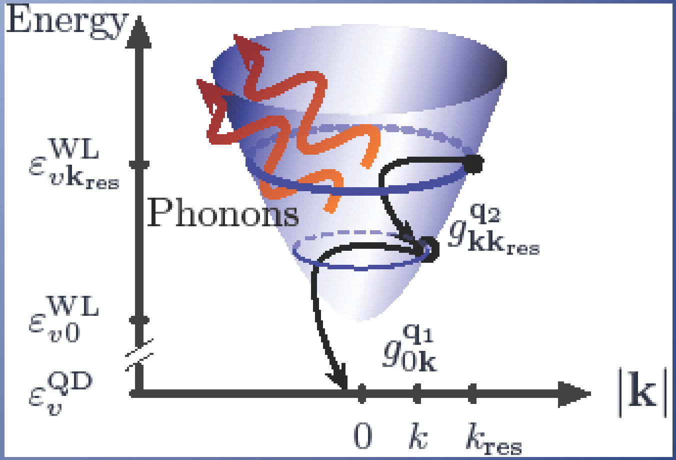
Low carrier-density limit:

- ❑ 3D bulk: Electron-phonon interaction
- ❑ 2D WL: Electron-electron interaction
- ❑ 0D QD: Electron-photon



Phonon-assisted carrier scattering from the WL into the QD

- In an effective Hamiltonian approach a higher order Markovian process is assumed
- Probability of a subprocess depends on how strong the subprocess violetes the energy conservation



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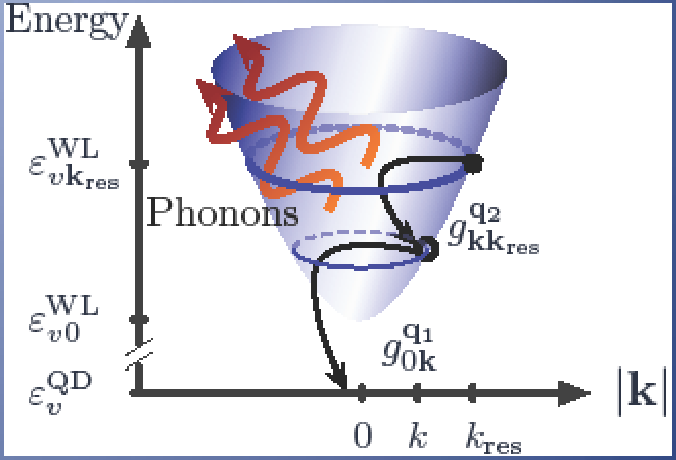
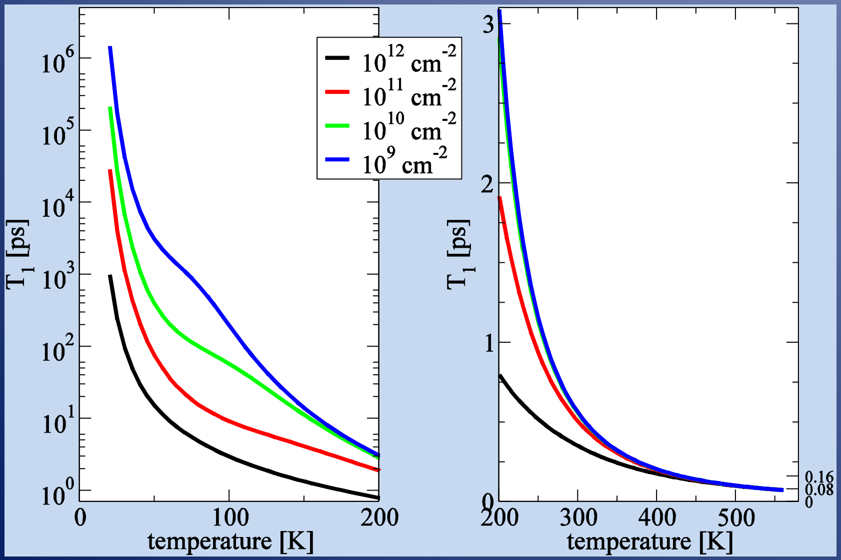
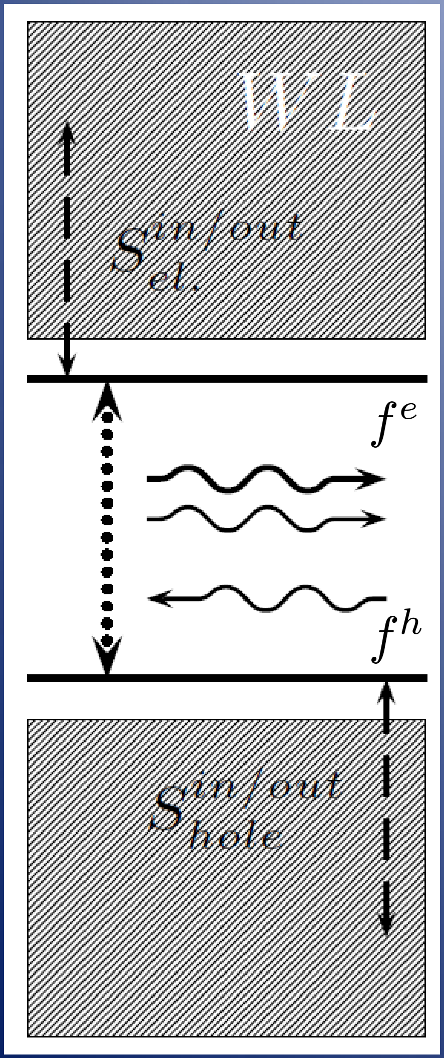


Relaxation rates[1]:



- The relaxation rates depend on the temperature of the bulk material
- Dependence corresponds to a square of the Bose-Einstein-distribution function
- The higher the temperature, the shorter the T1 - Time

[1] PSSB, accepted (2009)



Electrically driven QD is a source for single-photons on demand

Electrons scatter into the QD

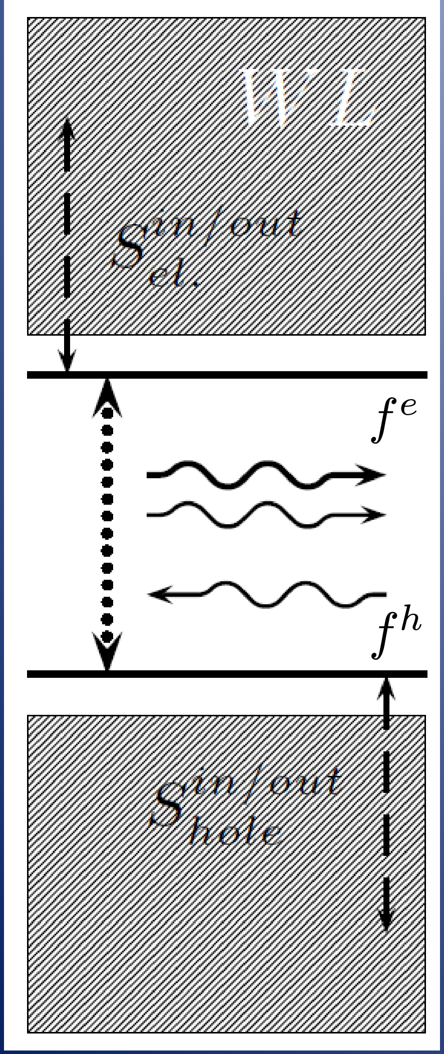
$$\partial_t f^e_n|_{pump} = S^{in}_e (p_n - f^e_n) - S^{out}_e f^e_n$$

$$\partial_t f^h_n|_{pump} = S^{in}_h (p_n - f^h_n) - S^{out}_h f^h_n$$

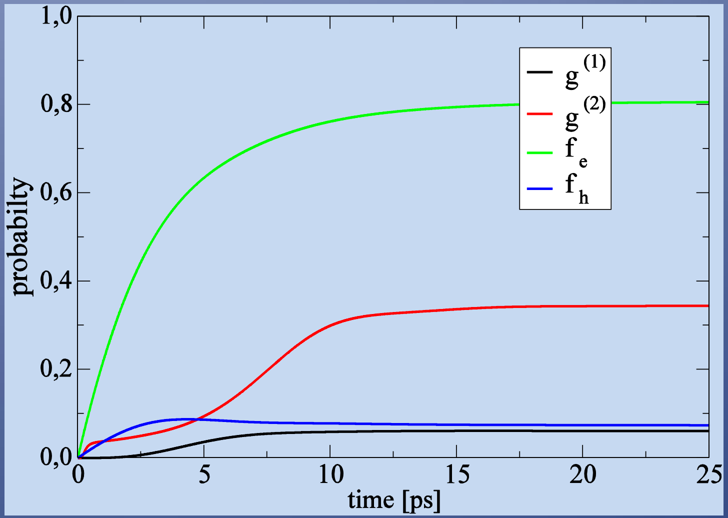
$$\partial_t \langle |n+1\rangle\langle n| a^\dagger_v a_c\rangle|_{pump} = -\left(\frac{S^{in}_e}{2} + \frac{S^{in}_e}{2} + \frac{S^{out}_e}{2} + \frac{S^{out}_h}{2}\right) \langle |n+1\rangle\langle n| a^\dagger_v a_c\rangle$$

Derived via a bath assumption for electrons and holes in the wetting layer

Quantum optics in the semiconductor

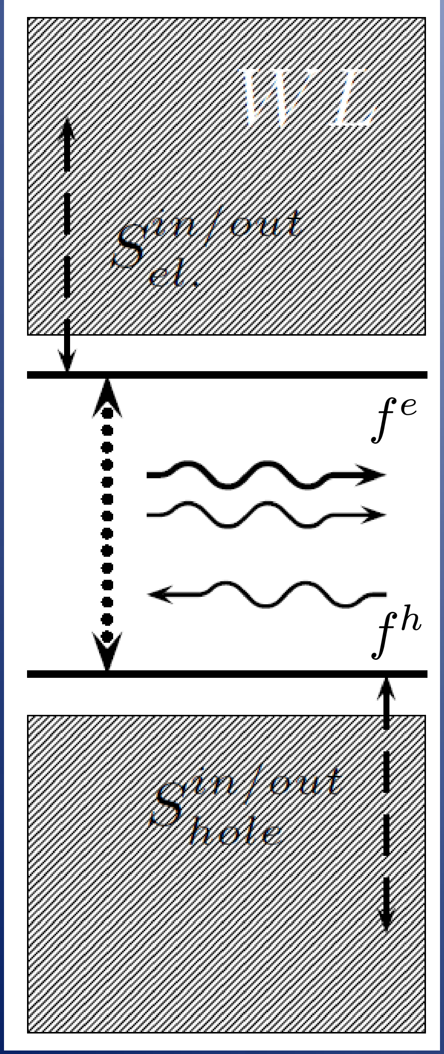


The single photon emitter in a steady state condition.

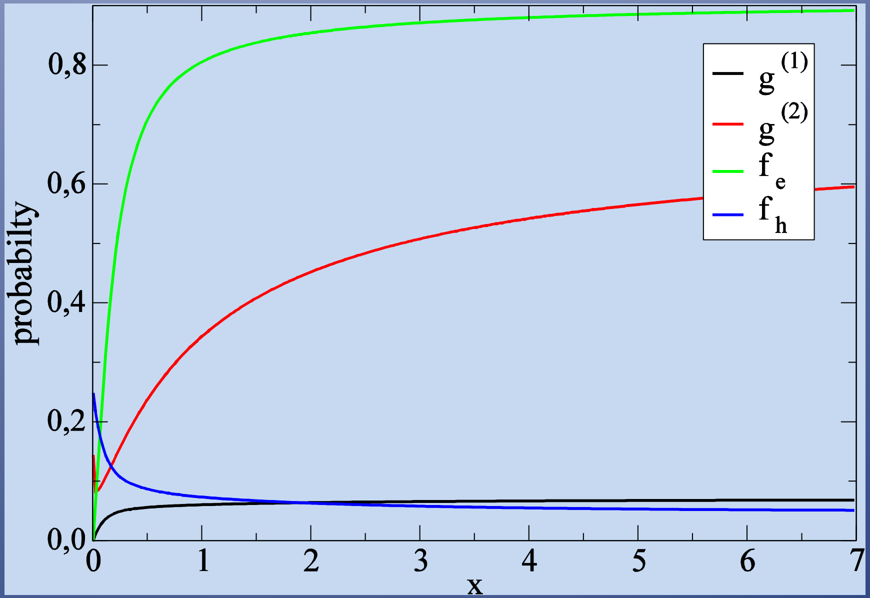


Material dependent photon-statistics

Quantum optics in the semiconductor



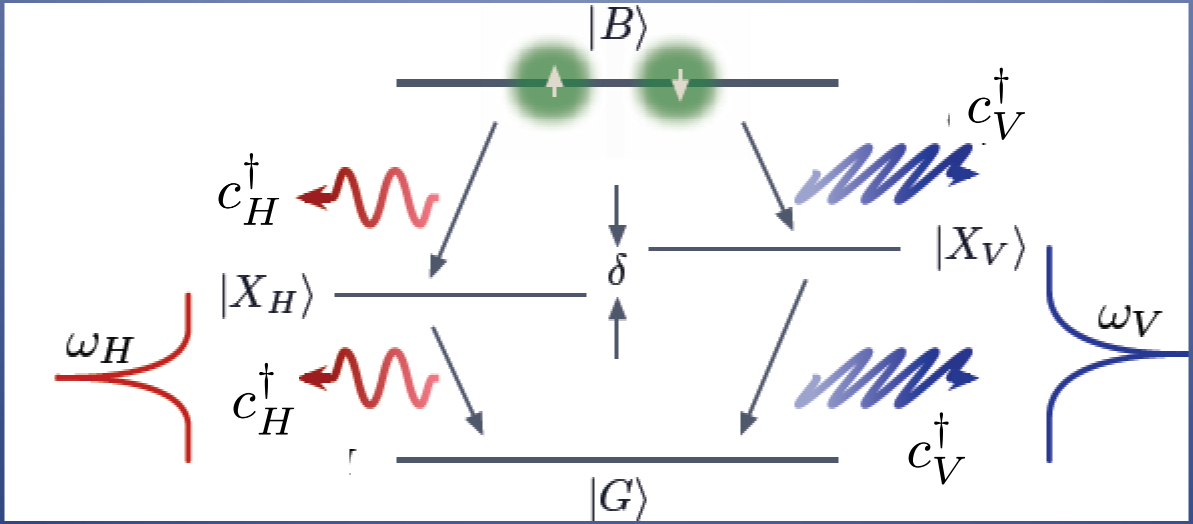
For weak pumping, a single-photon emitter is realized



$$S_{in}^{e} = \frac{x}{4ps}, S_{out}^{e} = \frac{x}{40ps}$$

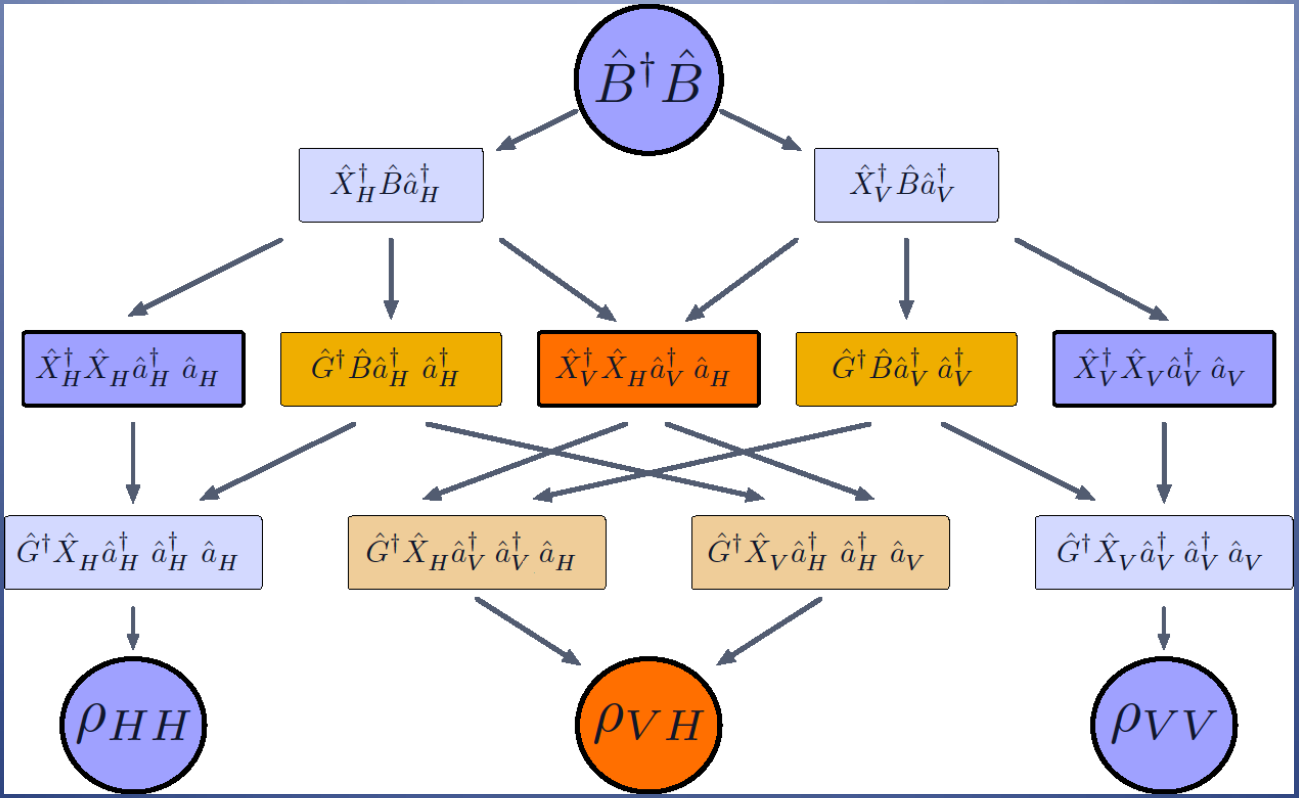
Source of polarization entangled photon pairs:

We assume a two-mode cavity with a quantum dot inside, coupled to the wetting layer via multi-phonon processes.



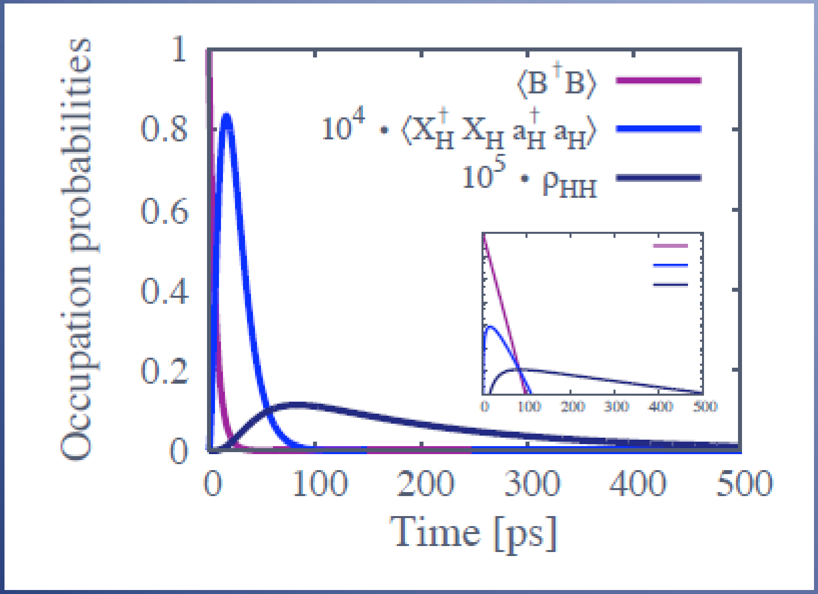
Biexciton $|B\rangle$ decays via two intermediate exciton states $|X_H\rangle, |X_V\rangle$ to the ground state $|G\rangle$

Weak coupling limit:

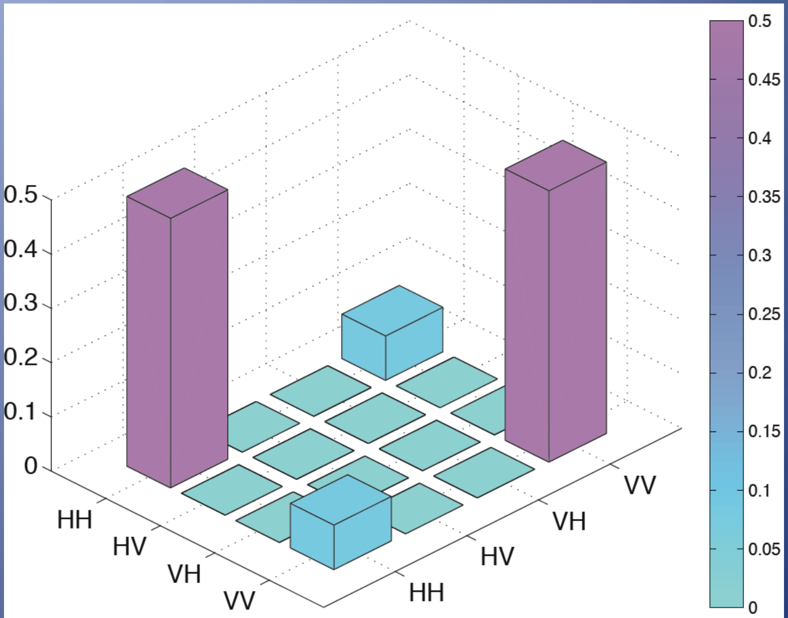


Cavity loss , radiative and phonon dephasing stronger than the electron-light coupling

Application: Source of polarization entangled photon pairs



The biexciton and exciton density decays with the radiative damping. The diagonal element of the polarization sub-space density matrix decays with the cavity loss.



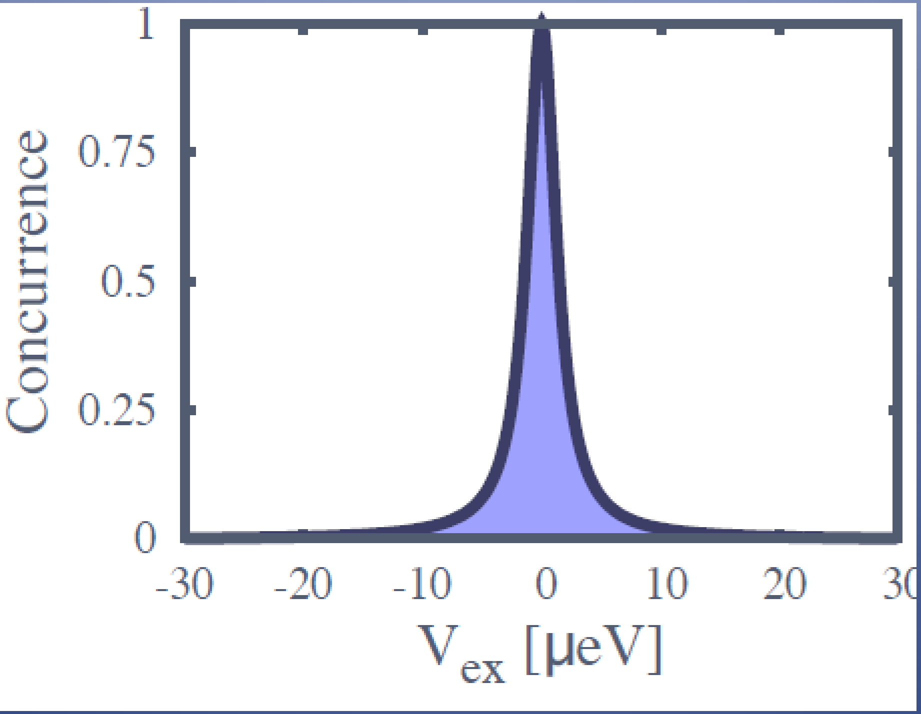
Quantum state tomography for fine structure splitting of 10µeV

Application: Source of polarization entangled photon pairs

Concurrence is an accepted measure for entanglement and defined via the off-diagonal element:

$$C = 2|\rho_{HV}|$$

$$\rho_{HV} \propto \langle c_H^\dagger c_H^\dagger c_V c_V \rangle$$

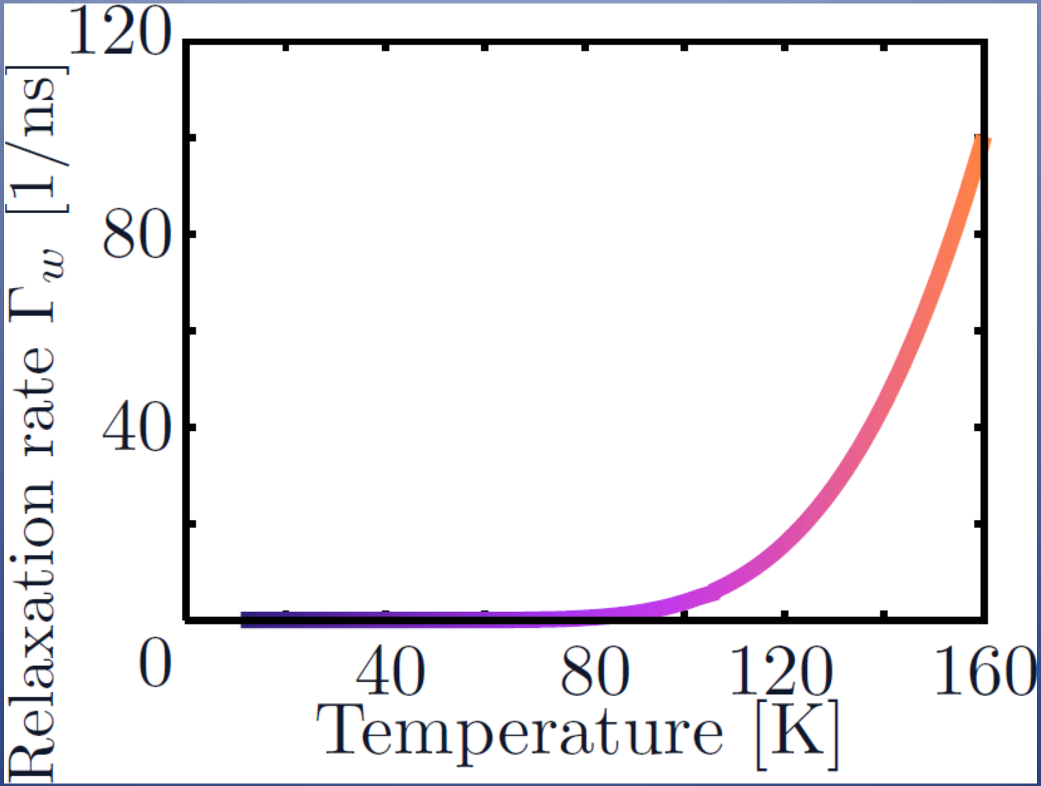


For a strong fine structure splitting, entanglement vanishes

Application: Source of polarization entangled photon pairs

Wetting layer contributions lead to an additional dephasing.

$$\Gamma = \Gamma_{rad} + \Gamma_{WL}$$



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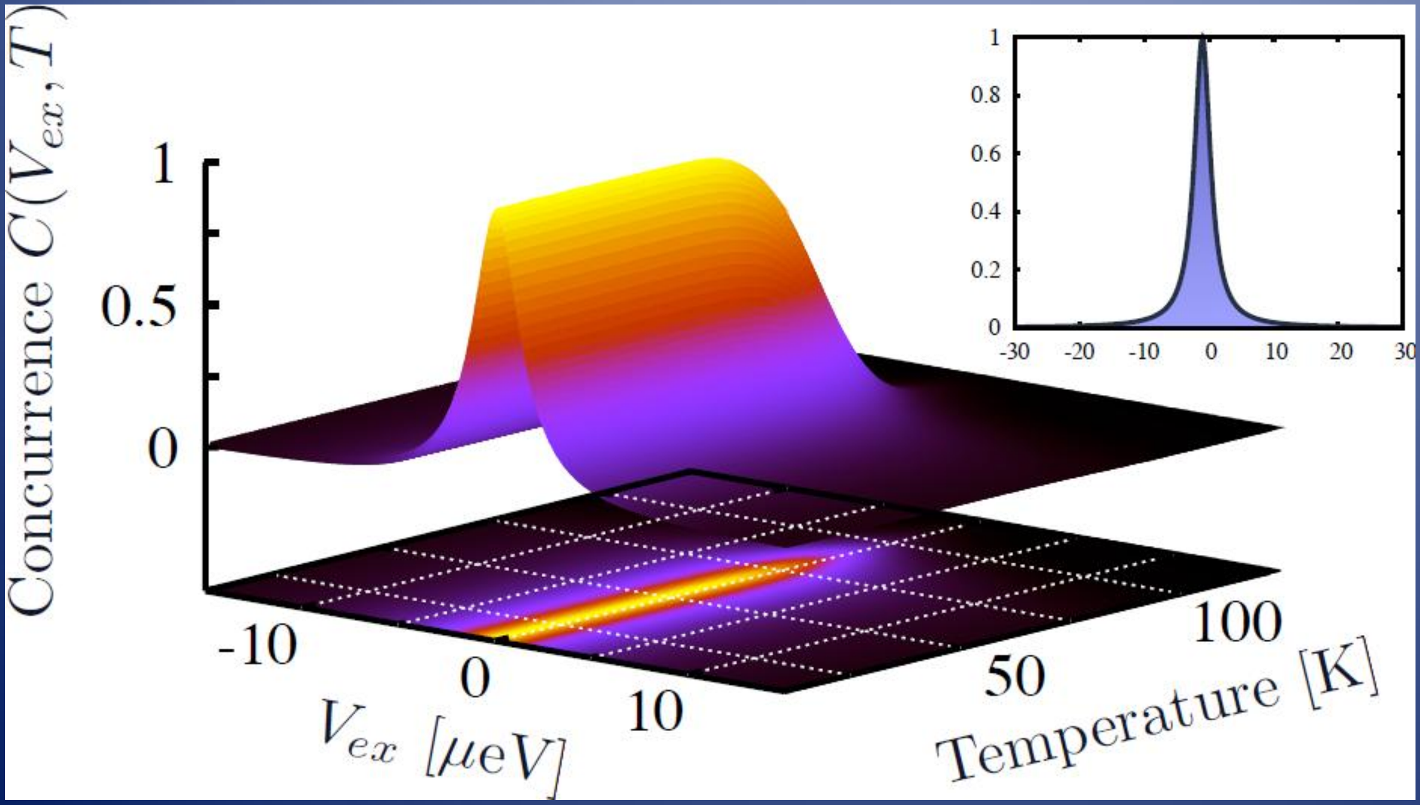
Multiphonon processes attack the generation of polarization entangled photons



[1]arxiv, 0910.5445 (2009)

Summary

Strong coupling – low carrier limit:

- ❑ Jaynes-Cummings model – photon statistics
- ❑ Decreased amplitude of the Rabi oscillations
- ❑ Electrically driven single-photon emitter – photon statistics

Weak coupling – low carrier limit:

- ❑ Polarization entangled photon pairs: temperature dependent concurrence

thank you!!