Addressing phonons in semiconductor quantum dot-QED: entanglement, non-equilibrium phonon, and photon distributions

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Self-assembled semiconductor quantum dots (QD) allow the study of a true quantum regime, in which the fluctuation properties of lattice vibrations (phonons) and photon distributions have a strong impact on the optical and electronic response of the system. These fluctuations draw a lot of attention in recent experimental and theoretical work with respect to non-classical photon distributions (anti-bunching), polarization entanglement of photons from a biexciton cascade and temperature effects due to hot bulk phonons.

In our contribution, we present a fully non-Markovian, quantized theoretical framework to study the quantum optical properties of a QD, including the solid-state environment. Our framework is based on the equation of motion approach, which allows us to generate numerically exact solutions for the combined photon, phonon and photon dynamics, and furthermore gives access to the full photon and phonon distributions in the case of a fixed number of electrons inside the QD (exciton, biexciton).

First, we focus on the multi-phonon assisted quantum emission from an externally excited semiconductor quantum dot. Using our non-perturbative equation of motion method, we predict several strong coupling features including multi-phonon-assisted Mollow-triplets and additional anti-crossings between the Mollow sidebands and the phonon satellites. The anti-crossings come along with a remarkable change in the phonon-statistics, evolving from equilibrium to hot phonon- and non-equilibrium distributions. Via specific optical excitation, the QD can be used as a single or coherent phonon emitter.

Secondly, we investigate the biexciton cascade in a QD in the strong coupling regime numerically exact and discuss the impact of phonons on the degree of entanglement. We derive in the weak coupling limit an analytical solution of the quantum state tomography of the QD biexciton cascade and show that pure dephasing does not affect the degree of polarization entanglement for temperatures below 60K. These analytical formulas are valid for arbitrary photon loss, dephasing, relaxation and detuning in the material, and are widely usable as a parameter study tool and as a fit formula for experiments.