Can the exciton–polariton regime be defined by its quantum properties?

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Contents

Motivation

- Macroscopic coherence, Bose-Einstein condensation. Solid-state realization of BEC: strong coupling between photons and excitons in semiconductor cavities $-M_{pol} \sim 10^{-8} m_{_H}$.
- Quantum information technology: quantum logic devices, quantum memories, quantum repeaters and quantum gates.

Polariton

Matter–light interaction is described by the Jaynes–Cummings Hamiltonian:

$$\hat{H} = \omega_C \hat{a}^\dagger \hat{a} + (\omega_C - \Delta)\hat{\sigma}^\dagger \hat{\sigma} + g(\hat{a}\hat{\sigma}^\dagger + \hat{a}^\dagger \hat{\sigma})$$

- Vacuum–Rabi splitting.
- Anticrossing in the dispersion relation.

Polaritons:

$$|n,+\rangle = \sin\Phi_n |G,n\rangle + \cos\Phi_n |X,n-1\rangle$$
$$|n,-\rangle = \cos\Phi_n |G,n\rangle - \sin\Phi_n |X,n-1\rangle$$

$$\tan 2\Phi_n = 2g\sqrt{n}/\Delta$$

Dynamical regimes

$$\frac{d\hat{\rho}}{dt} = i[\hat{\rho}, \hat{H}] + \frac{1}{2}P(2\hat{\sigma}^\dagger\hat{\rho}\hat{\sigma} - \hat{\sigma}\hat{\sigma}^\dagger\hat{\rho} - \hat{\rho}\hat{\sigma}\hat{\sigma}^\dagger) + \frac{1}{2}\kappa(2\hat{a}\hat{\rho}\hat{a}^\dagger - \hat{a}^\dagger\hat{a}\hat{\rho} - \hat{\rho}\hat{a}^\dagger\hat{a})$$

i) $g \ll P, \kappa$. The pumping keeps the QD in its excited state while the dissipation steers the electromagnetic field to its ground state. Other states are not significantly populated because matter excitation cannot be converted into photons.

ii) $g \gg P, \kappa$. The coherences $\rho_{Gn,Xn-1}$ are different from zero. In resonance they are purely imaginary. For small detunings they acquire a small real part. For $\Delta \gg g$, the matter-light interaction becomes dispersive, i.e., the mechanism which converts matter excitations into photons is suppressed.

Dynamical regimes

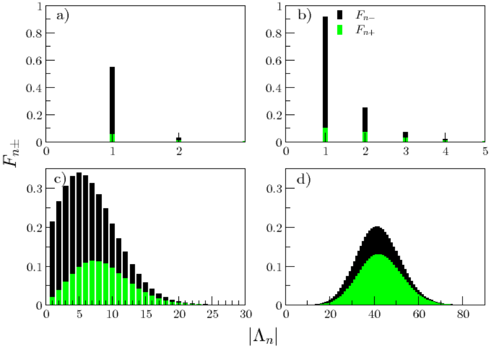
iii) $g \ggg P, \kappa, \Delta$. The long-time density matrix becomes (almost) diagonal in the basis of bare states $|G/X, n\rangle$. The larger the coupling g the smaller the difference of the populations of $|G, n\rangle$ and $|X, n-1\rangle$ ($\propto 1/g^2$). The coherences $|\rho_{Gn,Xn-1}|$, which decay as $1/g$, also vanish as the coupling g increases.

We conclude that in the regime $|\Delta| \sim g \gg P, \kappa$, the steady state of the system is expected to exhibit a polaritonic behavior.

The “optimum” polariton

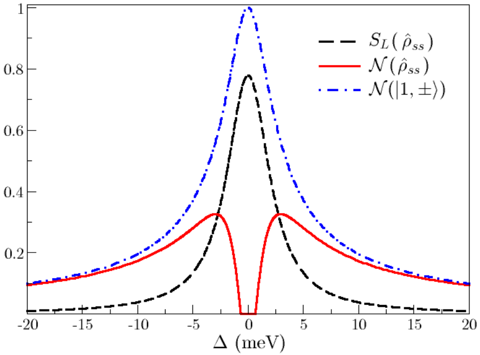
The steady state $\hat{\rho}_{ss}$ is compared with the polariton states $|n,\pm\rangle$ using the sequence of fidelities

$$F_{n\pm} = \sqrt{\langle n,\pm|\hat{\rho}_{ss}|n,\pm\rangle}$$

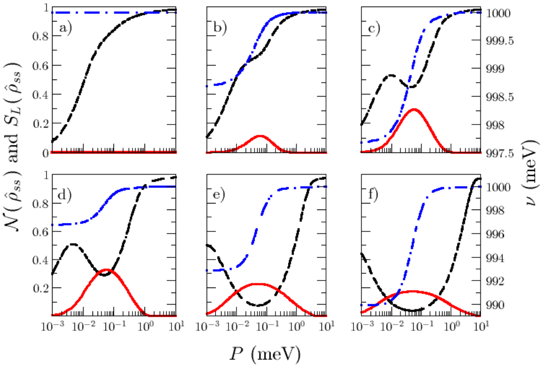


Quantum properties of the steady state

Mixedness and matter–light entanglement of the steady state.

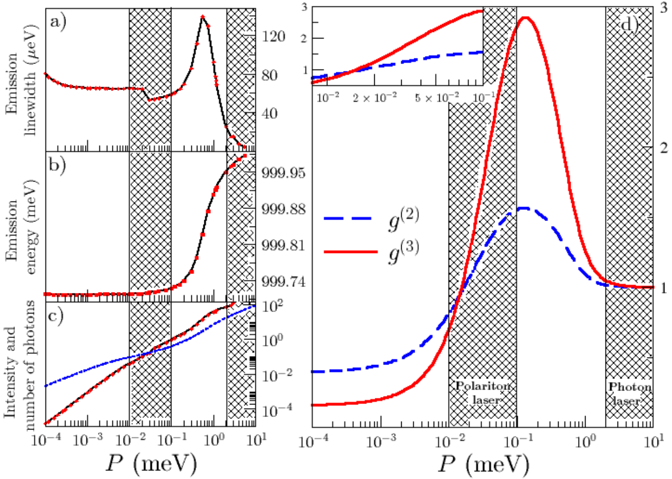


Resonance is not the better choice!



$\mathcal{N}(\hat{\rho}_{ss})$ (red line), $S_L(\hat{\rho}_{ss})$ (black line) and ν (blue line) as functions of P, for (a) $\Delta = 0$, (b) $\Delta = 1$ meV, (c) $\Delta = 2$ meV, (d) $\Delta = 3$meV, (e) $\Delta = 7$ meV and (f) $\Delta = 10$ meV.

Photoluminescence



Conclusions

1. We stress that the mesoscopic regimes identified through the characteristics of the emitted light, mirror quantum properties of the system state. We describe those quantum properties by entanglement and mixedness of the steady state.
2. The "optimum" polariton exhibits maximum negativity, minimum linear entropy, and an inflection point of the differential energy per excitation, provided that the system is in strong coupling.
3. Polaritons cannot be sustained neither for small nor for large detunings.