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Indirect strong coupling regime between a quantum emitter and a cavity mediated by a mechanical resonator

J.E. Ramírez-Muñoz *, J.P. Restrepo Cuartas, H. Vinck-Posada

Universidad Nacional de Colombia – Sede Bogotá, Facultad de Ciencias, Departamento de Física, Carrera 45 No. 26-85, C.P. 111321, Bogotá, Colombia

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A B S T R A C T

Achieving strong coupling between light and matter is usually a challenge in Cavity Quantum Electrodynamics (cQED), especially in solid state systems. For this reason is useful taking advantage of alternative approaches to reach this regime, and then, generate reliable quantum polaritons. In this work we study a system composed of a quantized single mode of a mechanical resonator interacting linearly with both a single mode cavity and a quantum two-level system. In particular, we focus on the behavior of the indirect light-matter interaction when the phonon mode interfaces both parts. By diagonalization of the Hamiltonian and computing the density matrix in a master equation approach, we evidence several features of strong coupling between photons and matter excitations. For large energy detuning between the cavity and the mechanical resonator it is obtained a phonon-dispersive effective Hamiltonian which is able to retrieve much of the physics of the conventional Jaynes–Cummings model (JCM). In order to characterize this mediated coupling, we make a quantitative comparison between both models and analyze light-matter entanglement and purity of the system leading to similar results in cQED.

1. Introduction

In the last decades solid state systems have been widely used as a platform to interface light with matter in the cavity and circuit quantum electrodynamics (cQED) frames [1–3]. This opens the route towards quantum computation and quantum information processing devices [4–6]. Different regimes of light-matter interaction have been studied and each of them are useful to play some role in current technologies. On the one hand, weak coupling between light and matter can be used to generate single-photons on-demand; on the other hand, strong coupling regime is exploited to transfer quantum information between light and matter and perform quantum logic operations. Additionally, the control over the light-matter interaction rate and the spontaneous emission decay are a desired feature in order to achieve versatility and efficiency.

Since strong coupling between a quantum emitter and a cavity is difficult to achieve in many cQED systems due to fabrication issues and incoherent processes [7–9], it is really useful taking advantage of other mechanisms that allow to reach this regime. Mechanical modes of semiconductor structures, surface acoustic waves (SAW) and micro/nanomechanical resonators in superconducting circuits are now used to handle the properties of artificial atoms and cavities in the optical and microwave regimes [10–13]. Usually, the interaction of quantized mechanical modes with quantum emitters and electromagnetic cavities are modeled with electromechanical [14,15,13] and optomechanical [16–18] Hamiltonians, respectively. Large optomechanical and electromechanical coupling rates have been achieved in different systems, particularly in superconducting circuits [12,18,19] and semiconductor nanostructures [20,21].

Furthermore, it is well known that linear coupling between cavity and mechanical resonators raises in the so-called *resolved side-band regime* [17,22,23], i.e., when phonon energy is larger than the cavity decay rate ($\omega_m > \kappa$), in that regime the cavity is pumped by a large coherent field. In addition, there has been recently proposed a coherent field-mediated emitter-phonon linear coupling produced by variations of the spatial distributions of the cavity field [12,24,25]. The aim of this work is to study alternative models in polariton cavity optomechanics, different from the standard hybrid optomechanical Hamiltonians in the dispersive regime [13, 26–29]. This alternative way is exploited to obtain an enhancement of the light-matter coupling rate and its quantum features such as entanglement which is a key resource for quantum information operations [30–33].

The rest of the paper is organized as follows, in section 2 we set the theoretical model for the tripartite cavity-emitter-mechanics system. Then, in section 3, by diagonalization of the Hamiltonian we discuss the possibility of achieving strong coupling regime me-

* Corresponding author.
E-mail address: jeramirezm@unal.edu.co (J.E. Ramírez-Muñoz).

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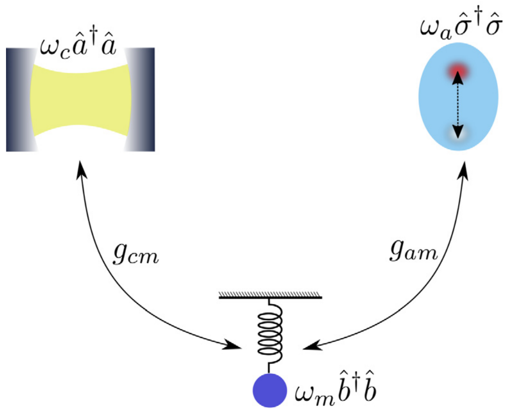

Fig. 1. Sketch of the hybrid cQED-optomechanical system [26]. Linear coupling is assumed between the cavity and the mechanical resonator, and also between the two-level system and the mechanical resonator. Throughout this work there is no direct interaction between the cavity and the two-level system.

diated by phonons and study the dispersive limit of the Hamiltonian. In section 4, using the density operator in the steady state we quantify light-matter entanglement and linear entropy, and show the tomography in different important situations. Finally, in section 5 we make and overview and conclude.

2. Theoretical framework

As stated above, the tripartite system in Fig. 1 is typically modeled with optomechanical and electron-phonon dispersive interactions. However, we will alternatively use an approximate Hamiltonian; linear coupling between different parts of the system as is justified in the appendix A. Here, we do not consider light-matter interactions directly. Thus, the Hamiltonian is:

$$\hat{H} = \hat{H}_0 + \hat{H}_{int} \tag{1}$$

with

$$\hat{H}_0 = \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar\omega_a\hat{\sigma}^\dagger\hat{\sigma} + \hbar\omega_m\hat{b}^\dagger\hat{b}, \tag{2}$$

and

$$\hat{H}_{int} = \hbar g_{cm}\left(\hat{a}\hat{b}^\dagger + \hat{a}^\dagger\hat{b}\right) + \hbar g_{am}\left(\hat{\sigma}\hat{b}^\dagger + \hat{\sigma}^\dagger\hat{b}\right). \tag{3}$$

ω_c, ω_a and ω_m are the cavity, emitter and mechanical frequencies, respectively. $\hat{a}$ ($\hat{a}^\dagger$) and $\hat{b}$ ($\hat{b}^\dagger$) are the annihilation (creation) bosonic operators for photons and phonons, respectively. $\hat{\sigma} = |G\rangle\langle X|$ is the atomic ladder operator for the two-level system (TLS). The parameters g_{cm} and g_{am} are the optomechanical coupling strength and the atom-phonon coupling strength, respectively.

Losses and decoherence arise in the system when it is affected by its environment. These are effectively considered in a master equation approach for the density operator in the Markov approximation [34,35]:

$$\frac{d\hat{\rho}}{dt} = \frac{i}{\hbar}\left[\hat{\rho}, \hat{H}\right] + \kappa\mathcal{L}_{\hat{a}}(\hat{\rho}) + P_X\mathcal{L}_{\hat{a}^\dagger}(\hat{\rho}), \tag{4}$$

where κ is the cavity decay rate and P_x is an incoherent excitation to the quantum emitter. The Lindblad term for the operator representing a dissipative channel, $\hat{C}$, is defined as $\mathcal{L}_{\hat{C}}(\hat{\rho}) = \hat{C}\hat{\rho}\hat{C}^\dagger - \frac{1}{2}\hat{C}^\dagger\hat{C}\hat{\rho} - \frac{1}{2}\hat{\rho}\hat{C}^\dagger\hat{C}$.

Throughout this work, we assume high mechanical coupling rates, $\omega_a/g_{am} \approx \omega_c/g_{cm} \approx 50$, which could be obtained taking advantage of large coherent driven as is shown in the appendix A.

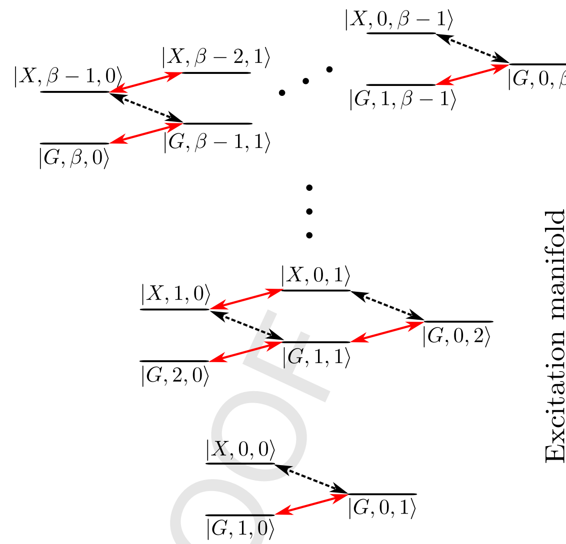

Fig. 2. States ladder of the Hamiltonian. Black-dashed arrows represent exciton-phonon interactions (g_{am}) and the red ones correspond to photon-phonon interactions (g_{cm}). A β-excitation manifold has $2\beta + 1$ states $\{|G, \beta-k, k\rangle, |X, \beta-k-1, k\rangle\}$, $k = 0, 1, \ldots, \beta - 1$. (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

As we will see, the ratio ω_c/g_{cm} is a key parameter to set validity regimes of the phenomena explored. While mechanical frequencies considered here are out of resonance with cavity frequencies ($\omega_c/\omega_m = 10$), cavity and atom frequencies are close each other, i.e. $|\Delta| = |\omega_a - \omega_c| < g_{am}$. We perform all computations in units of g_{cm} and assume $g_{cm} = g_{am} = g_m$. These parameters are not far from experimental works, for example, in the context of circuit QED [13,18] parameter ratios have been achieved as follows $\omega_c/g_m \approx 190$, $\omega_c/\omega_m \approx 67$ and $\omega_m/g_m \approx 3$.

3. Indirect light-matter strong coupling regime

Strong coupling between quantum emitters and photonic modes is a hard feature to achieve; usually it requires high control in the positioning of the quantum emitters inside the cavity, small field modal volume and high quality factor. However, indirect mechanism can be harnessed to reach the vacuum Rabi splitting regime such as coupling to an auxiliary photon cavity [36] or coupling to a mechanical resonator which is the goal of this work. We consider a quantized mechanical mode interacting simultaneously with both the cavity and emitter in a linear way according to equation (3). Since the Hamiltonian commutes with the total number operator ($N = \hat{a}^\dagger\hat{a} + \hat{\sigma}^\dagger\hat{\sigma} + \hat{b}^\dagger\hat{b}$), then it can be diagonalized for each excitation manifold as shown in Fig. 2.

By numerical diagonalization of the Hamiltonian in a large energy detuning regime between cavity (emitter) and mechanical oscillator, is found that the eigenstates of the system are separable in a polariton state and a phonon Fock state: $\left|\psi_n^\ell\right\rangle \approx |n\pm\rangle \otimes |\ell\rangle$. From here on, polariton in this context will be understood as a *phonon-induced polariton* (PIP). Moreover, similarly to the Jaynes–Cummings model, the dispersion diagram exhibits anticrossing between two dressed states; the upper and lower polaritons, $|n+\rangle \otimes |\ell\rangle$ and $|n-\rangle \otimes |\ell\rangle$. Each polariton is a superposition of light-matter bare states: $|n\pm\rangle = \cos\theta_n |G, n\rangle \pm \sin\theta_n |X, n-1\rangle$, where θ_n depends on the system parameters and photon number. This situation is illustrated in the Fig. 3 for the third-excitation manifold.

In the limit of large cavity-photon detuning [37], ($|\Delta_c| = |\omega_c - \omega_m| \gg 1$) and close to the emitter-cavity resonance ($\omega_a \approx \omega_c$), as

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