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# QUANTUM BEHAVIORS OF OPTICAL AND OPTOMECHANICAL SYSTEMS POSSESSING ARTIFICIAL ATOMS

**131.01 - MATHEMATICAL PHYSICS**

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## CONCEPTUAL GUIDELINES OF THE RESEARCH

### Actual research status:

The implementation of quantum information technologies, as well as various light based sensing and imaging applications, requires a good degree of control and manipulation of photon emission, propagation and detection phenomena. Artificial atoms possess some important features which make them good candidates for such technological implementations. Various types and architectures of artificial atoms allow one to engineer optical emitters with some particular characteristics suitable for a specific setup requirements. Especially in the framework of low-loss integrated quantum photonics circuits and on-chip realisation of optical setups, the technical aspects of a setup may impose important limitations and constraints. In this context, superconducting circuits and semiconductor artificial atoms, such as quantum-dots, have shown good efficiency as on-demand single-photon sources [1], which is a key ingredient for quantum information technologies.

Artificial atoms also possess several important differences from real atoms, as they interact with electrical signals and with the mechanical motion. Their optoelectrical and optomechanical couplings suggest various applications in optical sensing and metrology techniques, as well as, applications for hybrid quantum technologies as an interface for the integration of photonic devices into modern electronics. Moreover, their optomechanical coupling opens a new door to quantum confinement of the mechanical motion of matter at mesoscopic scales.

The optomechanical interactions become an important actor for nanoscale optical devices such as nanofibers, superconducting photon detectors, photonic crystal cavities and various photonic integrated circuits. At this size scales, the mechanical vibrations of the device intrinsically influence the quantum optical effects via the light radiation force. Reciprocally, the manipulation of the quantum mechanical motion can be achieved via optical control.

The implementation of artificial atoms into optomechanical devices introduces a completely new coupling regime between the optical and mechanical parts, as the effective optomechanical coupling strength is increased a few orders of magnitude [2]. Among various coupling schemes, quantum-dots embedded on different mechanical resonators possess a particularity to not require any additional electric or magnetic fields to couple to the mechanical motion. The intrinsic optomechanical coupling of the quantum-dot embedded on a crystal originates from the deformations of the quantum-dot which appear due to the mechanical vibrations of the crystal lattice.

Strong optomechanical coupling regimes can be explored to optically control the quantum state of the mechanical motion. Quantum optics dispose of a broad gamut of precise tools able to manipulate optomechanical setups. Unprecedentedly, this has allowed the preparation of various exotic quantum states of motion of matter at macroscopic scales. In this regard, important achievements have been reported in the recent years due to a continuous advance in the state-of-the-art techniques of engineering of optomechanical devices [2]. A single-phonon state has been observed in an optically cooled nanomechanical resonator [3]. Quantum squeezed states of mechanical motion had been successfully observed within a micrometer-scale mechanical resonator [4]. The acoustic analogue of the optical laser has been experimentally observed in various optomechanical setups based on electromechanical resonators [5], compound microcavities [6] or pumped ions [7]. Meanwhile, theoretical investigations suggest a large variety of phonon laser schemes, whereas setups based on quantum-dots embedded on quantum mechanical resonators have been described in [8, 9, 10]. A particular attention has been paid to identify optomechanical setups able to prepare the mechanical resonator in a pure quantum state. In this regard, remarkable optomechanical schemes had been identified for the generation of phonon fields with specific quantum statistics such as antibunching [10], negative Wigner function of the phonon states [11] and sub-Poissonian phonon distributions [12].

A major technological challenge to the implementation of artificial atoms into optical and optomechanical experiments arises when collective phenomena are considered. Collective effects often require the use of ensembles of identical emitters. Although this condition is easily validated by setups based on real atoms, in the case of artificial atoms there is a severe limitation in engineering quasi-identical artificial atoms. The current limitations of quantum-dot growth techniques are defined by the required high degree of resemblance in size and geometry of the quantum-dots. Moreover, the physics of collective phenomena also imposes additional restrictions to the spatial distribution of considered emitters, which becomes particularly challenging in the case of experimental setups based on quantum-dots.

A brilliant experimental realisation of a two-photon interference scheme has been reported in [13]. The considered setup is based on two separate quasi-identical quantum-dots with a high degree of resemblance. Remarkably, a different experiment based on Dicke collective states of closely-spaced quantum-dots has successfully reported the observation of superradiance effect [14].

**Objectives of the thesis:**

• Identification of various emitter-resonator coupling schemes related to different characteristic features of artificial atoms.

• Demonstration of the quantum statistics of an optical or mechanical resonator when interacting with an artificial atom.

• Identification of possible quantum interferences in systems possessing multi-level artificial atoms.

• Observation of the behaviour of the quanta distribution of a nanomechanical resonator under different interaction conditions.

• Demonstration of the influence of collective phenomena on the behaviour of an optomechanical system.

**Research hypothesis:**

Quantum systems based on artificial atoms possess distinctive features when compared those based real atoms. Quantum systems with unique properties can be identified when exploring the characteristics of the coupling of the artificial atoms with phonon and photon fields.

**Analytical methods:**

• The density matrix formalism has been adopted in order to apply the general reservoir theory to characterize the environmental damping phenomena required for the description of open quantum systems.

• The rotating wave approximations, the secular approximation, the dressed-state transformation, the perturbation theory and different changes of representations have been applied to the system dynamics in order to accurately reduce its complexity.

• The method of projecting the master equation into the system state basis has been applied in order to solve the system of equations for the modified density matrix elements.

• The method of building the equations of motion directly from the master equation has been applied in order to solve the system of equations describing the quantum dynamics.

• The method of factorization of high order correlations has been applied in order to reduce the complexity of systems of equations involving collective operators.

## CONTENT OF THE THESIS

**In the first Chapter** it is discussed various approaches of implementation of artificial atoms into modern nanoscale quantum optics. Important experimental realisations in cavity electrodynamics and optomechanical devices containing different types of artificial atoms are described. Various challenges, advantages and limitations related to specific types of artificial atoms and their integration into optical cavities and quantum mechanical resonators are discussed. The general discussion aims to give an overview on how optical and optomechanical nanoscale devices develop nowadays in order to define the framework of this thesis.

**In the second Chapter**, the general theoretical framework of the thesis is demonstrated and adapted to the following investigations. The fundamentals of the thesis rely on the theory of an emitter interacting with a quantum harmonic oscillator. One uses artificial atoms as emitters and considers their specific properties when compared to atoms. Namely, artificial atoms as quantum-dots may be deposed on different types of quantum mechanical resonators and interact with phonons in the good cavity limit. While other type of artificial atoms as quantum-wells allow to engineer their energetic levels to form an equidistant three-level emitter, which allows one to obtain strong quantum interferences when interacting with an optical resonator. The investigations following in the next chapters rely on the same fundamental theory, although each particular case requires a specific treatment. Therefore, this chapter regroups the fundamental physics of all the following investigations, in order to give the reader a clearer overview on the physical processes to be discussed.

The optical part of quantum systems is discussed in the first paragraph of this chapter. Both, optical and opto-mechanical setups are directly related to the quantum interaction of the emitter with an electromagnetic field. Moreover, damping processes as the spontaneous emission decay, which is omnipresent in quantum system with atomic-like emitters, may be fully explained only through the prism of the qubit-field interaction. All the necessary details for the description of a system interacting with an electromagnetic field are deduced and discussed and will be applied into the following chapters. The description of the laser pumping effect of a two-level quantum-dot, given in the Chapter 3, will rely on the semi-classical interaction. Also, Chapter 4 will require a fully quantum description of the interaction of the electromagnetic field with a quantum-well.

The mechanical part of opto-mechanical systems is treated in the second paragraph of the chapter. This type of treatment may affect both, the optical and the mechanical behaviour of such systems. The particularity of this treatment consists in considering the phonons as bosonic fields and, therefore, all the tools of the quantum optics theory will be applied in order to describe them. Although the phonons and the photons are treated as bosons from the analytical point of view, their physical meaning is completely different and requires a separate approach. The studies of quantum systems of Chapters 3 and 5, are focused on the investigation of the quantum statistics of the mechanical resonator phonons.

All quantum systems presented in the thesis are open quantum systems, where each of its elements, e.g., the artificial atoms, the phonons and the photons, are exposed to the damping effect of the surrounding environment. The photon leaking into the electromagnetic vacuum, the thermal phonon surroundings or the spontaneous emission of the artificial atoms are described and defined in the third paragraph of the chapter. For each type of damping mechanics, one applies the general reservoir theory for the specific type of interaction.

**In the third Chapter**, a system composed of an artificial atom placed on a quantum mechanical resonator is studied . The system dynamics is investigated for moderate strong couplings of the artificial atom with the mechanical vibrations. For these coupling regimes, the analytical approach requires a treatment beyond the secular approximation of the system Hamiltonian in the interaction picture. One identifies that within strong coupling regimes, the generated mechanical vibrations show pure quantum features as sub-Poissonian distribution of the vibrational quanta. Moreover, within the cooling configuration, the quantum cooling effect is enhanced for this regime.

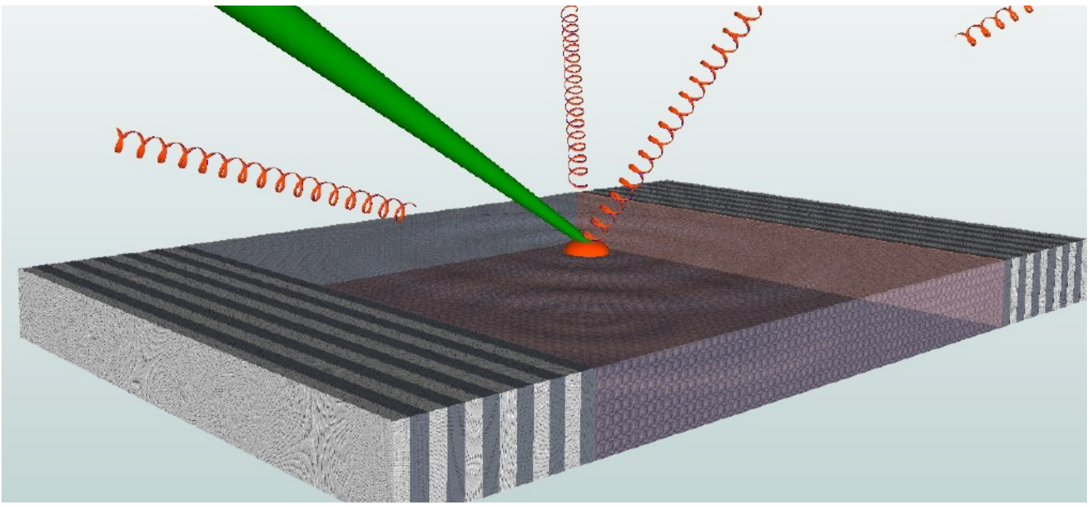

Fig. 1: The schematic of the investigated model: A two-level quantum-dot is embedded in a multilayered acoustical nanocavity. The quantum-dot is pumped near resonance with a coherent laser source and may spontaneously emit a photon.

One considers a model consisting of a driven two-level quantum-dot embedded in a mechanical resonator made of a multi-layered acoustical nano-cavity. In Fig.1 one shows how the quantum-dot is pumped by an intense laser field and interacts with cavity single-mode phonon field. This setup allows the cavity phonons to be created or annihilated depending on the chosen laser-quantum-dot detuning. The physics of this processes is explained as follows. The excitation of the quantum-dot corresponds to the formation of an exciton (electron-hole) localized within the quantum-dot. The interaction of the exciton charge with the deformation of the lattice is described via the deformation potential. Therefore, for a detuned laser, Raman-type transitions occur.

For a blue-detuned laser, i.e., when the laser is set above the resonance frequency, the laser excitation leads to the creation of an exciton and phonons in the cavity through anti-Stokes-type transitions. This scheme does not lead to steady-state generation of phonons because the created phonons are annihilated when the transition occurs in the opposite sense. This is valid as long as one does not consider the interaction of the quantum-dot with the surrounding electromagnetic vacuum, i.e., the quantum-dot spontaneous decay phenomenon. The last one, gives another possibility to the quantum-dot to decay, but this time without annihilating the mechanical vibrations. If considering both decay mechanisms, the system generates phonons but their field is infinitely increased as long as the mechanical resonator is considered perfect, i.e., no damping phenomena are introduced. Therefore, a third effect is introduced in order to describe a realistic system, which is the cavity damping by a thermal environmental reservoir. Thus, the leaking effect of the cavity will not allow the vibrational quanta to cumulate infinitely.

The investigated dynamics is determined from the system Hamiltonian and the master equation which also includes the surrounding damping phenomena. The model consists of a pumped two-level quantum-dot described by the transition frequency $\omega_{qd}$ between its excited state $|e\rangle$ and ground state $|g\rangle$. The atomic operators are defined as $S^{+} = |e\rangle\langle g|$, $S^{-} = |g\rangle\langle e|$, $S_z = (|e\rangle\langle e| - |g\rangle\langle g|)/2$ and obey the standard commutation relations of the SU(2) algebra. The laser pumping effect is expressed via a semi-classical interaction term described by the laser of frequency $\omega_L$ and the Rabi frequency $\Omega$. The quantum-dot is embedded on a mechanical resonator of frequency $\omega_{ph}$, which is described via the bosonic annihilation and creation operators, $b$ and $b^{\dagger}$ respectively. The interaction of the quantum-dot with the quantum mechanical resonator is described via the coupling constant $g$. The system Hamiltonian $H$ is built as:

$$H = \hbar\omega_{qd}S_z + \hbar\omega_{ph}b^{\dagger}b + \hbar\Omega(S^{+}e^{-i\omega_L t} + e^{i\omega_L t}S^{-}) + \hbar g S^{+}S^{-}(b^{\dagger} + b). \tag{1}$$

The master equation of the system density matrix operator $\rho$, is formed from the Liouville-von Neumann equation together with the damping terms describing the quantum-dot's spontaneous emission decay defined by the rate $\gamma$, the dephasing effect defined by the rate $\gamma_c$ and the resonator's phonon field damping and pumping effects resulting from its interaction with a thermal environment at a damping rate $\kappa$. The thermal reservoir is described by the mean phonon number $\bar{n} = 1/\left[\exp\left(\hbar\omega_{ph}/k_B T\right) - 1\right]$, where $k_B$ is the Boltzmann constant and $T$ denotes the environmental temperature.

$$\frac{\partial \rho}{\partial t} = -\frac{i}{\hbar}[H, \rho] + \kappa(1+\bar{n})\mathcal{L}(b) + \kappa\bar{n}\mathcal{L}(b^\dagger) + \gamma\mathcal{L}(S^-) + \gamma_c\mathcal{L}(S_z), \quad (2)$$

where the damping effects are expressed by the Liouville superoperator $\mathcal{L}$, which acts on a given operator $\mathcal{O}$ as $\mathcal{L}(\mathcal{O}) = 2\mathcal{O}\rho\mathcal{O}^\dagger - \mathcal{O}^\dagger\mathcal{O}\rho - \rho\mathcal{O}^\dagger\mathcal{O}$.

In what follows, the system dynamics is determined by projecting the master equation within the quantum-dot-phonon state basis. This leads to a system of coupled equations that may be numerically solved since the properties of the physical model allow the system to be truncated. A series of transformations is applied in order to bring the master equation to a solvable form without loosing the generality of the investigation. More precisely, the system dynamics is solved by applying the dressed-state transformation to the quantum-dot state basis and then, in the interaction picture, one focusses on simplifying the Hamiltonian and different master equation terms.

In this representation, one is able to distinct different resonator-quantum-dot interaction terms rotating at different frequencies. Considering the phonon frequency $\omega_{ph}$ and the generalized Rabi frequency $\bar{\Omega} = \sqrt{\Omega^2 + (\Delta/2)^2}$ of same order, one separates the slow-rotating terms of the Hamiltonian from the fast-rotating ones. Furthermore, as long as $g \ll \omega_{ph}, \bar{\Omega}$, one may neglect the fast terms via a secular approximation [15, 16]. This condition applied on the quantum-dot-phonon coupling strength $g$ defines the weak coupling regime. When the coupling constant $g$ is increased closer to the magnitudes of $\omega_{ph}$ and $\bar{\Omega}$, the contribution of the fast-terms to the system dynamics continues to be small, however it cannot be completely neglected all the time. In this case, one may treat their contribution as a first order perturbation [17, 18]. One refers to this coupling regime as a strong coupling regime, although one will further consider only moderate strong coupling constants in order to justify the perturbative treatment of first order.

The final Hamiltonian is defined as a sum of the slow-rotating terms $H_{slow}$ and the first-order contribution of the fast-rotating terms $H^{eff}_{fast}$, namely:

$$\begin{aligned} H &= H_{slow} + H_{fast}^{eff}, \\ H_{slow} &= \hbar(\omega_{ph} - 2\bar{\Omega})b^\dagger b - \hbar g \frac{\sin(2\theta)}{2}\left(b^\dagger R^- + R^+ b\right), \\ H_{fast}^{eff} &= -\hbar\bar{\Delta} R_z + \hbar\beta b^\dagger b R_z, \end{aligned} \tag{3}$$

where, $\theta = \arctan(2\Omega/\Delta)/2$, $\Delta = \omega_{qd} - \omega_L$. The new set of atomic operators given in the dressed-state basis $\{|+\rangle, |-\rangle\}$ is defined as $R^\pm = |\pm\rangle\langle\mp|$, $R_{\pm\pm} = |\pm\rangle\langle\pm|$, $R_z = R_{++} - R_{--}$. The contribution of the fast terms is defined by the constants:

$$\bar{\Delta} = \frac{g^2}{2}\left(\frac{\cos(2\theta)}{\omega_{ph}} - \frac{\sin^2(2\theta)}{4(\omega_{ph} + 2\bar{\Omega})}\right) \quad \text{and} \quad \beta = g^2 \frac{\sin^2(2\theta)}{4(\omega_{ph} + 2\bar{\Omega})}. \tag{4}$$

Note that for $g \ll \omega_{ph}, \bar{\Omega}$, one has $\{\bar{\Delta}, \beta\} \simeq 0$ similarly to the case of a secular approximation.

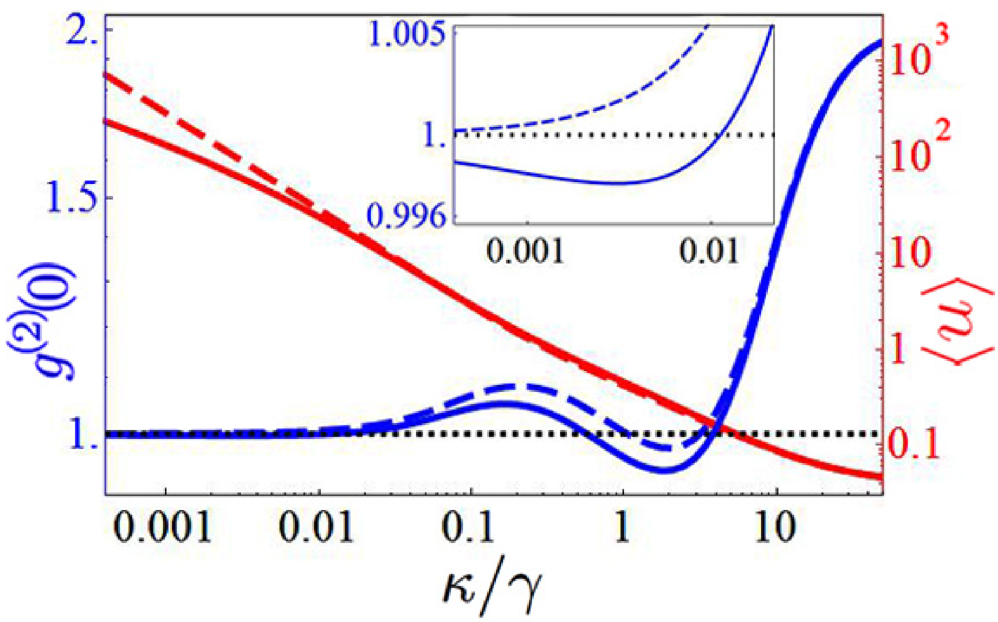


Fig. 2: The phonon statistics given by the second-order correlation function $g^{(2)}(0)$ represented in blue curves and the mean phonon number $\langle n \rangle$ plotted in red curves, as functions of the normalized cavity damping rate $\kappa$. The beyond the secular approximation treatment is given in continuous curves, whereas the dashed curves represent the treatment within the secular approximation [$5^a$].

The most distinctive aspect of the current theoretical model consists in the implementation of a perturbation treatment. This method allows one to go beyond a traditional secular approximation and consider the regime of moderate strong couplings where the fast terms may be treated as a perturbation of the system Hamiltonian, instead of being definitively neglected. In order to highlight the contribution of the fast terms to the system dynamics, the current model is compared to a similar model where a secular approximation was applied. Fig.2 shows the phonon statistics for the two different models, i.e., the one that goes beyond the secular approximation (continuous curves) and the other treated within the secular approximation (dashed curves). The second order correlation function $g^{(2)}(0)$ is represented in blue lines and the mean phonon number $\langle n \rangle$ in red lines. The other system parameters are $2\Omega/\gamma = 25$, $\Delta/(2\Omega) = -0.7$, $\bar{n} = 0.04$, $\gamma_c/\gamma = 0.1$, $g/\gamma = 15$ and $\omega_{ph}/\gamma = 35$.

One observes that the estimated second-order correlation functions in both cases converge for higher and smaller cavity damping rates. Although both models predict $g^{(2)}(0) \simeq 1$ for lower values of $\kappa/\gamma$, the quantum features are proper only beyond the secular approximation. The inset of Fig.2 gives a close look on how the second-order correlation function converges to a quasi-coherent field in the weak damping regime, in the region around $10^{-3} \leq \kappa/\gamma \leq 10^{-2}$. This is the region of interest as within this damping regime a significant number of phonons are generated. The secular approximation model predicts a classical field as its distribution is always a bit larger than the Poissonian, i.e., one observes $g^{(2)}(0) > 1$ while asymptotically converging. On the contrary, the treatment beyond the secular approximation predicts a similar quasi-coherent phonon distribution, but with $g^{(2)}(0) < 1$. Thus, only in the beyond the secular approximation model, quantum features of the phonon field may be revealed. Moreover, for the weak damping regime, a significant change in the estimation of the mean phonon number $\langle n \rangle$ is introduced by the model beyond the secular approximation.

**In the fourth Chapter**, the case when a three-level equidistant ladder-type quantum-well is placed in an optical cavity is investigated. As shown in Fig.3, the quantum-well is pumped via two lasers with different phases. Each laser is applied resonantly on one of the two quantum-well transitions. Under the laser driving, the energetic levels of the quantum-well are subject to the dynamical Stark splitting effect. Various transitions with different transition frequencies appear among the split energy levels. In the case of driven two-level emitter, one observes three different transitions in the emitter emission spectra called the Mollow triplet. The Mollow triplet is made of a central peak corresponding to the free emitter transition energy and two sidebands equally shifted on both sides of the central peak. In the case of a driven three-level emitter even more sidebands appear. In this research, one has considered an equidistant three-level emitter. As both transitions occur at same frequency, the emission spectra of the laser driven quantum-well is made of a central peak and two pairs of sidebands.

As the quantum-well architecture has equidistant energy levels and orthogonal transition dipoles,

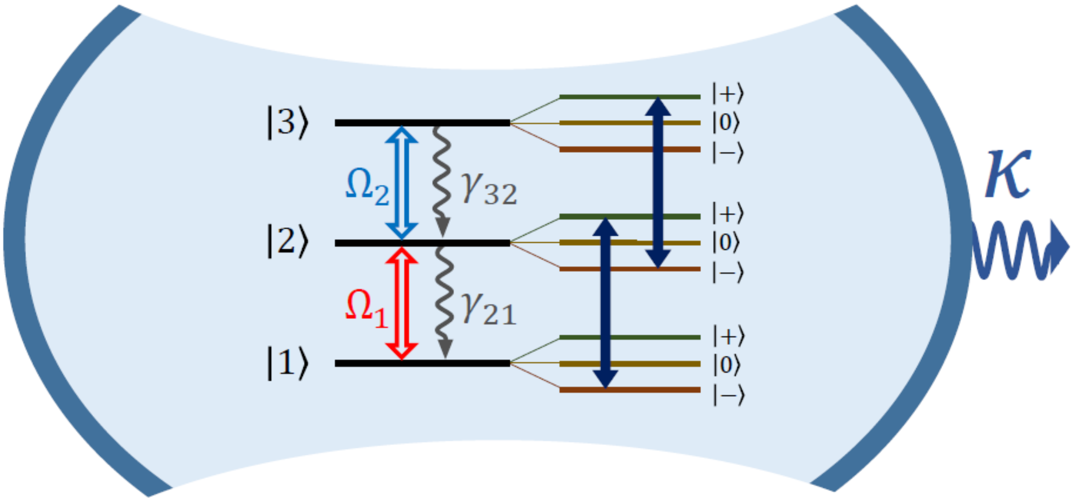


Fig. 3: Schematic of the model. A three-level quantum-well, placed in a leaking optical cavity, interacts with external coherent fields with $\Omega_{2,1}$ being the corresponding Rabi frequencies. $\gamma_{32}$ and $\gamma_{21}$ are the respective spontaneous emission decay rates. The full arrows depict the dressed-state transitions in resonance with the cavity mode frequency leading to cavity quantum interference phenomena.

the optical cavity couples to both of the emitter transitions in the good cavity limit. As under the laser pumping the quantum-well is prepared in a superposition of states, the cavity indistinguishably interacts with the upper and lower transitions. These indistinguishable amplitudes of the cavity interaction with different quantum-well transitions lead to the interference effect. In order to solve the system dynamics, one was able to significantly reduce the complexity of the quantum dynamics without loosing much of generality of the problem by successively tuning the cavity in resonance with one of the frequencies of the emitter's spectra.

As the interaction amplitudes may be influenced by laser intensities and phases, one is able to achieve strong destructive quantum interferences. Therefore, the cavity field may be emptied for a well-chosen laser phase difference as the laser phases are transferred to the interactional amplitudes. In this case, the pumped quantum-well spontaneously decays in all directions except the cavity. Furthermore, this behaviour of the interfering quantum-well-cavity system is associated with a quantum switch, where the income laser signals may switch the cavity field on and off by varying their phase difference and intensity.

The quantum-well is described by its bare-states $|i\rangle$, $\{i = 1, 2, 3\}$ and their corresponding energies $\hbar\omega_i$. The atomic operators of the three-level emitter are defined as $S_{ij} = |i\rangle\langle j|$, $\{i, j = 1, 2, 3\}$ and obey the commutation rule $[S_{\alpha,\beta}, S_{\beta',\alpha'}] = \delta_{\beta,\beta'}S_{\alpha,\alpha'} - \delta_{\alpha',\alpha}S_{\beta',\beta}$. The highest energetic level $|3\rangle$ may spontaneously decay to the intermediate level $|2\rangle$ with a emission rate $\gamma_{32}$, while the last one decays to the ground level $|1\rangle$ with a rate $\gamma_{21}$.

The system Hamiltonian, in its general form, is defined as:

$$\begin{aligned}
H &= \hbar\omega_c a^\dagger a + \hbar\sum_{i=1}^{3}\omega_i S_{ii} + i\hbar g_1(a^\dagger S_{12} - S_{21}a) + i\hbar g_2(a^\dagger S_{23} - S_{32}a) \\
&+ \hbar\Omega_1(S_{21}e^{-i(\omega_{L1}t+\phi_1)} + S_{12}e^{i(\omega_{L1}t+\phi_1)}) \\
&+ \hbar\Omega_2(S_{32}e^{-i(\omega_{L2}t+\phi_2)} + S_{23}e^{i(\omega_{L2}t+\phi_2)}). \qquad (5)
\end{aligned}$$

The pumping of the quantum-well is performed by applying different lasers for each atomic transition. The laser driving the lower transition is described by its frequency $\omega_{L1}$ and phase $\phi_1$, while the laser applied on the upper transition is given by $\omega_{L2}$ and $\phi_2$. The quantum-well pumping is described via semi-classical interactions given by the Rabi frequencies $\Omega_1$ and $\Omega_2$ for the lower and upper transitions, respectively. The cavity-quantum-well fully quantum interaction is expressed via two separate Hamiltonian terms, one for each of the transitions. The corresponding terms are described by the coupling constants $g_1$ and $g_2$. The first coupling constant represents the quantum interaction of the optical resonator with the lower transition, while the second one - with the upper transition. The quantized cavity field is defined by its frequency $\omega_c$ and the bosonic creation operator $a^\dagger$ and annihilation operator $a$.

The system quantum dynamics is described by the master equation for the density operator $\rho$ as:

$$\frac{\partial\rho}{\partial t} = -\frac{i}{\hbar}[H,\rho] + \frac{\kappa}{2}\mathcal{L}(a) + \frac{\gamma_{32}}{2}\mathcal{L}(S_{23}) + \frac{\gamma_{21}}{2}\mathcal{L}(S_{12}), \qquad (6)$$

where the first term represents the coherent part based on the von-Neumann equation, while the other terms describe the damping phenomena. The second term of the equation represents the cavity photon leaking term, which appears due to the interaction of the optical resonator with environmental electromagnetic vacuum. The last two terms represent the spontaneous emission of the two excited states, with two different rates corresponding to each of the transitions of the quantum-well. In the case of a multi-level atomic structure, as in our case, the reservoir theory may be applied to each transition separately. Therefore, the spontaneous decay dynamics will be defined by separate damping terms adapted for each of the possible decay transitions.

Similarly to the previous chapter, the master equation is too complex to be directly solved. Therefore, a series of changes of representation according to different rotating frames is done in order to apply the dressed-state transformation for a three-level emitter. Within the dressed state basis and within the interaction representation, one is able to distinct various cavity-quantum-well interaction terms rotating at different frequencies according to various possible transitions among the dressed states. This allows one to significantly simplify the system Hamiltonian by tuning the optical cavity in resonance with one of the possible transitions of the pumped quantum-well. The resonance case would allow one to keep only the resonant interaction term and neglect other interactions via a secular approximation. The simplified Hamiltonian shall accurately describe the quantum dynamics within the adopted secular approximation as long as $g_{1,2}/\Omega \ll 1$, where the generalised Rabi frequency is defined as $\Omega = \sqrt{\Omega_1^2 + \Omega_2^2}$. In what follows one will study separately each of the possible resonant cases.

A first case to discuss represents the cavity tuned in resonance with one of the external sidebands. The dynamics and the results are similar when the cavity is tuned with either the most or the less energetic external sideband, i.e., when $\omega_c = \omega_L + 2\Omega$ or $\omega_c = \omega_L - 2\Omega$, respectively. When tuning the cavity as $\omega_c = \omega_L + 2\Omega$, the dressed-state Hamiltonian is reduced to:

$$H \;=\; i|g|\left(a^\dagger R_{-+}e^{i\psi} - e^{-i\psi}R_{+-}a\right), \quad \text{where} \quad g = \frac{1}{2}(g_2 e^{-i\phi_2}\sin\theta - g_1 e^{-i\phi_1}\cos\theta), \quad (7)$$

$\psi = \arg(g)$ and $\theta = \arctan(\Omega_2/\Omega_1)$.

The obtained Hamiltonian is similar to the Jaynes-Cummings model of a two-level atom interacting with a cavity with an effective coupling $g$. This effective coupling originates from the quantum interference of the two dressed-state transition amplitudes, contributing to the pumping of the cavity mode by the quantum-well. Note that the effective coupling vanishes when the two terms defining the expression of $g$ become equal, i.e., $g_1/g_2 = \Omega_2/\Omega_1$, and in-phase, i.e., $\phi_2 = \phi_1 + 2\pi m, m \in \mathcal{Z}$.

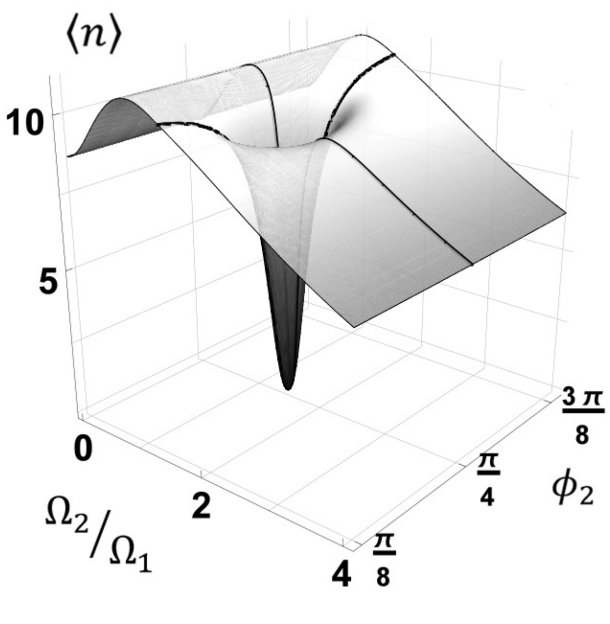


Fig. 4: The cavity mean photon number $\langle n \rangle$ as function of Rabi frequencies ratio $\Omega_2/\Omega_1$ and the laser phase $\phi_2$ whereas the other laser frequency is fixed at $\phi_1 = \pi/4$ [$2^a$].

The steady-state behaviour of the mean cavity photon number is shown in Fig.4, for a system defined by $g_1/\gamma_1 = 6$, $g_2/\gamma_1 = 4$, $\gamma_2/\gamma_1 = 2$ and $\kappa/\gamma = 10^{-3}$. One has fixed the phase of the laser pumping the lower frequency at $\phi_1 = \pi/4$ and has varied the phase of the laser pumping the upper transition $\phi_2$, as well as the ratio $\Omega_2/\Omega_1$. A dip in the photon number is clearly visible when the effective coupling $g$ vanishes. It is due to quantum interference effects having a destructive nature on the cavity field photons. The interference occurs because both dressed-state transitions of the atom are coupled to the cavity mode leading to indistinguishable interaction amplitudes. When the interaction amplitudes of these two couplings become equal and in-phase, the cavity field completely vanishes and the atom effectively decouples from the cavity field. In this case, the atom is pumped and spontaneously emits photons in all other directions, but there is no photon emission on the axis of the optical cavity.

A similar case of destructive quantum interference is achieved when the cavity is tuned with the central peak of the pumped quantum-well, i.e., when $\omega_c = \omega_L$. Note that although one sets here the cavity in resonance with the free quantum-well transition, the model still requires the laser pumping to be applied. For this case, the resonant Hamiltonian is obtained after neglecting the fast-terms as:

$$H = i|g|\left(a^\dagger e^{i\psi} - e^{-i\psi} a\right) R_z, \qquad g = \frac{1}{2}(g_1 e^{-i\phi_1}\cos\theta + g_2 e^{-i\phi_2}\sin\theta), \tag{8}$$

here $\psi = \arg(g)$.

As in the case of eq.(7), an effective coupling constant appears in the term of the resonant Hamiltonian. The difference with the previous case is that the laser phases have to be offset by $\pi$, i.e., in anti-phase, in order to obtain destructive interference phenomena. Namely, the effective coupling vanishes when the interaction amplitudes are equal, i.e., $g_1/g_2 = \Omega_2/\Omega_1$ and in anti-phase, i.e., $\phi_2 = \phi_1 + (2m+1)\pi, m \in \mathcal{Z}$. This condition is verified in Fig.5, where one shows the cavity mean photon number $\langle n \rangle$ as function of Rabi frequencies ratio $\Omega_2/\Omega_1$ and laser phase $\phi_2$, while keeping the phase of the laser pumping the lower transition at a fixed value of $\phi_1 = 0$. The other system parameters are $\gamma_{32} = \gamma_{21} = \gamma$, $g_1/\gamma = 4$, $g_2/\gamma = 2$ and $\kappa/\gamma = 10^{-3}$. The two deeps in the surface of $\langle n \rangle$ correspond well to the previously mentioned interference condition with $g_1/g_2 = \Omega_2/\Omega_1 = 2$ and $\phi_2 = \phi_1 + \pi$ or $\phi_2 = \phi_1 + 3\pi$. In these particular points, similarly to the deep of Fig.4, one observes an empty optical cavity due to the effective decoupling of the quantum-well from the cavity.

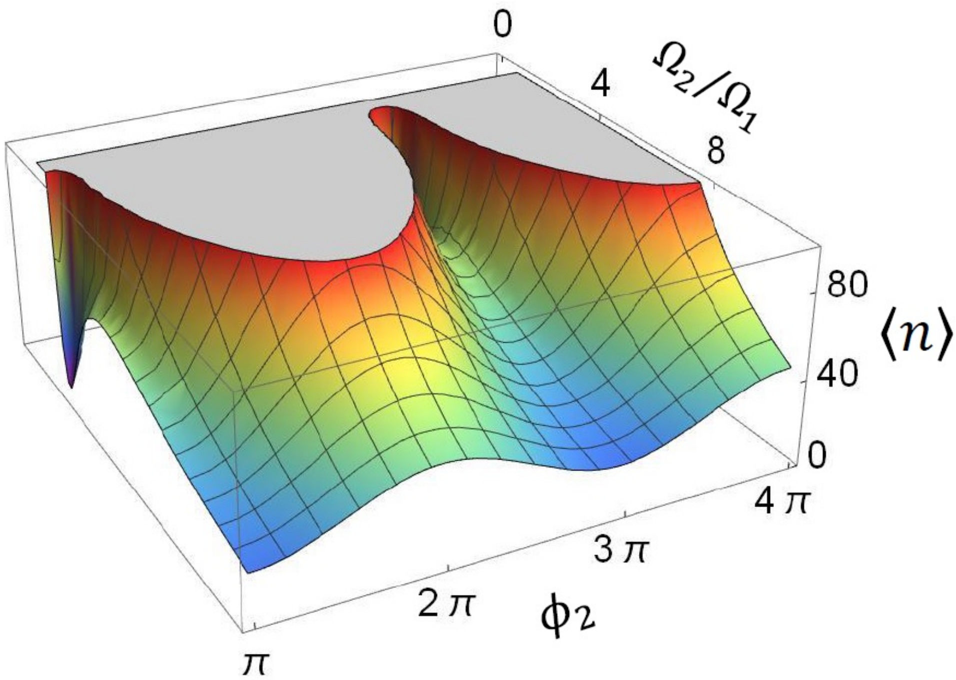


Fig. 5: The cavity mean photon number $\langle n \rangle$ as function of Rabi frequencies ratio $\Omega_2/\Omega_1$ and laser phase $\phi_2$, for a fixed value of $\phi_1 = 0$ [$8^a$]

**In the fifth Chapter**, a setup where collective radiative effects and nanomechanical motion are brought together, is considered. In particular, one envisions a model of a collection of initially excited two-level quantum-dots which are embedded on a nanomechanical resonator. The quantum-dots are spatially arranged to allow for a superradiant collective decay. The nanomechanical vibrations couple to the quantum-dots excited states, leading to a modified phonon dynamics. The system quantum dynamics is solved by considering a large number of emitters embedded on the mechanical resonator. This allows one to neglect some statistical fluctuations of high order correlation in the phonon-quantum-dot interactions.

The decay of the excited quantum-dots contributes to the phonon emission into the mechanical resonator. One of the features of the superradiant behaviour is the fast dynamics of the emitters' decay. One shows here that this feature is transferred to the mechanical resonator. Therefore, one observes that the resulting dynamics of the mechanical resonator has superradiant features in both the phonon emission time scales and the intensity of the generated phonon field. However, the intensity of the phonon emission is also subject to damping phenomena which appear due to the interaction of the resonator with the environmental temperature reservoir. In consequence, the superradiant behaviour of the photon emission intensity cannot be equivalenced with its phonon counterpart.

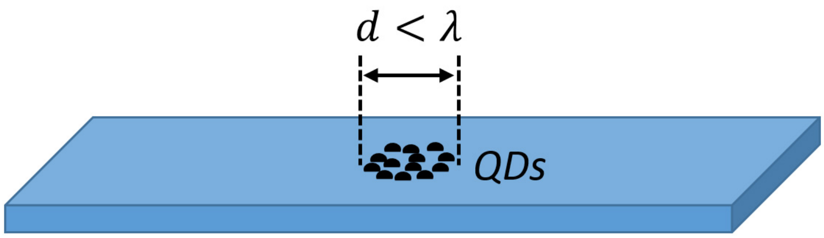


Fig. 6: Schematic of the model: An initially excited ensemble of two-level quantum-dots (QDs) is fixed on a vibrating nanomechanical resonator. The linear dimension $d$ of the sample is smaller than the relevant transition photon wavelength $\lambda$, *i.e.,* $d < \lambda$.

The model is made of a collection of $N$ initially excited two-level quantum-dots fixed on a vibrating membrane as shown in Fig.6. The membrane acts as a quantum harmonic oscillator vibrating at a frequency $\omega$. It is damped by an environmental thermal reservoir of temperature $T$. The mechanical oscillator couples to each quantum-dot of the sample in an equal manner, with a coupling constant $\eta$. At lower environmental temperatures one can consider the fundamental mechanical mode only. Therefore, one may treat the oscillator in the single-mode approximation, whereas other modes at different frequencies contribute weakly to the whole quantum dynamics. This is the case if the length $L$ of the nanomechanical resonator is considerably bigger than its width $l$ and thickness $a$ [19], i.e., $L \gg l \gg a$. For $L \sim 10^3$nm, $a \sim 30$nm and $l \sim 100$nm, one can still have a sufficient number of quantum-dots fixed on the nanomechanical resonator in order to obtain the superradiance effect, considering that the sizes of quantum-dots are approximately within few to several nanometres.

The system Hamiltonian is built as:

$$H = \hbar\omega b^\dagger b + \sum_{j=1}^{N} \hbar\omega_{\text{qd}} S_z^{(j)} + \sum_{j=1}^{N} \hbar\eta |e\rangle_{jj}\langle e|(b + b^\dagger). \tag{9}$$

The first term of $H$ is the membrane's free single-mode Hamiltonian, expressed via the phonon annihilation and creation operators $b$ and $b^\dagger$. The second term represents the free Hamiltonian of the quantum-dot sample, where $\omega_{\text{qd}}$ denotes the quantum-dot's transition frequency. In the second term, one has assumed that all quantum-dots are identical. Which allows one to represent the sum over all of the free individual quantum-dot Hamiltonian terms via the collective inversion operator of the quantum-dot sample expressed as $S_z = \sum_{j=1}^{N} S_z^{(j)}$. Here, the $j^{\text{th}}$ quantum-dot is described by its excited $|e\rangle_j$ and ground $|g\rangle_j$ levels. The corresponding single QD operators are $S_j^+ = |e\rangle_{jj}\langle g|$, $S_j^- = |g\rangle_{jj}\langle e|$, and $S_z^{(j)} = \big(|e\rangle_{jj}\langle e| - |g\rangle_{jj}\langle g|\big)/2$.

Finally, the last interactional term of the Hamiltonian represents the interaction of the quantum-dot sample with the phonon field. One has considered that the membrane's spatial scale is larger than the extent of the quantum-dot sample. Consequently, the coupling strengths of each quantum-dot with the vibrational degrees of freedom are identical and have the same magnitude $\eta$. This allows one to express the sum over each individual quantum-dot-membrane interaction via the the collective operator for the quantum-dots' upper state defined as $S_{22} = \sum_{j=1}^{N} |e\rangle_{jj}\langle e|$. Thus, after introducing the atomic collective operators in eq.(9), the system Hamiltonian is expressed as:

$$H = \hbar\omega b^\dagger b + \hbar\omega_{\rm qd} S_z + \hbar\eta S_{22}(b + b^\dagger). \tag{10}$$

The system dynamics is described by the master equation for the density matrix operator $\rho$. One is able to introduce the collective operators into the system master equation, as well [16]. The quantum dynamics equation is defined as:

$$\frac{\partial\rho}{\partial t} = -\frac{i}{\hbar}[H, \rho] + \kappa\bar{n}\mathcal{L}(b^\dagger) + \kappa(1+\bar{n})\mathcal{L}(b) + \gamma\mathcal{L}(S^-). \tag{11}$$

Here, as usually, the first term of the master equation represents the coherent evolution as given by the Liouville-von Neumann equation, whereas the second and the third terms, respectively, denote the pumping and the damping of the mechanical resonator via the environmental thermal reservoir. The last damping term characterizes the collective spontaneous emission from the sample of quantum-dots as a result of the interaction of the sample with the environmental electromagnetic vacuum field modes. This term is characterized by the spontaneous decay rate $\gamma$ and is expressed via the collective operator $S^{\pm} = \sum_{j=1}^{N} S_j^{\pm}$. By expanding the Liouville superoperator $\mathcal{L}(S^-)$ term, one observes that the collective spontaneous emission term does not simply contains the sum of the separate independent atomic spontaneous emission terms. It also contains the cross-atomic interactions which occur if one assumes that the spatial separation between different quantum-dots in the sample is much smaller than the quantum-dots' transition wavelength, i.e., a small-volume sample.

The system dynamics is solved from a system of equations of motion of parameters of interest. These equations of motion are built from the master equation. Namely, one investigates the temporal evolution of the membrane's mean phonon number $\langle n\rangle = \langle b^\dagger b\rangle$ and a system of equations of motion is built in order to estimate this evolution. One considers samples made of a large number of quantum-dots, i.e., $N \gg 1$, which allows the factorization of the higher-order correlations terms. One assumes that $\langle S_z^2\rangle \simeq \langle S_z\rangle^2$, which is equivalent to neglecting the fluctuations of the collective population inversion of the quantum-dot sample. This assumption does not break the symmetry of the system as there are no new variables introduced. The symmetry of the system of equations is also maintained if one chooses either $\langle S_z^2 b\rangle \simeq \langle S_z\rangle\langle S_z b\rangle$ or $\langle S_z^2 b\rangle \simeq \langle S_z\rangle^2\langle b\rangle$. Similarly, one proceeds with the $\langle S_z^2 b^\dagger \rangle$ term. Note that these two schemes are justified for larger quantum-dot ensembles and for larger phonon numbers [20]. Under these conditions, one verifies that both decoupling schemes lead to a similar result in the system quantum dynamics. After the factorization of the higher-order correlations terms, the system of equations of motion is closed and numerically solved.

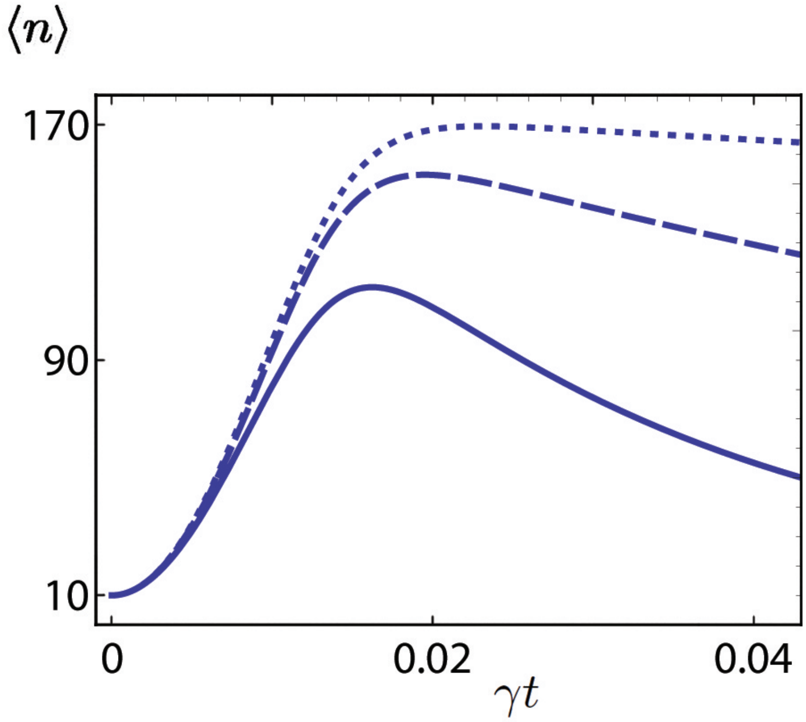


Fig. 7: Temporal evolution of the mechanical resonator's mean phonon number $\langle n \rangle$. Here, a collection of $N = 200$ quantum-dots is excited initially. The results are shown for different damping rates $\kappa$, *i.e.*, for $\kappa/\gamma = 1$ (dotted curve), $\kappa/\gamma = 5$ (dashed curve), and $\kappa/\gamma = 20$ (solid curve) [$3^a$].

In Fig. 7 one depicts how the phonon dynamics is affected by the collective effect within the quantum-dot sample. For this plot, the system is defined via the parameters $\omega/\gamma = 50$, $\eta/\gamma = 5$, and $\bar{n} = 10$. One initially excites the two-level quantum-dot sample with a short laser pulse of duration $\Delta t < 1/\eta$ in order to avoid the influence of vibrational phonons on the preparation stage. The other initial conditions are: $\langle S_z \rangle_{t=0} = j$, $\langle S_z b \rangle_{t=0} = 0$, $\langle S_z b^\dagger \rangle_{t=0} = 0$, $\langle b \rangle_{t=0} = 0$, $\langle b^\dagger \rangle_{t=0} = 0$, $\langle b^\dagger b \rangle_{t=0} = \bar{n}$.

A superradiant behaviour is observed in both: a reduced lifetime and an enhanced mean phonon number. This can be explained as follows. The membrane's vibrations interact with the quantum-dots' excited states and, therefore, the time scale for when phonons are created is related to the decay rate of the atomic sample. Then, when the quantum-dot sample approaches its collective ground state, the phonon dynamics become dominated by damping phenomena due to the environmental reservoir. Hence, the mean phonon number decreases to its initial value $\bar{n}$, characterizing equilibrium with the thermal reservoir. Further, the superradiance effect exhibits a bell-like behaviour for the collective intensity. However, the intensity does not simply scale as $N^2$ although one has a clear enhancing of phonon emission. Although the phonon superradiance is interconnected to the collective effects within the quantum-dot sample and, therefore, to the number $N$ of quantum-dots, the maximum mean phonon number is also determined by the damping rate $\kappa$. This can be seen in Fig. 7 as the superradiant phonon emission increases in width and maximum for weaker damping, i.e., for smaller $\kappa$, resembling a good or bad cavity limit, respectively.

## CONCLUSIONS AND RECOMMENDATIONS

The objectives of the thesis have been fulfilled and various quantum effects had been identified when studying the scientific problem of artificial atoms interacting with optical or mechanical resonators. Following the objectives, three distinct models had been proposed and investigated, each requiring a separate solving approach in order to accurately estimate the quantum dynamics. Namely, the investigation of different emitter-resonator coupling schemes had allowed the identification of two distinct cases. In the first case, a special treatment for moderately strong optomechanical couplings has allowed to identify quantum distributed quanta in the vibrational motion of the mechanical resonator. In the second case, a quantum interference phenomenon has been identified when considering a three-level quantum-well where both transitions couple to an optical resonator. The investigation of collective phenomena of a closely spaced ensemble of artificial atoms coupled to a nanomechanical resonator, has allowed to identify a superradiant-like behaviour of the mechanical motion.

The main scientific results presented in this thesis are summarized as follows:

**1)** The novel treatment applied to the model of a quantum-dot embedded on a quantum mechanical resonator has contributed to an improved description of the system quantum dynamics for strong optomechanical coupling regimes. For characteristic couplings strength of same order of magnitude as the mechanical frequency, a perturbation treatment introduces new fast-rotating terms into the Hamiltonian describing the system coherent dynamics. The observation of quantum features as sub-Poissonian distribution of the mechanical vibration quanta, becomes possible only when considering the new terms. Moreover, a different mean phonon number had been estimated comparing to the case when a secular approximation is applied in order to neglect the fast-rotating terms. The corresponding study is published in [$5^a$].

**2)** The model adapted for moderately strong optomechanical couplings, has been investigated in other possible scenarios such as quantum cooling regime and strong damping regimes. A stronger cooling effect has been predicted via the novel approach for strong coupling regimes. For strong damping regimes, phonon assisted population inversion has been observed as expected. The study on the quantum cooling effect is published in [$1^a$].

**3)** The investigation of the quantum dynamics of a three-level ladder-type quantum-well interacting with an optical resonator has been made possible by adapting the numerical solving technique to the case of a three-level emitter. Quantum interferences among different atomic transition which appear from the splitting of the energetic levels of the quantum-well under the laser pumping have been investigated. Different interference schemes have been identified. The laser phase and intensity are used in order to tune the system to a completely destructive interference which leads to the cancellation of the cavity field. The first study on this model is published in [$4^a$], while the phase-dependence was lately described in [$2^a$].

**4)** Although the described quantum interference effect requires the implementation of an equidistant three-level emitter, the solved model may also be applied for emitters with different transition energies, e.g., He atoms with the upper transition in visible range and the lower one in extreme ultraviolet. In this case, the solved model has predicted a coherent population trapping where the emitter had been prepared in a dark state by well choosing the suitable intensities ratio of the pumping lasers.

**5)** Fast phonon dynamics was observed when a collection of quantum-dots embedded on a vibrating membrane had been considered. When the closely-spaced quantum-dots reach the superradiant condition, the collective behaviour of faster decay dynamics is transferred to the dynamics of the mechanical resonator. A superradiant characteristic of $N$ times faster dynamics has been observed in the phonon emission dynamics of a sample of $N$ quantum-dots. The system dynamics has been solved assuming a large number of emitters and a large number of vibrational quanta, which has allowed to split the high order correlations and define a closed system of equations of motion. The presented results are published in [$3^a$] and have been one of the firsts reports on the effect of phonon superradiance.

Considering the conclusions above, one would highlight the following recommendations:

**1)** The method applied to the theoretical treatment of the model of a quantum-dot placed on a mechanical resonator, has significantly improved the estimation of the quantum statistics of the mechanical resonator for specific optomechanical coupling strengths. Therefore, one would recommend further investigation of the validity of the secular approximation in other models based on optomechanical devices possessing quantum-dots in order to identify the cases where treatments beyond the secular approximation could improve the accuracy of the estimated results.

**2)** A strong destructive quantum interference phenomenon predicted in the model of a quantum-well placed in an optical resonator, leads to a complete cancellation of the cavity field for a specific ration of laser intensities. This model can be implemented for measuring the coupling constants of the emitter, as their ratio is proportional to the ratio of laser intensities when the cavity field is completely cancelled. This case can be experimentally detected with ease.

**3)** A quantum switch where the cavity field is turned on and off via the input laser parameters is recommended as an application for the model of a quantum-well placed in an optical resonator.

Moreover, a potential inclusion of other effects which would influence the interfering interaction amplitudes could suggest an application for sensing techniques. One would recommend the inclusion of optomechanical couplings to the current model which will affect only the excited states of the emitter.

**4)** The study of the collective phenomena of an ensemble of quantum-dots placed on a mechanical resonator has revealed a superradiant-like behaviour of fast phonon dynamics. One recommends the implementation of this effect to phonon based sensing techniques where short enhanced phonon pulses may be required.

**5)** One would also recommend a further investigation of the influence of phonon superradiant features on other optomechanical effects. For example, the increase of the decay dynamics due to the superradiant phenomenon could affect the dynamics of phonon cooling and generation processes described in Chapter 3, for a single emitter. One has predicted that the phonon lasing and quantum cooling effects via a detuned laser pumping are dependent of the spontaneous emission effect. Therefore, one would recommend the implementation of collective dynamics into these models due to the enhancement of the collective decay rate for superradiant conditions.

**The limitation of presented results** is related to the theoretic models disclosed in the previous chapters. In Chapter 2, one has presented the theoretical framework related to each element of the dynamics, where a series of assumptions were applied in order to define the Hamiltonians describing various interactions as well as the damping phenomena. All these assumptions were strictly respected when solving the models. Moreover, further theoretical treatment presented in chapters 3, 4 and 5, has required the application of several approximations, e.g., the rotating wave approximation, the secular approximation. The validity of these approximations has been discussed and further respected when plotting the results. The numerical solving techniques applied in chapters 3 and 4, have required another series of approximations due to the infinite number of quantum states of the optical or mechanical resonator. These assumptions and approximations do not affect the generality of the studied problems and have been experimentally approved in different scenarios.

**The personal contribution of the author** to the presented results: The author had participated to the identification of the presented objectives, tasks and models; for each model slightly-advised he had solved the theoretical treatment applied to the quantum dynamics and had independently numerically solved the different systems of equations defining the quantum dynamics; he had written the firsts drafts of the publications related to the results presented in this thesis.

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## SUMMARY

### to the thesis ”Quantum behaviors of optical and optomechanical systems possessing artificial atoms”, presented by Victor Ceban for conferring the scientific degree of Ph.D. in Physics, Speciality 131.01 ”Mathematical Physics”, Chişinau, 2020.

The thesis has been written in English language and consists of the introduction, 5 chapters, general conclusions and recommendations, and the list of 200 references. The thesis contains 127 pages of basic text, 25 figures and 145 formulas. The results presented in the thesis are published in 20 scientific publications.

**Key words:** sub-Poissonian phonon laser, quantum interferences, phonon superradiance, fast phonon dynamics, phonon assisted population inversion, artificial atoms, quantum-dots, quantum-wells, quantum optomechanics, cavity quantum electrodynamics.

**The goal:** The determination and analysis of different quantum properties of the dynamics of an optical or mechanical resonator interacting with semiconductor artificial atoms.

**Research objectives:** The identification of various emitter-resonator coupling schemes related to different characteristic features of artificial atoms; The demonstration of the quantum statistics of an optical or mechanical resonator when interacting with an artificial atom; The identification of possible quantum interferences in systems possessing multi-level artificial atoms; The observation of the behaviour of the quanta distribution of a nanomechanical resonator under different interaction conditions; The demonstration of the influence of collective phenomena to the behaviour of an optomechanical system.

**Scientific novelty and originality of the results:** the phonon superradiant behaviour has been demonstrated in solid matter quantum nanomechanical resonators; the phenomenon of destructive quantum interference has been manipulated in order to effectively decouple an artificial atom from an optical cavity; a perturbation treatment of moderately strong quantum-dot-acoustic-resonator dynamics has allowed the observation of sub-Poissonian distributed phonon fields, i.e., quantum phonon lasing.

**The main scientific problem solved** consists in analysing the phenomena related to the quantum statistics of different types of quantum oscillators interacting with artificial atoms, in order to predict the conditions required to prepare the quantum oscillator in a specific quantum state.

**Theoretical significance and applicative value:** in this thesis it was demonstrated the quantum dynamics of open quantum systems with an elevated degree of complexity, which include diverse interactions among various components such as artificial atoms, laser light, optical cavities, nanomechanical resonators and the surrounding environment.

The model of a pumped two-level quantum-dot coupled to a quantum mechanical resonator operating in a moderately strong coupling regime has been solved. A coherent phonon generation scheme with sub-Poissonian quantum distribution of the vibrational quanta of the acoustic nanomechanical resonator has been proposed in order to improve phonon based sensing techniques.

A setup made of an equidistant ladder-type three-level quantum-well with perpendicular dipoles placed in an optical cavity has been investigated in the good cavity limit. A scheme for a quantum switch based on quantum interference effect was proposed. The cavity electromagnetic field is turned on and off by varying the parameters of the input pumping lasers.

The collective behaviour of a sample of initially excited two-level quantum-dots placed on a quantum mechanical resonator has been reported among the firsts investigations in the current literature. Therefore, a mechanism generating phonons with fast dynamics has been established. Ultra-short intense phonon pulses are generated via this mechanism, similarly to the superradiance effect.

**The implementation of the scientific results:** the research presented in this thesis has been successfully implemented in the framework of the bilateral moldo-german project 13.820.05.07/GF and national institutional project 15.817.02.09F; and may be further used for educational purposes.

## ADNOTARE

**la teza ”Dinamica cuantică a sistemelor optice și optomecanice cu atomi artificiali”, elaborată de Victor Ceban pentru conferirea gradului științific de doctor în științe fizice la specialitatea 131.01 ”Fizică matematică”, Chișinău, 2020.**


Teza este scrisă în limba engleză și constă din introducere, 5 capitole, concluzii generale și recomandări, și lista a 200 titluri bibliografice. Teza conține 127 pagini de text de bază, 25 figuri și 145 formule. Rezultatele prezentate în teză sunt publicate în 20 lucrări științifice.

**Cuvinte cheie:** laser fononic de tip sub-Poissonian, interferențe cuantice, superradianță fononică, dinamică rapidă a fononilor, inversia populației asistată de fononi, atomi artificiali, puncte cuantice, gropi cuantice, optomecanică cuantică, electrodinamica cuantică de cavitate.

**Scopul tezei:** Determinarea și analiza diferitor proprietăți cuantice ale dinamicii unui rezonator optic sau mecanic care interacționează cu un atom artificial pe bază de semiconductor.

**Obiectivele tezei:** Identificarea diferitor scheme de cuplare emițător-rezonator legate de diferite proprietăți caracteristice atomilor artificiali; Demonstrarea statisticii cuantice a unui rezonator optic sau mecanic, când acesta interacționează cu atomii artificiali; Identificarea eventualelor interferențe cuantice în sisteme care conțin atomi artificiali cu mai multe nivele; Observarea comportamentului distribuției cuantelor unui rezonator nanomecanic pentru diferite condiții de interacțiune; Demonstrarea influenței fenomenelor colective asupra comportamentului sistemelor optomecanice.

**Noutatea științifică și originalitatea rezultatelor:** Comportamentul superradiant al fononilor a fost demonstrat pentru rezonatoare nanomecanice cuantice pe bază de materie solidă; Fenomenul de interferență destructivă a fost manipulat pentru a decupla efectiv un atom artificial de o cavitate optică; Tratarea dinamicii la nivel perturbativ a permis observarea fononilor distribuiți sub-Poissonian, adică observarea efectului laser fononic cuantic, pentru regimuri de cuplare moderat intens a punctului cuantic cu rezonatorul acustic.

**Problema științifică soluționată** constă în analiza fenomenelor legate de statistica cuantică ale diferitor tipuri de oscilatoare cuantice care interacționează cu atomi artificiali, cu scopul de a prezice condițiile necesare pentru a pregăti oscilatorul cuantic într-o stare cuantică specifică.

**Semnificația teoretică și valoarea aplicativă:** în această teză, este demonstrată dinamica cuantică a sistemelor cuantice deschise cu un grad înalt de complexitate, care includ diverse interacțiuni între diferite componente, cum ar fi: atomi artificiali, lumină laser, cavități optice, rezonatoare nanomecanice și mediul ambiant.

Modelul unui punct cuantic pompat, cu două nivele, care interacționează cu un rezonator nanomecanic a fost rezolvat pentru un regim de cuplare moderat intens. A fost popusă o schemă de generare a fononilor coerenți, în care a fost obținută o distribuție sub-Poissoniană ale cuantelor vibraționale a rezonatorului nanomecanic acustic.

Un dispozitiv constituit dintr-o groapă cuantică cu trei nivele echidistante amplasată într-o cavitate optică a fost investigat în limita cavității cu factor de calitate înalt. A fost propusă o schemă a unui întrerupător cuantic bazată pe efectul de interferență cuantică. Câmpul electromagnetic a cavității apare și dispare variind parametrii laserelor de pompare.

Comportamentul colectiv a unui eșantion de puncte cuantice cu două nivele, inițial excitate, amplasate pe un rezonator nanomecanic, a fost studiat printre primii în literatura de specialitate. Astfel, a fost stabilit un mecanism de generare a fononilor cu dinamică rapidă. Prin intermediul acestui mecanism sunt generate pulsuri ultra-scurte și intense de fononi, similar efectului de superradianță.

**Implementarea rezultatelor științifice:** studiile prezentate în această teză au fost cu succes implementate în cadrul proiectului bilateral moldo-german 13.820.05.07/GF și proiectului național instituțional 15.817.02.09F; și pot fi utilizate cu scop didactic pentru studenții ciclului universitar și post-universitar.

## АННОТАЦИЯ

### к диссертации «Квантовая динамика оптических и оптомеханических систем искусственных атомов», представленной Виктором Чебан на соискание ученой степени доктора физических наук по специальности 131.01 «Математическая физика», Кишинэу, 2020.

Диссертация написана на английском языке и состоит из введения, пяти глав, общих заключений и рекомендаций, и списка цитируемой литературы из 200 источников. Диссертация содержит 127 страниц базового текста, 25 графиков и 145 формул. Результаты диссертационной работы опубликованы в 20 научных публикациях.

**Ключевые слова:** фононный лазер субпуассоновского типа, квантовая интерференция, фононное сверхизлучение, инверсия населенности обусловленной фононами, искусственные атомы, квантовая оптика и квантовая оптомеханика.

**Цель диссертации:** Определение и изучение различных квантовых свойств оптического либо механического резонатора, взаимодействующего с искусственными атомами, возникающими в полупроводниковой среде.

**Задачи диссертации:** Выявление различных схем соединения излучатель-резонатор в зависимости от характеристических свойств искусственных атомов. Доказательство квантовой статистики оптического либо механического резонатора при его взаимодействии с искусственными атомами. Выявление возможных явлений квантовой интерференции в системах, содержащих многоуровневые искусственные атомы. Изучение поведения распределения квантов возбуждения наномеханических резонаторов в различных условиях их взаимодействия с искусственными атомами. Доказательство влияния коллективных явлений на поведение оптомеханической системы.

**Научная новизна и оригинальность результатов:** Выяснены особенности поведения фононов в сверхизлучательном состоянии в случае твердотельных квантовых наномеханических резонаторов; установлена возможность манипулирования явлением деструктивной квантовой интерференции с целью эффективного отключения взаимодействия искусственного атома и оптического резонатора; доказана возможность получения субпуассоновских фононов, т.е. возможность осуществления квантового фононного лазера.

**Основная научная задача, решаемая диссертацией,** заключается в исследовании явлений, обусловленных видами статистики различных квантовых осцилляторов, взаимодействующих с искусственными атомами, в целях определения условий, необходимых для создания квантового осциллятора в определенном квантовом состоянии.

**Теоретическая значимость и прикладная ценность:** в настоящей диссертационной работе изучена квантовая динамика сложных открытых квантовых систем, включающих различные виды взаимодействия между разными компонентами системы, такими как искусственные атомы, лазерное излучение, оптические и наномеханические резонаторы, и окружающая среда. Исследована динамика двухуровневой модели квантовой точки в поле лазера, умеренно сильно взаимодействующей с наномеханическим резонатором. Предложен способ генерации когерентных фононов, которым получено субпуассоновское распределение вибрационных квантов акустического наномеханического резонатора, способствующий улучшению сенсорных технологий, основанных на фононах. Теоретически предложена схема устройства, состоящего из эквидистантной многозвенной трехуровневой квантовой ямы с перпендикулярными диполями, расположенной в оптическом резонаторе высокой добротности. На базе последней предлагается создать квантовый триггер на основе явления квантовой интерференции. Показано, что изменяя параметры лазеров накачки возникает возможность манипулирования интенсивностью электромагнитного поля в резонаторе. Впервые изучен коллектив возбужденных двухуровневых квантовых точек, расположенных на квантовом наномеханическом резонаторе и показана возможность излучения интенсивных ультракоротких импульсов фононов по аналогии со сверхизлучательным эффектом.

**Внедрение научных результатов:** представленные в настоящей диссертации результаты были успешно применены в рамках двухстороннего молдавско-немецкого проекта 13.820.05.07/GF и национального институционного проекта 15.817.02.09F.

**CEBAN VICTOR**

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**131.01 - MATHEMATICAL PHYSICS**

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