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Proposition de stage/thèse
Laboratoire LUMIN
ENS Paris-Saclay, Université Paris-Saclay

How robust collective effects are against dephasing processes ?

Ce stage théorique d'optique quantique s'inscrit dans le cadre d'une collaboration entre le Laboratoire Lumière, Matière et Interfaces (LuMIn) de l'ENS Paris-Saclay et le Laboratoire de Physique de l'ENS de Paris (LPENS). Le stage (et la thèse qui suit) sont financés par un projet ANR.

Mots-clés : Optique quantique, effets collectifs, superradiance, déphasage

The quantum technologies roadmap is marked by several milestones. Among them, the realization of strong interactions between single photons has been a driving force for a large community over the past decades. Since photons propagating in vacuum do not interact, photon-photon interactions can only be mediated by matter. Therefore, achieving strong light-matter interactions at the single photon level is a long-standing goal of both fundamental and technological importance, and various approaches have been explored to reach it. The most well-known is probably cavity quantum electrodynamics (QED), which consists in placing an "atom" (atom, quantum dot, super-conducting qubit…) in a high-finesse cavity. The interaction is increased because the photon bounces between the cavity mirrors, thereby "seeing" many times the atom. The field of cavity QED has been (and still is) very successful, providing major advances in quantum optics. Nevertheless, using a cavity to enhance light-matter interactions also presents some drawbacks, especially a narrow bandwidth and the difficulty to couple photons in and out of the cavity with high efficiency.

Because of these limitations, many recent works have studied **cavity-free systems composed of a large number of atoms in free-space.** When the interatomic distance is reduced below the wavelength associated to the atomic transition, the atoms can couple **collectively** to the light through **superradiant and subradiant atomic modes** [Cha18]**.** Superradiant modes (respectively subradiant modes) consists in collective excitations of the atomic ensemble that couple more efficiently (respectively less efficiently) to the light than a single atom. As a consequence, superradiant modes can be used to absorb/emit very efficiently photons in/out the atomic ensemble, while subradiant modes can be used to perform a quantum memory for the photons [Fay23].

Collective effects have been observed and studied in disordered and ordered cold ensembles [Gob15, Fer21]. Because of their extreme level of control and protection against the environment, cold atoms platforms are very well suited to observe those effects. However, the diffraction limit of the light used to trap the atoms at a precise position often makes difficult the reach of the subwavelength regime in which collective effects emerge.

On the opposite, **quantum dots are "dirty",** in the sense that it is very difficult to make two of them perfectly identical. On top of that, they are usually coupled to their environment via **dephasing processes**.
A dephasing process is a coupling process between the quantum dot and its environment that does not involve the exchange of an excitation such as a photon, but rather breaks the phase relation between the different component of the collective mode. As a direct consequence, **dephasing is known to destroy collective effects**. This simple argument has been sufficient for a long time, but recently, strong collective

effects have been observed in quantum dots "super-lattices" at room temperature (hence with a large dephasing rate) [Bil22]. The particularity of those lattices represented in Figure 1 is that the distance between two QDs is extremely small $\simeq 10-30$ nm (more than 20 times smaller than the wavelength associated to the transition $\simeq 600$ nm). As a consequence, the strength of the dipole-dipole interaction between two adjacent QDs is extremely large and seems to overcome the effect of the dephasing.

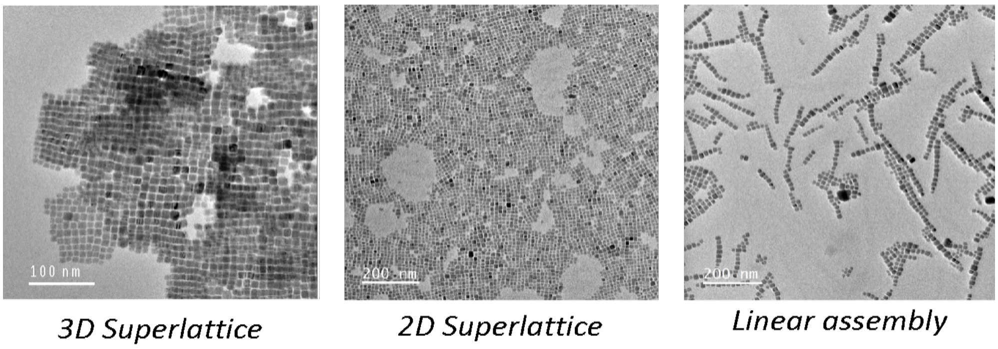

Figure 1: TEM images of pNC superlattices of different geometries, fabricated at LuMIn by modified LARP method

The chemistry team in LuMIn lead by Prof Cedric Mayer recently managed to synthetize those supperlattices in 1D, 2D and 3D [Rub24]. This triggered a collaboration between LuMIn and LPENS led by Prof Carole Diederichs in order to observe collective effects, and more precisely superfluorescence in those systems.

The objective of the internship is to understand theoretically the interplay between pure dephasing and dipole-dipole interaction in order clarify the regimes where collective effects can be observed. During the PhD, the candidate will also interact with the experimental teams of LuMIn and LPENS in order to model their experiment.

The study will rely on **quantum electrodynamics theory and numerical calculations**. The internship and the PhD will extend some previous theoretical work done at LuMIn for N=2 QDs in the presence of dephasing [Qui25].

It is preferable that the internship be followed by a PhD thesis (already funded by the ANR project). The candidate will work at the LuMin's laboratory (Palaiseau).

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