Single quantum dots in microcavities

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ABSTRACT

In 2004 two groups have reported observation of the strong coupling regime in 3D microcavities with single quantum dots (QD). We present the quantum theory of non-linear emission of photons by such structures. We derive the exciton creation operator which coincides with a Fermi one for QDs smaller than the exciton Bohr radius and with Bose one for very large QDs. In intermediate size dots excitonic statistics is in between the Fermi and Bose ones. Consequently, the non-linear optical spectra change from the Mollow triplet in the fermionic case to the Rabi doublet in the bosonic case. We predict appearance of a characteristic multiplet structure of the non-linear emission in the intermediate regime.

Keywords: quantum dots, microcavity, exciton, Rabi oscillations

Semiconductor quantum dots (QDs) are a leading technology for the investigation of the quantum realm. They offer exciting possibilities for quantum computation and are important candidates for the next generation of light emitters. In most cases, the best control of the states of the confined carriers in QDs is obtained through coupling to light cite. This light-matter interaction can be considerably enhanced by including the dot in a microcavity, with pillars[1], photonic crystals[2] and microdisks[3] being the currently favoured realizations. References [1-3] describe the first reports, in each of these structures, of vacuum field Rabi splitting, whereby one excitation is transferred back and forth between the light and the matter fields.

This contrasts with the weak coupling regime previously studied[4-5], where only quantitative perturbations of the dynamics occur, such as reductions in the lifetimes of the dot excitations (Purcell effect). In the case of strong coupling, however, the coherent exchange of energy merges the light and matter excitations into a new entity. This is commonly referred to as an exciton-polariton in semiconductor physics[6], with an important example being the two-dimensional polaritons in planar microcavities, first observed by Weisbuch et al. [7] In cavity quantum electrodynamics (cQED), the equivalent concept is the dressed state of atoms by the quantised electromagnetic field.

In QDs, optical interband excitations create electron-hole pairs or excitons, confined by a three-dimensional potential which makes their energy spectrum discrete. If this potential is much stronger than the bulk exciton binding energy, and if the size of the dot is smaller than the corresponding exciton Bohr radius, the Coulomb interaction between electrons and holes can be considered as a perturbation. For the lowest exciton states, this is the fermionic limit where the Pauli exclusion principle dominates. In the opposite limit, if the confining potential is weak or the size of the dot is much greater than the exciton Bohr radius, the exciton is quantized as a whole particle. In this case, the bosonic nature of excitons is expected to prevail over fermionic nature of individual electrons and holes. An important question for the description of emission from QDs embedded into cavities in the strong coupling regime is whether the dot excitations coupled to light behave like fermions or like bosons. Here we address the question of which statistics (Bose-Einstein, Fermi-Dirac or a variation thereof) best describes excitons in QDs. This is a question which is very topical in view of the

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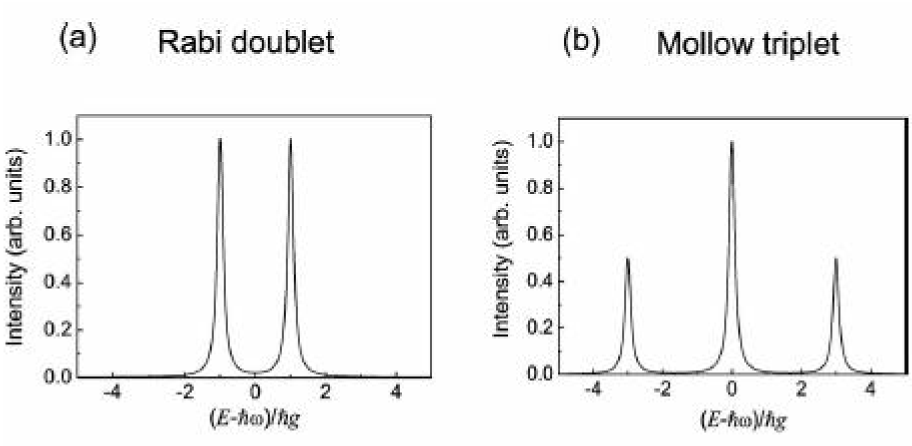
recent experimental achievements. Indeed the linear optical response of a strongly coupled system is always a Rabi doublet whatever the statistics describing the QD. However, the non-linear regime optical response (namely when the number of excitation) drastically depends on the nature of QDs. The optical response remains whatever the excitation number if the dot shows a bosonic behaviour whereas it exhibits a Mollow triplet if this is fermionic as sketched on Fig. 1.



Fifure 1. Energy diagrams of the two limiting cases of dressed bosons (a) and fermions (right).

In this presentation we derive the exciton creation operator in a QD in the intermediate realistic case which allows the calculation of nonlinear optical spectra of QDs in microcavities[8,9]. The model we develop takes into account the saturation of the transition due to Pauli exclusion alone and does not attempt to solve the complex manybody problem which arises when Coulomb interactions between excitons are included. Hence the model is most accurate in describing the departure from ideal bosonic behaviour in large dots rather than near the fermionic limit in small dots. We analyze the dot size effect on the statistics of excitons and demonstrate the transition from the fermionic to bosonic regime. The resulting spectrum of light emitted by quantum dot excitons in leaky modes of a microcavity (which could be typically lateral emission) is a signature of the quantum statistics of excitons. A multiplet structure is theoretically predicted with various features which can help identify the exciton field statistics as sketched on fig 2 extracted from[8].

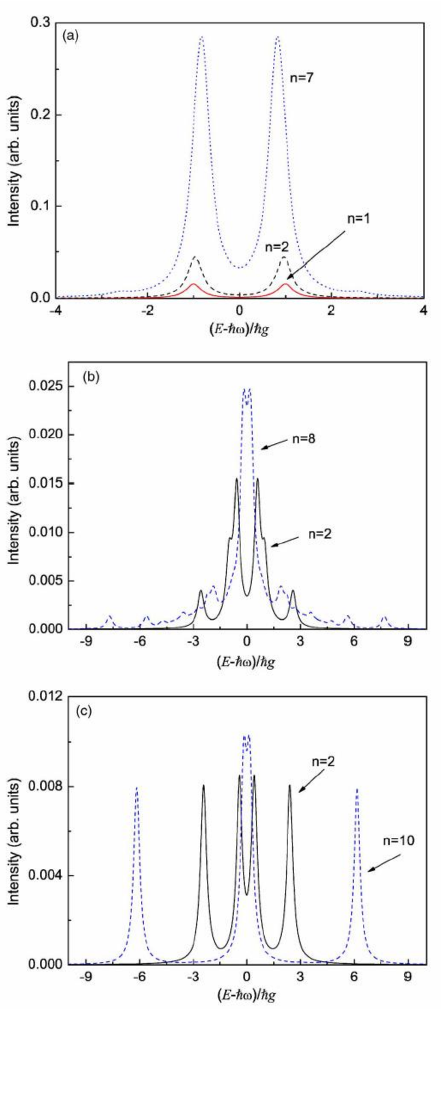


Figure 2. Spectra for various intensities of the light field.

(a) Close to the bosonic limit with for a number of excitation n=1 (solid red), 2 (dashed blue), and 7 (dotted black). This case features a broadened and redshifted Rabi doublet as the intensity increases.
(b) Intermediate case between a bosonic and fermionic behavior for n=2 (solid black) and 10 (dashed blue) demonstrating a complicated multiplet structure.
(c) Close to the fermionic case for n=2 (solid black) and 10 (dashed blue) featuring a quadruplet structure going towards Mollow triplet at high intensities.

In conclusion, we provide the formalism to obtain the spectra expected for a general dot in various geometries based on the form of the single exciton wavefunction. We investigated a generic case analytically through a Gaussian approximation. The richness and specificity of the resulting spectra provides a means to determine, through the peak splittings and strength ratios, the parameter that measures how close excitons are to ideal fermions or bosons. Although heavy numerical computations are required for realistic structures, physical sense motivates that in small dots a Fermi-like behaviour of excitations with separately quantised electrons and holes is expected, while in larger dots behaviour should converge towards the Bose limit. These trends should be observable experimentally in the nonlinear regime (where more than one exciton interacts at a single time with the radiation mode): depending on whether Rabi splitting is found, or if a Mollow triplet or a more complicated multiplet structure arises, one will be able to characterize the underlying structure of the exciton field.

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