Phase-Space of Strong Coupling of Two Bosonic Modes

F. P. Laussy, and E. del Valle

Citation: AIP Conference Proceedings **1399**, 585 (2011); doi: 10.1063/1.3666515
View online: http://dx.doi.org/10.1063/1.3666515
View Table of Contents: http://aip.scitation.org/toc/apc/1399/1
Published by the American Institute of Physics

Phase-Space of Strong Coupling of Two Bosonic Modes

F. P. Laussy* and E. del Valle†

*Walter Schottky Institut, Technische Universität München, Am Coulombwall 3, 85748 Garching, Germany
†School of Physics and Astronomy, University of Southampton, SO17 1BJ, Southampton, United Kingdom

Abstract. We give an overview of the phases of strong and weak coupling of two quantum modes under incoherent pumping.

Keywords: Strong coupling, bosons, quantum dot, microcavity
PACS: 05.30.Jp, 85.30.-z, 42.55.Sa, 42.50.Gy

The coupling of two quantum modes in presence of dissipation has as its central problem, the question whether this coupling is "strong" or "weak", or, in physical terms, if its dynamics is dominated by the quantum coupling—that gives rise to new modes, a quantum superposition of the original states—or if it is dominated by dissipation, therefore leaving the bare states essentially unaffected. This question is easily answered when dissipation only consists of decay of the excitations. Calling g the coupling strength between the two modes (a and b) and γ_a, γ_b their respective decay rates, the criterion for strong coupling reads:

$$|\gamma_a - \gamma_b| \leq 4g\,. \tag{1}$$

This equation describes the physics of the quantum coupling of one atom in a cavity, for instance. Semiconductors give us the opportunity to take a more general stance of this problem, by including the excitation process, not always necessary in other fields (e.g., because a well-known and controlled initial state can be prepared, which is the case of Rydberg atoms in cavities where a beam of atoms goes from the oven into an empty photon field). A standard characterization of a semiconductor sample is however done with incoherent excitation, and this excitation is typically noisy and pervasive. For instance, in a semiconductor, it is difficult to excite one quantum dot in isolation, and the effect of other dots, most in weak-coupling, perturb the dynamics of the system [1]. A description of weak and strong coupling in this context requires to add in the dynamics the effect of incoherent excitation, both that of the quantum dot itself, at rate P_b, and also of the cavity, at rate P_a. This brings a rich extension of the particular case of an initial state, first from the fact that arbitrary initial states can now be elegantly described, and second from quantum statistics to take Bose stimulation and Pauli blocking into account [2]. For the first input, spontaneous emission of the excited state of the emitter is considered. By playing with the ratio of P_a versus P_b, both vanishingly small, we recover with the incoherent pumping description all the particular cases where the initial state is $\propto P_a|1,0\rangle + P_b|0,1\rangle$. This is an important input in semiconductors where, again, the excitation process can be so noisy as to be, although initially of an electronic character (exciting electron-hole pairs in the system), ultimately generating essentially photons in the system. The corresponding atom-in-a-cavity initial state would be that of the ground-state atom in a cavity with one photon, a configuration not so easily realized in such a system. Semiconductors, oddly, make it natural to study spontaneous emission of a photon. For the second input, one first needs to know the underlying statistics. It is always of a Bose character for the cavity, but is expectedly of a Fermi character for the emitter (of course more exotic variations can be thought of [3]). In this text, for simplicity, we shall only consider the case where the emitter is also bosonic. Indeed the problem is much more complex in the Fermi case, and we refer the reader to other works on that topic in the line of this one [4, 5, 6]. The two coupled-bosons case nevertheless has its advantages: it is solvable exactly, it is the limit of vanishing excitation of the boson-fermion (Jaynes-Cummings) system and it also describes physical systems of its own, e.g., large quantum dots or the ground state of quantum wells (polaritons [7]).

Including incoherent pumping, the criterion for strong-coupling between two bosonic modes gets upgraded from Eq. (1) to the equally simple inequality [2]:

$$|\Gamma_a - \Gamma_b| \leq 4g\,, \tag{2}$$

where $\Gamma_c = \gamma_c - P_c$ ($c = a,b$) is renormalized by pumping. Strong and weak coupling is technically determined by oscillations or damping, respectively, of some two-time correlator [2], that expresses the existence or absence of coherence exchanges between the modes. This innocent-looking variation of Eq. (1) has far-reaching consequences. The phase-space of weak and strong-coupling is now a four-dimensional (4D) space, with parameters $(\gamma_a, \gamma_b, P_a, P_b)$ (g providing the unit). We show in Figs. 1 and 2 some 2D slices of this phase-space,

Physics of Semiconductors
AIP Conf. Proc. 1399, 585-586 (2011); doi: 10.1063/1.3666515

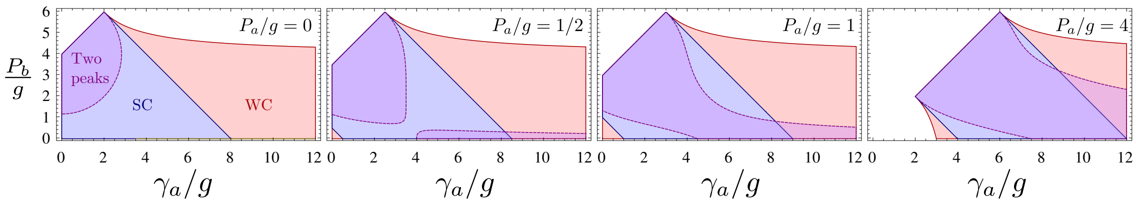

FIGURE 1. Regions of coupling in (γ_a, P_b) slices of the 4D phase space for the given values of P_a and $\gamma_b/g = 4$. In blue, regions of strong-coupling (SC), in red, regions of weak-coupling (WC). Overimposed in purple, the region where the cavity photoluminescence spectrum is split. Note that it overlaps both regions of strong and weak coupling. In other areas (white), the system has no steady state.

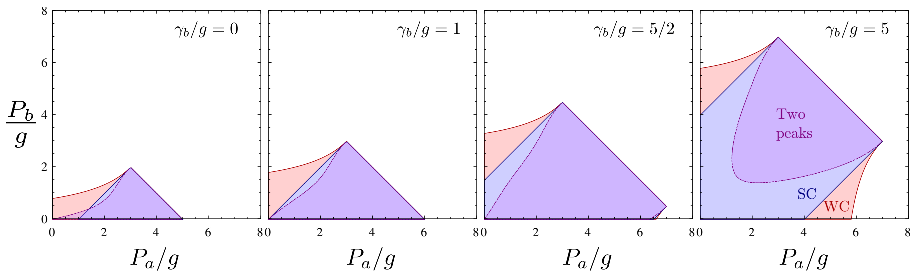

FIGURE 2. Same color code as in Fig. 1 now for (P_a, P_b) slices of the same phase-space, for the given values of γ_b and $\gamma_a/g = 5$.

where are separated, in blue, the regions of strong-coupling, and in red, those of weak-coupling. The phase-space is bounded as not all parameters yield a steady-state. One of the most important features shown on these figures is that, although such a system has a clear and simple mathematical definition for strong (and weak) coupling (given in Ref [2]), it has a complex behaviour in its optical emission spectra. In purple, we superimpose to the various regions, that where the cavity emission is split [8].[1] Photoluminescence splitting is often regarded as an evidence of strong-coupling, being linked to Rabi splitting (which is valid only in very strong coupling). This association would be correct in general if the purple and blue areas were equal. As can be seen through the various projections shown here, there is a rather weak correlation in this sense. Splitting is observed both in weak and strong coupling. Note in particular from left-most panel of Fig. 1 how difficult of access is the spectral splitting in absence of cavity pumping. Cavity QED with atoms does not suffer of this although they have no cavity pumping, since the detection is directly that of the atom itself (whereas we are probing the cavity emission here, as is natural with most microcavities). By symmetry, this hindrance for the semiconductor makes it a facility for the atomic system. There is a qualitative change in the system when crossing the strong to weak coupling frontier. In the mathematics, some real analysis becomes complex. In the physics, some damped correlations become oscillatory. In the photoluminescence spectrum, this striking modification is blurred, crossing the frontier is done smoothly.

We hope we could give a glimpse of the considerable complexity—in the sense of richness—that is brought by incoherent pumping to the fundamental physics of coupling two quantum modes (a simple system—in the mathematical sense—in the linearity conferred by their bosonic nature). Much physics is unveiled, such as the effect of the effective quantum state, the quantum dynamics due to statistics, the relationship between dressed state splitting and photoluminescence splitting (and more which we haven't touched upon here). All this physics also impacts, naturally, systems where nonlinearities come into play [4], even, in fact, in those such systems that are also solvable exactly [9].

[1] There is a typo in Eq. (3) of Ref. [8] ($\Gamma_b \to -\Gamma_b$).

REFERENCES

1. F. P. Laussy *et al.*, Phys. Rev. Lett. **101**, 083601 (2008).
2. F. P. Laussy *et al.*, Phys. Rev. B **79**, 235325 (2009).
3. F. P. Laussy *et al.*, Phys. Rev. B **73**, 115343 (2006).
4. E. del Valle *et al.*, Phys. Rev. B **79**, 235326 (2009).
5. A. Gonzalez-Tudela *et al.*, Opt. Express **18**, 7002 (2010).
6. E. del Valle *et al.*, Phys. Rev. Lett. **105**, 233601 (2010).
7. F. P. Laussy *et al.*, Phys. Rev. Lett. **93**, 016402 (2004).
8. A. Gonzalez-Tudela *et al.*, Superlatt. Micr. **47**, 16 (2010).
9. E. del Valle, Phys. Rev. A, **81**, 053811 (2010).