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PART B

SQOD

Contents

B1 SCIENTIFIC AND TECHNOLOGICAL QUALITY

B1.1 Scientific and technological quality

Controlling the coupling of quantum states in a regime that is ruled by quantum physics is one of the principle goals of both fundamental and applied research. At the pinnacle of its development, this level of control offers the possibility to perform quantum information processing. The best known examples and most obvious manifestations of this emerging technology are *quantum cryptography* [1]—that allows to secure privacy of information with absolute reliability—and *quantum computation* [2]—known to outperform classical computations in a set of important problems (breaking classical cryptography and database sorting having the greatest practical impact).

From a technological point of view, it is argued by experts that by 2019 at most, the current technological trend based on ever finer photolithography will not be able to adhere to Moore's law, that paces the progress of silicon-age computer hardwares [3]. To sustain the ongoing progress, a shift in paradigm into the quantum realm is necessary. Current strategies for technological advances consist in continued size reduction of devices. When this approach hits the atomic level, quantum mechanics will inevitably take over. This limit, however, can be turned positive and become an asset. Quantum computation is indeed more general as well as more powerful than classical computation. The conversion of technology to quantum based chips is, therefore, unavoidable but also welcome. It is a timely technological concern since, by most estimates, the limit of classical-physics based technologies spans a period from five to ten years. Meeting this major challenge for industry will not only allow the continued progress of our technology, it will also facilitate a better usage of resources, such as reducing energy consumption, without prejudicing to our exponentially increasing recourse to communication. In these ways the progress towards truly quantum coherent devices will help to address one of the major socio-economic problem of tomorrow.

From a fundamental research point of view, quantum physics is the latest of the great revolutions in science. The theory of quantum electrodynamics (QED), that models the interaction of matter and radiation, is the most powerful theoretical edifice with respect to its predictive and explanatory powers. QED has long been the mainstay of high energy physics, but recently increased attention has been devoted to *cavity-QED* (cQED), i.e., the coupling of matter and radiation in the confines of a cavity, that allows to sustain and control its quantum character. In the regime of so-called *Strong Coupling*, the new concepts of the quantum theory are realized [4], such as superposition of states (e.g., the superposition of a photon and an excited state of an atom, a so-called "*dressed state*" or "*polariton*") [5] or entangled states (such as "cat states", in reference to Schrödinger's cat) [6]. These states are precisely those that served the founding fathers to pinpoint shortcomings or even absurdities of the quantum worldview. However they can now be realized and investigated in the laboratory. As quantum correlations of the polaritons are mapped to the photons emitted outside of the cavity, cQED allows a continuous and real-time monitoring of the system dynamics. As a result, cQED offers a unique testbed to explore quantum physics and its more far-fetched ramifications. Fundamental models have been proposed and are now beginning to be explored in laboratory-based microcavity physics. Some recent proposals are of Mott insulator/superfluid transitions through the XY [7] or Hubbard models [8], or Fermionization through the Tonks-Girardeau gas model [9] and the optical analogue of the Josephson effect [10].

The cavity allows to harness quantum phenomena in a wealth of different systems and study the relationships between different physical objects, at the same time as it allows parallel efforts and results in a cross fertilization of ideas between different scientific communities. Pioneering reports focused on atoms in cavities [11–13] (see [14] for a review), later followed by electron-hole pairs (excitons) in microcavities [15–17] (see [18] for a review) and superconducting qubits [19]. Most recently, a new class of physical object was added to the list, namely, mechanical resonators, bringing quantum physics still closer to our macroscopic world [20; 21].

In this project, I propose to focus specifically on the topical case of light-matter coupling in zero-dimensional semiconductor structures. Semiconductors are the leading systems for possible technological implementation, thanks to their predisposition for scalability [22] as well as mature material and nanofabrication technologies. State of the art growth techniques allow to engineer devices on demand and design microscopic laboratories to unravel, control and study quantum phenomena [23]. The *Quantum Dot* (QD) [24] is the nanostructure of choice for this purpose, since it confines the material excitation, namely, the electron-hole pair (or "*exciton*") in all dimensions. As a result, the exciton behaves as an artificial atom [25], that can be permanently embedded inside a microcavity. The possibility to do so with a *single* quantum dot within tens of nanometers accuracy has been demonstrated [26]. For the finite number of quanta they involve, quantum dots are superior to higher dimensional semiconductor systems (typically, in the 2D plane of a quantum well) [27] that couple light and matter to a very large number of excitations, bringing the system back into the classical realm (of a continuous field rather than of discrete excitations). Quantum dots by themselves have a long record of achievements to service various technological and fundamental research areas. A full advantage is taken of their predisposition for optics by embedding them in a cavity [28], leading to control of their spontaneous emission [29; 30] (known as the Purcell effect, the dawn of cavity QED), micro-lasing [31; 32], single-photon sources [33; 34], etc… But their real prospects lie in a full control and understanding of their strong coupling.

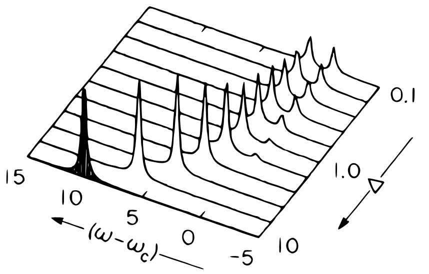

Fig. 1: Theoretical anticrossing of the modes as a manifestation of Strong-Coupling, in the simplest picture—without dissipation—pioneered by Sanchez-Mondragon *et al.* [35]. Agarwal and Puri later added cavity decay [36] and Carmichael *et al.*, atom decay [37]. Recently, I added cavity and exciton incoherent pumping [38].

The expected manifestation of strong coupling is the splitting of the modes of the system when they are at resonance (i.e., with both the same energy). This is shown on Fig. 1, where a stationary spectral doublet is formed as detuning Δ goes to zero. At the quantum level, this is interpreted as the emergence of new modes (the polariton modes), that superpose the light and matter states into new entities that acquire a mixed character (such as a interacting photons or almost massless material particles). This light-matter state is a quantum object with no classical counterpart. At the classical level, the same effect arises merely from the renormalization of the energies of coupled oscillators, and has obviously no prospect for the powerful applications of its quantum counterpart, such as performing quantum information processing. This is a well known particularity of the *linear regime* that it provides essentially identical results from the classical or quantum-mechanical viewpoint [39]. For this reason, investigating the *nonlinear response* of the system is a very desirable task to guarantee that it behaves quantum mechanically, with all the consequences and applications this opens. An unmistakable signature of this purely quantum effect is the $\sqrt{n}$ splitting that follows from full-field quantization (i.e., quantizing both the material and the optical fields), where n is the number of photons in the cavity. These phenomena are predicted by the so-called Jaynes-Cummings model [40], the drosophila of quantum optics [41]. Such a characteristic quantum nonlinear response was first reported for the strong coupling of atoms, initially in an indirect way through anharmonic oscillations in a time-resolved experiment [42], then more recently, directly from the spectral response to weak coherent excitation [43] (see [44] for an outlook). It has also been remarkably demonstrated with superconducting qubits [45; 46]. However, despite striking advances, an unmistakable demonstration of nonlinear fully quantum phenomena still lacks from the semiconductor community.

Quantum dots in microcavities are the topic of investigations of numerous research groups in the world. It was, however, only in late 2004 [15; 16], early 2005 [17], that they have been first reported to reach the strong coupling regime. The proof relied on observation of an *anticrossing* between the modes as they are brought to resonance, similar to that shown in Fig. 1. Such an anticrossing is observed routinely in semiconductors of higher dimensionality [47] where it is now well established. However, it lacks the discreteness of the quantum regime, as described above, that are needed for quantum information processing. It is still nowadays not every research group that can experimentally access this regime using single quantum dots, but progress has been steady and there is now a fair distribution of groups worldwide able to achieve it. An overview of most notable achievements is given on Fig. 2, where the impact of quantum dots is emphasized but other systems (atoms and superconducting qubits) also appear for comparison. With semiconductors, an element of chance is typically involved, since the most widespread growth techniques generate many QDs in the cavity. In this case, investigations of many different samples is needed in order to find a working system where a dot couples efficiently to the cavity. The approach has been largely based on a trial and error quest for a working system. In the case where technical prowess and dedicated effort allowed the fabrication of a cavity around a single dot, unexpected features were observed, such as a spectral triplet at resonance [48], in stark contrast with the canonical mode-splitting (doublet) of strong coupling. The third peak was initially proposed to be an irrelevant addition to the conventional doublet [48]. At the same time, it was proven by a photon-counting experiments that the light-matter coupling involved only a single quantum of excitation, and was, therefore, a viable realization of the quantum regime [48; 49]. Recently, a triplet structure has been reported again [50], this time from the conventional strong coupling doublet (so called *Rabi doublet*) and the central peak was observed to become more prominent under conditions of stronger excitation. Another puzzling feature of these systems that attracted much attention has been the identification of a feeding mechanism for the cavity emission, that is strong even when the dot is far detuned from the cavity mode. It has been recently suggested [51], understood [52], demonstrated [53] and quantified [54] that a pure dephasing of the exciton is involved (complementary mechanisms have been advanced [55; 56]).

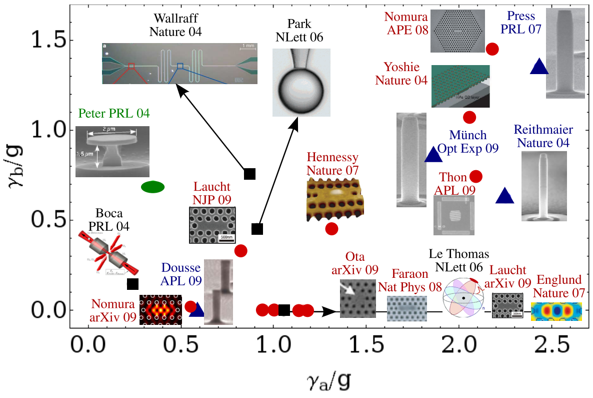

Fig. 2: Experimental state of the art in coupling light with a two-level system. Most common semiconductor realizations are with a photonic crystal (circle), a pillar (triangle) or a microdisk (ellipsis). Other systems (square), such as a microsphere, a superconducting qubit or atoms, are also indicated. Systems are positioned on an emitter/cavity decay rates diagram (in units of the coupling strenght g). The closer to zero, the best is the system for quantum applications. Parameters are taken from the literature, and their accuracy is indicative only, relying in most cases on a qualitative reading of the data; one outcome of this proposal would be to provide a correct version of this diagram, based on a quantitative analysis (this program has been initiated in my work [38] and has been followed up in Refs. [54] and [57]).

This introduction provides a brief overview of the state of the art: whilst the system has reached strong-coupling [15–17; 49; 58–62], and has been shown to be amenable to the nonlinear regime under coherent excitation, for instance by displaying the so-called photon blockade [63; 64], it still lacks a good theoretical understanding and experimental control of its nonlinear response under incoherent excitation, when it is left to its own dynamics, rather than being coherently driven. Both control and understanding are requisites to perform quantum information.

I recently took part in the theoretical development of this field of research through a description that generalizes and adapts the textbook light-matter coupling case [38; 65; 66]. The latter is suited to describe the canonical atomic case, but misses some crucial specificities of the semiconductor case, such as decoherence and effect of a continuous, incoherent pumping (cf. Sec. B3.2 below). As part of this formalism, I could contribute to this field a new reading of the experimental data, demonstrating that universally agreed upon signatures, such as anticrossing, are in fact not a guarantee for, nor an evidence of strong-coupling. This led me to define a new criterion for strong-coupling, taking into account the effect of pumping. Another consequence concerns the accuracy of the estimations of parameters from the experimental results, that my model allows to raise to the standard of statistical analysis. I also evidenced the need for certain practices in this endeavor, such as global fitting of spectral shapes rather than of the anticrossing curves, for which there is no mathematical closed-form expression [67]. My model was confronted to the experiment, as shown on Fig. 3, where strong-coupling was accounted for the first time with a fitting theoretical model rather than from general guidelines and qualitative analysis. For instance, I could show how the photon character of the quantum state realized in the system due to cavity pumping was helping to resolve spectrally the anticrossing, without which the poor splitting-to-broadening ratio would give the illusion of a weakly-coupled system that anticrosses (Fig. 3b). This suggests an explanation for the difficulty of many groups to observe strong coupling, by making more stringent the chance factor. Understanding of the correct theory could help to circumvent these shortcomings. Concerning the spectral triplet, my results also suggest that rather than being uninteresting complications, as advanced previously, they could be, in strong contrast, the disguised manifestation of the long-sought nonlinear response of quantum dots [68]. I have, thus, demonstrated the rich and subtle (and unexpected) impact of semiconductor specificities, such as pumping, that were previously thought a minor or secondary ingredient in the physics at play. More details on my contributions to the state of the art are to be found in the dedicated sections below (see page 13).

Primary goals

The impetus of this proposal is to build upon my successful theoretical modelling of the simplest system (one quantum dot in strong coupling with one microcavity mode), in order to access more ambitious and realistic configurations, called to perform useful tasks or display fundamental and novel phenomena. Within the bounds of my previous work, it was not possible to easily establish direct collaboration with experimentalists who had mastered strong-coupling. The results of Fig. 3, for instance, were not obtained in collaboration with the authors, but from their published data. This current proposal aims at addressing this issue by establishing an internal, full-scale and full-fledged collaboration with one of the best experimental groups operating at the forefront of research in this field. Technologically, rapid progress has been made, in particular by the host group, towards on-chip implementations, using electrical contacts to control the light-matter coupling [59; 70]. This is a major advance compared to less direct means, such as temperature tuning [15–17] or refractive index tuning by gas injection [71]. This promises fantastic applications as well as a much cleaner environment for studying this delicate quantum system and controlling in-situ a range of system parameters (detuning, pumping, lattice temperature. . .) The all-important inclusion of a correct description of the excitation scheme as well as of other sources of dissipations, that I have shown to be important even in the simplest system, will be generalized and extended to these more elaborate systems,

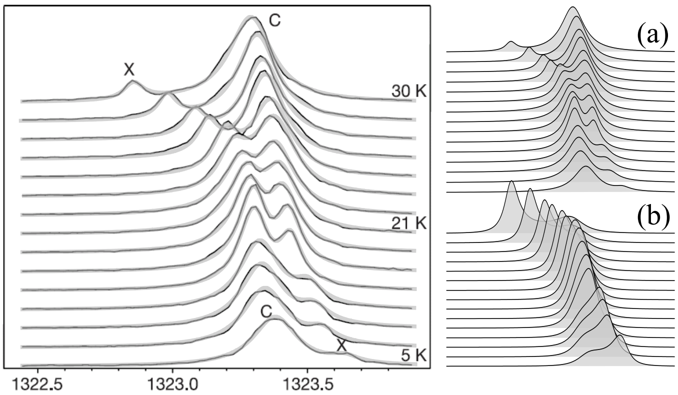

Fig. 3: Experimental anticrossing of the modes, as reported by Reithmaier *et al.* [16] with a QD in a pillar microcavity. Superimposed in light-gray and reproduced in panel (a), is my fitting with a theoretical model—the first ever attempted—including pumping [38; 69]. In panel (b), same parameters only *without* cavity pumping: the *same* system now *appears* to be in weak-coupling because of the exciton-like effective quantum state.

continuously improved in the laboratory. Features that I have previously suggested will be put to the test by an on-site careful analysis of the experimental data and comparison with an adequate theory. The predictive power will be exploited to push forward the development of devices in the laboratory and their application in performing quantum information processing. The physics that is particularly sought after by the host group in the context of their own research lines—such as spin-coupling, control with externally-applied magnetic fields, charge effects, coherent excitations, etc.—will motivate the course of my own theoretical investigations. Specific goals to be achieved by this proposal are detailed in the workplan (cf. section B4.4).

The topic is clearly multi-disciplinary since, being of such a fundamental character, it shares a lot of the basic physics and most of the terminology of other fields that study different systems. Even in the semiconductor community, it connects with different implementations such as quantum-wells where the cutting-edge research addresses the remote thematics of Bose-Einstein condensation, superfluidity and superconductivity. The successful realization of even the most basic quantum information processing task is a considerable achievement for the entire physics community.

B1.2 Research methodology

The systems will be described theoretically in the powerful and general framework of quantum dissipative master equations, that combines the Hamiltonian H (quantum) and the Liouvillian $\mathscr{L}$ (decoherence, dissipation and incoherent excitation) dynamics of the system ρ:

$$i\hbar\partial_t\rho = [H,\rho] + \mathscr{L}\rho\,.$$

Choices of H and $\mathscr{L}$ will be made and adapted by the results and directions taken by this proposal in close relation to the experimental findings, with—ab initio—room for inclusion of spin, Coulomb interaction, various dots in various geometries (cavity arrays or networks), various levels (exciton complexes), coherent or/and incoherent excitation, electric field, temperature, etc. Increasing pumping, multi-particles effects manifest, such as charged excitons and biexcitons [72], that add another type of nonlinearity to the Jaynes-Cummings dressing of the single particle state. They are important to take into account because they bring a powerful new degree of freedom, namely, polarization. Spin can also be deleterious, for instance because it allows dark states, ± 2 spin configurations which are not coupled to light and are, therefore, long-lived, thus blocking the dynamics and efficiency of the device [73]. Polarization is, thus, both an asset and a possible inconvenience. There is need of a careful analysis of its dynamics in the semiconductor (incoherently pumped) strong-coupling problem.

A quantum system is notoriously more complicated to model numerically than its classical counterpart (historically, the field of quantum computation was sparked by this observation from Feynman [74]). Previous modelizations based on an initial condition benefited from a very advantageous truncation, up to the number of excitation at $t = 0$, but a proper modelization of incoherent pumping requires much larger Hilbert spaces to accommodate for all the fluctuations caused by the excitation. Thermal fluctuations, typical of incoherent pumping, reach to very high number of excitations even when the average number of excitation remains low. When the quantum regime is pushed into its nonlinear response in this way, not only the number of correlators becomes very large, also their numerical values become very small, that is to say in practical terms, smaller than the machine precision. This is the numerical consequence of a physical trait of the system to cross from a quantized regime ruled by a finite number of large correlators, to a classical continuous field where such a discretization breaks down for an infinite number of vanishing correlators (that is of course increasingly difficult to track with the computer). It is important to retain the full quantum picture however because even in presence of many excitations, the lasing properties of a single quantum emitter differ from the semi-classical equation of conventional lasers. To study the nonlinear regime of the Jaynes-Cummings model, I have developped dedicated computer-code based on arbitrary-precision arithmetics, able—at the price of computer time and memory—to maintain such an exact, full quantum description of a particular system, by identifying correlators that get linked to the dynamics as parameters are varied. The same framework will be continued, as such difficulties will be made even more stringent in more complex systems, and, since we aim for the quantum features, they will have to be solved exactly.

The quantum qualities of a system reside in its non-classical *correlations*, and such correlations are the objects of major interest to be described theoretically and measured experimentally. While first-order correlations have been amply described in the literature [75], there are some gaps in the theoretical description of the second-order correlations, of crucial importance for quantum information. A typical quantity that is not fully described theoretically is the cross-correlation of the photon-counting type by frequency filtering [76] (for instance correlating a photon of the cavity mode with a photon of the exciton mode, or correlating distinct peaks of the Jaynes-Cummings nonlinear spectrum). This is a fairly straightforward experimental measurement, that consists in filtering the energy of the emission [77]. But an accurate theoretical description requires the computation of a four time correlator, of the type $\langle a^\dagger(t_1)a^\dagger(t_2)a(t_3)a(t_4)\rangle$ (a is the cavity mode), to be Fourier-transformed with a particular time ordering of the indices, e.g., $t_1 < t_2 < t_3 < t_4$. This is a nontrivial procedure but that is necessary to assess meaningfully two-particles correlations, such as is needed in a realistic description of entangled photon pairs [78]. There have been recent theoretical advances in the field of single molecule spectroscopy [79], but they have not been applied to the semiconductor case.

Finally, while the linear case is relatively straightforward to quantitatively compare with experimental data through standard fitting methods (e.g., Levenberg-Marquardt) [38; 59; 69], the nonlinear case calls for more elaborate procedures, such as genetic algorithms, that will be applied to bring theoretical and experimental understanding together. This will allow to provide a systematic quantitative support of the experiment with standard statistical estimators of goodness of fit, whenever the strong qualitative effects of a nonlinear quantum system are not manifested (because they are too weak, impaired by decoherence or noise, or simply not present.) We believe this research methodology is likely to lead to breakthroughs in this field by minimizing the number of uncertainties or mysteries with each new report.

B1.3 Originality and innovative nature of the project

Although the need for the approach that is proposed in this project has been recognized (see on page 15 for the reception of my work by the community), it is still largely unattended to, due to its complexity as compared to a qualitative reading of the results. In contrast, in the few cases where it has been implemented, it was done so in the particular case of the linear regime. This often falls outside the scope of quantum information processing, which typically probes the nonlinear response. A full-scale and dedicated deployment of joined theoretical/experimental efforts along the lines described above to pursue strong-light matter coupling in semiconductors from a systematic quantitative point of view, has not been yet attempted. We aim to bring additional impetus to the field with this innovative approach. From this, we will strive to raise the standards of the claims made in view of quantum information processing (that are typically very optimistic in largely idealized configurations). This approach, that has proven to yield unexpectedly rich and important consequences on the fundamental cases, will only achieve its full potential by guiding experiment and when it is itself guided by experiment.

B1.4 Timeliness and relevance of the project

After a relative dormancy following the seminal reports of strong-coupling with QDs in microcavities, there has been a recent surge of activities and reports on these systems. The number of groups now controlling strong coupling in their laboratory has multiplied at the same time as breakthroughs and puzzles are reported. The same recent upsurge of interest has also been manifested by other systems, particularly by superconducting qubits, that have became very strong candidates for solid-state implementation, both in the linear and nonlinear regimes [80]. The scientific panorama thus presents a perfect conjuncture for undertaking a joint research such as described by this proposal, and boost quantum-dot in microcavities in the race for achieving a scalable solid-state implementation.

The host group will participate to the FP7 integrated project SOLID starting January 2010, also on the topical thematics of nonlinear quantum optical phenomena in dot-cavity systems. Partners in this project include the world-leading group of A. Ĭmamoḡlu and A. Walraff from the ETH of Zurich, as well as others world-class experts on these thematics. A strong synergy would result from supporting this project and its Munich component by a FP7 individual person project.

B1.5 Quality of the host/group/supervisor

The *Technische Universität München* (Technical University of Munich, TUM) is one of the best universities in Europe. It formed four Nobel prizes in physics in the last 25 years. TUM's departments, with approximately 400 professors, 6 500 staff members and 22 000 students, are among the top institutions in national and international rankings. After having received numerous previous awards, in 2006, TUM became one of the prestigious institutions to be selected for an excellence award of 125M€ by the German Council for Science and the German Research Foundation as part of their "Excellence Initiative." TUM received the highest prize for its Entrepreneurial University concept within the so called Excellence Initiative competition by the German Federal and State Governments.

The *Walter Schottky Institute* (WSI) is a purpose built research institute of the TUM founded in 1988 to establish and strengthen interaction between basic physics and semiconductor quantum electronics. The *nanophotonics and spectroscopy group* in the Walter Schottky Institute led by Prof. Jonathan Finley, was founded in 2002 and currently has 2-postdocs, 8-PhD students and 7-Masters students. The group performs its research in the framework of several domestic research contracts, funded by the Deutsche Forschungsgemeinschaft (DFG) and German National Science foundation (BMBF). The group was involved in the foundation of SFB-631 focussing on Solid State Quantum Information Processing and Prof. Finley is a Principle Investigator within the cluster of excellence Nanosystems Initiative Munich and coordinator of NIM Area-B dealing with nanophotonic systems. The group also has two projects funded by IGGSE (`www.igsse.tum.de`) and TUM-IAS (`www.tum-ias.de`) that focus on the use of complex photonic systems for cryptography and Silicon based photonics, respectively. Over the past six years the cumulative value of the research projects conducted by the group of Prof. Finley is 3.6M€ (2003-2009). Furthermore, as discussed above, the group will participate in the EU-funded integrated project SOLID, with a focus on realizing solid-state based hybrid systems for quantum information processing.

B1.6 Host scientific expertise in the field

The host group conducts research into a diverse range of topics that focus on understanding, manipulating and exploiting electronic, spin and photonic quantum phenomena in semiconductors and nanostructured electronic and photonic materials. Principle research interests include: optical, electronic and spintronic properties of semiconductor quantum dots, wires and tube based on III-V (Arsenides, Antimonides), group-IV materials (Si, SiGe, C) and II-VI semiconductors and oxides (CdSe, ZnO). Another major research focus concerns quantum optical studies of dielectric and metallic nano-photonic materials and the application of such systems for applications in quantum information processing, metrology and sensing. The experimental activities center around several low temperature confocal microscopy systems that facilitate optical experiments on single semiconductor nanostructures (quantum dots, photonic crystals, quantum dot molecules and quantum wires) when subject to coherent laser excitation, high magnetic fields and at temperatures down to 0.5 Kelvin. Using this type of apparatus, the group has applied CW and time resolved laser spectroscopy to study:

- Cavity QED phenomena for quantum dots embedded within photonic crystal nanocavities.
- Charge and spin excitations in quantum dot nanostructures.
- Spin dependent coupling phenomena in vertically stacked double dot systems.
- Coherent phenomena and solid-state implementations of quantum information technologies.

Three optical spectroscopy laboratories will be available to the project. They are equipped with high-resolution spectrometers and both multichannel CCD and single channel photon counting detectors. Two magneto confocal microscopes allow emission and absorption measurements to be performed on single quantum nanostructures subject to magnetic fields up to 15 T. A range of tuneable CW (700-1050 nm) and pulsed (0.7-3 m) laser sources are in place.

The principal members of staff who will be involved in the project are Prof. Jonathan Finley and two postdocs (Dr. S. Frederick and Dr. M. Kaniber). Prof. Jonathan Finley has been a professor at the WSI since May 2002, and was awarded tenure in July 2007. Over the past few years he has built up a group of more than fifteen researchers investigating the fundamental electronic and optical properties of semiconductor and photonic nanostructures. Prof. Finley is recipient of a number of awards, fellowships and prizes including:

- the University of Manchester Prize for Physics (1991, 1992, 1993),
- the Walter Schottky Prize für Festkörperforschung, Deutsche Physikalische Gesellschaft (2007),
- the Deutsche Physikalische Gesellschaft (2007),
- the ISCS Young Scientist prize (2008),
- prizes from Fachschaft für Physik (TUM) for Excellent Teaching (2004, 2006, 2007, 2008),
- Royal Society (1997) and Max Planck European Research Fellowships (2002-2003).

Prof. Finley has authored and co-authored over eighty publications over the course of the past ten years (with and *h*-index of 19, he has 8 papers cited 50 times, 4 cited more than 100 times and 2 more than 280 times, demonstrating the significant impact of the group's research activites). A selection of papers of particular interest for the project are:

1. *Dephasing of quantum dot exciton polaritons in electrically tunable nanocavities*, A. Laucht, N. Hauke, J. M. Villas-Bôas, F. Hofbauer, M. Kaniber, G. Böhm and J. J. Finley, Phys. Rev. Lett, in Press, arXiv:0904.4759.
2. *Optically probing spin and charge interactions in a tunable artificial molecule.*, H. J. Krenner, E. C. Clark, T. Nakaoka, M. Bichler, C. Scheurer, G. Abstreiter, and J. J. Finley. Phys. Rev. Lett., **97**, 076403 (2006)
3. *Optically programmable electron spin memory using semiconductor quantum dots*, M. Kroutvar, Y. Ducommun, D. Heiss, M. Bichler, D. Schuh, G. Abstreiter, and J. J. Finley. Nature, **432**, 81 (2004).
4. *Inverted electron-hole alignment in InAs-GaAs self-assembled quantum dots.*, P. W. Fry, I. E. Itskevich, D. J. Mowbray, M. S. Skolnick, J. J. Finley, J. A. Barker, E. P. O'Reilly, L. R. Wilson, I. A. Larkin, P. A. Maksym, M. Hopkinson, M. Al-Khafaji, J. P. R. David, A. G. Cullis, G. Hill, and J. C. Clark. Phys. Rev. Lett., **84**, 733 (2000).
5. *Continuum transitions and phonon coupling in single self-assembled stranski-krastanow quantum dots*, R. Oulton, J. J. Finley, A. I. Tartakovskii, D. J. Mowbray, M. S. Skolnick, M. Hopkinson, A. Vasanelli, R. Ferreira, and G. Bastard. Phys. Rev. B, **68**, 235301 (2003).
6. *Fine structure of charged and neutral excitons in InAs-*$Al_{0.6}Ga_{0.4}As$ *quantum dots*, J. J. Finley, D. J. Mowbray, M. S. Skolnick, A. D. Ashmore, C. Baker, A. F. G. Monte, and M. Hopkinson. Phys. Rev. B, **66**, 153316 (2002).
7. *Observation of multicharged excitons and biexcitons in a single InGaAs quantum dot*, J. J. Finley, P. W. Fry, A. D. Ashmore, A. Lemaître, A. I. Tartakovskii, R. Oulton, D. J. Mowbray, M. S. Skolnick, M. Hopkinson, P. D. Buckle, and P. A. Maksym. Phys. Rev. B, **63**, 161305 (2001)
8. *Charged and neutral exciton complexes in individual self-assembled In(Ga)As quantum dots*, J. Finley, A. D. Ashmore, A. Lemaître, D. J. Mowbray, M. S. Skolnick, I. E. Itskevich, P. A. Maksym, M. Hopkinson, and T. F. Krauss. Phys. Rev. B, **63**, 073307 (2001).
9. *Enhanced phonon-assisted absorption in single InAs/GaAs quantum dots*, A. Lemaître, A. D. Ashmore, J. J. Finley, D. J. Mowbray, M. S. Skolnick, M. Hopkinson, and T. F. Krauss. Phys. Rev. B, **63**, 161309 (2001).
10. *Electrical detection of optically induced charge storage in self-assembled inas quantum dots*, J. J. Finley, M. Skalitz, M. Arzberger, A. Zrenner, G. Böhm, and G. Abstreiter. Appl. Phys. Lett., **73**, 2618 (1998).

B2 TRAINING

B2.1 Research training objectives for the researcher

This proposal and theme of research provides outstanding possibilities for my development as a researcher.

* *Leading my own project*: Undertaking this proposal will offer me the first occasion to fully develop my own line of research, and assuming all the responsabilities for it, a role that was shadowed in my previous post-doctoral experiences by the nature of the position, even if technically I was assuming the scientific lead role for the activity. I will here assume at their full extent the responsibilities for scientific progress, assemblage and dissemination of the results, as well as taking charge of nurturing the political and scientific environment ideal for the welfare of my proposal, in terms of establishing, fructifying and developing contacts and collaborations.

* *Tutoring new students*: As it befits to an experienced researchers and a dynamic research project, I will supervise one or more students and develop and increase many of the communication, teaching and directive techniques that I have previously exercised by implicit and/or delegated authority from the formal head of group.

* *Daily collaboration with an experimental group*: I have had only limited or partial collaboration with experimentalists in the past, working essentially as an independent (or pure) theorist. This proposal will allow me to push to its maximum the potential of such collaborations and train my ability to exchange ideas and work with experimentalists. Clearly, this direct interexchange of ideas, from experiments and from theory, is a catalyst for innovative work that is likely to have a very strong scientific impact.

* *New scientific environment*: I will join a prestigious university of significantly higher status than in my previous experiences. The host organization will allow me to be in closer contact with a wider spectrum of experts narrowly related to my research, in contrast with my past experience where I was evolving in much smaller institutions or where other fields where not significantly overlapping with my own area of research. The excellent scientific environment fostered by the close proximity of the Max Planck Institut für Quantenoptik, the Ludwigs Maximilians Universität and the TUM, is expected to significantly broaden my network of collaborators and colleagues. The close proximity of the theory groups of Peter Vogl,[1] Ignacio Cirac,[2] and Wilhelm Zwerger[3] will guarantee a rich theoretical enviroment that is expected to lead to strong synergy effects with the experimental team led by Jonathan Finley.

B2.2 Relevance and quality of additional scientific training

There are numerous asides to the scientific life that I will have the opportunity to develop:

* *Interactions skills*: Working in a dynamic and large group implies daily exchanges with highly skilled and versatile people, intense brainstorming, regular group-meetings and a higher standard of inner competition and criticism, improving my abilities enormously in this respect.

  Working in a prestigious and impactful group also implies continuous exchanges and contacts with a large community. I will thus have more occasions for giving talks and seminars in international conferences and schools, presenting and defending my work at an enhanced level.

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[1] `http://www.wsi.tum.de/Research/VoglgroupT33/tabid/116/Default.aspx`.

[2] `http://www.mpq.mpg.de/Theorygroup/CIRAC/wiki/index.php/Prof._Dr._Cirac.html`.

[3] `http://einrichtungen.physik.tu-muenchen.de/T34`.

- *Cultural skills*: At the exception of English, my language skills all evolve around the romance languages (French, Spanish and Italian). This stay will offer me the occasion to learn German. I have benefited enormously from my research stays outside of my native country (France), in terms of European integration, discovery of other cultures and contact with different working habits. This positive experience will be strengthened and further explored by my living in Germany.

B2.3 Host expertise in training experienced researchers in the field

The scientist in charge, Prof. Finley, has to date completed the supervision of three postdoctoral students, two of whom were funded by prestigious schemes (from the Alexander Von Humboldt Foundation). Recently, after his postdoctoral stay with Prof. Finley, Dr. José Maria Villas-Bôas has been awarded a permanent position in Brazil.

The scientific exploration of concepts for solid state based quantum information processing and quantum physics is naturally highly interdisciplinary calling for (*i*) the implementation of a sound strategy for sharing of information and methodologies within and outside the research group and (*ii*) effective cross training of my own students and researchers. TU München is planning to establish a comprehensive TUM Graduate School which will be open to all Ph.D. students at the Technische Universität München. Based on the structure of the successful International Graduate School of Science and Engineering (IGSSE), the TUM Graduate School will promote the development of young scientists at TUM in terms of both research and personality. The main focus is on the scientific excellence of every graduate's individual doctoral research and thesis. The Graduate School will offer a program that will generate a considerable added value in terms of (multi-) disciplinary experience, international networking, scientific and entrepreneurial know-how as well as personality development.

B3 RESEARCHER

B3.1 Research experience

I was awarded my Ph. D. diploma in theoretical physics in 2005 in Université Blaise Pascal, Clermont-Ferrand, France, with the highest distinction ("*Très honorable avec félicitations du jury*") awarded by a prestigious jury (Prof. Stephan Koch, Prof. Paolo Schwendimann, Prof. David Whittaker, Prof. Carlos Tejedor and Dr. Jacqueline Bloch).

My Ph. D. research topic was the quantum dynamics of exciton-polaritons in planar cavities. My interest turned to quantum dots in microcavities in late 2004 when strong-coupling was reported in these systems, and constituted the last chapter of my thesis.

I have post-doctoral experience from (*i*) the University of Sheffield, UK, in the group of Maurice Skolnick, working with David Whittaker (2005–2006), (*ii*) the Universidad Autonoma de Madrid, Spain, in the group of Carlos Tejedor (2007–2008) and (*iii*) to this date, from the University of Southampton, UK, in the group of Alexey Kavokin. In all these stays I have pursued simultaneously the two-dimensional (QWs) and zero-dimensional (QDs) systems.

The salient points of my scientific output are resumed below:

- I have published 31 papers in peer-reviewed journals, among which 12 in high impact (> 3) journals (1 article in Nature, 4 in Phys. Rev. Lett.) As of August 2009, I have over 180 citations according to the ISI web of science, with an h-index of 8. A selection of my finest work is:[4]

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[4] The list of *all* my publications can be found at `http://laussy.org/bibliography/laussy`.

1. *Strong coupling of quantum dots in microcavities*, F. P. Laussy, E. del Valle, C. Tejedor, Phys. Rev. Lett., **101**, 083601 (2008).
2. *Luminescence spectra of quantum dots in microcavities. I. Bosons*, F. P. Laussy, E. del Valle and C. Tejedor. Phys. Rev. B, **79**, 235325 (2009).
3. *Luminescence spectra of quantum dots in microcavities. II. Fermions*, E. del Valle, F. P. Laussy, and C. Tejedor. Phys. Rev. B, **79**, 235326 (2009).
4. *Collective fluid dynamics of a polariton condensate in a semiconductor microcavity*, A. Amo, D. Sanvitto, F. P. Laussy, D. Ballarini, E. del Valle, M. D. Martin, A. Lemaître, J. Bloch, D. N. Krizhanovskii, M. S. Skolnick, C. Tejedor and L. Viña., Nature, **457**, 291 (2009).
5. *Impact of pure dephasing on the Jaynes-Cummings nonlinearities*, A. Gonzalez-Tudela, E. del Valle, C. Tejedor, D. Sanvitto and F. P. Laussy, submitted to Phys. Rev. Lett., arXiv:0907.1302.
6. *Spontaneous Coherence Buildup in a Polariton Laser*, F. P. Laussy, G. Malpuech, A. Kavokin, and P. Bigenwald, Phys. Rev. Lett. **93**, 016402 (2004).
7. *Effects of Bose-Einstein condensation of exciton polaritons in microcavities on the polarization of emitted light*, F. P. Laussy, I. A. Shelykh, G. Malpuech and A. V. Kavokin, Phys. Rev. B **73**, 035315 (2006).
8. *Dynamics of formation and decay of coherence in a polariton condensate*, E. del Valle, D. Sanvitto, A. Amo, F.P. Laussy, A. André, C. Tejedor and L. Viña, Phys. Rev. Lett, in Press.
9. *Exciton-polariton mediated superconductivity*, F. P. Laussy, A. Kavokin and I. A. Shelykh, submitted to Phys. Rev. Lett., arXiv:0907.2374.
10. *Statistics of excitons in quantum dots and their effect on the optical emission spectra of microcavities.*, F. P. Laussy, M. M. Glazov, A. Kavokin, D. M. Whittaker, and G. Malpuech. Phys. Rev. B, **73**, 115343 (2006).
11. *Dynamical theory of polariton amplifiers*, Y. G. Rubo, F. P. Laussy, G. Malpuech, A. Kavokin and P. Bigenwald, Phys. Rev. Lett., **91**, 156403 (2003).
12. *Optical spectra of the jaynes-cummings ladder*, F. P. Laussy and E. del Valle, AIP Conference Proceedings, **1147**, 46 (2009).
13. *Optical spectra of a quantum dot in a microcavity in the nonlinear regime*, E. del Valle, F. P. Laussy, F. M. Souza, and I. A. Shelykh. Phys. Rev. B, **78**, 085304 (2008)
14. *Polariton laser and polariton superfluidity in microcavities*, A. Kavokin, G. Malpuech and F. P. Laussy. Phys. Lett. A, **306**, 187 (2003)
15. *Anticrossing in the PL spectrum of light-matter coupling under incoherent continuous pumping*, A. Gonzalez-Tudela, E. del Valle, C. Tejedor and F.P. Laussy, Superlattices and Microstructures, in Press (2009).
16. *Entanglement and lasing with two quantum dots in a microcavity*, E. del Valle, F. P. Laussy, F. Troiani, and C. Tejedor, Phys. Rev. B, **76**, 235317, (2007).
17. *Electrostatic control of quantum dot entanglement induced by coupling to external reservoirs*, E. del Valle, F. P. Laussy and C. Tejedor, Europhys. Lett., **80**, 57001 (2007).
18. *Coherence dynamics in microcavities and polariton lasers*, F. P. Laussy, G. Malpuech, A. V. Kavokin and P. Bigenwald, J. Phys.: Condens. Matter, **16**, S3665 (2004).
19. *Dissipative quantum theory of polariton lasers*, F. P. Laussy, Y. G. Rubo, G. Malpuech, A. Kavokin, and P. Bigenwald, Phys. Stat. Sol. C, **0**, 1476, (2003).
20. *The steady state of two quantum dots in a cavity*, E. del Valle, F.P. Laussy, F. Troiani and C. Tejedor, Superlatt. Microstruct., **43**, 465 (2007).
21. *Two-photon lasing by a single quantum dot in a high-Q microcavity*, E. del Valle, S. Zippilli, F. P. Laussy, A. Gonzalez-Tudela, G. Morigi and C. Tejedor, submitted to Phys. Rev. B, arXiv:0907.1861.
22. *Multiplets in the optical emission spectra of large quantum dots in microcavities*, F. P. Laussy, A. Kavokin, and G. Malpuech, Solid State Commun., **135**, 659 (2005).
23. *Single quantum dots in microcavities*, F. P. Laussy, M. M. Glazov, A. V. Kavokin and G. Malpuech, Proc. SPIE, **6328**, 63280S (2006).
24. *Polariton laser: thermodynamics and quantum kinetic theory*, G. Malpuech, Y. G. Rubo, F. P. Laussy, P. Bigenwald and A. V. Kavokin, Semicond. Sci. Technol., **18**, S395 (2003).
25. *Polariton Bose condensation in microcavities*, G. Malpuech, A. Kavokin, and F. P. Laussy, Phys. Stat. Sol. A, **195**, 568 (2003).

- * I have co-authored a 432 pages textbook (Oxford University Press) entitled "*Microcavities*", with A. Kavokin, J. J. Baumberg and G. Malpuech (2008), classed 6th in the list of best-selling books in the category "Quantum ElectroDynamics" on amazon.co.uk.
- * I have participated to 16 international conferences, 6 scientific meetings/symposiums/workshops and 4 summer schools,[5] where I have given in total 15 talks (6 of which invited) and presented 11 posters. A selected list of the most notable events I attended is:
  - ICPS28, NOEKS7, ICTOPON.
  - ICSCE 1, 2 & 4, OECS9.
  - PLMCN 3, 4, 5, 7, 8 & 9.
  - CL & CL1 International School of Physics "Enrico Fermi", Varenna.
  - International School of Nanophotonics of Maratea, 2005 & 2009.
- * I was guest editor of two conferences volumes [Phys. Stat. Sol. (c), Vol. 1, No. 6 (2003) and Superlattices & Microstructures Vol. 43, Issues 5-6, Pages 383-654 (2008)]; I was the Scientific Secretary for the most successful and largest edition so far of the Physics of Light-Matter Coupling in Nanostructures (PLMCN) international conference, the PLMCN7 in Habana, Cuba (2007).
- * I am a regular referee for the Physical Review (Lett. and B), and an occasional referee for Solid State Communication, Journal of Luminescence, the European Journal of Physics, Superlattices and Microstructures, etc…
- * I have been invited for a two-month stay in the International Center of Condensed Matter Physics (ICCMP) in Brasilia (Brasil) in 2007.

B3.2 Research results

My research topic is semiconductor microcavity physics, and therefore in direct line with the present proposal. Beside the zero-dimensional case, that is the one targeted by this proposal, I also study the two-dimensional case of quantum wells in planar cavities, where I have had significant and early contributions in all the major trends of this topic, namely, Bose-Einstein condensation of polaritons, superfluidity of polaritons and, very recently, superconductivity of polaritons.

For the sake of clarity, I will separate the two activities, starting with 2D polaritons that I will briefly overview, and I will detail the 0D case which is central to the goals of this proposal. The number of citations is as given by the Web of Knowledge by the time of submitting this proposal.

Light-matter coupling in 2D microcavities

1. I demonstrated the possibility to grow coherence spontaneously in a planar microcavity and realize a polariton laser; Laussy *et al.*, Phys. Rev. Lett. (2004). (47 citations).
2. I offered the theoretical description and chiefly contributed to the interpretation of the experiments of A. Amo and D. Sanvitto *et al.* reporting the superflow of a polariton bullet; Amo, Sanvitto, Laussy *et al.*, Nature (2009). (8 citations).
3. I highlighted with I. Shelykh and A. Kavokin the role of polarization in the Bose-Einstein condensation of polaritons; Laussy *et al.*, Phys. Rev. B (2006). (23 citations).

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[5] The list of events I have attended and the details of my participation can be found at `http://laussy.org/conferences-and-meetings`.

4. I recently proposed with A. Kavokin and I. A. Shelykh a new concept of superconductivity, mediated by polaritons, with prospects of record-breaking critical temperatures; Laussy *et al.*, arXiv:0907.2374, submitted to Phys. Rev. Lett.

Other notable works to which I contributed significantly on this thematics are Rubo, Laussy *et al.*, Phys. Rev. Lett. (2003) (25 citations), Kavokin *et al.*, Phys. Lett. A (2003) (28 citations), Malpuech *et al.*, Semicond. Sci. Technol. (2003) (23 citations) and del Valle *et al.*, arXiv:0903.1954, accepted for publication in Phys. Rev. Lett. (2009).

Light-matter coupling in 0D microcavities

1. I studied the strong coupling of particles with exotic statistics (neither fermion nor boson), realized in quantum dots of varying sizes; Laussy *et al.*, Phys. Rev. B. (2006) (8 citations).
2. I studied the effect of pumping in the *linear* regime of light-matter coupling; Laussy *et al.*, Phys. Rev. Lett. (2008) (8 citations) & Laussy *et al.*, Phys. Rev. B. (2009) (1 citation).
3. I studied the effect of pumping in the *nonlinear* regime of light-matter coupling; del Valle *et al.*, Phys. Rev. B. (2009) (1 citation).
4. I studied the impact of pure dephasing on the Jaynes-Cummings nonlinearities, offering an explanation to the perplexing spectral triplets reported by various experiments; Gonzalez-Tudela *et al.*, arXiv:0907.1302, submitted to Phys. Rev. Lett.

Other notable works to which I contributed significantly on this thematics are del Valle *et al.*, Phys. Rev. B, (2007) (2 citations), del Valle, Laussy *et al.*, Phys. Rev. B (2008) (1 citation) and del Valle *et al.*, arXiv:0907.1861, submitted to Phys. Rev. B.

More details on my recent work on light-matter coupling in 0D microcavities

With the 2004 breakthroughs [15; 16], I started to investigate the problem of strong light-matter coupling in quantum dots. I then followed the standard procedure of focusing on the Hamiltonian (coherent) dynamics. I thus investigated the effect of Pauli statistics in large dots [82] or in collection of dots [83], culminating with a study of the excitons statistics due to Pauli blocking of the underlying electron-hole constituents [84]. Upon joining the group of Sheffield, I attempted on the same grounds a description of the experiments carried out there, but could only get a weak qualitative agreement.

I understood that a very important specificity of the semiconductor experiment was not properly taken into account, namely, the pumping. The typical practice—inherited from the canonical case of atomic cavity QED, where atoms are injected in their excited state into the cavity—was to consider the spontaneous emission of the excited state of the exciton. In some limit, this also covers the coherent excitation scheme. But experiments with dots in microcavities are in their great majority conducted under the action of a continuous incoherent excitation (for instance by exciting above the bandgap). Another particularity of the semiconductor case is that the environment is very noisy, and there are typically a lot of neighboring dots around the one that enters the strong-coupling (quantum) dynamics with the cavity. These can get excited too and contribute photons in the cavity, that provide an effective cavity pumping to the strongly-coupled dot. As a result, the dot-cavity system should not be considered in the spontaneous-emission picture of an excited (pure) state $|\psi\rangle$, but rather in the general case of an arbitrary *mixed* state ρ, which can be photon-like or exciton-like depending on the ratio of the effective cavity/electronic pumping (which is determined by many factors such as the geometry of the experiment, quality of the device, etc.)

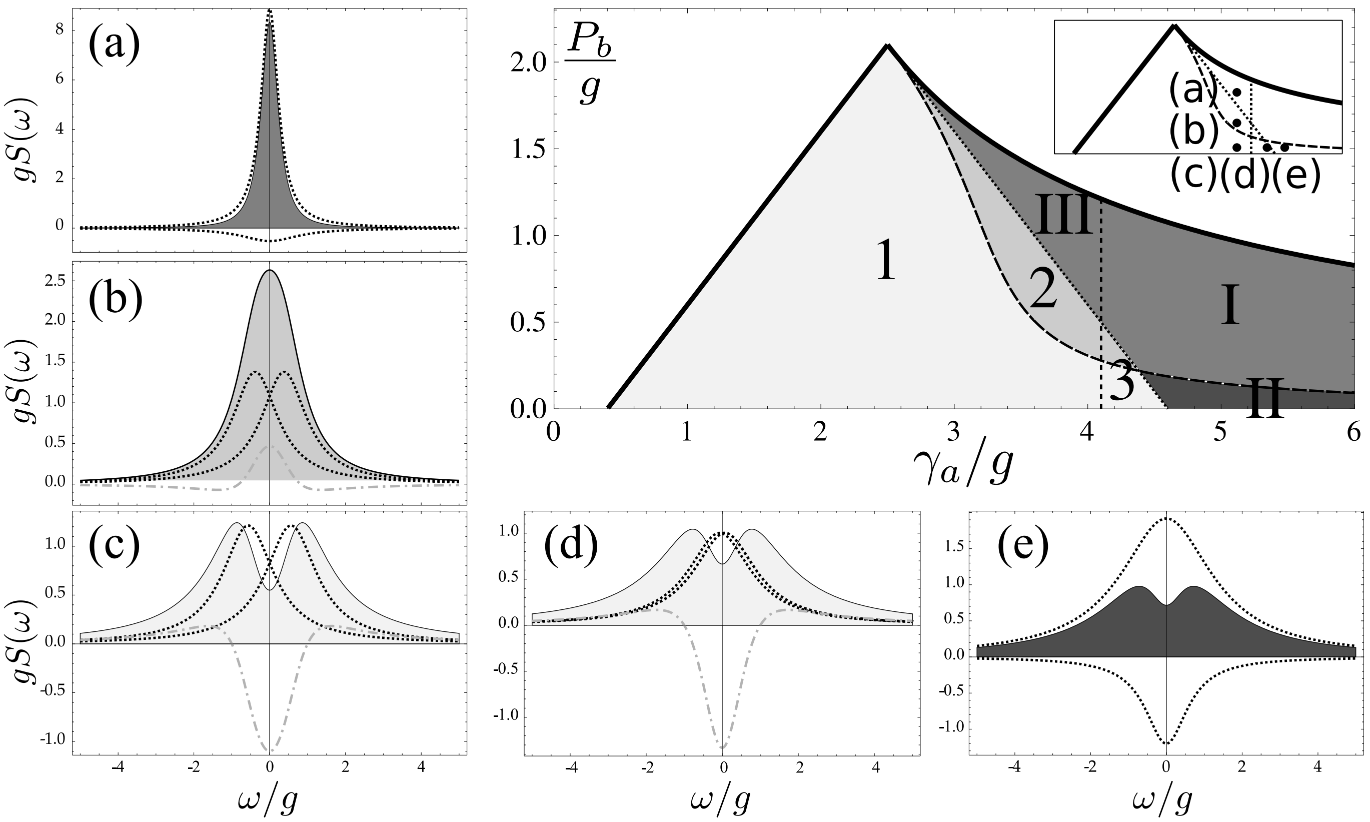

Fig. 4: *A new outlook at light-matter coupling*, as provided by my work [66]. Pumping P_b adds a new dimension to the problem (γ_a is the cavity decay rate, all quantities are in units of the coupling strength g). This phase-diagram of strong (light shades of grey/latin numerals)/weak (dark shades of grey/roman numerals) coupling, provides an extended picture of the textbook case. Zone 1 is the conventional strong-coupling, zone 2 is strong-coupling that cannot be resolved because of too large broadening-to-dressed-modes-splitting ratio, zone 3 is in strong-coupling in the new theory that includes pumping [66] when it is in weak-coupling according to the one that neglects it. Zone I is the conventional weak-coupling, zone II is in weak-coupling but features two-peaks at resonances from a Fano effect [81], zone III is in weak-coupling because of pump-induced decoherence when it would be in strong-coupling neglecting pumping. In inset, selection of five points in these various regions of interest, whose optical spectra $S(\omega)$ are displayed in panels (a)–(e), showing, in solid, the photoluminescence spectral line, in dotted, the Lorentzian emission (the dressed-states when in strong-coupling) and in dash-dotted, the dispersive correction due to strong-coupling. *Line-splitting at resonance neither implies nor is implied by strong-coupling*.

Pumping also becomes of paramount importance when considering the nonlinear regime, that is, when more than one-particle effects are involved. The arbitrary choice of some initial condition in the linear case becomes dramatically wrong in the nonlinear case as it misses all the dynamic effects of the statistics, namely, line-narrowing that goes like the inverse occupancy of a bosonic mode (Schawlow-Townes effect) and, on the opposite, line-broadening of a saturating fermionic mode due to phase-space filling. Also the fluctuations of particles contribute importantly in the semiconductor, as compared to the initial-state (or atomic) case. Thermal states are fluctuating wildly, and therefore nonlinear effects contribute significantly even at pumping powers that are deemed weak. Increasing pumping in the hope of evidencing a nonlinear quantum response, would in fact bring the system to the nonlinear *classical* response (lasing). I have estimated that with structures of today, the nonlinear quantum regime is at reach, but possibly requiring careful analysis or preparation (such as ensuring a photon-like character of the effective state realized in the system).

All these ingredients put together brought me to an elegant, self-contained and complete description of light-matter coupling, that extends the textbook system, calling to redefine one's understanding of what characterizes strong coupling. For instance, I have shown from this generalized viewpoint that anticross-

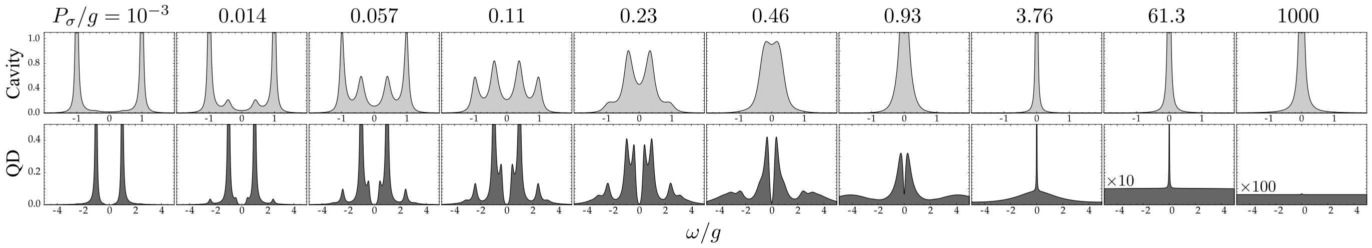

Fig. 5: Exact quantum-optical calculation of the photoluminescence of a single-QD as electronic pumping P_σ is varied (in units of the QD-cavity coupling strenght g), from Ref. [65]. In light-grey (upper row), the cavity emission, in dark-gray (lower row), the direct exciton emission. This study shows the various regime of the light-matter coupling under continuous excitation: the linear regime, with only the Rabi doublet (note the different x-scale), the quantum regime, with a few quanta ruling the dynamics, the transition to lasing, lasing, and quenching. This theory still lacks some of the complications of the experiment (such as dephasing) or the experiment is still not ripe to evidence this prediction of the theory. This proposal will aim at identifying the source and reason for such mismatches.

ing in the photoluminescence spectrum is neither necessary nor sufficient to evidence strong-coupling. In the boson model, that also provides a generalized picture of the standard theory in the limit of vanishing pumping, I have defined a new phase-diagram of strong-coupling, depicted on Fig. 4.

As a consequence of my analysis, I have shown the limitation and possible mistakes in the practices of the community to read their data with the spontaneous-emission (atomic) models. I attempted the first confrontation of the complete theory with the quantum dot/cavity strong-coupling experiment [38], choosing for this purpose the seminal report of Reithmaier *et al.*, Nature (2004). I obtained a very good agreement (see Fig. 3), and demonstrated the risk of important errors by fitting with Lorentzian lineshapes, rather than using the exact quantum-optical spectral shape. I commented on the need for a more careful and joint effort between experimentalists and theorists in this endeavor, so as to extract relevant statistical estimators of the analysis [69], and confront various models against each other (e.g., the boson vs the fermion model). Later, I showed that—due to the Abel-Ruffini theorem—fitting of the data could only be performed with the entire spectral line, and that fitting of the maxima of an anticrossing experiment was not possible by standard procedures [67].

Recently, I included in our nonlinear model (see Fig. 5) a pure dephasing term, that has has been demonstrated by experimentalists and theoreticians alike to be an important factor. I obtained a robust tendency of the system to display a triplet-like structure instead of the Jaynes-Cummings quadruplet, as would be obtained without dephasing. I therefore believe this could have brought under a unified formalism various experimental findings that have remained so far unexplained, or based on negative conclusions (like, the central peak being irrelevant).

Reception of my work by the community

(I will address only my work on 0D systems, that is the one relevant to this proposal.)

Although recent, the work has attracted much attention from the community. I will overview here the cases where, beyond a mere quotation, a direct and explicit mention was made to my approach and/or results.

Two leading experimental groups have since adapted my model to describe their experimental findings in a *quantitative* way:

1. Laucht *et al.* (Finley's group) have included pure dephasing in the linear limit, and could obtain an impressive agreement. Their fit (on their own data) is a markedly progress on my first attempt (on published—not raw—data), showing the viability and the potential of the approach. They could indeed perform a global fitting constraining for a given spectrum more parameters than I did, letting

vary only those that were clearly expected to, and access a new reading of the physics of dephasing, in particular, from the results [54].

2. Münch *et al.* (Forchel's group) compared my theory with their data varying pumping power and also obtained a very good agreement [57], evidencing a collapse of the Rabi doublet that, in the model they have chosen (also the linear model), translates a pump-induced loss of strong coupling. This confirms my earlier analysis of similar systems [38].

There are great prospects in extending such practices, and one outcome of this proposal would be to demonstrate it and motivate its generalization in the community (that is still recurring to methods that I have shown are mathematically impossible [67]).

Other leading experimental groups have called on to my work in its *qualitative* lines:

1. Dousse *et al.*, (Bloch's group) relied on my results to justify the varying visibility of the line-splitting in their scalable implementation of strong-coupling [22].
2. Nomura *et al.* (Arakawa's group) invoked my generalized definition of Strong-Coupling in the non-linear case, when higher manifolds of the Jaynes-Cumming ladder are excited. [85].
3. Yamaguchi *et al.* (Noda's group) adapted my independent pumping scheme in an exciton-complex hamiltonian [86].

It is interesting in particular to compare the evolution of the different versions of the preprint of Nomura *et al.* [85], that shows an increasing reliance upon my work. In their last version (v2), they now interpret transition to lasing as a nonlinear progression in the strong-coupling regime, as described by my model and shown on Fig. 5. Technology is still behind a direct manifestation of such Jaynes-Cummings multiplet structures, as seen on this figure. Unravelling them through a careful interpretation of and recourse to the theory is one of the chief goals of this proposal.

B3.3 Independent thinking and leadership qualities

I have presented most of the results above as mine, and I regard them as such, although I have, naturally, benefited tremendously from my co-authors in pursuing and interpreting them. They have been, however, mainly the product of my independent thinking. I list here some factors that support my personal merit in formulating/developing them:

1. I self-handedly introduced the notion of quantum Boltzmann master equations in the group of Pr. A. V. Kavokin while a student, that coupled to their expertise in simulating semi-classical Boltzmann equations, led to one of the most highly quoted papers of the group.
2. I led the theory efforts, conceptual interpretation and writing of the text that led to a publication in Nature, reporting superflow of polaritons. (This work has been for me a revealing example of a successful collaboration between experimentalists and theorists).
3. I led the activity of Strong-Coupling of quantum dots in Microcavities in the group of Madrid, that resulted in the papers [38; 66–68; 87], as among the most notable. I still lead the efforts there although at a distance, which has resulted in a considerable slow-down of the activity.

One the main prospect of this grant would be to allow me to strenghten my role as an independent thinker and leader of my own activity. In the past, I had circumstantial opportunities to put these to the test:

1. I have supervised daily the work of Elena del Valle upon joining the group of Prof. Carlos Tejedor in Madrid in 2007, where she was a Ph. D. student. This resulted in her publication of four letters (one in Nature, two in Physical Review), four regular articles (all in physical reviews) and various communications in conference proceedings. She only has one publication on a similar duration of time (in a conference proceedings) before my tutoring her. Her formation has been successful since Elena has since demonstrated herself an independent researcher leading successfully various derived activities on her own ([88; 89]).
2. I involved Alejandro Gonzalez-Tudela, a beginning Ph. D. student also in the group of Prof. Carlos Tejedor, on similar thematics, which resulted so far in a conference proceedings communication [67] and a strong paper currently under consideration for publication in Phys. Rev. Lett. [68]

B3.4 Match between the fellow's profile and project

The project is a full-scale implementation with expert experimentalists on a theme that I have contributed to shape in the last couple of years, as attested by the echo it received in the community. There is therefore no doubt that my profile fits perfectly with the ambitions advanced by this proposal.

B3.5 Potential for reaching a position of professional maturity

From there on, the successful undertaking of this proposal is the best assurance of a positive outcome to my application for a position in the academia, or for another important fellowship or tenure/track that would open wider the doors to a prestigious position. Given the knowledge and know-how that I would have acquired in the mean-time in the administration and handling of scientific, human and technical problems, I believe this would also be a perfect preparation for it.

B3.6 Potential to acquire new knowledge

The prestigious host and the excellence of its network of contacts and collaborators would be an obviously brainstorming environment to work, that has been unmatched in my previous post-doctoral stays. I would widen considerably my circle of scientific acquaintances and collaborators, which would result in new ideas, research habits, working skills and a fresh outlook on the field at large.

B4 IMPLEMENTATION

B4.1 Quality of infrastructures/facilities and international collaborations of the host

The Technische Universität München (TUM) has earned a high international reputation that is apparent from research collaborations with more than 140 partner Universities, and its involvement in about 150 FP6 projects, 420 Projects financed by the German federal Ministry of Science and in 17 special research programs financed by the German Research Association (DFG). Moreover, TU Munich has very close collaboration with DTU Kopenhagen and Technical University Eindhoven which build a European University Alliance in Science and Technology.

The crystal growth expertise and capabilities required to realize quantum dot and photonic nanostructures is well established at the WSI. It is built around a state of the art clean room facility that contains state of the art equipment for semiconductor device growth and fabrication. Extensive nanofabrication facilities exist on site including state of the art electron-beam lithography, ion beam lithography and RIE systems together with the required know how to realize single dot photonic crystal devices. When combined with a wealth of experience in low temperature CW and time resolved magneto-optical spectroscopy, the extensive infrastructure at the WSI lends itself well to the requirements of the project.

Two of the projects of Prof. Finley's group that are relevant to the present proposal, are supported by the DFG via SFB-631,[6] NIM[7] and the German National Science foundation (BMBF) and are worth a total of ≈1.5M€ and ≈1M€, respectively. They will continue to run at least until the end of 2011, thus, guaranteeing close collaboration within the framework of this proposal. Collectively, the projects aim to achieve control of the light-matter interaction at the single photon-single emitter level with a view to realizing devices such as efficient single photon emitters, low threshold nano-lasers and circuit QED in the optical regime. Such, QD-nanocavity systems provide the promise to realize "on-chip" quantum optics using single photons with many applications in the field of quantum and classical communications and optoelectronics. They are now described in more details.

Solid state quantum optics using semiconductor nanostructures

The nanostructures fabricated in the host group are among the state-of-the-art worldwide (cf. Fig. 2), providing mode quality factors in excess of 10^4 and cavity field volumes $V < (\lambda/n)^3$. Currently, the group of Prof. Finley are exploring techniques to deterministically place the cavity around specific QDs and have successfully attached wires to single nanocavities to electrically control the frequency detuning between the QD exciton and cavity mode. This is a major development on which I will capitalize in this proposal. Earlier this year, the group of Prof. Finley were amongst the first worldwide to achieve strong coupling in an electrically tunable photonic crystal nanocavity. Time resolved and CW spectroscopy has been used to probe the photonic properties of these systems and study the light-matter coupling in the weak and strong coupling regimes. Achieving strong coupling for a single quantum dot (QD) in a tunable solid-state optical cavity is of utmost importance, since it provides access to rich new phenomena in a novel device with widespread potential applications in quantum information science and "few-photon" photonics. In the near future, the group plans to investigate spin-polarization inter-conversion. Such experiments are complicated for neutral atoms or ions in cavities due to the difficulty of localizing the atom at the field maximum of a cavity for a long time or achieving sufficiently small mode volumes due to the electrodes in ion traps. In contrast, electrons with a well defined spin can be optically or electrically injected into the QD and detected optically with high external efficiency via the polarization of the emitted photon.

Optical control of electron and hole spin states in optically active quantum dots

The ability to control charge and spin in solids at the single electron level is a key requirement for future devices in the fields of quantum information science and spintronics. Isolation of carriers within self-assembled quantum dots (QDs) inhibits spin relaxation, serves to extend coherence times and provides strong potential for spin based opto-electronic devices with new functionality. In these projects, the group of Prof. Finley have been focusing on electrically tunable single and double QD nanostructures that can be controllably populated by one or two electrons. Techniques have been developed that allow them to optically prepare a single charge and monitor its spin dynamics. Most recently, they successfully measured the spin dynamics of a single electron, work that will soon be published. Current activities focus primarily on coherently manipulating the spin of isolated electrons and combination with strategies for manipulating spin-spin couplings in electrically tunable double QD nanostructures. In the very near future, the group expect to achieve coherent control of individual spins by dot selective, optically detected magnetic resonance.

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[6] `www.wmi.badw-muenchen.de/SFB631`.

[7] `www.nano-initiative-munich.de`.

To do this, they have equipped their confocal microscopy setup with an X-band microwave delivery system (7-14GHz). Studies of the electron-nuclear spin coupling are also underway in double dots, a system that provides the intriguing possibility to realize electro-optically switchable nano-magnets.

B4.2 Practical arrangements for the implementation and management of the scientific project

The Technische Universität München offers Scientists benefiting from international funding programmes high quality services regarding all research related questions. In particular, the Centre for Research Support and Technology Transfer (TUM Forte, `http://portal.mytum.de/forte`) and its EU-office give advice in the management and implementation of the project.

B4.3 Feasibility and credibility of the project

The project builds upon a research topic that I have previously successfully addressed, to be paired with a very successful and dynamic group of experimentalists. It is expected that the strengths of the respective components will reinforce each other and lead to strong synergy effects. Unravelling the powerful and dedicated methods I developped recently [38; 65; 66] has moreover already proven flexible and successful to be generalized to more ambitious cases (such as two-photon lasing [89]). I fully expect that this project will reach most of its objectives. The most advanced goal of this proposal, namely the realization of working, efficient quantum devices, is a very ambitious objective, but it is not excessively risk-taking as even if it is not fulfilled during the project time, there are strong indications pointing to significant advances towards it, in any case.

B4.4 Work plan

The primary goals of this project can be articulated around the following list of main objectives, that will be undertaken as soon as the proposal will start, roughly in chronological order, as they are of increasing difficulty, but they are called to be adapted to the progresses realized throughout the collaboration. The main objectives are:

1. Observe or evidence the Jaynes-Cummings $\pm(\sqrt{n+1}\pm\sqrt{n})$ nonlinearities.
2. Develop the theory of colored photon-counting and account quantitatively for relevant quantum correlations in the experiment.
3. Develop the theory to describe the quantum dynamics of strongly-coupled semiconductor quantum dots under incoherent pumping, taking into account the spin degree of freedom and Coulomb interaction of carriers, and match it to (or guide it with) the experiment.
4. Model theoretically and assist the experimental realization of elementary but working and usable quantum devices, such as single-photon sources and entangled-photons pair emitter.

In more detailed regarding the above points:

1. This first goal will set on rail the spirit of the collaborative efforts central to this proposal. Observing directly—through the fine-structure splitting—or evidencing indirectly—through a resonant probe—the Jaynes-Cummings nonlinearity will be a breakthrough, albeit an expected one, in the fundamental physics of cQED with semiconductors, demonstrating without any ambiguity (and thus for the first time), the correctness of the full-quantization picture. They will demonstrate the field is ripe for implementing fully quantized schemes. The lack of such an experimental demonstration will mean that some assumption on

the system is fundamentally mistaken, with dramatic consequences for the community at large. The anticipated outcome is that they are present and follow the widely expected Jaynes-Cummings physics, with possible variations that we shall seek to pinpoint (such as the effect of pure dephasing, in which case this first goal would consist in demonstrating that the spectral triplet indeed arises as a consequence of dephasing from the Jaynes-Cummings nonlinearities, and follows the trends predicted by the theory).

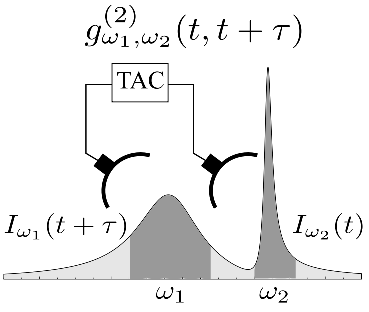

Fig. 6: Schematic representation of a colored photon-counting experiment, a technique increasingly used experimentally [48]. The theory for describing it is only emergent and from other fields [79]. I will adapt and extend it to the semiconductor case.

2. Theoretically, it is straightforward in most models to compute the zero-delay ($\tau = 0$) two-photon counting of a given well-defined mode, typically of the cavity emission (with intensity I):

$$g^{(2)}(\tau) = \lim_{t\to\infty} \frac{\langle : I(t+\tau)I(t) : \rangle}{\langle I(t)\rangle^2} .$$

Even the τ dynamics is relatively direct to obtain, from the quantum regression theorem. However, as discussed previously, the theory of frequency-dependent ("*colored*") and time resolved photon counting has not been yet fully developed and in particular not applied to the case of a quantum dot in a microcavity. I will work toward developing the formalism and techniques required to compute this quantity, $g^{(2)}_{\omega_1,\omega_2}(t,t+\tau) \propto \langle : I_{\omega_1}(t+\tau)I_{\omega_2}(t) : \rangle$, in the semiconductor case, e.g., self-consistently with pumping (see Fig. 6), and confront it to the experimental results, where the counterpart quantity is already being measured. Proper use of this tool—in particular extending it to spin—will also endow us with a powerful and relevant description of entanglement achievable with these systems. After all, quantum optics and quantum information processing is essentially a study of the quantum correlations.

3. This goal is fairly self-explanatory: I will extend my previous models to include the spin degree of freedom and Coulomb interaction between careers, which will bring into the picture all the rich physics of exciton-complexes (such as bi-exciton lines, charged dots) and of polarization. The methods previously or simultaneously developped will be applied in this extended model as well, that, closer to the experimental reality, will have demultiplied descriptive and predictive power.

4. Empowered by all the theoretical machinery and know-how developed as part of this collaboration, we shall aim at impactful realizations of working, efficient and useful devices, with potential immediate spin-off in terms of technological applications. In particular, we shall focus on realizing single photon-emitter, based on mastering all the key elements involved, in particular, again, pumping, that has been typically neglected in the measure of quantum efficiency of such devices [90], whereas I have already shown it to affect dramatically the antibunching ($g^{(2)}(0)$) [65]. Joint theoretical/experimental effort could lead to important advances in the technology of single-photon sources, important for quantum cryptography applications. Prospects of electrically controlled, steady state operation of a single-photon source could lead to a patent. Beyond single-photon sources, that are already implemented in a wealth of systems, we shall study the topical case of entangled-photon pairs emitters. However, there have been recent theoretical proposals [91; 92] that neglect the excitation scheme altogether, and are more likely to be completely disconnected from a realistic realization, despite relying on a correct (and insightful) mechanism.

B4.5 Practical and administrative arrangements and support for the hosting of the fellow

TU München offers a wide range of services to welcome guest scientists and help them in adjusting to the new conditions in Munich. Contacts are established before the arrival of the scientist. After receiving the contact details from the inviting Chair, the International Office gets in touch with the guest scientist offering help concerning administrative application processes and/or finding accommodation in Munich. Special support is offered for the family of the scientists that is to join them. Also the further bureaucratic processes after the arrival and in the first days of the stay will be continuously supported by the International Office. This support comprises help in obtaining a residence and working permit, registering for a health insurance and other questions arising from the stay in Germany (e.g. opening a bank account, public transport system in Munich, language courses, etc. . .) All these services are coordinated by the International Office and take place in close cooperation with the related offices at TUM (e.g. Language Center, Career Service, Admission Office). To give the scientist (and his family) also the opportunity to meet researchers from other faculties and to quickly feel socially integrated, there is a special service-programme for international guests at TUM organized by the International Office containing guided-tours, workshops, lectures, etc. Moreover, TU München has childcare facilities at all its locations and are continuously extended. The family service office gives support in child care and elder car. Therefore, TU München achieved the Certificate "Familiengerechte Hochschule" (Hertie-Stiftung).

Language support for the applicant would be welcome (more than necessary) as I have only elementary notions of German, but am otherwise an eager linguist fluent in three languages (French, English, Spanish) and with good level in a fourth one (Italian). There would be however no problem whatsoever at any stage of my stay to communicate in English with my collaborators, who are all researchers of the highest international status.

B5 IMPACT

B5.1 Potential of acquiring competencies

This proposal is expected to complete my formation from a beginning researcher with much post-doctoral experience, to a fully-fledged independent researcher able to start the dynamics of an independent group. All the required competencies for this ultimate goal are within the scope of a successful undertaking of this project.

B5.2 Contribution to career development

This proposal will contribute to my career development by the expected output in terms of high-impact publications and original findings. It will help establish my visibility and reputation in the community at large, which will help me constitute a scientific curriculum that will allow me to claim to continued strong career moves.

B5.3 Contribution to European excellence and European competitiveness

This proposal will support and push forward the achievements of the European union in one of the key sector of today's fundamental and applied research. It is possible that patents are issued among some of the leading results of this proposal, that will otherwise be measured in terms of publications in high-impact journals and number of quotations.

This research program is also of high interest for various other groups of the European Union, which work on similar thematics, also at a high international level, and with whom I am in contact, such as groups in Sheffield (M. Skolnick, A. Tartakovskii, A. Ramsay), Paris (J. Bloch, P. Senellart), Madrid (D. Sanvitto, C. Tejedor, J. Calleja,), etc. . . I will endeavor to keep them associated and/or interested to our research efforts and results, so as to endow them with as much impact as possible. In return, this will participate to increase European collaboration.

B5.4 Benefit of the mobility to the European Research Area

Although myself (the applicant) and the host institution have known each other through our respective scientific production, we have never collaborated together. I have worked for extended periods of time in a French university (my Ph. D. alma mater), two different British universities and one Spanish university, but never in Germany, that I actually only visited twice (at the occasion of the CoPhen04 in Dresden and the NOEKS7 in Karlsruhe). The mobility for me is therefore optimum. It will be beneficial for the European Research Area through the links it will establish between research groups that have no or little direct interactions between them.

B6 ETHICAL ISSUES

I confirm that my proposal is not concerned by any of the ethical issues regarding human beings, human embryo/fœtus, people's informed consent and privacy, animals, terrorism, military and/or developing countries, or of any other kind.

References

[1] Gisin, N., Ribordy, G., Tittel, W. & Zbinden, H. Quantum cryptography. *Rev. Mod. Phys.* **74**, 145 (2002).

[2] Nielsen, M. A. & Chuang, I. L. *Quantum Computation and Quantum Information* (Cambridge University Press, 2000).

[3] Zhirnov, V. V., III, R. K. C., Hutchby, J. A. & Bourianoff, G. I. Limits to binary logic switch scaling—a Gedanken model. *Proc. IEEE* **91**, 1934 (2003).

[4] S. J. van Enk, H. J. K. & Mabuchi, H. Quantum information processing in cavity-qed. *Quantum Information Processing* **3**, 75 (2004).

[5] Cohen-Tannoudji, C., Dupont-Roc, J. & Grynberg, G. *Photons et atomes* (EDP Sciences, 2001).

[6] Raimond, J. M., Brune, M. & Haroche, S. Manipulating quantum entanglement with atoms and photons in a cavity. *Rev. Mod. Phys.* **73**, 565 (2001).

[7] Angelakis, D. G., Santos, M. F. & Bose, S. Photon-blockade-induced mott transitions and XY spin models in coupled cavity arrays. *Phys. Rev. A* **76**, 031805 (2007).

[8] Makin, M. I., Cole, J. H., Tahan, C., Hollenberg, L. C. L. & Greentree, A. D. Quantum phase transitions in photonic cavities with two-level systems. *Phys. Rev. A* **77**, 053819 (2008).

[9] Carusotto, I. *et al.* Fermionized photons in an array of driven dissipative nonlinear cavities. *Phys. Rev. Lett.* **103**, 033601 (2009).

[10] Gerace, D., Türeci, H. E., Ĭmamoḡlu, A., Giovannetti, V. & Fazio, R. The quantum-optical josephson interferometer. *Nature Phys.* **5**, 281 (2009).

[11] Haroche, S. & Kleppner, D. Cavity quantum electrodynamics. *Physics Today* **42**, 24 (1989).

[12] Thompson, R. J., Rempe, G. & Kimble, H. J. Observation of normal-mode splitting for an atom in an optical cavity. *Phys. Rev. Lett.* **68**, 1132 (1992).

[13] Boca, A. *et al.* Observation of the vacuum Rabi spectrum for one trapped atom. *Phys. Rev. Lett.* **93**, 233603 (2004).

[14] Walther, H., Varcoe, B. T. H., Englert, B.-. & Becker, T. Cavity quantum electrodynamics. *Rep. Prog. Phys.* **69**, 1325 (2006).

[15] Yoshie, T. *et al.* Vacuum Rabi splitting with a single quantum dot in a photonic crystal nanocavity. *Nature* **432**, 200 (2004).

[16] Reithmaier, J. P. *et al.* Strong coupling in a single quantum dot–semiconductor microcavity system. *Nature* **432**, 197 (2004).

[17] Peter, E. *et al.* Exciton-photon strong-coupling regime for a single quantum dot embedded in a microcavity. *Phys. Rev. Lett.* **95**, 067401 (2005).

[18] Khitrova, G., Gibbs, H. M., Kira, M., Koch, S. W. & Scherer, A. Vacuum Rabi splitting in semiconductors. *Nature Phys.* **2**, 81 (2006).

[19] Wallraff, A. *et al.* Strong coupling of a single photon to a superconducting qubit using circuit quantum electrodynamics. *Nature* **431**, 162 (2004).

[20] Gröblacher, S., Hammerer, K., Vanner, M. R. & Aspelmeyer, M. Observation of strong coupling between a micromechanical resonator and an optical cavity field. *Nature* **460**, 724 (2009).

[21] Hammerer, K. *et al.* Strong coupling of a mechanical oscillator and a single atom. *Phys. Rev. Lett.* **103**, 063005 (2009).

[22] Dousse, A. *et al.* Scalable implementation of strongly coupled cavity-quantum dot devices. *Appl. Phys. Lett.* **94**, 121102 (2009).

[23] Henini, M. Properties and applications of quantum dot heterostructures grown by molecular beam epitaxy. *Nanoscale Res. Lett.* **1**, 32 (2006).

[24] Reed, M. A. Quantum dots. *Sci. Am.* **268**, 118 (1993).

[25] Reed, M. A. *et al.* Observation of discrete electronic states in a zero-dimensional semiconductor nanostructure. *Phys. Rev. Lett.* **60**, 535 (1988).

[26] Badolato, A. *et al.* Deterministic coupling of single quantum dots to single nanocavity modes. *Science* **308**, 1158 (2005).

[27] Weisbuch, C., Nishioka, M., Ishikawa, A. & Arakawa, Y. Observation of the coupled exciton-photon mode splitting in a semiconductor quantum microcavity. *Phys. Rev. Lett.* **69**, 3314 (1992).

[28] Winger, M., Badolato, A., Hennessy, K., Hu, E. & Ĭmamoḡlu, A. Quantum dot spectroscopy using cavity QED. *arXiv:0808.2890* (2009).

[29] Noda, S., Fujita, M. & Asano, T. Spontaneous-emission control by photonic crystals and nanocavities. *Nature Photon.* **1**, 449 (2007).

[30] Bayer, M. *et al.* Inhibition and enhancement of the spontaneous emission of quantum dots in structured microresonators. *Phys. Rev. Lett.* **86**, 3168 (2001).

[31] Xie, Z. G. *et al.* Influence of a single quantum dot state on the characteristics of a microdisk laser. *Phys. Rev. Lett.* **98**, 117401 (2007).

[32] Nomura, M. *et al.* Photonic band-edge micro lasers with quantum dot gain. *Opt. Express* **17**, 640 (2009).

[33] Chang, W.-H. *et al.* Efficient single-photon sources based on low-density quantum dots in photonic-crystal nanocavities. *Phys. Rev. Lett.* **96**, 117401 (2006).

[34] Michler, P. *et al.* A quantum dot single-photon turnstile device. *Science* **290**, 2282 (2000).

[35] Sanchez-Mondragon, J. J., Narozhny, N. B. & Eberly, J. H. Theory of spontaneous-emission line shape in an ideal cavity. *Phys. Rev. Lett.* **51**, 550 (1983).

[36] Agarwal, G. S. & Puri, R. R. Exact quantum-electrodynamics results for scattering, emission, and absorption from a rydberg atom in a cavity with arbitrary Q. *Phys. Rev. A* **33**, 1757 (1986).

[37] Carmichael, H. J., Brecha, R. J., Raizen, M. G., Kimble, H. J. & Rice, P. R. Subnatural linewidth averaging for coupled atomic and cavity-mode oscillators. *Phys. Rev. A* **40**, 5516 (1989).

[38] Laussy, F. P., del Valle, E. & Tejedor, C. Strong coupling of quantum dots in microcavities. *Phys. Rev. Lett.* **101**, 083601 (2008).

[39] Zhu, Y. *et al.* Vacuum Rabi splitting as a feature of linear-dispersion theory: Analysis and experimental observations. *Phys. Rev. Lett.* **64**, 2499 (1990).

[40] Jaynes, E. & Cummings, F. Comparison of quantum and semiclassical radiation theory with application to the beam maser. *Proc. IEEE* **51**, 89 (1963).

[41] Shore, B. W. & Knight, P. L. The Jaynes-Cummings model. *J. Mod. Opt.* **40**, 1195 (1993).

[42] Brune, M. *et al.* Quantum Rabi oscillation: A direct test of field quantization in a cavity. *Phys. Rev. Lett.* **76**, 1800 (1996).

[43] Schuster, I. *et al.* Nonlinear spectroscopy of photons bound to one atom. *Nature Phys.* **4**, 382 (2008).

[44] Carmichael, H. Cavity QED: Signs of anharmonicity. *Nature Phys.* **4**, 346 (2008).

[45] Fink, J. M. *et al.* Climbing the jaynes–cummings ladder and observing its $\sqrt{n}$ nonlinearity in a cavity QED system. *Nature* **454**, 315 (2008).

[46] Bishop, L. S. *et al.* Nonlinear response of the vacuum Rabi resonance. *Nature Phys.* **5**, 105 (2009).

[47] Skolnick, M. S., Fisher, T. A. & Whittaker, D. M. Strong coupling phenomena in quantum microcavity structures. *Semicond. Sci. Technol.* **13**, 645 (1998).

[48] Hennessy, K. *et al.* Quantum nature of a strongly coupled single quantum dot–cavity system. *Nature* **445**, 896 (2007).

[49] Press, D. *et al.* Photon antibunching from a single quantum dot-microcavity system in the strong coupling regime. *Phys. Rev. Lett.* **98**, 117402 (2007).

[50] Ota, Y. *et al.* Investigation of the spectral triplet in strongly coupled quantum dot-nanocavity system. *arXiv:0906.4622* (2009).

[51] Naesby, A., Suhr, T., Kristensen, P. T. & Mork, J. Influence of pure dephasing on emission spectra from single photon sources. *Phys. Rev. A* **78**, 045802 (2008).

[52] Auffèves, A., Besga, B., Gérard, J.-M. & Poizat, J.-P. Spontaneous emission spectrum of a two-level atom in a very-high-Q cavity. *Phys. Rev. A* **77**, 063833 (2008).

[53] Suffczyński, J. *et al.* Origin of the optical emission within the cavity mode of coupled quantum dot-cavity systems. *Phys. Rev. Lett.* **103**, 027401 (2009).

[54] Laucht, A. *et al.* Dephasing of quantum dot exciton polaritons in electrically tunable nanocavities. *To be published in Phys. Rev. Lett., arXiv:0904.4759* (2009).

[55] Kaniber, M. *et al.* Investigation of the nonresonant dot-cavity coupling in two-dimensional photonic crystal nanocavities. *Phys. Rev. B* **77**, 161303(R) (2008).

[56] Winger, M. *et al.* Mesoscopic cavity-QED: the physics behind off-resonant cavity excitation by a single quantum dot. *arXiv:0907.1881* (2009).

[57] Münch, S. *et al.* The role of optical excitation power on the emission spectra of a strongly coupled quantum dot-micropillar system. *Opt. Express* **17**, 12821 (2009).

[58] Thomas, N. L. *et al.* Cavity QED with semiconductor nanocrystals. *Nano Lett.* **6**, 557 (2006).

[59] Laucht, A. *et al.* Electrical control of spontaneous emission and strong coupling for a single quantum dot. *New J. Phys.* **11**, 023034 (2009).

[60] Nomura, M., Ota, Y., Kumagai, N., Iwamoto, S. & Arakawa, Y. Large vacuum Rabi splitting in single self-assembled quantum dot-nanocavity system. *Appl. Phys. Express* **1**, 072102 (2008).

[61] Thon, S. M. *et al.* Strong coupling through optical positioning of a quantum dot in a photonic crystal cavity. *Appl. Phys. Lett.* **94**, 111115 (2009).

[62] Ota, Y. *et al.* Vacuum rabi splitting with a single quantum dot embedded in a H1 photonic crystal nanocavity. *Appl. Phys. Lett.* **94**, 033102 (2009).

[63] Englund, D. *et al.* Controlling cavity reflectivity with a single quantum dot. *Nature* **450**, 857 (2007).

[64] Faraon, A. *et al.* Coherent generation of non-classical light on a chip via photon-induced tunnelling and blockade. *Nature Phys.* **4**, 859 (2008).

[65] del Valle, E., Laussy, F. P. & Tejedor, C. Luminescence spectra of quantum dots in microcavities. II. Fermions. *Phys. Rev. B* **79**, 235326 (2009).

[66] Laussy, F. P., del Valle, E. & Tejedor, C. Luminescence spectra of quantum dots in microcavities. I. Bosons. *Phys. Rev. B* **79**, 235325 (2009).

[67] Gonzalez-Tudela, A., del Valle, E., Tejedor, C. & Laussy, F. Anticrossing in the PL spectrum of light–matter coupling under incoherent continuous pumping. *Superlatt. Microstruct.* (2009). In Press.

[68] Gonzalez-Tudela, A., del Valle, E., Tejedor, C., Sanvitto, D. & Laussy, F. Effect of pure dephasing on the Jaynes-Cummings nonlinearities. *arXiv:0907.1302* (2009).

[69] Laussy, F., del Valle, E. & Tejedor, C. Quantitative description of strong-coupling of quantum dots in microcavities. *arXiv:0808.3215* (2008).

[70] Kistner, C. *et al.* Demonstration of strong coupling via electro-optical tuning in high-quality qd-micropillar systems. *Opt. Express* **16**, 15006 (2008).

[71] Mosor, S. *et al.* Scanning a photonic crystal slab nanocavity by condensation of xenon. *Appl. Phys. Lett.* **87**, 141105 (2005).

[72] Landin, L., Miller, M. S., Pistol, M.-E., Pryor, C. E. & Samuelson, L. Optical studies of individual InAs quantum dots in GaAs: Few-particle effects. *Science* **280**, 262 (1998).

[73] Strauf, S. *et al.* High-frequency single-photon source with polarization control. *Nature Photon.* **1**, 704 (2007).

[74] Feynman, R. P. Simulating physics with computers. *Int. J. of Th. Phys.* **21**, 467 (1982).

[75] Carmichael, H. J. *Statistical methods in quantum optics 1* (Springer, 2002), 2 edn.

[76] Nienhuis, G. Spectral correlations in resonance fluorescence. *Phys. Rev. A* **47**, 510 (1993).

[77] Badolato, A., Winger, M., Hennessy, K. J., Hu, E. L. & Ĭmamoḡlu, A. Cavity QED effects with single quantum dots. *C. R. Physique* **9**, 850 (2008).

[78] Akopian, N. *et al.* Entangled photon pairs from semiconductor quantum dots. *Phys. Rev. Lett.* **96**, 130501 (2009).

[79] Bel, G. & Brown, F. L. H. Theory for wavelength-resolved photon emission statistics in single-molecule fluorescence spectroscopy. *Phys. Rev. Lett.* **102**, 018303 (2009).

[80] Levi, B. G. Superconducting qubit systems come of age. *Physics Today* **62**, 14 (2009).

[81] Keldysh, L. V., Kulakovskii, V. D., Reitzenstein, S., Makhonin, M. N. & Forchel, A. Interference effects in the emission spectra of QD's in high quality cavities. *Pis'ma ZhETF* **84**, 584 (2006).

[82] Laussy, F. P., Kavokin, A. & Malpuech, G. Multiplets in the optical emission spectra of large quantum dots in microcavities. *Solid State Commun.* **135**, 659 (2005).

[83] Laussy, F. P., Glazov, M. M., Kavokin, A. V. & Malpuech, G. Multiplets in the optical emission spectra of Dicke states of quantum dots excitons coupled to microcavity photons. *Phys. Stat. Sol. C* **2**, 3819 (2005).

[84] Laussy, F. P., Glazov, M. M., Kavokin, A., Whittaker, D. M. & Malpuech, G. Statistics of excitons in quantum dots and their effect on the optical emission spectra of microcavities. *Phys. Rev. B* **73**, 115343 (2006).

[85] Nomura, M., Kumagai, N., Iwamoto, S., Ota, Y. & Arakawa, Y. Laser oscillation in a strongly coupled single quantum dot-nanocavity system. *arXiv:0905.3063* (2009).

[86] Yamaguchi, M., Asano, T., Kojima, K. & Noda, S. Quantum electrodynamics of a nanocavity coupled with exciton complexes in a quantum dot. *arXiv:0904.3697* (2009).

[87] del Valle, E., Laussy, F. P. & Tejedor, C. Quantum regression formula and luminescence spectra of two coupled modes under incoherent continuous pumping. *AIP Conference Proceedings* **1147**, 238 (2009).

[88] del Valle, E. *et al.* Dynamics of formation and decay of coherence in a polariton condensate. *To be published in Phys. Rev. Lett.* (2009).

[89] del Valle, E. *et al.* Two-photon lasing by a single quantum dot in a high-Q microcavity. *arXiv:0907.1861* (2009).

[90] Cui, G. & Raymer, M. Quantum efficiency of single-photon sources in the cavity-qed strong-coupling regime. *Opt. Express* **13**, 9660 (2005).

[91] Johne, R. *et al.* Entangled photon pairs produced by a quantum dot strongly coupled to a microcavity. *Phys. Rev. Lett.* **100**, 240404 (2008).

[92] Pathak, P. K. & Hughes, S. Generation of entangled photon pairs from a single quantum dot embedded in a planar photonic-crystal cavity. *Phys. Rev. B* **79**, 205416 (2009).

END PAGE

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PART B

SQOD