Theory and modeling of quantum coherence in polaritonic nanodevices

INTRODUCTION

Can theoretical physics find its right place in a nationwide research project on quantum photonics? Yes indeed, and in many respects. Knowing how to model the electronic and vibrational degrees of freedom in a semiconductor, and how they interact with light, is of great help for the interpretation of many experimental findings. Theory is also essential at a deeper level, for explaining the physics underlying fundamental phenomena – such as the recent breathtaking discovery of polariton Bose-Einstein condensation – and tracing them back to universal behaviors. Finally, theory is extremely useful to predict how the details of an artificial structure (size, shape, material composition, structural disorder, etc.) affect its electronic and optical properties. Models then serve as a virtual laboratory for designing and testing new devices prior to fabrication.

RESEARCH OBJECTIVES

This project aims at developing a comprehensive theory of polaritons in semiconductor systems under various experimental conditions. A polariton is a state of a semiconductor in which energy is transferred back and forth between light and electronic degrees of freedom, very much like in the oscillation of two coupled pendulums. This hybrid state is unique, in which it shares the properties of long-range coherence of an electromagnetic wave, and the quantum mechanical properties of matter. It thus manifests the wave-like nature of matter, predicted by quantum mechanics, over macroscopic spatial scales. Recently, a novel kind of artificial structure has been developed within Project 3A: a polariton quantum box able of confining polaritons along the three spatial directions. As predicted by quantum mechanics, this system manifests discrete energy levels in the same way as an atom. However, its size is much larger, in the range of a few microns. The quantum energy levels of these structures can be predicted by a theoretical model accounting for the coupling of light and matter and for the geometry of the device. An example is shown in Fig 1, where the measured spectra in the first prototypes are compared to the predictions of theory. The theory is currently being applied to model the energy relaxation mechanisms and the many-body interactions in these structures. This is done using the powerful tool of quantum field theory. As an example, it is predicted that under specific conditions of density and temperature, polaritons form a quantum fluid, either driven by an external laser source, as in the parametric oscillations, or spontaneously as in Bose-Einstein condensation (BEC). In a quantum fluid, millions of particles display a collective quantum mechanical behavior, producing a spectacular manifestation of quantum mechanics at the macroscopic scale. The many-body theory of quantum fluids predicts very singular effects, such as, for example, spontaneous Josephson oscillations in coupled quantum boxes, as sketched in Fig 2.

Fig 1. Top: Energy- and angle-resolved emission spectra of cylindrical polariton quantum boxes. Bottom: simulated optical spectra for the same structures.

Fig 2. Theoretical prediction of Josephson oscillations of a polariton quantum fluid in the coupled quantum boxes sketched on the right. The fabrication of this polariton microdevice is now shortly planned, within Project 3A.

A polariton quantum fluid can also arise in a fully spontaneous way, from a conventional gas of polaritons.
This is the phenomenon of Bose-Einstein condensation, predicted in 1925 for a gas of quantum particles. BEC physics is a very complex and intriguing phenomenon, with fascinating implications. As an example, the BEC quantum fluid has long-range quantum coherence, namely it behaves like a single macroscopic quantum object. It will also display superfluidity (flow without viscosity) and is generally considered as the fifth state of matter. The theoretical description of BEC is a challenging task, because the phenomenon is intrinsically many-body and escapes all conventional approximations. The task is made even more difficult in a semiconductor where the interplay with other mechanisms involving the specific nature of the semiconductor must be included.

Fig 3. Top: Predicted distribution of the polariton population as a function of energy, showing a relaxation bottleneck at low excitation intensity and the occurrence of polariton Bose-Einstein condensation at higher intensity. Bottom: The same quantity, measured in a very recent experiment. This is exactly one of the tasks of this project: to develop a realistic quantum field theory of polariton BEC and show how universal properties can be extracted from the complex mechanisms taking place in a semiconductor. Fig 3 shows how this theory can explain BEC kinetics, namely the formation of a condensate over time, accounting for energy relaxation mechanisms and the finite polariton lifetime. Finally, the theory we have developed can indicate how to design the next generation of samples for studying fundamental properties. Fig 4 shows a theoretical prediction of how the polariton lifetime affects thermal equilibrium. The best sample design strategy is to increase the polariton lifetime, using materials like GaAs/AlGaAs that allow the highest quality of heterointerfaces, while at the same time choosing a moderate light-matter interaction strength (the polariton Rabi splitting). This acquired knowledge will be invaluable for future sample design.

Fig 4. Comparison between the prediction of a kinetic theory (black) and a thermal equilibrium theory (red) for the effective polariton temperature (top) and the total polariton number (bottom) at the BEC threshold. The parameter on the abscissa is the polariton radiative lifetime.

APPLICATION PERSPECTIVES

Polariton quantum coherence is not only an interesting fundamental phenomenon. It is also very promising in a long-term perspective of a polariton implementation of a quantum information device. 

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http://itp.epfl.ch/page17707.html