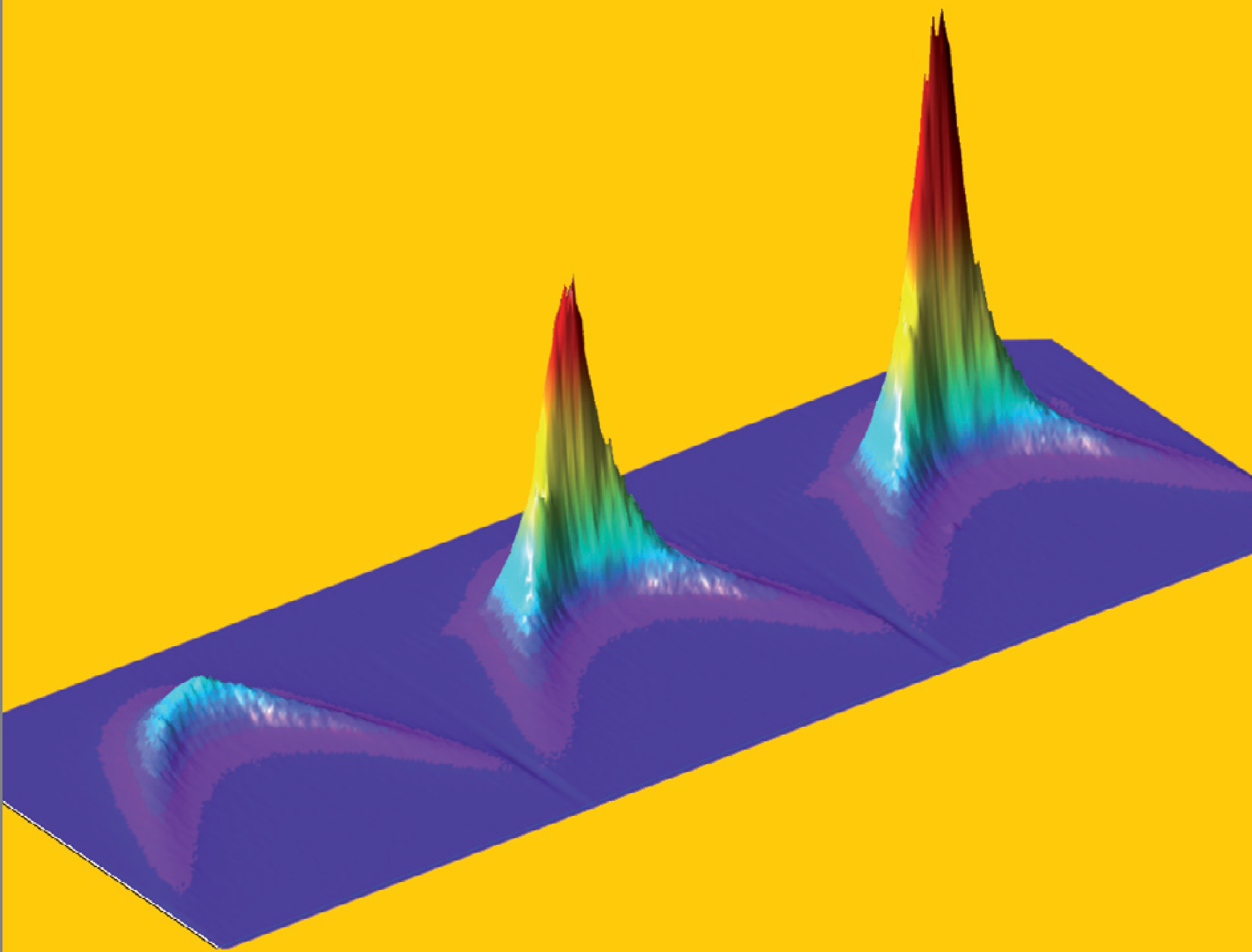
EUROPEAN SCIENCE FOUNDATION
SETTING SCIENCE AGENDAS FOR EUROPE

RESEARCH NETWORKING PROGRAMME

COMMON PERSPECTIVES FOR COLD ATOMS, SEMICONDUCTOR POLARITONS AND NANOSCIENCE (POLATOM)

Standing Committee for Physical and Engineering Sciences (PESC)



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Cover picture:
Direct image of the distribution function of polaritons in the Fourier plane of the polariton emission. The transition to the Bose-Einstein condensed state is directly demonstrated by the huge increase of the distribution around $k = 0$ upon increasing the excitation density.
Provided by Benoît Deveaud-Plédran, École Polytechnique Fédérale de Lausanne, CH.

Introduction

One of the fundamental rules of quantum mechanics dictates that all particles in nature are either ‘fermionic’ or ‘bosonic’. The difference between the two is very important: no two fermionic particles can occupy the same quantum state, in contrast to bosonic particles which may occupy the same state irrespective of their number. As a result, matter is usually associated with fermionic particles, while radiation and the carriers of forces are associated with bosonic particles.

Clearly this classification is at the heart of quantum mechanics. While the behaviour of fermionic particles is easy to confirm, the behaviour of bosonic particles has proven more difficult to probe. Einstein predicted already in the 1920s that an ideal gas of bosonic particles may undergo a phase transition to a phase in which a macroscopic number of such particles occupy a single, coherent quantum state, the so-called Bose-Einstein condensed state. Apart from strongly-interacting systems like, e.g., liquid helium, the experimental discovery of this phenomenon in more dilute systems had to wait many decades.

In recent years, there has been tremendous progress in achieving this phase transition in two different systems, namely in dilute vapours of atoms and in polaritons in semiconductors. In the field of cold atoms this phase transition to a Bose-Einstein condensed phase was realised in vapours of (bosonic) alkali-metal atoms in 1995. These celebrated experiments clearly marked the beginning of a new era in quantum physics.

Part of the vitality of the field of cold atoms is due to the fact that the systems investigated are very clean, very dilute and very cold. The ability that we have to probe them optically has made possible measurements with a precision difficult to match in other systems. In addition, most of the properties of these gases are tuneable externally. For example, one may control the density, the temperature, the external potential – and thus the effective dimensionality – and even the coupling strength between the atoms. Finally, many different species of atoms, each with a variety of internal states, may be used experimentally – a fact that has contributed to the richness of the field.

With regards to semiconductors, new prospects for monolithic semiconductor structures, comprising a ‘microcavity’ with embedded semiconductor material, were put on a firm footing by technological progress in semiconductor growth during the 1980s. The interaction of cavity modes in such a structure with the two-dimensional excitons – the elementary optical excitations in a direct-gap semiconductor quantum well – was shown in 1992 to enter the ‘strong coupling’ regime. Such a system shows a new spectrum of states, the coupled exciton-photon modes, known as ‘exciton polaritons’. Because the polaritons are bosons, there is an enhanced scattering probability into the lowest-energy state if it is already occupied; very large populations have been shown to develop under appropriate circumstances. The research community is now convinced that these cavity polaritons show true Bose-Einstein condensation, and the condensate has become the subject of research rather than an elusive goal.

Remarkably, the two fields of cold atoms and of exciton polaritons have much in common. The most important link between the two fields is the phenomenon of Bose-Einstein condensation. The macroscopic occupancy of a single quantum state of the system gives rise to fascinating and often counterintuitive effects, which show up in both fields. These include the collection of effects associated with ‘superfluidity’ (quantised vortex states, persistent currents, nonclassical moment of inertia, etc.), collective effects, coherence effects, lasing, nonlinear effects, etc. Interestingly, there are some differences between the two systems, too. Probably the most important is the fact that exciton-polaritons decay, emitting light, and as a result they have to be pumped continuously. Also, the atomic systems require much smaller temperatures than polaritons, as they are many orders of magnitude heavier than polaritons, and thus more ‘classical’.

The running period of the ESF POLATOM Research Networking Programme is five years, from June 2010 to June 2015.

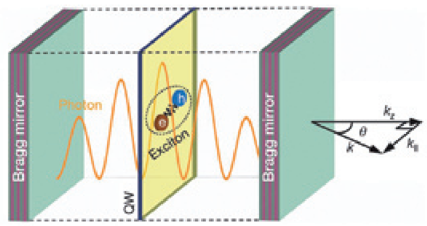

Figure 1. A microcavity is a planar Fabry–Perot resonator with two Bragg mirrors at resonance with excitons in quantum wells. The exciton is an optically-active dipole that results from the Coulomb interaction between an electron in the conduction band and a hole in the valence band. In microcavities operating in the strong coupling regime of the light–matter interaction, two-dimensional excitons and two-dimensional optical modes give rise to new eigenmodes, called microcavity polaritons.
Nature 443, 409 (2006). Reproduced with permission from Benoît Deveaud-Plédran, École Polytechnique Fédérale de Lausanne, CH.

Aims and Objectives

POLATOM consists of numerous experimental and theoretical groups, which are located all over Europe. Both fields, that of exciton-polaritons as well as that of cold atoms, are multidisciplinary and require combined knowledge from many different fields of physics. The main goals of the POLATOM network include the following:

- To keep up with all the important developments of the two rapidly-developing fields;
- To promote research on the two fields. Both have shown remarkable achievements, and have the potential for further progress and important technological applications;
- To develop links and to trigger collaborations amongst the scientists working on the two fields. Given the many common problems that appear in these two fields, investigating the possibilities of applying ideas from one field to the other is one of the basic goals of the present network;
- To develop links between the above fields and the field of nanotechnology. Nanotechnology – which is a very extensive, highly diverse and multidisciplinary field – has been making impressive progress in fabricating and studying mesoscopic/nanoscale systems and devices. This has strong parallels to the field of polariton condensates and to cold-atomic physics. It is clear that many of the key goals are now attainable, and a coordinated exchange of knowledge within Europe will certainly have a very substantial impact;
- To investigate the links of the two fields with other fields;
- To provide, through regular scientific meetings, not only a forum for presentation of papers but also sessions of an educational character, in which young researchers will learn new approaches and will swap ideas. The various activities that will be organised will give junior scientists the chance to interact with the leading European research groups in the two fields, and to build up contacts with a truly European perspective for the future. The ESF Research Networking Programme will also have an extensive link to the already existing Graduate Schools that various members of the network are coordinating, or are involved in;
- To make links with other networks and relevant activities on similar and/or related problems, and to serve as a natural continuation of other networking programmes which have been completed recently.

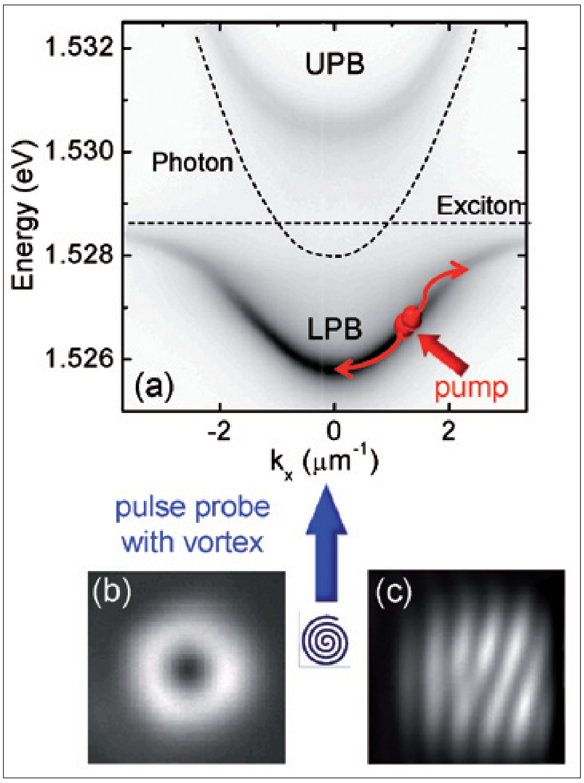

Figure 2. (a) Lower (LPB) and upper polariton branch (UPB) dispersions, together with the schematic representation of the optical parametric oscillator excitation. Resonantly pumping the LPB initiates, above threshold, stimulated scattering to a signal close to zero momentum and an idler at higher momentum.
(b) An m = 1 Laguerre-Gauss beam resonant with the signal is used as a weak pulsed triggering probe to stir the superfluid.
(c) The corresponding interference image.
Nature Physics 6, 527 (2010). Reproduced with permission from the group "Semicuam", Universidad Autónoma de Madrid Campus de Cantoblanco, ES.

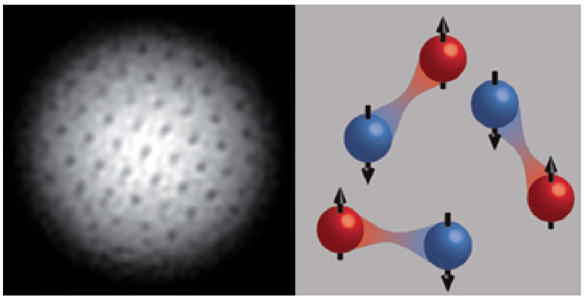

Figure 3. Vortices (left) in a paired strongly-interacting Fermi gas, as shown on the schematic graph on the right.
Picture: Wolfgang Ketterle, Massachusetts Institute of Technology, US.

Topic Areas

The variety of topics in the POLATOM Research Networking Programme is remarkably wide, as a result of the multidisciplinary character of the fields of cold atoms and of polaritons. A brief description of the topics which will be investigated within POLATOM follows below:

- Growth of microcavities with a higher quality factor than those formerly studied and increase of the photon lifetime within the cavity, in order to facilitate polariton cooling in the case of non-resonant injection;
- Planar microcavities containing quantum dots. Achievement of sufficient density and field enhancement to permit shaped-pulse-driven condensate formation;
- Planar microcavities containing bulk semiconductor;
- Novel structures for polariton Bose-Einstein condensates. Growth and electro-optical studies of designed 0D, 1D and 2D heterostructures;
- Polariton Bose-Einstein condensation at room temperature;
- Exploitation of polariton lasing;
- Electrical injection and maintenance of strong coupling at room temperature;
- Investigation of polaritonic effects in new materials;
- Polariton Josephson junctions, parametric scattering;
- Dynamics of polariton condensation. Theoretical treatment of non-equilibrium effects in microcavity polariton condensates. Development of quantum-kinetic approaches to polariton condensation, in close collaboration with the scientists working on cold-atomic systems;
- Development of real-space traps for exciton condensation phenomena, in close connection with cold-atomic systems;
- Superfluid properties of microcavity polariton condensates, in close connection with atomic gases;
- Development of the field of ‘polaritronics’: use of the quantum effects of superfluidity, entanglement, squeezing of light, etc. for the construction of optoelectronic devices, like new light sources, optical switches, modulators and memory elements;
- Design of quantum nanodevices in cold atomic systems, taking advantage of:
  - (i) The effect of persistent flow
  - (ii) The nonlinear effects, which give rise to solitary waves
  - (iii) The effectively reduced dimensionality in elongated/oblate traps, in connection also to the field of polaritons
  - (iv) The effect of the disorder (introduced either by design, or because of unavoidable irregularities), again in close connection with the field of exciton polaritons;
- Engineering and coherent control of single quantum-mechanical degrees of freedom of cold atoms confined in traps, in optical lattices, etc.;
- Manipulation of cold atoms, combined with their macroscopic quantum-mechanical properties, in connection with the design of nanoscale devices;
- Investigation of the possible combination of solid-state devices with cold atoms;
- Performance of high-precision measurements with cold atoms, based on the coherence property of cold atomic gases, and possible applications in nanotechnology;
- Study of the cross-over between microscopic and macroscopic, thermodynamic behaviour with increasing atom number, with obvious relevance to the design of nanoscale devices;
- Further development of the field of ‘atomtronics’, taking advantage of the low thermal noise due to the macroscopic coherence in these systems;
- Dipolar gases and possible applications in the design of nanodevices;
- Investigation of the pairing mechanisms between fermionic atoms, in connection with high-temperature superconductivity.

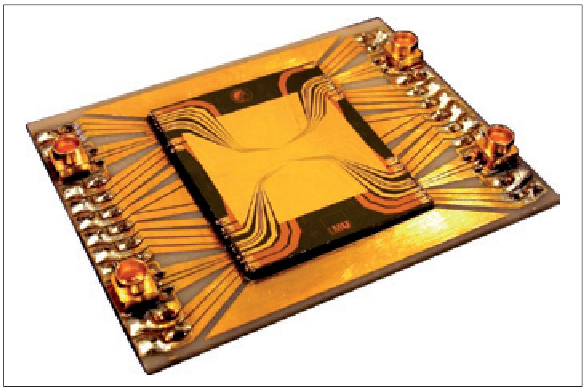

Figure 4. Atom chip with integrated microwave guiding structures. The chip is used for the production of Bose-Einstein condensates, for the operation of chip-based atomic clocks and atom interferometers, and for the generation of spin-squeezed and entangled states of a Bose-Einstein condensate.
Picture: Philipp Treutlein, Fakultät für Physik, Ludwig-Maximilians-Universität München, DE.

Activities

POLATOM supports exchange visits, conferences and schools. The details about these activities may be found on the ESF website, as well as on the POLATOM website, and include:

Short visits and exchange grants

POLATOM supports collaborations among groups in the field by short visit grants for periods of up to three days. These will allow reciprocal visits between most of the centres, and will provide a resource to help introduce new contacts to the network.

POLATOM also finances exchange grants covering stays between two weeks to six months. These will allow extended work by researchers visiting host laboratories within the Research Networking Programme to permit exchange of experimental facilities and expertise, and also allow more substantial theoretical projects to be undertaken collaboratively.

Applications may be submitted online on the ESF website, and they will be received on a continuous basis.

Schools and conferences

POLATOM will finance/co-finance various conferences and schools. A preliminary list of these activities includes the following:

- April 2011: School and Conference, Crete, Greece
- July 2011: Workshop, Trento, Italy
- July 2012: Summer School, Spain
- September 2012: Conference, Cambridge, United Kingdom
- June 2015: Conference, Bad Honnef, Germany

The details of the above activities, as well as other activities, will be posted on the POLATOM website, www.polatom-esf.org, as well as on the ESF site, www.esf.org/polatom.

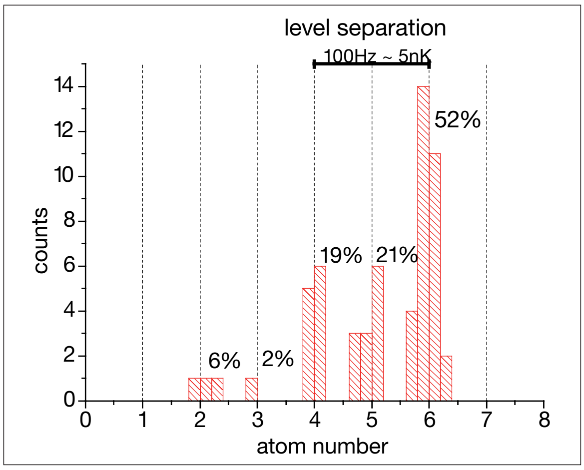

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Figure 5. Histogram of the number of fermionic atoms prepared in a micrometer-sized trap.
Data: Selim Jochim, Heidelberg University, Heidelberg, DE.

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