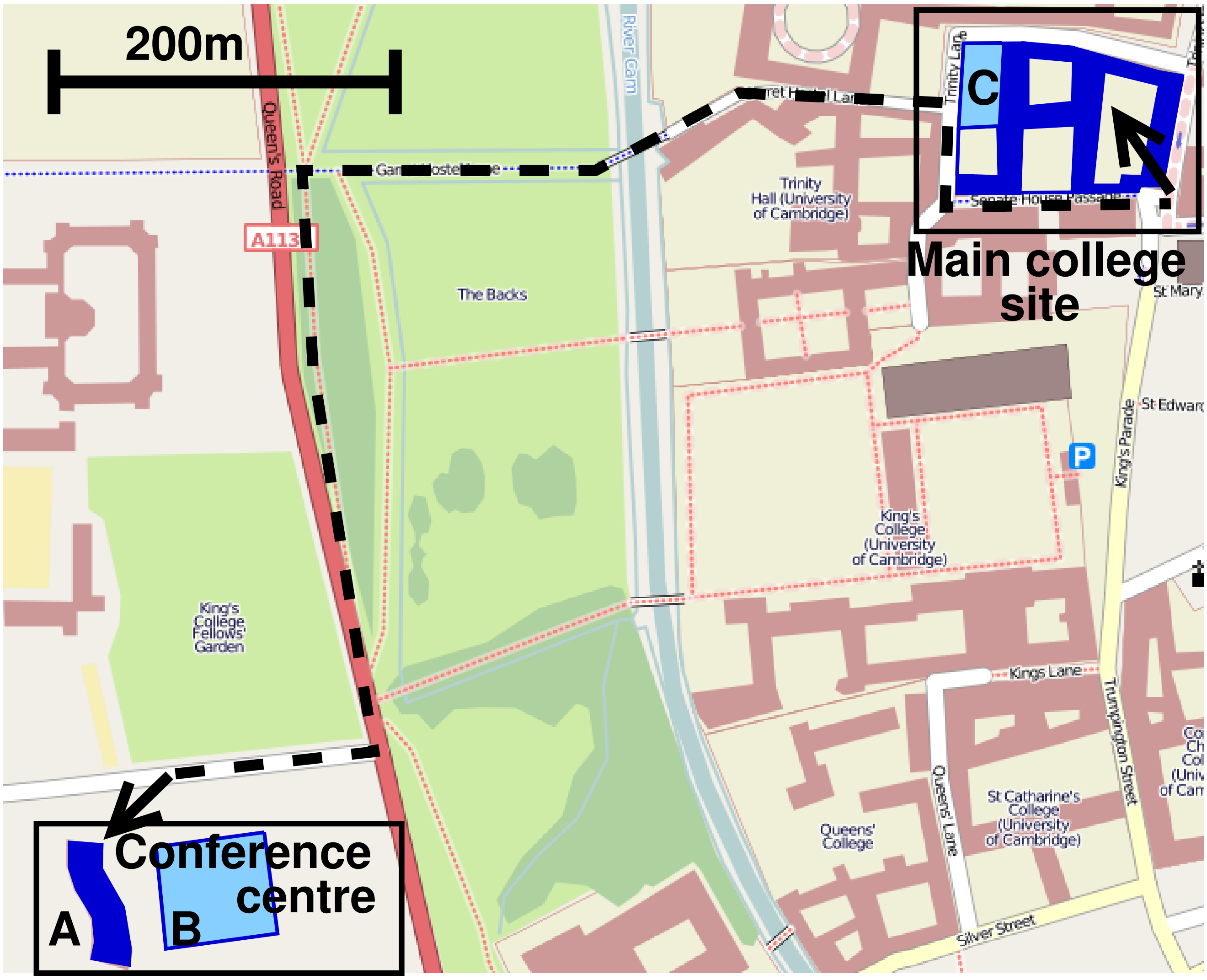
4^{th} International Conference on Spontaneous Coherence in Excitonic Systems

8–12^{th} September 2008

Cambridge, UK

ICSCE4 At-a-glance schedule

Monday	Tuesday	Wednesday	Thursday	Friday
Session Begins: 09:00				
Chair: Snoke	Chair: Carusotto	Chair: Savona	Chair: Ritchie	Chair: Rapaport
Dang	Guery–Odelin	Yamamoto	Tutuc	Lilly
Deveaud	Hope	Bloch	Tiemann	Das Gupta
				Lozovik
Coffee: 10:40 – 11:10				10:50 – 11:20
Chair: Baumberg	Chair: Kavokin	Chair: Yamamoto	Chair: Tutuc	Chair: Littlewood
Lagoudakis	Krizhanovskii	Cerna	Karmakar	Voros
Wouters	Whittaker	Sanvitto	Su	Snoke
Keeling	De Liberato	Laussy	Sebastian	Session Ends:12:40
Lunch: 13:00 – 14:30				
Chair: Szymanska	Chair: Deveaud	Chair: Atature	Chair: Marchetti	
Haug	Baumberg	Daley	Ogawa	
Malpuech	Butte	Esslinger	Gorbunov	
Carusotto	Tischler	Eastham	Rapaport	
Tea: 16:00 – 16:30	Tea: 16:20 – 16:50	Tea: 16:40 – 17:00	Tea: 16:20 – 16:50	
Chair: Whittaker	Posters	17:00 Free Afternoon	Chair: Haug	
Rubo			Butov	
del Valle			Yang	
Shelykh			Ivanov	
Dinner: 19:30				



Key

A Stephen Hawking building, containing Cavonius Centre and ensuite accommodation.

B Harvey Court, containing Harvey Court Dining Room; breakfasts and lunches.

C Old Court Main Hall; dinners.

Accommodation

Accommodation is separated between ensuite rooms, in the Stephen Hawking building, West Road (marked **A** on map) and non-ensuite accommodation in Tree Court on the main college site of Caius (marked **Main college site** on map).

Arrival and registration

If arriving on Sunday evening, please make your way either to the Stephen Hawking building (if you are in ensuite accommodation), or to the main college site, entrance off Trinity Street (if non-ensuite accommodation). In both cases, at the entrance from the street there is a reception, marked "Porters' Lodge" where you can collect your keys, badge and programme. If arriving on Monday morning, please make your way directly to the Cavonius Centre in the Stephen Hawking building; you will be able to collect your badge and programme either from 8:45–9:00, or during the breaks.

Oral presentations

Conference sessions will take place in the lecture theatre in the Cavonius Centre, in the Stephen Hawking building. Oral presentations are either 40 minutes presentation + 10 minutes discussion, or 20 minutes presentation + 10 minutes discussion. A laptop will be provided for those speakers who wish to use it, **we can only guarantee that this will display pdf presentations**, if you wish to use powerpoint you are encouraged to use your own laptop.

Poster presentations

The poster session is on Wednesday afternoon, from 16:50 until dinner (19:30), and will be in the lecture theatre in the Cavonius Centre. Posters can be up to 140cm (horizontal) by 100cm (vertical). At the start of the poster session, each person presenting a poster will be given an opportunity to present a 1 minute overview of their poster, with up to one viewgraph. These summaries will take place at 16:50.

Dining

Breakfast (from 8:00), and Lunches (Monday–Friday) will be held in the Harvey Court Dining room (marked **B** on map), in the building opposite the Stephen Hawking building . Dinners will be held in the Main Hall, on the old college site (marked **C** on map). Dinner is at 19:30 Monday to Thursday. Tea and Coffee breaks will be in the lounge area in the Cavonius Centre

Please note, there is no dinner on Sunday or Friday evenings; instead a list and map of a variety of Cambridge restaurants is provided.

Free afternoon

There are no fixed activities for this free afternoon, a list of possible itineraries will be available to sign up to during the conference.

ICSCE4 Full Schedule

Monday

08:00— 09:00	*Breakfast*	
08:45— 09:00	*Registration*	
09:00— 09:50	**Dang**	Introduction to Bose-Einstein condensation of microcavity polaritons
09:50— 10:40	**Deveaud**	Condensation in a non ideal polariton gas
10:40— 11:10	*Coffee*	
11:10— 11:40	**Lagoudakis**	Quantised vortices in an exciton-polariton condensate
11:40— 12:30	**Wouters**	Non-equilibrium physics of Bose-Einstein condensates of microcavity polaritons
12:30— 13:00	**Keeling**	Nonequilibrium quantum condensates: from microscopic theory to macroscopic phenomenology
13:00— 14:30	*Lunch*	
14:30— 15:00	**Haug**	First and second order coherence of a polariton condensate
15:00— 15:30	**Malpuech**	Formation of the cavity polariton condensate: thermodynamic versus kinetic regimes
15:30— 16:00	**Carusotto**	The meaning of superfluidity for polariton condensates
16:00— 16:30	*Tea*	
16:30— 17:20	**Rubo**	Vortices and vortex interactions in exciton-polariton condensates
17:20— 17:50	**del Valle**	Dynamics of formation and decay of coherence in a polariton BEC
17:50— 18:20	**Shelykh**	Superfluidity, localisation and Josephson effect of spinor cavity polaritons
19:30—	*Dinner*	

Tuesday

08:00— 09:00	*Breakfast*	
09:00— 09:50	**Guery-Odelin**	Quasi-monomode guided atom-laser
09:50— 10:40	**Hope**	Theory of continuous atom lasers
10:40— 11:10	*Coffee*	
11:10— 12:00	**Krizhanovskii**	Intrinsic decoherence mechanisms and formation of coexistent polariton condensates in CdTe semiconductor microcavities
12:00— 12:30	**Whittaker**	Coherence of the microcavity polariton condensate
12:30— 13:00	**De Liberato**	Stimulated scattering and lasing of intersubband cavity polaritons
13:00— 14:30	*Lunch*	
14:30— 15:20	**Baumberg**	Spontaneous polarisation build up in a room temperature polariton laser
15:20— 15:50	**Butte**	Room temperature polariton lasing and condensation effects in III-nitride microcavities
15:50— 16:20	**Tischler**	Polaritonic devices utilizing nanoscale films of J-aggregate
16:20— 16:50	*Tea*	
16:50— 19:00	*Posters*	
19:30—	*Dinner*	

Wednesday

08:00— 09:00	*Breakfast*	
09:00— 09:50	**Yamamoto**	Exciton-polariton Bose-Einstein condensation
09:50— 10:40	**Bloch**	Polariton laser in micropillar cavities
10:40— 11:10	*Coffee*	
11:10— 11:40	**Cerna**	Controlling the wave function of zero-dimensional microcavity polaritons
11:40— 12:30	**Sanvitto**	Quantum polariton fluid in microcavities
12:30— 13:00	**Laussy**	Propagation of polariton wavepackets
13:00— 14:30	*Lunch*	
14:30— 15:20	**Daley**	Atomic lattice excitons
15:20— 16:10	**Esslinger**	Bose-Einstein condensation meets Cavity QED
16:10— 16:40	**Eastham**	Quantum condensation from tailored exciton populations
16:40— 17:00	*Tea*	
17:00—	*Free Afternoon*	
19:30—	*Dinner*	

Thursday

08:00— 09:00	*Breakfast*	
09:00— 09:50	**Tutuc**	Exciton superfluid in two dimensional hole bilayers
09:50— 10:40	**Tiemann**	Critical currents in excitonic electron bilayer systems
10:40— 11:10	*Coffee*	
11:10— 11:40	**Karmakar**	First-order metal-excitonic insulator transition in quantum Hall electron bilayers
11:40— 12:10	**Su**	How to make a bilayer exciton condensate flow
12:10— 13:00	**Sebastian**	*Title to be confirmed*
13:00— 14:30	*Lunch*	
14:30— 15:20	**Ogawa**	Exciton Mott transition and quantum pair condensation in electron-hole systems: Dynamical mean-field theory
15:20— 15:50	**Gorbunov**	Linear polarization of the luminescence of dipolar exciton Bose condensate
15:50— 16:20	**Rapaport**	Particle correlations in a quantum degenerate trapped dipolar exciton fluid
16:20— 16:50	*Tea*	
16:50— 17:40	**Butov**	Cold exciton gases in coupled quantum wells
17:40— 18:10	**Yang**	Spontaneous coherence and kinetics of macroscopically ordered exciton state
18:10— 18:40	**Ivanov**	Transport, thermalization and first-order coherence of indirect excitons
19:30—	*Dinner*	

Friday

08:00— 09:00	*Breakfast*	
09:00— 09:50	**Lilly**	Coulomb drag in the exciton regime in electron-hole bilayers
09:50— 10:20	**Das Gupta**	Transport experiments on electron-hole bilayers
10:20— 10:50	**Lozovik**	Strong correlated 2D dipole exciton system
10:50— 11:20	*Coffee*	
11:20— 11:50	**Voros**	Accumulation of dark excitons in stress-induced potentials
11:50— 12:40	**Snoke**	*Title to be confirmed*
12:40— 13:00	*Free*	
13:00— 14:30	*Lunch*	

Posters

Bradley	Predicting the linear optical response of J-aggregate microcavity exciton-polariton devices
Hammack	Low temperature behavior of excitons in an optically-induced trap
High	Control of exciton flux through tunable potential reliefs
De Liberato	Quantum theory of electron tunneling into intersubband cavity polariton states
Mouchliadis	Screening of short-range quantum well disorder by indirect excitons
Nardin	Optical imaging of exciton-polaritons probability density in cylindrical traps
Paraiso	Relaxation dynamics of confined microcavity polaritons
Pietka	Formation dynamics of an exciton-polariton condensate
Wertz	Polariton parametric oscillation in a single micropillar semiconductor cavity

Monday

Introduction to Bose-Einstein condensation of microcavity polaritons

Jacek Kasprzak[1], Maxime Richard[2], Régis André[2], and Le Si Dang[2]
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Polaritons in semiconductor microcavities are two-dimensional quasi-particles which result from the strong coupling between exciton modes confined in quantum wells and photon modes confined in the planar microcavity embedding the quantum wells. These bosons are 10^9 times lighter than rubidium atoms, which would permit Bose-Einstein condensation (BEC) at low density and high temperature. On the other hand, since BEC is a thermodynamic phase transition, thermal equilibration in the polariton gas could be highly challenging due to the extremely short polariton lifetime on the order of one picosecond. Nevertheless BEC has been claimed in various polariton systems in recent years [1].

The purpose of this talk is to provide a basic understanding of BEC in microcavity polaritons to non specialists, leaving more specific and hot issues of polariton condensation to be addressed in other talks during this conference. First we present the polariton system, whose dispersion in the plane perpendicular to the microcavity and quantum well confinement axis is displayed in Figure 1. Polariton states of interest for BEC are those at $k_{//} \sim 0$ in the lower polariton branch. Then we examine the two defining BEC signatures, as observed in CdTe microcavities, i.e. massive occupation of the ground state and macroscopic spatial coherence (see J. Kasprzak et al. in Ref. [1]). Figure 2 shows the polariton population in the lower polariton branch and how the bimodal distribution, typical of BEC at finite temperature, appears when increasing the polariton density at around 20 K. Finally, an overview of issues and recent advances in the field of polariton BEC and "lasing" will be given.

This work is a collaboration program between Institut Néel and EPFL (A. Baas, K. Lagoudakis, M. Wouters, B. Pietka, G. Nardin, B. Deveaud-Plédran). We acknowledge collaboration with Universita di Trento (I. Carusotto), Université Blaise Pascal (D. Solnyshkov, G. Malpuech), and University of Cambridge (F. Marchetti, M. Szymanska, J. Keeling, P. Littlewood).

References

[1] J. Kasprzak et al., *Bose-Einstein Condensation of Exciton Polaritons*, Nature 443, 409 (2006); R. Balili et al., *Bose-Einstein Condensation of Microcavity Polaritons in a Trap*, Science 316, 1007 (2007); H. Deng et al., *Spatial Coherence of Polariton Condensate*, Phys. Rev. Lett. 99, 126403 (2007).

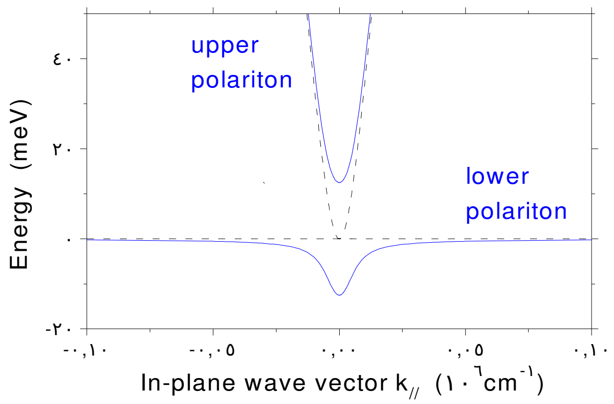

Figure 1. In-plane dispersion of polaritons (solid lines), exciton and photon modes (dashed lines) calculated for a CdTe microcavity embedding 16 quantum wells. Energy is scaled with respect to the exciton energy at 1690 meV in CdTe quantum wells. Polaritons at $k_{//} \sim 0$ in the lower polariton branch can undergo BEC.

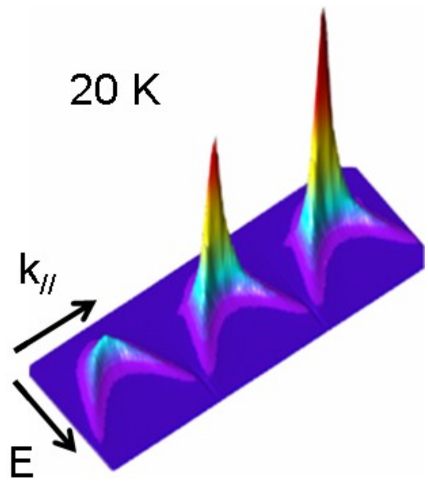

Figure 2. Pseudo-3D images of the population distribution in the lower polariton branch in energy-momentum space (E, $k_{//}$), for polariton densities just below (left) and above condensation threshold (center and right).

Condensation in a non ideal polariton gas

Benoit Deveaud

With the invaluable work of

K. Lagoudakis, T. Paraiso, G. Nardin, R. Cerna, M. Richard, A. Baas, B. Pietka, Y. Léger, F. Morier-Genoud, M. Portella Oberli,

Laboratory of Quantum Optoelectronics, EPFL, Station 3, CG1015 Lausanne

In this talk, I will expand on the properties of the microcavity sample described in the previous talk by my colleague Dang. He has shown that polaritons in II-VI microcavities display all the properties expected for a Bose Einstein condensate, and in particular, the spontaneous appearance of long range order. I will further discuss here two different aspects:

- Can the observed system be differentiated from a VCSEL, and can it be called a polariton condensate or a polariton laser? Here, the measurement of the second order coherence properties brings interesting clues, and clearly show differences with the behavior of a VCSEL.
- What is the influence of the non-ideality of the sample on the properties of the condensate. We will in particular discuss the effects of disorder on the condensation dynamics, showing that long-range order is driven by proper synchronization between the different regions of the sample. We will then show that vortices may be observed, that are not driven by the exciting laser, but are explained by the dynamics of the polaritons and the potential landscape.

I will terminate this talk by some views about future experiments, in particular in polariton traps.

Quantised Vortices in an Exciton-Polariton Condensate

K. G. Lagoudakis[1], M. Wouters[2], M. Richard[1], A. Baas[1], I. Carusotto[3], R. André[4], Le Si Dang[4], B. Deveaud-Plédran[1]

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The quantum nature of low temperature interacting Bosons may give rise to superfluidity. First observed in liquid ^{4}He this phenomenon has been intensively studied in various systems for its amazing features such as the vanishing of viscosity and the appearance of vortices with quantised angular momentum. The achievement of Bose-Einstein condensation (BEC) in dilute atomic gases provided an exceptional opportunity to observe and study superfluidity and its features. In the solid state, exciton polaritons have proved very good candidates for the achievement of BEC due to their extremely low effective mass. Exciton-polaritons are strongly interacting light-matter bosonic quasi-particles, naturally occurring in semiconductor microcavities in the strong coupling regime and constitute a very interesting example of composite bosons. Although BEC of exciton polaritons has now been reported several times, the superfluid nature of their quantum phase still remains an open question.
In the present experimental work, we report the spontaneous formation of deterministic pinned quantised vortices in the condensed phase of a polariton fluid by means of phase and amplitude imaging. Additionally, we provide a theoretical insight to the possible origin of such vortices by means of a model based on the generalised Gross-Pitaevskii equation that captures the mean field dynamics of the polariton condensate, and we discuss fundamental differences and similarities with vortices in different optical systems.

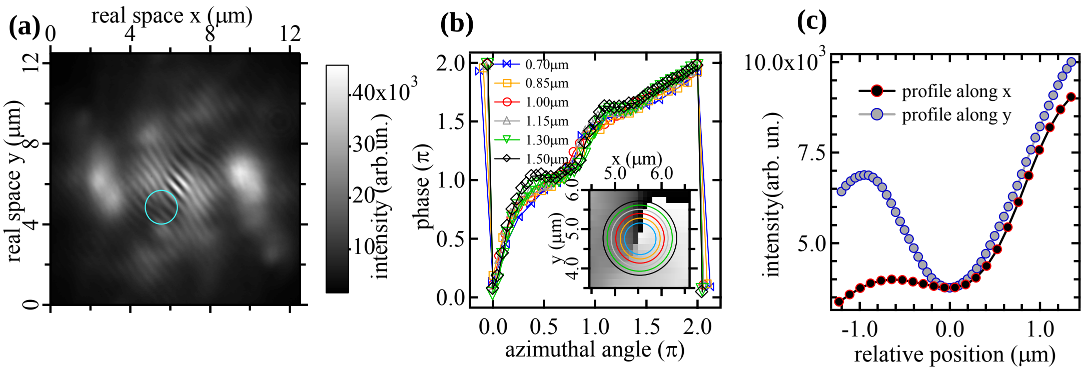

Figure: **(a)** Real space interferogram of the condensate luminescence containing a vortex. The vortex singularity is evidenced by the forklike dislocation of the interference fringes (here located within the solid circle). **(b)** Extracted phase of the polariton quantum fluid around the vortex core for different radii. The phase is always giving a well defined 2π phase shift. **(c)** population at the location of the vortex along the x and y directions. The vortex is located to a population minimum.

Reference: *arXiv*:0801.1916 and references therein. Nature Physics in press.

Non-equilibrium physics of Bose-Einstein condensates of microcavity polaritons

M. Wouters,[1] I. Carusotto,[2] D. Sarchi,[1] V. Savona,[1] K. G. Lagoudakis,[3] M. Richard,[4] A. Baas,[5] and B. Deveaud-Pledran[3]

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For the theoretical modeling of a polariton condensate, it is important to take into account that it has the crucial novelty of being an intrinsically non-equilibrium system: because of the finite lifetime of polaritons, the condensate has to be continuously replenished from the relaxation of optically injected high energy excitations (e.g. free carriers or hot polaritons), and its steady state results from a dynamical balance of pumping and losses. From this point of view, the polariton condensate shares some similarities with a spatially extended laser, but a direct analogy is made impossible by the strong nonlinearity due to polariton-polariton collisions.

We have proposed a generalization of the Gross-Pitaevskii equation that takes into account the pumping and dissipation of polaritons [1]. Within this model, the elementary excitation spectrum of the polaritons is dramatically changed at long wave lengths: the Goldstone mode acquires a diffusive instead of the sound character of equilibrium BECs.

Due to the non-equilibrium character of the polariton condensates, new phenomena arise: in the disordered potential landscape of the semiconductor microcavities, vortices may spontaneously form in the polariton condensate without setting the system into rotation. Such vortices have been observed in recent experiments and theoretically modeled with the generalized Gross-Pitaevskii equation [2].

At thermodynamical equilibrium, the chemical potential sets a single condensate frequency for the whole system. In the non-equilibrium case on the other hand, the condensate frequency may vary spatially, depending on the potential landscape. Recent experiments have shown that indeed, either a single frequency condensate or a fragmented state with different frequencies may form [3]. Our mean field model provides insight in the conditions under which a single or multiple frequency condensate appears [4].

Fluctuations can be included in the classical field model through the formalism of quasi-probability distributions from quantum optics. Within the resulting stochastic classical field model, we have studied the built up of spatial correlations across the condensation transition.

[1] M. Wouters and I. Carusotto, Phys. Rev. Lett. **99**, 140402 (2007).
[2] K. G. Lagoudakis, *et al.* arXiv:0801.1916, Nat. Phys. in press.
[3] A. Baas *et al.*, Phys. Rev. Lett. **100**, 170401 (2008).
[4] M. Wouters, Phys. Rev. B **77**, 121302 (2008).

Nonequilibrium quantum condensates: from microscopic theory to macroscopic phenomenology

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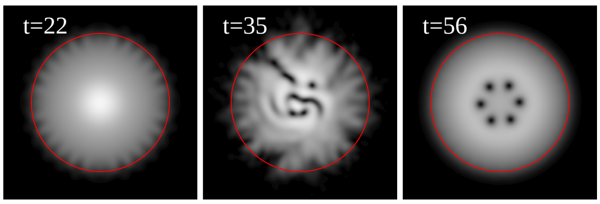
Microcavity polariton condensates provide an opportunity to explore a novel regime of nonequilibrium quantum systems, which both differ from the equilibrium Bose-Einstein condensate and also differ from any previous studied laser. In this talk, I will review our approach to microscopic modelling of an out-of-equilibrium polariton condensate [1, 2], discussing the distinction between those properties of quantum condensates that can be derived from mean-field (i.e Gross-Pitaevskii approaches), and those which involve correlations not described in mean-field theory.

Our microscopic theory starts from a model of disorder-localised excitons, coupled to propagating photon modes in a microcavity, where interactions between excitons are caricatured as exclusion [3]. This model is then driven out of equilibrium by coupling to baths that describe pumping and decay. We study the steady state behaviour of this non-equilibrium model by constructing the Keldysh path integral, and finding the saddle point (i.e. self-consistent steady state), and fluctuations around this state.

The Keldysh approach provides a natural formalism from which can be derived many of the other approximations used for non-equilibrium polariton systems, such as the Boltzmann equation and quantum kinetics; density matrix evolution, Dyson equations for the Keldysh Green's functions, and mean-field theory, i.e. Gross-Pitaevskii equations including pumping and decay. As such it provides a way to understand how these various methods relate to one another. The mean-field equation provides a clear way to understand how the steady state condition interpolates between that of an equilibrium condensate and that of a laser. By considering correlation functions for a finite two-dimensional non-equilibrium system one can gain further insights into the range of behaviour between the single mode laser, a polariton condensate and an equilibrium 2D weakly-interacting Bose gas.

To describe macroscopic phenomena such as the large scale spatial structure of the condensate, details of the microscopic theory become less important. This can be seen by noting that, in appropriate limits, the mean-field equation derived from the microscopic model can be written as a complex Gross-Pitaevskii equation, the form of which is strongly constrained by general symmetry considerations. Such an equation allows one to investigate how pumping and decay influence the spatial profile of the condensate. One dramatic consequence is that for harmonic trapping and uniform pumping, the Thomas-Fermi condensate profile can become unstable and is replaced by a non-stationary spontaneously rotating vortex lattice solution [4].



Spontaneous vortex lattice formation from the competition of pumping and trapping.

References

[1] M. H. Szymańska, J. Keeling, and P. B. Littlewood, Phys. Rev. Lett. **96**, 230602 (2006).

[2] M. H. Szymańska, J. Keeling, and P. B. Littlewood, Phys. Rev. B **75**, 195331 (2007).

[3] J. Keeling, F. M. Marchetti, M. H. Szymańska, and P. B. Littlewood, Semicond. Sci. Technol. **22**, R1 (2007).

[4] J. Keeling and N. G. Berloff, Phys. Rev. Lett. **100**, 250401 (2008).

† Presenting author

First and second order coherence of a polariton condensate

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We investigate with a Boltzmann-Master equation approach the coherence properties of microcavity (mc) polaritons and compare the results with corresponding experiments in GaAs mc's. The spatial first-order coherence function is determined by the polariton population of the ground state and the excited states which are known from the solution of the Boltzmann equation. Fig. 1 shows how the spatial correlation increases with increasing pump powers. The results are in very good agreement with the double-slit experiment by Deng et al. [1] for GaAs mc's with a cavity life time of 2ps. The results do not leave much room for depletion effects in these mc's which have been predicted for CdTe mc's with stronger interactions[2].

The second-order correlation function $g^{(2)}$ of the polariton condensate is calculated by a Master equation for the probabilty to find n particles in the ground state. The rates between the excited states and the ground state known from the solution of the Boltzmann equation are corrected by a gain saturation [3]. The resulting $g^{(2)}(P/P_{th})$ show a smooth transition from the thermal limit ($g^{(2)} = 2$) below threshold to the coherent limit ($g^{(2)} = 1$) not to far above treshold. In order to explain the observed large correlations above the coherent limit which persist for a wide range of pump powers [4, 5, 6], we study the non-resonant two-polariton scattering processes introduced by [7] and also a kinetic depletion model. A fully satisfactory understanding is however up to now not reached.

References

[1] H. Deng, G.S. Solomon, R. Hey, K.H. Ploog, Y. Yamamoto, Phys. Rev. Lett. 99, 126403 (2006)

[2] D. Sarchi, V. Savona, Phys. Rev. B 75, 115326 (2007)

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[6] J. Kasprzak, M. Richard, A. Baas, B. Deveaud, R. Andre, J. Ph. Piozat, Le Si Dang, Phys. Rev. Lett. 100, 067402 (2008)

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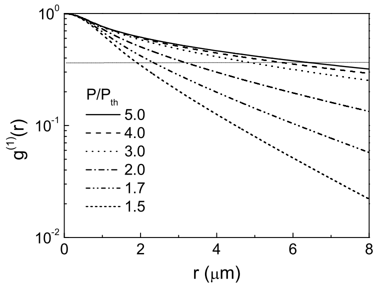

Figure 1: Calculated first-order coherence function $g^{(1)}(r)$ versus distances r for various normalized pump powers P/P_{th}

Formation of the cavity polariton condensate: thermodynamic versus kinetic regimes

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[2]*School of Physics and Astronomy, Cardiff University, Queens Buildings, 5 The Parade, Cardiff, CF24 3AA, UK*
[3] *LASMEA, CNRS and University Blaise Pascal, 24 Avenue des Landais, 63177 Aubière cedex, France*
*Presenting author

Imamoglu first proposed in 1996 [1] to use cavity polaritons to make a new kind of laser without inversion, for which the driving force is not the stimulated emission of photons, but stimulated scattering of polaritons towards a condensate, which leaks out of the microcavity by spontaneously emitting coherent photons. This was a dual-sided concept. It can be interpreted as a new proposal for the realization of laser-type sources [2, 3, 4, 5]. It can also be seen as an example of Bose-Einstein condensation of quasi-particles in a solid state system [6, 7, 8, 9]. The question of the interpretation of the recent experimental findings in terms of polariton lasing or in terms of Bose-Einstein condensation remains hot nowadays. The arguments for the first point of view are that the achievement of a quasi-equilibrium distribution of polaritons is not needed for a coherent emission to take place and that the driving force of the condensate formation is not the constitution of a Bose-Einstein distribution function for the Bose gas. The arguments supporting the second point of view are that, in well defined experimental situations, in spite of the short polariton lifetime, the relaxation kinetics can be fast enough to achieve a steady state Bose distribution.

In this presentation we give an answer to this question. We report the measurements of the polariton distribution function and of the condensation threshold versus the exciton-photon detuning and the lattice temperature in a CdTe microcavity under non-resonant pumping. The results are reproduced by simulations using semi-classical Boltzmann equations. At negative detuning we find a kinetic condensation regime: the distribution is not thermal both below and above the condensation threshold which is governed by the relaxation kinetics. It is found to increase when decreasing the temperature and going to more negative detuning as shown on the figure. At positive detuning, the situation is dramatically different. The distribution function is thermal both below and above the threshold which is now governed by the thermodynamic parameters of the system. Its value is found to increase with temperature and detuning and is well reproduced by thermodynamic calculations. Both regimes are a manifestation of polariton lasing, whereas only the latter is related to the text book Bose Einstein condensation defined as an equilibrium phase transition. Finally we identify a 3rd case close of zero detuning when the transition takes place between the non-equilibrium non condensed state and the equilibrium condensed state. We propose to call this intermediate case kinetically driven Bose condensation because the final state is the state which should be reached by the system at thermal equilibrium.

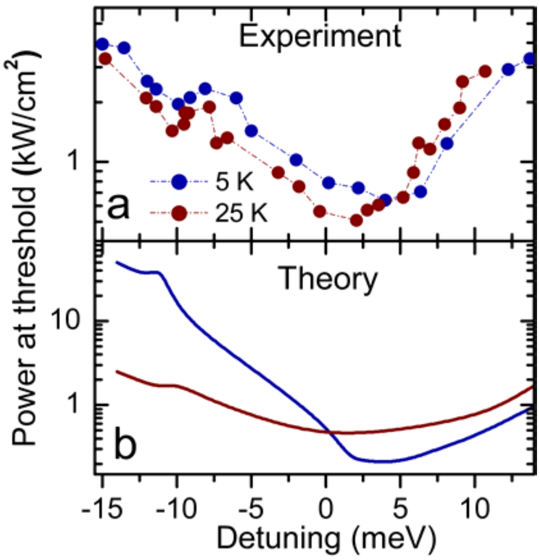

Figure : Pump threshold versus cavity-exciton detuning at 5 K and 25 K. Experiment (a) and theory (b)

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The meaning of superfluidity for polariton condensates

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Since its first discovery in 1937 in liquid 4-Helium, several definitions have been proposed to summarize in simple but precise terms the ever surprising phenomenon of superfluidity [1]. Among the most important definitions, one can mention the absence of drag force onto a slowly moving object through the fluid, the gyroscopic rigidity in the fixed stars frame (the so-called Hess-Fairbank effect), the metastability of supercurrents, and the absence of response to a transverse gauge field.

Remarkably, for most systems at (or close to) thermal equilibrium such as liquid Helium and ultracold atoms, all these criteria agree in defining whether a specific system is superfluid or not, and superfluidity appears to be linked in a quite tight way to Bose-Einstein condensation. The situation is completely different for intrinsecally non-equilibrium objects such as exciton-polariton condensates: in this case, no complete consensus exists so far between the different definitions, and the concept of superfluidity still remains very elusive.

In our contribution we shall try to illustrate recent progress in the theoretical analysis of the different aspects of polariton superfluidity, and we shall try to summarize which issues can be considered in our opinion as understood and which ones are still open.

Most of our discussion will be focussed on the so-called Landau criterion, which defines superfluidity in terms of the perturbation created in the fluid by a weak and uniformly moving defect: in traditional systems at equilibrium, no drag force appears if the speed of the object is lower than the speed of sound.

The consequences of such a criterion on resonantly pumped polariton systems have been investigated in [2], and the results seem to quite agree with the physical expectations: regimes of well-developed superfluidity have been identified, as well as regimes where peculiar Čerenkov patterns can be observed in both the near- and the far-field emission patterns. New results for realistic finite-spot geometries will be presented and the prospects towards experimental observations discussed.

The situation seems more complicate when non-resonantly pumped condensates are considered: the diffusive nature of the BEC Goldstone mode [3–5] fixes the Landau critical velocity to zero, still the drag force suddenly drops to almost zero when the speed of the defect drops below a non-vanishing critical value [6]. We shall show how a suitable generalization of the Landau criterion is able to solve this apparent contradiction.

We shall conclude by reviewing the directions we plan to explore in the next future and the prospects towards a unified theory of non-equilibrium superfluidity.

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Vortices and vortex interactions in exciton-polariton condensates

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I will discuss the properties of topological defects (vortices) in exciton-polariton condensates. For linearly polarized condensates the vortices carry two winding numbers, k and m, which define the polarization and phase change after encircling the vortex core [1]. The winding numbers (k, m) can take integer or half-integer values simultaneously. In particular, the (0,1) vortex is the usual phase vortex with polarization being constant. The (1,0) vortex is the hedgehog with constant phase and the linear polarization rotating by 2π. Both polarization and phase can change together by encircling the vortex core and this is the case of half-vortices with $k,m = \pm 1/2$, where polarization and phase are changed by $\pm\pi$. The half-vortices are basic topological defects in linearly polarized polariton condensates formed in microcavities with cylindrical symmetry.

Four half-vortices can be divided by two pairs, left and right ones, depending on the sign of the product km, and they correspond to the singularities in right and lift circular component of the condensate wave function. In the simple case of isotropic parabolic dispersion the left and right half-vortices do not interact with each other. I will describe how the coupling between left and right half-vortex subsystem appears due to longitudinal-transverse splitting (also referred as TE-TM splitting) of polariton bands. Interestingly, with an account for TE-TM splitting the (1/2,-1/2) and (1/2,1/2) half-vortices start to interact logarithmically, while the other left and right half-vortices still remain decoupled in logarithmic approximation.

Real microcavities present a broken cylindrical symmetry. Namely, there is a small splitting between [110] and [1-10] polarized condensates, so that polarization is pinned to [110]-direction (x-direction). The preferential pinning of the condensate polarization to a specific direction in the microcavity plane has a pronounced effect on the half-vortex texture. When one encircles the half-vortex core polarization remains pinned to x-direction everywhere except a narrow region where it rotates by $\pm\pi$. This narrow region defines a string that goes from the half-vortex to an anti-half-vortex or to the system boundary. String connecting a pair of half-vortices carries additional positive energy, so that the energy of the pair acquires additional term linearly increasing with the distance between half-vortex and anti-half-vortex.

I will also present recent results [2] on the coherent excitation and dynamics of polariton condensates with embedded vortex lattices. Polariton condensates containing vortex lattices can be excited resonantly by the interference of several (three or more) optical pumps. Vortex-antivortex pairs can also appear in polariton condensates due to scattering with disorder. The dynamics of vortex lattices is strongly nonlinear and is characterized by interactions of vortex cores and vortex-antivortex recombination. This dynamics of vortices is studied by the numerical solution of the time-dependent Gross-Pitaevskii equation, both with and without static disorder in the microcavity plane.

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Dynamics of formation and decay of coherence in a polariton BEC

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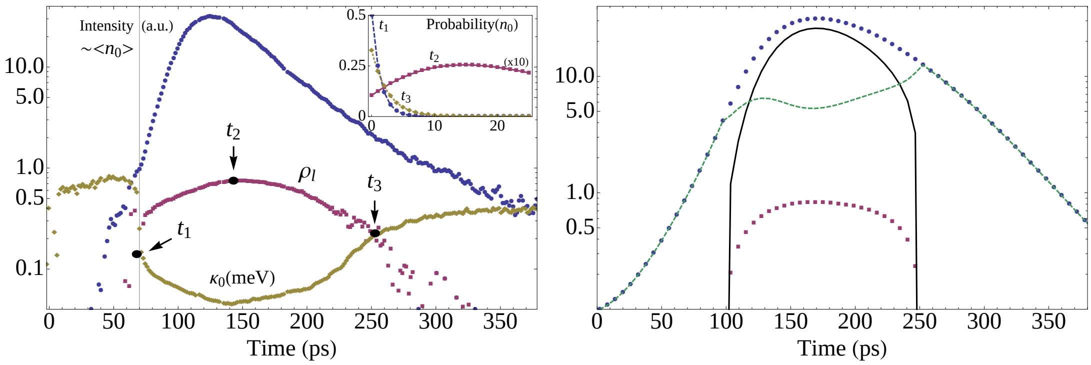
We report on the experimental observation of polariton BEC dynamics, by studying simultaneously the time resolved photoluminescence and the degree of linear polarization ρ_l [1]. We monitor the evolution of the condensate coherence from its spontaneous appearance till its complete decay (left figure). High energy polaritons are injected via a circularly polarised picosecond pulsed laser, and quickly relax into the ground state where they Bose condense. This is evidenced by the emission of linearly polarised light, whose degree provides an order parameter for the BEC transition [2]. After reaching a maximum value of about $\rho_l = 74.5\%$, the order parameter goes to zero as the population decays (polaritons have a short lifetime at $k = 0$), but with a different rate.

We support these experimental results with a simple model that contains all the ingredients to reproduce qualitatively this process (right fig.). We provide the quantum state of the ground state polaritons (inset of left fig.) and show that a coherent fraction can be extracted (right fig.) from the degree of linear polarization, explaining the lag between the linear polarization degree (coherence) and the total population of the ground state. We discuss the possibilities that polaritons open for investigation of out-of-equilibrium quantum phase transitions.



Left: Experimental results on the dynamics of BEC formation after the arrival of the non-resonant pulse. In blue dots, the population of the bottom of the lower polariton branch (photoluminescence intensity normalised so that the phase transition happens when $\langle n_0 \rangle \approx 1$); in brown rhombus, the linewidth (in meV) of the emission peak; and in purple squares, the linear polarization degree, order parameter of the phase transition. In inset, the theoretical distribution of particles in the ground state corresponding to times marked with circles $t_{1,2,3}$ in the plot. The phase transition occurs around the vertical line. **Right**: Theoretical dynamics with the same code of markers. The lines correspond to the extracted condensate (solid black) and thermal (dashed green) fractions.

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Superfluidity, Localisation and Josephson effect of spinor cavity polaritons.

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In this work, we present the derivation of the spinor Gross Pitaevskii equation and we review the main properties of the Bose Condensate of cavity polaritons, taking into account their unique spin structure.

We demonstrate that the polariton polarisation is the true order parameter of the Bose Einstein condensation. In the case of GaAs and CdTe microcavities, at equilibrium the condensate is linearly polarised [1,2] because of the anisotropy of the polariton-polariton interaction. The excitation spectrum of the condensate (Bogoliubov modes) is composed by two distinct branches, which are moreover anisotropic in space because of the interplay of the broken symmetry state of the condensate and the isotropic splitting existing between the TE and TM polarised modes [3]. In contrast, bulk GaN cavities [4] are characterised by isotropic polariton-polariton interaction because of the mixing between the heavy and light hole excitons, usually labelled A and B. As a result, any polarisation state, including the circular one can be randomly chosen during the symmetry breaking process leading to the appearance of the order parameter.

In the second part we analyse the impact of the in-plane potential on the superfluid properties of polaritons. We first consider the simple situation of two coupled potential wells and describe two different types of Josephson effects: the extrinsic effect, related to the coherent tunneling of particles with the same spin between two spatially separated potential traps, and the intrinsic effect, related to the "tunneling" between different spinor components of the condensate within the same trap [5]. We show that the Josephson effect in nonlinear regime can lead to nontrivial polarization dynamics and produce spontaneous separation of the condensates with opposite polarization in real space. As a second step we consider the more complex situation of a condensate moving in a random extended potential [6]. We show that the condensation is accompanied by the onset of Anderson localisation recently observed experimentally for cold atomic systems [7,8]. We describe the formation of the Anderson Glass, which is gapless, phase coherent, but which shows no superfluidity. Contrary to the Bose Glass phase, the increase of the interaction strength (which can be achieved for polariton systems by increasing the polariton density) tends to delocalize the condensate, which can eventually percolate to form a superfluid phase.

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Tuesday

Quasi-monomode guided atom-laser

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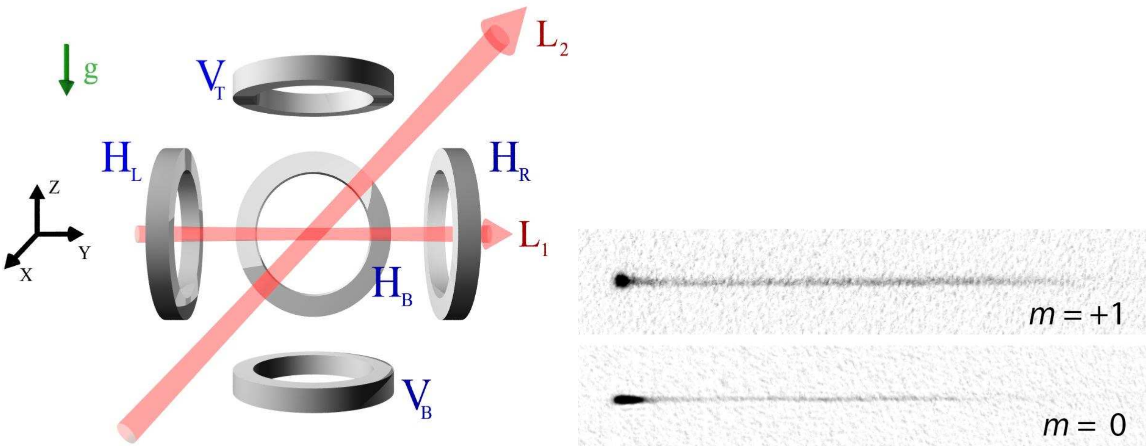
We report the achievement of an optically guided and quasi-monomode atom laser, in all spin projection states ($m_F = -1$, 0 and $+1$) of $F = 1$ in Rubidium 87 [1]. The atom laser source is a Bose-Einstein condensate (BEC) in a crossed dipole trap, purified to any one spin projection state by a spin-distillation process applied during the evaporation to BEC. The atom laser is outcoupled by an inhomogenous magnetic field, applied along the waveguide axis. The mean excitation number in the transverse modes is $\langle n\rangle = 0.65 \pm 0.05$ for $m_F = 0$ and $\langle n\rangle = 0.8 \pm 0.3$ for the low field seeker $m_F = -1$. Using a simple thermodynamical model, we infer from our data the population in each transverse excited mode. We will discuss the ultimate limitations for our outcoupling scheme. An interesting prospect deals with the study of atomic intensity fluctuations and the investigation of the longitudinal coherence with guided atom lasers produced in different interacting regime including out-of-thermal equilibrium state.



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Theory of Continuous Atom Lasers

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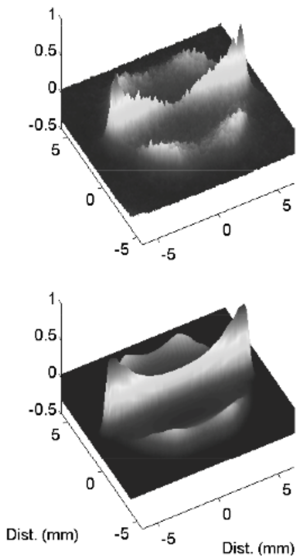
When the Bose-Einstein condensation (BEC) of dilute atomic gases became feasible in the last decade, one of the most exciting prospects was the possibility of producing an atom laser. Atom lasers are formed from output coupling from a Bose-Einstein condensate (BEC), and the spatial properties and quantum statistics of the resulting beam are strongly dependent on those of the source field. This talk will focus on the specific advantages of providing a continuous pumping scheme for the atom laser. Pumped atom lasers offer the promise of an atomic source with dramatically narrow linewidth, high coherence, and a high atomic flux. While experiments demonstrating continuous loading of atom lasers are in their infancy, there are still many unanswered questions about the correct design of such a device. This talk will give an overview of theoretical and experimental progress towards this goal.

Early first principles calculations suggested that BECs might commonly be formed in an excited state. This possibility is consistent with current experiments, where examining the atom laser output often gives the most sensitive measure of the state of the condensate. Simple models of pumping for Bose-Einstein condensates suggest that spatially independent pumping also leads to excitations in the spatial modes, except potentially in the presence of very large nonlinearities. While this instability can be reduced with spatially selective pumping, such processes are difficult to produce experimentally. Large nonlinearities create another problem, in that the phase diffusion of the BEC mode becomes extremely large on the other energy scales of the problem, and this creates an output laser beam with broad linewidth even when the BEC is in a single spatial mode. In practice, therefore, atom lasers will operate best in an intermediate regime.

To date, BEC numbers have been maintained experimentally by preparation of multiple condensates and creating an irreversible coupling from one condensate to another. When this is done without the use of a Bose-enhanced process, the phase diffusion is maximal. When a Bose-enhanced process is used, the phase diffusion of a Poisson pumping process is minimal. When this is achieved by an optical emission stimulated by the existence of the target BEC, the coupling from one condensate to another is restricted to a narrow spread of atomic momenta. A broader momentum resonance can be achieved with continuous evaporation from a thermal source, but there is obviously a balance between the pumping and heating effects.



Comparison of experiment and theory for the transverse spatial profile of a metastable helium atom laser.

To provide a highly coherent atomic source, both the spatial and statistical properties of the lasing mode of an atom laser must be controlled. One way to do this is with active measurement-based feedback control. Feedback control of quantum systems is comparatively undeveloped compared to classical control engineering, but most of the concepts from classical control can be applied directly to atom lasers. Simulating the resulting highly multimode conditional master equations requires the development of new methods, however. In fact, even in the absence of feedback control, simulating these systems in all their multimode complexity is a very difficult process that can be achieved using stochastic techniques. We demonstrate how these techniques have been applied to model atom laser experiments quantitatively and also show how they can be extended for conditional systems.

Intrinsic decoherence mechanisms and formation of coexistent polariton condensates in CdTe semiconductor microcavities

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The recent observations[1] of polariton condensation in semiconductor microcavities have provided a new, solid state system for the study of non-equilibrium Bose-Einstein Condensate (BEC)-related phenomena. We show that the polariton BEC is able to reveal new physics of interacting BECs, not accessible so far for the case of atom condensates.

We investigate fundamental quantum properties of this coherent, matter-wave system by studying the temporal and spatial coherence of a CdTe polariton condensate using continuous wave excitation. Above threshold, the observed polariton emission consists of several (up to 6) narrow lines, separated by ~0.1-0.4 meV (Fig.1). The peaks exhibit superlinear behaviour with power. This indicates the formation of coexisting condensates with different energies. The polariton wavefunctions in real space corresponding to the narrow lines strongly overlap and have a size of 10-20 μm. The spatial coherence lengths λ_C of 10-20 μm above threshold are also observed by Michelson interferometry. The multimode structure of the stimulated emission, and hence of the polariton condensates, arises from spatial fluctuations of the photonic potential (~0.5–0.7 meV), which occur on a length scale of 3-4μm. This result in the formation of discrete localised polariton levels. Above threshold condensation into each localised level occurs, resulting in multimode stimulated polariton emission. Higher energy condensates (E>0.5 meV) are delocalised, but their finite k-vectors (Fig.1) are also determined by the photonic potential.

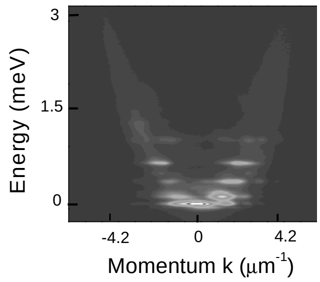

Fig 1 Image of polariton condensate emission above threshold in energy-momentum (E-k) space

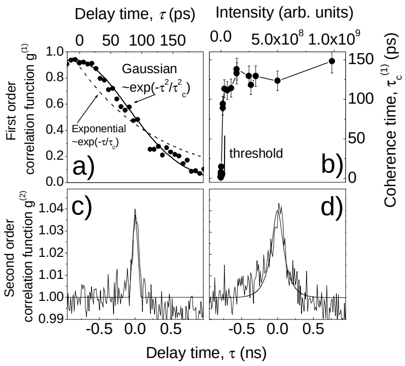

Fig.2 a) Decay of $g^{(1)}$-function. b) Coherence time ($g^{(1)}$) vs emission intensity from condensate. c) and d) Decay of $g^{(2)}$-function below (c) and above (d) threshold

We observe coherence times of the individual modes of ~100-200 ps for both the $g^{(1)}$ phase correlation function and the second order intensity correlation function, $g^{(2)}$. The $g^{(1)}$ function is found to have a Gaussian shape and a decay time which saturates with increasing numbers of particles in the condensate. The coherence times are nearly two orders of magnitude longer than the polariton lifetime (~1.5 ps). Such slowing occurs because stimulated scattering from the polariton reservoir into the condensate dominates over spontaneous processes. We explain quantitatively the slowing down of the decay of the $g^{(2)}$ function and show that the decay of $g^{(1)}$ with its Gaussian form are determined by the effects of interactions between polaritons in the coherent state. The interactions cause spontaneous number fluctuations in the coherent state which translate into random energy variations, leading to decoherence. These decoherence processes would occur in a true equilibrium system.

In conclusion, we report the observation of coexisting condensates with long temporal and spatial coherence in a non-equilibrium polariton system. The transverse photonic potential plays an essential role in the selection of k-vectors to which the condensation is triggered. We also show that a single polariton condensate can behave like an equilibrium BEC on timescales much longer than the cavity lifetime.

We will show finally that there is a very strong similarity between the coherence properties of the polariton BEC and the Optical Parametric Oscillator (OPO) in GaAs-microcavities. Long OPO temporal coherence is again observed with coherence times 200-500 ps for both $g^{(1)}$ and $g^{(2)}$ –functions, where polariton interactions determine the $g^{(1)}$ decay. The OPO also exhibits long spatial coherence lengths ~12-15 μm and spontaneous quantized vortices in its phase spatial profile, characteristic of the interacting polariton BEC subject to its transverse photonic potential[2].

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Coherence of the Microcavity Polariton Condensate

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The demonstration of coherent polariton emission from a CdTe microcavity structure [1] has provided a new system for the study of condensate physics. Unlike atomic condensates, the microcavity system is not in equilibrium; the polariton life-time in the cavity is only $\sim$ 2ps, so the population has to be maintained by pumping. This raises interesting questions about how the properties of such a non-equilibrium condensate differ from those of an equilibrium system.

Recent experimental measurements of the first ($g^{(1)}$) and second ($g^{(2)}$) order correlation functions of the emitted light have shown that the decay times of both are $\sim 100-200$ps, much longer than the cavity life-time. In this work, we present a theroetical treatment which provides a quantitative explanation of these results, and shows that the ultimate cause of the coherence decay is interactions between polaritons in the condensate.

The microcavity polariton condensate is a mesoscopic quantum system, consisting of $N \sim 10^2$ polaritons within the finite size excitation spot. As a result, number fluctuations of $\sim N^{\frac{1}{2}}$ are expected. For a finite equilibrium condensate of interacting particles, it is straight forward to show that the decay of $g^{(1)}(t)$ has a Gaussian form [2]. The physics behind this is the effect of self phase modulation: the interactions translates number fluctuations in the condensate into random changes to its energy, and so the coherence is lost. The calculated time for this decay turns out to be $\tau_c \sim$ 200ps, in good agreement with the measured values.

The problem with this picture is that the decay time, τ_c, is much longer than polariton life-time, due to emission from the cavity. These losses, and the corresponding gain processes which maintain the population, interrupt the unitary evolution of the system under the interaction Hamiltonian. We argue that the coherence decay should then have an exponential form, with a much longer time constant τ_c^2/τ_r, where τ_r is the effective time-scale of the gain and loss. To explain the observed Gaussian decay, it is thus necessary for the τ_r to be much greater than the empty cavity life-time, τ_0, so the self-phase-modulation decay is completed before it is interrupted.

The explanation for this slowing comes from laser physics. The gain process, which replaces the polariton losses, involves stimulated scattering, which does not interrupt the unitary evolution. This means that the effective time-scale, τ_r, can be much longer than τ_0. As the same physics determines the decay of the second order intensity correlation function, we can deduce $\tau_r \sim$ 150ps directly from the experimental data. This provides sufficient slowing to see the Gaussian decay of the first order correlation function.

To put these ideas on a more quantitative footing, we have developed a simple model of the polariton condensate which correctly predicts the time decay of both correlation functions. The coherent mode is treated as a harmonic oscillator with a Kerr non-linearity representing their interactions. The mode is coupled to a reservoir, using the master equation formalism. Reservoir losses are offset by a laser-like saturable pump term and we assume the system is well below saturation, so the mode population $N \ll N_s$, its saturation value. We find that the decay of the second order function is slowed, to $\tau_r \sim \tau_0 N_s/N \sim$ 50ps, comparable to the experimental value. Furthermore, when we solve our model for $g^{(1)}(t)$, we find that there are indeed two limiting regimes, with behaviour predicted by the arguments given above; for short timescales, compared to this slowed τ_r, we get the Gaussian decay of the isolated condensate, with decay time τ_c, while for long time scales the decay is exponential with time constant τ_c^2/τ_r.

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Stimulated scattering and lasing of intersubband cavity polaritons

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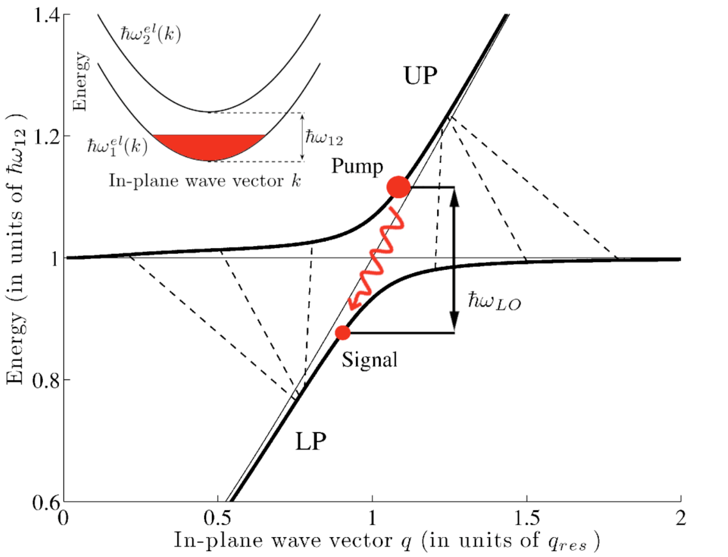
We present a microscopic theory describing the stimulated scattering of intersubband polaritons [1-3] in a microcavity-embedded two-dimensional electron gas. In particular, we consider the polariton scattering induced by the spontaneous emission of LO-optical phonons.



An intersubband polariton initially pumped in the upper polariton (UP) branch can scatter into a final state (signal mode) in the lower polariton (LP) branch by emitting an optical phonon. Inset: the energy dispersion of the quantum well electronic conduction subbands versus electron wave vector. In the ground state, a dense electron gas populates the first conduction subband.

In contrast to other composite bosons in condensed matter such as Cooper pairs or excitons, intersubband excitations do not correspond to any bound state and are thus robust up to room temperature. However, their bosonic nature and thus the possibility of obtaining a stimulated scattering with them has been questioned.

Starting from the fermionic Hamiltonian for the cavity embedded quantum well electronic system and by using an exact iterative commutation procedure, we are able to determine the phonon-induced polariton scattering for an arbitrary number of excitations in the initial and final intersubband cavity polariton modes and explore the regime of stimulated scattering [4]. Our exact results demonstrate the possibility of final-state stimulation for such composite excitations and describe the deviations from perfect bosonicity occurring at high excitation densities. The degree of bosonicity in such a system can be controlled by the background density of the two-dimensional electron gas.

By using realistic parameters for a GaAs semiconductor system, we predict how to achieve a quantum degenerate regime, leading to ultralow threshold lasing without population inversion, operating in the mid (or far) infrared.

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Spontaneous Polarisation Build up in a Room Temperature Polariton Laser

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Semiconductor microcavities (MCs) offer a unique system for producing novel types of low threshold laser. This arises from the strong coupling between cavity photons and bound electron-hole pairs in the semiconductor emitters.[1] We previously predicted that such polariton lasers can operate without inversion, reducing emission thresholds considerably.[2-3] Here such systems are fabricated from lattice-matched monolithic GaN-based multilayers, including both bulk GaN and QW microcavities, which operate at room temperature. Coherent emission with a threshold below 0.1mW is demonstrated, which is nearly two orders of magnitude than the best previous GaN lasers.[4,5] These devices offer a new route to robust long-lived GaN lasers.

We demonstrate here that polaritons are thermalised to T~360K on sub-picosecond timescales below threshold, suggesting that they are indeed able to Bose condense at room temperature. However the most peculiar and novel feature of these emitters is that the coherent emission from this polariton condensate differs strongly in its polarisation properties from any previous laser. Each time the coherence is initiated using high-energy optical excitation, the polariton condensate chooses a different elliptical polarisation. The average spontaneous vector polarisation is ~50%. This spontaneous symmetry breaking is a signature for BEC, and by measuring single-shot polarisation dynamics we provide convincing additional evidence for BEC in these GaN microcavities.[6]

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Room temperature polariton lasing and condensation effects in III-nitride microcavities

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The recent demonstration of room temperature (RT) polariton lasing in a bulk GaN microcavity (MC) has established the possibility to use nitride semiconductors for the realization of polariton-based devices [1]. Indeed, those structures could be used as novel low threshold coherent light emitting sources or micro optical parametric amplifiers. Unfortunately, achieving an efficient electrical injection within a bulk GaN active region is difficult. As a result the realization of an electrically pumped polariton laser based on such bulk samples should reveal highly challenging. A way to push forward polariton-based devices consists in achieving a well-grounded RT strong coupling regime (SCR) and demonstrating nonlinear effects in quantum well (QW) MCs for which the realization of an electrically pumped device should be more realistic. This would add to the recent demonstration of GaAs-based polariton light-emitting diodes operating at cryogenic temperatures [2]. In this context, we have recently proposed an approach different from that commonly employed in III-arsenides, namely the use of a GaN/AlGaN multiple QW active region [3]. This structure has allowed the demonstration of the SCR at RT with a record vacuum Rabi splitting value for a semiconductor QW MC (~50meV) [3].

Here, we will report on the emission properties of this type of MCs under nonresonant optical pumping. It will be shown that the samples exhibit a nonlinear emission threshold at RT while remaining in the SCR (Figs. 1(a)-(b)) [4]. Experimental results will thus be depicted within the picture of polariton lasing and prospects regarding the realization of an electrically pumped polariton laser will be given. Furthermore, we will also address how these results can be linked to RT Bose-Einstein condensation of polaritons [5-6]. In this context, the thermalization process of the photogenerated quasiparticles will be described. The behavior of the nonlinear emission threshold versus polariton trap depth and temperature as well as that of the polarization of the emitted light below and above threshold will also be discussed.

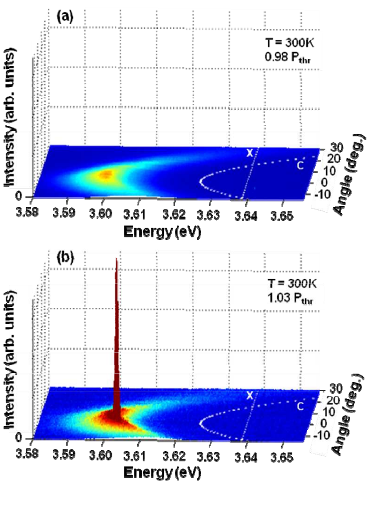

Fig. 1: (a) 3D representation of the far-field emission with emission intensity displayed on the vertical axis (linear vertical scale) below and (b) above threshold. The position of the cavity mode (C) and the uncoupled exciton (X) is also reported.

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Polaritonic Devices Utilizing Nanoscale Films of J-Aggregates

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Exciton-polariton based photonic devices are a novel platform for realizing low threshold lasing [1] and optical switching [2] in a scalable integrated architecture. Use of organic materials as the excitonic component facilitates room temperature operation of such devices [3, 4]. Here we report room temperature exciton-polariton devices consisting of layer-by-layer (LBL) assembled thin films of polyelectrolyte and the J-aggregates of the cyanine dye TDBC [4] inserted in a resonantly-tuned planar λ/2n optical microcavity with metal mirror and dielectric Bragg reflector (See Figure 1). Rabi-splitting and polaritonic dispersion are observed in the reflectance, transmittance, and photoluminescence measurements of the device (See Figure 2a,b). The devices exhibit Rabi-splitting of $\Omega_R = 125 \pm 7$ meV with a polyelectrolyte/J-aggregate layer that is only 5.1 ± 0.5 nm thick [6]. Furthermore, the linewidth of the lower energy polariton state, measured on resonance, is $\Gamma = 12.1$ meV. Hence, the ratio $\Omega_R/2\Gamma = 5.1$ indicates devices operating in a limit where the light-matter coupling (Ω_R) significantly exceeds competing dephasing processes (Γ). These figures of merit are achieved by virtue of the nanostructured film's large absorption coefficient of $\alpha \sim 1.0\text{x}10^6$ cm^{-1} and location of the layer at the microcavity anti-node. Because strong coupling is achieved with thin films of nanometer scale thickness control, the majority of the microcavity modal volume is available for integrating optically active materials such as colloidal quantum dots and fluorescent polymers in structures that can be used to investigate fundamental physical phenomena such as non-radiative energy transfer, and ultimately leverage the coherent properties of the strongly coupled states.

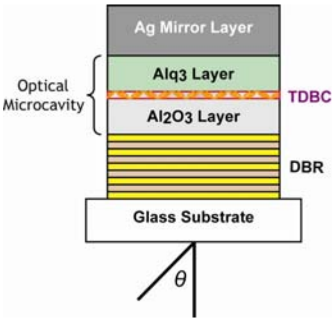

Figure 1: Device design of polaritonic structure. Microcavity consists of a DBR and a silver mirror layer. On top of the J-aggregate layer, a film of the small molecule Alq_3 is thermally evaporated.

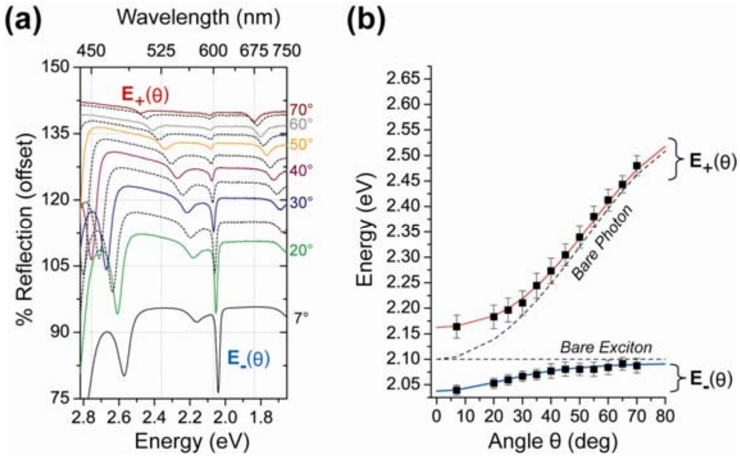

Figure 2: (a) Angularly resolved reflectance measurements and (b) dispersion relation for resonantly tuned polaritonic structure. The microcavity is resonantly tuned at normal (at $\theta = 0°$) to the exciton resonance of 2.10 eV. $E_-(\theta)$ denotes the lower energy polariton states, $E_+(\theta)$ the higher energy polariton states. Reflectance measured with TE polarized light. Measurements from $\theta = 20°$ to $70°$ are relative values. Data at $\theta = 7°$ is absolute reflectance.

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Wednesday

Exciton-polariton Bose-Einstein Condensation

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An experimental technique of controlling spontaneous emission of an atom by use of a cavity is referred to as cavity quantum electrodynamics and has been extensively studied for atoms[1] and excitons[2]. Due to a strong collective dipole coupling between microcavity photon fields and QW excitons, a semiconductor planar microcavity features a reversible spontaneous emission or normal mode splitting into upper and lower branches of exciton-polaritons[3]. A metastable state of lower polariton at zero in-plane momentum (k=0) has emerged as a new candidate for the experimental study of Bose-Einstein condensation (BEC) in solids[4]. An exciton-polariton has an effective mass of four orders of magnitude lighter than an exciton mass, so the critical temperature for polariton BEC is four orders of magnitude higher than that for exciton BEC at the same particle density. An exciton-polariton can easily extend a phase coherent wavefunction in space through its photonic component in spite of crystal defects and disorders, which is known as a serious enemy to exciton BEC.

In this talk we will discuss the recent progress on the dynamic condensation experiments of exciton-polaritons. Quantum degeneracy at thermal equilibrium condition was achieved by using a cooperative cooling with two spin components, evaporative cooling with a weak lateral trap and a blue detuning regime[5]. The formation of a first order coherence (off-diagonal long range order) was confirmed by the Young's double slit interferometer[6] and the excess intensity noise (photon bunching effect) was observed by the Hanbury-Brown and Twiss interferometer[7]. The spontaneous spin polarization was confirmed at condensation threshold[8], and the Bogoliubov excitation spectrum was observed above threshold[9]. The Landau's criterion for superfluidity is satisfied with a critical velocity of ~10^8cm/s. Finally the Bose-Hubbard model was implemented in a one-dimensional array of polariton condensates, in which the competition between a coherent zero state and pi state was observed[10].

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Polariton laser in micropillar cavities

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Semiconductor microcavities in the strong coupling regime have been the subject of intensive research efforts these last years. In this system, the eigenstates are exciton-photon entangled states (named cavity polaritons). Polaritons present strong non-linearities due to their excitonic part and obey to bosonic statistics, thus being able to massively occupy a single quantum state (quantum degeneracy).

We address here the physics of cavity polaritons confined in micron-sized micropillars. The photon lateral confinement defines a discrete spectrum of polariton states with an increasing energy separation as the pillar size is reduced. Low temperature photoluminescence measurements are performed on single micropillars. A marked threshold is observed in the excitation power above which a very large polariton population accumulates in the ground state (more than 1000 polaritons in the same quantum state). Spectral narrowing in the emission is the signature for the onset of coherence. A detailed analysis allows concluding that the observed features are due to polariton lasing and not to Bose Einstein condensation.

The advantages of micropillar cavities with a discrete polariton spectrum as compared to the quasi-continuum of a 2D cavity will be discussed.

At higher excitation powers, the strong coupling regime is bleached and the system behaves as a standard photon laser (VCSEL). The present zero-dimensional system thus offers the possibility to study both regimes, polariton lasing and photon lasing, in the very same device. The threshold for polariton lasing is found to be two orders of magnitude smaller than the threshold for photon lasing. Polariton lasers could potentially provide ultra low threshold sources of coherent light.

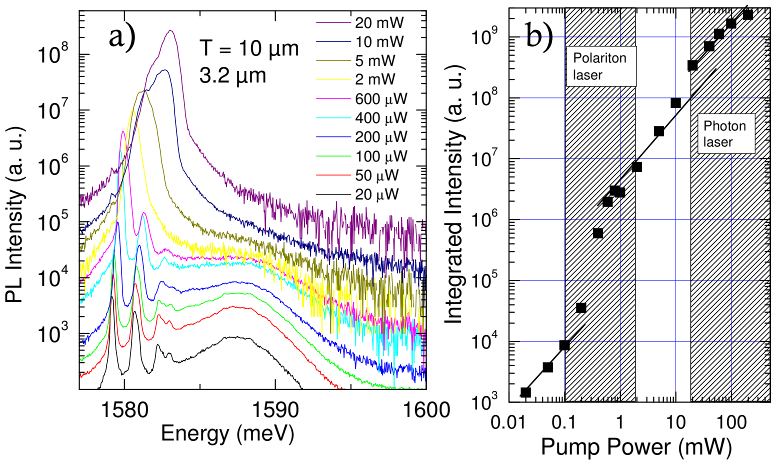

Fig : a) Emission spectra measured under non resonant excitation on a 3.2 µm micropillar; b) Integrated intensity measured on the lower energy mode as a function of the excitation power. Shaded areas indicate the excitation range for polariton lasing and for photon lasing.

“Polariton laser using single micropillar GaAs-GaAlAs semiconductor cavities”, D. Bajoni, P. Senellart, E. Wertz, I. Sagnes, A. Miard, A. Lemaître, and J. Bloch, Phys. Rev. Lett. 100, 047401 (2008)

Controlling the wave function of zero-dimensional microcavity polaritons

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We study the confined polariton states that are produced by including mesas in the spacing layer of a microcavity in the strong coupling regime [1]. Such states will be of major importance if we are indeed able to realize polariton condensates in such traps [2]. Since their sizes are of the order of the mesa sizes (from 3 to 20 microns), they can be accessed directly through conventional optical means. We have developed high quality imaging techniques both in real space and in reciprocal space [3].

In the present work, we will detail our study of the resonant excitation of confined polariton wave functions at well defined energies and positions in k space. A change in the position of the exciting beam in the two dimensional k-space allows to produce a rotation of the observed interference pattern of the excited polariton eigenstates i.e. a direct manipulation of their wave functions. This comes from a phase locking mechanism which locks the phase of the excited wave functions to the phase of the cw laser.

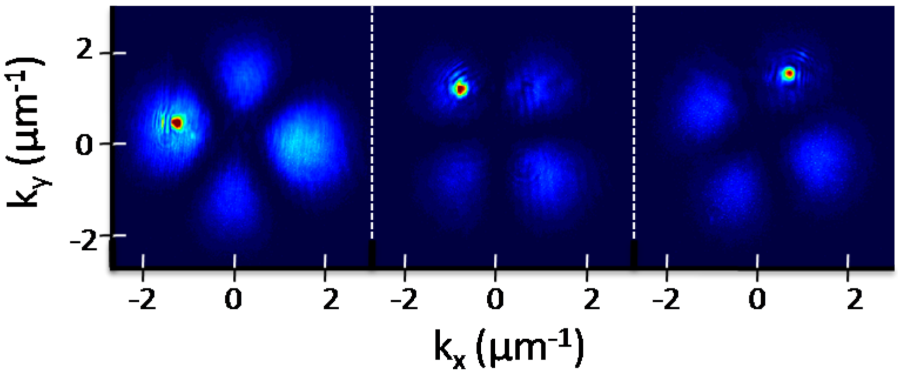

FIG. 1: Lobes of the degenerated (1,2) state in a 3 μm mesa following the rotation of the laser in k-space.

We also investigated the transition from a fully confined wave function in a 3 micron mesa, towards a two dimensional polariton, through 9 and 20 micron mesas. For the less confined polaritons in the larger mesas we observe a strong enhancement of the emission in the back scattering direction, which reminds of resonant Rayleigh scattering (RRS) in a two dimensional (2D) system [4]. However, the observed enhancement can be much bigger than for RRS in 2D and has a completely different origin, because we do not need to account for disorder.

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Quantum polariton fluid in microcavities

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Coherent collective behaviours of microcavity polaritons have recently shown close analogies with Bose condensates of atoms. In this work we will show the possibility to observe the dynamics of the elementary excitations of a coherent state of polaritons and the interesting phenomenology when this state is put in motion.

A very intriguing behaviour of the elementary excitations of the signal polaritons, created by resonantly exciting on the lower branch, is the strong decrease of the dumping rate when approaching from below the threshold power for the stimulated parametric scattering [1]. Using a combination of continuous wave (CW) excitation and pulsed probe, we are able to observe a slowing down of the dynamics of the signal elementary excitations by more than three orders of magnitude with respect to the empty cavity lifetime. This phenomenon is associated to the onset of a soft Goldstone mode when the threshold is crossed [2].

Thanks to the very long lifetime of the signal, by stimulating the parametric scattering at finite wavevectors, we demonstrate the possibility to create a coherent polariton flow travelling inside the CW pump [3,4]. A first finding is the linearization of the polariton dispersion around the signal state that results in a diffusionless motion of the polariton wavepacket travelling at velocities around 1% the speed of light. In spite of the very high velocity, the coherent polariton signal can show unperturbed motion when crossing a potential barrier, as well as quantum reflection and splitting when the size of the defect becomes comparable to that of the polariton droplet.

The complex phenomenology of the quantum fluid of polaritons, which shows similarities with the well known physics of ultra-cold atomic gases—such as Bose Einstein condensation and superfluidity—stimulates further investigation of the novel characteristics of non-equilibrium, strongly interacting, coherent polariton states.

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Propagation of polariton wavepackets

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We discuss the propagation of coherent polariton wavepackets in the two-dimensional plane of a semiconductor microcavity, in the presence of a continuous coherent pumping, finite photon lifetime, dissipation and potential fluctuations. Interpreting the wavepacket as a condensate wavefunction, this works addresses the topical issue of polaritons Bose-condensates [1].

We pay special attention to the case where nonlinearities arising from point-like particle-particle interactions dominate the system, especially in configurations where strong parametric oscillations occur from a highly populated state that scatters off particles into phase-matched so-called signal and idler states [2].

We discuss the coherent properties of the polariton field, evoking its vorticity [3], its superfluid velocity, its interactions with defects, long-lived propagation of shape-preserving, soliton-like excitations, and propose a tentative picture of the phenomena recently observed in time-resolved pump-probe experiment [4].

[1] Le Si Dang, D. Snoke, B. Deveaud, J. J. Baumberg, J. Bloch, invited contributions at this conference.
[2] M. Wouters, invited contribution at this conference.
[3] Yu. Rubo, invited contribution at this conference.
[4] D. Sanvitto, invited contribution at this conference.

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Atomic Lattice Excitons

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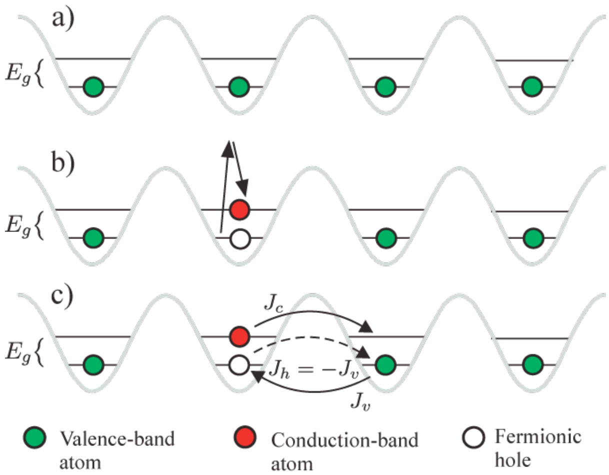
Systems of ultracold atoms in optical lattices offer a highly controllable realisation of many-body lattice models, in which we have a good understanding of the underlying microscopic physics. These systems also are free from uncontrolled disorder, and from strong dissipative processes (e.g., coupling to lattice phonons) that are typically present in solid state systems. As a result, these systems are ideal candidates to study the coherent dynamics of metastable many-body states on relatively long timescales. This was recently evidenced by the study of repulsively bound atom pairs in an optical lattice [1].

In precisely this way, optical lattice systems also offer the opportunity to study certain properties of excitons in an idealised environment. By considering a spin-polarised Fermi gas in an optical lattice in which some atoms are excited to a higher Bloch band, and in which repulsive interactions are engineered between atoms in different bands, it is possible to produce Atomic Lattice Excitons (ALEs) [2]. These bound particle-hole pairs can be described using Hubbard models, and would allow for the study of many properties predicted for semi-conductor excitons, but in a situation where the composite objects are long-lived. In particular, we showed that a condensate of ALEs could be prepared via an adiabatic state preparation process, and could be characterised using readily available experimental techniques, including rf-spectroscopy and noise correlation measurements.



At the same time, ALEs exhibit other interesting properties, in particular the possibility to form a crystalline phase. This arises because atoms in an excited band have a much larger tunnelling rate than those in the lowest band, making it possible for fast-moving excited atoms to mediate effective finite-range interactions between ALEs, for which the centre of mass is located near the slow-moving hole. We investigated these effective interactions and the resulting crystalline phase, both in a Born-Oppenheimer approximation and using numerical calculations based on time-dependent DMRG methods [3-5].

These ideas can be extended to the study of other metastable composite objects in optical lattices that also exhibit interesting quantum phases. One such possibility is the realisation of η-pairing states, which are exact excited eigenstates of the Hubbard model for two fermionic species [6]. These states exhibit off-diagonal long-range order in all dimensions, and if prepared in an experiment should be stationary in time. However, these states would be sensitive to perturbations in the Hamiltonian and imperfections in the state preparation, making them a potentially useful tool to characterise the fidelity of quantum simulation with cold atoms in optical lattices.

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Bose-Einstein condensation meets Cavity QED

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Cavity quantum electrodynamics (cavity QED) has proven to be exceedingly successful in illuminating matter-light interaction and in providing a platform to test ideas for quantum information processing. In this talk I will report on the strong coupling of a Bose-Einstein condensate to the quantized field of an ultrahigh-finesse optical cavity. The experiment brings us into a new regime of cavity QED where all atoms occupy a single mode of a matter-wave field and couple identically to the light, sharing a single excitation [1].

By coupling the field mode of the cavity to a collective density excitation of a Bose-Einstein condensate we have realized a cavity opto-mechanical system in the quantum regime and observed its strongly driven back-action dynamics. The results are surprising on a conceptual level and open a new avenue for cavity opto-mechanics and quantum gases with non-local interactions [2].

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Quantum condensation from tailored exciton populations.

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We present a proposal [1] of a new experimental approach to quantum condensation of excitons and photons in semiconductor microcavities. Whereas in existing approaches relaxation and inelastic scattering play a crucial, yet poorly-understood role, we show how condensates could form in their absence.

Our proposed experiment involves a microcavity containing an ensemble of quantum dots. In the first stage of our proposed experiment the microcavity is excited with a chirped laser pulse, which we show can create an energy-dependent population in the inhomogeneously-broadened exciton line. In the second stage of our proposed experiment, this incoherent population then spontaneously evolves into an off-equilibrium condensate. We demonstrate this phenomenon in simulations with realistic parameters, and explain that it is due to a dynamical analog of the BCS instability. The key to achieving it is the possibility of using a controlled laser pulse to directly create, in only a few picoseconds, an exciton population with an effective temperature of only 1 K.

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Thursday

"**Exciton Superfluid in Two Dimensional Hole Bilayers**"

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When two layers of two-dimensional carriers are brought into close proximity, new phenomena resulting form the carrier-carrier interaction in opposite layers occur. One remarkable experimental observation in these systems is a charge neutral superfluid in perpendicular magnetic field, at total Landau level filling (ν) factor one when equal and opposite currents are passed in the two layers (counterflow) [1,2,3]. This phenomenon can be explained by the formation of electron-hole pairs (excitons) in the two, half-filled layers, and the resulting excitonic condensation at the lowest temperatures (T) [4].

In this talk we present experimental results, which explore the counterflow transport properties of strongly interacting GaAs hole bilayers in the limit of zero inter-layer tunneling. At the lowest temperatures both Hall and longitudinal counterflow resistivities (ρ_{xx} and ρ_{xy}) vanish at ν=1, a finding which demonstrates the existence of a counterflow supefluid in the limit of T=0 at this filling factor. A noteworthy feature of our transport data is that the counterflow ρ_{xy} remains much smaller than the counterflow ρ_{xx} as the temperature is increased. This property becomes more prominent as the bilayer density is reduced, namely when the bilayer is in a stronger inter-layer interaction regime. The counterflow ρ_{xx} at ν=1 however, shows little dependence on total bilayer density, but can be greatly affected by small changes in the layer charge distribution. We discuss the counterflow resistivity dependence on total bilayer density, layer density imbalance, and temperature in terms of theoretical models which suggest that the finite dissipation is caused by the disorder-induced, mobile vortices in the counterflow superfluid [5,6].

Work performed in collaboration with M. Shayergan and D. A. Huse.

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Critical Currents in Excitonic Electron Bilayer Systems

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Electron correlation effects in two-dimensional electron systems (2DES) under strong perpendicular magnetic fields are responsible for a variety of states, such as the fractional quantum Hall effects. A very unique correlated state can emerge between two closely-spaced 2DES when the filling factor in each 2DES is close to 1/2. The ground state at this total filling factor of one is believed to be a Bose condensate of (quasi-)excitons. This correlated state can be investigated via magneto-transport or interlayer tunneling experiments. The latter have shown an I/V characteristic which has an astonishing resemblance to one of the Josephson effect of superconductivity [1]. Despite several similarities between the common superconductivity/superfluidity and the double quantum well system at a total filling factor of 1, certain aspects have failed to appear so far, such as a critical behavior. In our DC interlayer tunneling experiments, we could observe such a critical behavior [2] when then total current I becomes too large. For $I < I_{critical}$, the four-terminal interlayer resistance is very small but abruptly increases by many orders of magnitude once $I > I_{critical}$. The nearly vanishing 4-terminal interlayer resistance is most likely the direct consequence of the (interlayer) phase-coherence associated with the Bose condensation of excitons. It appears that the condensate changes the tunneling electrons into quasiparticles which are easily transferred between the layers.

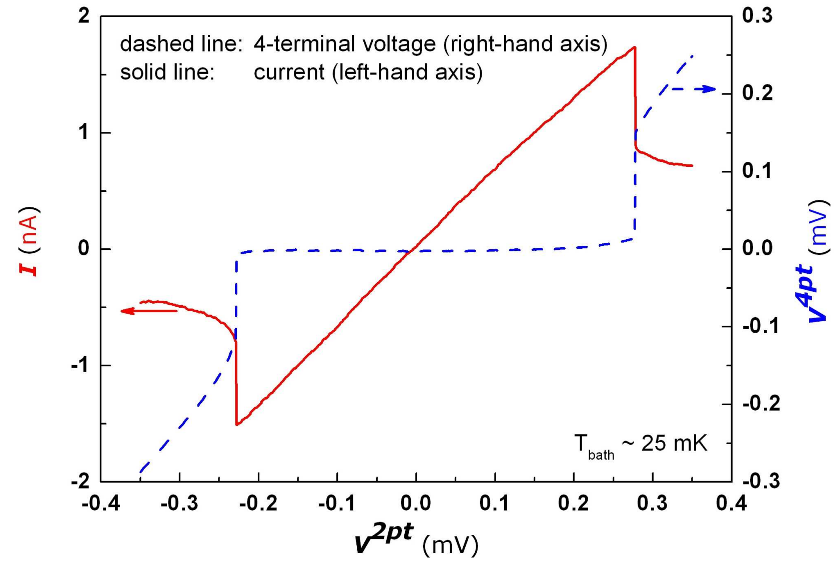

Figure 1: *DC current and 4-terminal voltage versus the applied 2-terminal bias voltage. The small 4-terminal voltage jumps to a finite value as soon as a critical current is exceeded. If the current is plotted versus the 4-terminal voltage, the curve collapses onto a Josephson effect-like characteristic.*

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First-order metal-excitonic insulator transition in quantum Hall electron bilayers

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The ground states of quantum Hall bilayers at total filling factor ν_T =1 are determined by the interplay between the ratio of the interlayer separation and magnetic length (d/l_B) and the tunneling gap Δ_{SAS}/E_C, the energy splitting between the symmetric and asymmetric combinations of quantum well levels in unit of the Coulomb energy ($E_C= e^2/\varepsilon l_B$)[1]. At large enough Δ_{SAS}/E_C or low d/l_B the ground state is incompressible and can be described as an excitonic state[2] due to population of electrons in the antisymmetric excited level induced by interlayer correlation. The order parameter of this excitonic quantum Hall state measures the excitonic density in the ground state and can be determined in inelastic light scattering experiments from measurements of the energy splitting between the spin wave at the Zeeman energy E_Z and spin flip excitation (SF_{SAS}) across the tunneling gap[2]. At low values of Δ_{SAS}/E_C or large values of d/l_B, the ground state is compressible[1].

Here we show the evolution of the order parameter of the excitonic insulating phase as the inter-layer correlations are continuously decreased by reducing Δ_{SAS}/E_C with the application of an in-plane component of the magnetic field[3] in a tilted-field geometry. The fine adjustment of the tilt angle with a precision of better than 0.1^o allows us to monitor the SF_{SAS} excitation energy and the mode intensity as the ν_T = 1 phase boundary is approached. Both the observed discontinuity of the order parameter at the phase transition and the sharp drop of SF_{SAS} integrated intensity suggest that a first-order quantum phase transition separates the excitonic incompressible state from the compressible phase[4]. We also demonstrate that the compressible state that emerges abruptly at the phase transition is a composite fermion (CF) metal[5] stabilized by the intra-layer electron correlation. Evidence for the occurrence of the CF phase in the bilayer at ν_T = 1 is linked to the observation of a low-lying continuum of spin excitations below the Zeeman gap in the inelastic light scattering spectra. These spin excitations are attributed to quasiparticle excitations across the Fermi energy of the CF metal. Their behavior as a function of the tilt angle suggests that the CF metallic phase becomes fully spin-polarized for E_Z/E_C > 0.013. The observed discontinuous phase transition highlights the competition between inter-and intra-layer electron correlations. The competition of the order parameters of the excitonic and composite fermion metal phases under the condition of weak residual disorder results in the observed first order character of the quantum phase transition[6].

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How to make a bilayer exciton condensate flow

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Among the many examples of Bose condensation considered in physics, electron-hole-pair (exciton) condensation has maintained special interest because it has been difficult to realize experimentally and because of controversy about condensate properties. Although ideal condensates can support an exciton supercurrent, it has not been clear how such a current could be induced or detected. This paper addresses the electrical generation of exciton supercurrents in bilayer condensates (systems in which the electrons and holes are in separate layers) and reaches a surprising conclusion. We find that steady state dissipationless currents cannot be induced simply by connecting the two layers in series to guarantee opposite currents in electron and hole layers, as has long been supposed. Instead, current should be injected and removed from the same layer, and a conducting channel supplied to close the counterflow portion of supercurrent in the other layer.

Title to be confirmed

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Exciton Mott transition and quantum pair condensation in electron-hole systems: Dynamical mean-field theory

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Quantum cooperative phenomena in electron-hole (e-h) systems are reviewed from a theoretical viewpoint, stressing the exciton Mott transition, the exciton Bose-Einstein condensation (BEC), the e-h BCS-type condensed state, and their crossover. To clarify these phenomena, modern theoretical tools are necessary which can cover not only low and high particle density regions but also intermediate density region.

Here, we confine ourselves to high-dimensional e-h systems, which are described simply by the e-h Hubbard model with both repulsive (e-e and h-h) U and attractive (e-h) U' *on-site* interactions. We study the metal-insulator transition called the "exciton Mott transition (EMT)" at zero and finite T temperatures, investigated with the dynamical mean-field theory (DMFT) [1] and with the slave-boson mean-field theory [2]. Away from half-filling we find two types of insulating phases: exciton-like and biexciton-like insulators in the (U, U') plane. Coexistence region between metallic and insulating phases is also found reflecting the first-order transition of the EMT. At the Mott-critical temperature such EMT disappears, and the crossover is observed above the critical temperature.

Effects of inter-site interaction on the EMT are investigated by the extended DMFT applied to the extended e-h Hubbard model, which incorporates both repulsive v and attractive v' *inter-site* interactions in addition to U and U'. The inter-site interactions do not change the nature of the EMT in high dimensions but tend to stabilize the metallic e-h plasma state when v and v' have the same strength. By contrast, small difference between v and v' drives the system to the insulator with the strong fluctuations of the mass density wave [3].

We discuss also the crossover between the exciton BEC and the e-h BCS states using the self-consistent t-matrix and local approximations [4] in the framework of the DMFT for the e-h Hubbard model. The transition temperature is calculated in the crossover regime. Then, we will discuss the whole phase diagram of the e-h system in the (U=U', T) plane. Optical absorption spectra are also introduced. We will mention comparison with the one-dimensional e-h systems [5].

The author thanks Y. Tomio, T. Ohashi, K. Asano, P. Huai, P. Littlewood, H. Akiyama, and M. Kuwata-Gonokami for fruitful discussion and collaboration.

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Linear polarization of the luminescence of dipolar exciton Bose condensate

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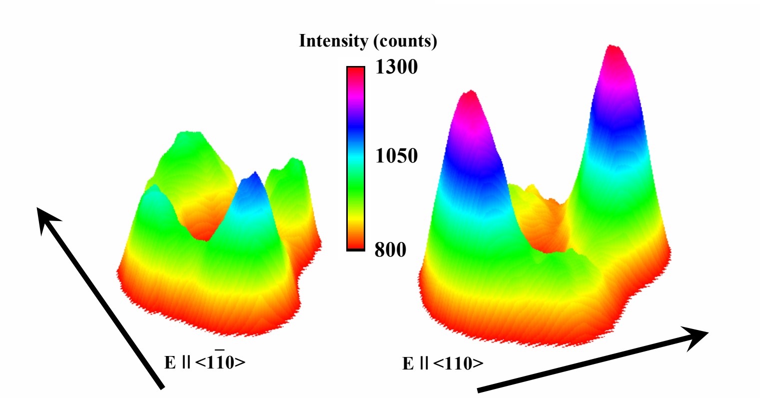
Recently, we have reported that spatially indirect, dipolar excitons in both double and single GaAs/AlGaAs quantum well (QW), when confined in a ring-shaped lateral potential trap, demonstrate a set of properties which can be explained in terms of exciton Bose-Einstein condensation (BEC) [1-2]. The properties include, in particular: a) rather narrow (≤300 μeV) line rising in photoluminescence spectrum in threshold manner with pumping and disappearing rapidly with temperature (at 4-10 K, depending on pumping rate), b) axially symmetric luminescent spot patterns within a ring trap, c) concentration of light emission close to the sample normal which enhances with pumping, d) symmetric far-field interference patterns (optical Fourier-transform) - typical for spatially-coherent light source, e) distinct interference of light emitted from two luminescent spots separated spatially as far as 4 μm. In addition, the luminescence of dipolar excitons in ring lateral trap exhibits linear polarization aligned along <110> direction in {001} crystallographic plane coinciding with the QW plane.



Now we have analyzed experimentally polarization properties of the luminescence light emitted by the dipolar exciton Bose condensate. A lateral trap was formed, as previously, by inhomogeneous electric field along the perimeter of a circular 5μm-window in Schottky-gate atop heterostructure. It is worth mention that the experiments were performed under compensation of extra charges in photoexcited exciton system within the trap. We have found that the sharp luminescence line of dipolar exciton Bose condensate is strongly linearly polarized. The polarization degree is maximal (around 70%) when the condensation threshold is slightly exceeded and it diminishes gradually with pumping due to the heating. The equidistant luminescent spot pattern observed in the ring trap is strongly linearly polarized as well (see Figure): two pairs of spots located at the ends of two orthogonal window diameters are polarized orthogonally, along directions [110] and [1$\bar{1}$0] coinciding with the diameter directions. Under the same experimental conditions the luminescence of direct excitons is completely depolarized. The observed spontaneous linear polarization does not depend on the state of polarization of exciting light.

We assume that the observed phenomenon originates from anisotropic electron-hole (e-h) exchange interaction caused by strong anisotropy of confining potential in the {001} crystallographic plane. The interaction results in exchange energy splitting of dipolar exciton states with $|m| = 1$. So, the produced split states represent linear combinations of the $m_z = \pm 1$ excitons. Finally, the mixing should result in a linear polarization of dipolar exciton emission. The anisotropy of confining potential in GaAs/AlGaAs heterostructures is usually oriented along either [110] or [1$\bar{1}$0] direction in the (001) crystallographic plane. Therefore, the spin split components should have orthogonal linear polarizations parallel to either [110] or [1$\bar{1}$0] direction. For GaAs/AlGaAs 250Å QW the splitting is less that 50 μeV, i.e. << k_BT in considered experiments. In our case it is not observed in the emission spectra below BEC threshold due to inhomogeneous broadening. However, above the threshold the system of interacting dipolar excitons selects the lower energy state, i.e. when BEC occurs the lowest of the two states split due to the e-h-exchange anisotropy becomes macroscopically occupied. Such a selection is a strong evidence of occurred phase transition. As a result of macroscopic occupation of the lower spin-split state, the experimentally observed luminescence of Bose-condensed excitons exhibits strong linear polarization along <110> direction. We believe that the discovered phenomenon is a direct evidence of *spontaneous symmetry breaking under BEC condensation* of dipolar excitons in a lateral trap.

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Particle correlations in a quantum degenerate trapped dipolar exciton fluid

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Dipolar excitons in bilayers are expected by many to exhibit a thermodynamic phase transition, in the quantum degenerate regime, to a macroscopic coherent state. It is generally assumed that such a state would most likely be similar to a Bose-Einstein condensate of weakly interacting particles, however it is not clear if and how the repulsive dipole-dipole interactions between excitons would affect the nature of their ground state [1].
Recent advancements in trapping techniques of cold dipolar excitons [2] allow studies of such systems under more controlled conditions and indeed various results suggest that spontaneous phase transitions do occur to some new ordered state [3].

Here we present experimental evidence and an accompanied theoretical model that suggest that the dipole-dipole interactions of trapped exciton fluids induce strong particle pair correlations. These correlations affect the measured interaction energy dependence on the fluid density that shows significant deviations from the linear mean field behavior.

The measurements where performed on dipolar exciton fluids optically excited with short optical pulses inside electrostatic traps in a GaAs/AlGaAs bilayer system. The spatial and spectral dynamics of the exciton fluid following its excitation were monitored and analyzed under different conditions to deduce the dependences of the exciton-exciton interaction-induced spectral blue shift on the fluid density and temperature. These measurements show substantial deviations from the mean field predictions at high fluid densities. The calculation of the exciton – exciton interaction energy reveals significant pair correlations between excitons, the main element of which is a depletion region near each of them [1,4], a region which is temperature dependent and grows fast as the excitons become quantum degenerate. The results of the calculation of the luminescence intensity and blue shift are in qualitative agreement with the experimental data. The pair correlation significantly reduces the blue shift and shows that exciton concentration values based on the mean field theory might be an underestimate. Strong correlations also suggest that the exciton system is not a weakly non-ideal Bose gas but rather a quantum liquid.

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Cold exciton gases in coupled quantum wells

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Excitons have a relatively high temperature of quantum degeneracy, of the order of a few Kelvin. The exciton gases with temperatures even well below 1 Kelvin can be realized in coupled quantum well structures (CQW). We present an overview of coherence, condensation, ordering, and other phenomena in the cold exciton gases in CQW. We also present an overview of control of excitons in CQW including trapping excitons with laser light, trapping excitons with electrode voltages, and excitonic circuits.

Spontaneous coherence and kinetics of macroscopically ordered exciton state

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Recently, a spatial photoluminescence (PL) pattern including internal and external exciton rings, localized bright spots, and the macroscopically ordered exciton state (MOES) was observed [1]. The external rings and localized spots are observed up to high temperatures, where the exciton gas is classical, and are attributed to exciton generation at the border between the electron- and hole-rich regions [2,3]. While the external ring is a classical object by itself it is the region where the coldest exciton gas is created: the external ring is far from the hot excitation spot and the excitons in the ring are formed from well-thermalized carriers. In contrast, the MOES - an array of beads with spatial order on macroscopic length - is a low-temperature state, which appears abruptly in the ring at temperatures below a few Kelvin, where the thermal de Broglie wavelength is comparable to the interparticle separation and the exciton gas is nonclassical. Here we report on the experimental study of coherence and kinetics of this cold quantum gas.

1. Coherence Length of Cold Exciton Gases

Spontaneous coherence is a basic property of condensed states, which can be described by spontaneous macroscopic occupation of a single mode, such as superconductors, superfluids, and atomic Bose-Einstein condensates (BEC). Spontaneous coherence was also predicted for exciton systems, namely it was predicted to be a signature of exciton BEC. Here a Mach-Zehnder interferometer with spatial and spectral resolution was used to probe spontaneous coherence in cold exciton gases, which are implemented experimentally in the ring of indirect excitons in coupled quantum wells. A strong enhancement of the exciton coherence length is observed at temperatures below a few Kelvin. The increase of the coherence length is correlated with the macroscopic spatial ordering of the excitons. The coherence length reaches about 2-3 microns at the lowest temperature (1.5K). This corresponds to a very narrow spread of the exciton momentum distribution, much smaller than that for a classical exciton gas. (Ref. [4,5])

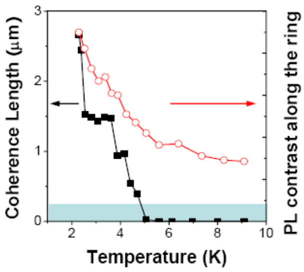

Fig. 1: The exciton coherence length (squares) and contrast of the spatial intensity modulation along the ring (circles) vs. T. The shaded area is beyond experimental accuracy.

2. Kinetics of the external ring, localized bright spots, and macroscopically ordered exciton state

The ring kinetics was studied by time-resolved imaging of the indirect exciton PL using rectangular laser excitation pulses (pulse duration was in the range 0.3-10 μs, edge sharpness about 1 ns, repetition frequency 50-75 kHz). After the start of the excitation pulse, the external ring appears, expands, and eventually reaches its equilibrium size. After the laser switching off, the ring contracts and disappears. On the contrary, the localized bright spots expand and form the rings inside the external ring after the laser switching off. The ring expansion and contraction times were measured as a function of carrier densities. These times are on the order of 1μs. The emergence and decay of the MOES occurs over a time period on the order of 100 ns.

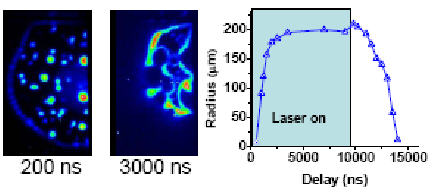

Fig. 2: (left two) snapshots of PL of indirect excitons. The time is respect to the end of laser pulse. (right) The radius of external ring vs. time.

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Transport, thermalization and first-order coherence of indirect excitons

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In this report we review our recent results in physics of statistically-degenerate indirect excitons in GaAs/AlGaAs coupled quantum wells (QWs).

(i) In order to explain and model the *inner ring* in photoluminescence (PL) patterns of indirect excitons in GaAs/AlGaAs coupled QWs, we have developed a microscopic approach formulated in terms of coupled nonlinear equations for the drift-diffusion, thermalization and optical decay of the particles [1]. It is shown that the inner ring occurs due to cooling of indirect excitons in their propagation from the excitation spot. We also discuss *fundamental solutions* of the quantum drift-diffusion equation: these attractor-like solutions are independent of the initial (compact supported) real-space distribution of particles, so that in many cases the drift-diffusion transport of indirect excitons can uniquely be described by the fundamental solutions.

(ii) *Laser-induced traps* for indirect excitons have recently been realized [2-3]. By using quantum drift-diffusion and thermalization equations, we have simulated transport, accumulation and thermalization of the particles in an optically-induced trap. It is shown that the loading of indirect excitons to the trap center occurs in tens of nanoseconds, in agreement with the experiment, and that the exciton temperature in the trap center is very close to the lattice one, giving rise to nonclassical population of the ground state mode with $N_{\mathrm{E}=0} \simeq 5 - 10$.

(iii) In order to explain PL centers associated with transverse current filaments crossing the QW structure, we model the in-plane carrier transport and charge distribution with a set of drift-diffusion, Poisson and thermalization equations for three species: electrons, holes and indirect excitons [4]. The quantum statistical corrections are included in our description via a generalized Einstein relationship and quantum mass action law. We show that an accumulated electron charge injected by a transverse current filament gives rise to an *anti-trap* for indirect excitons.

(iv) A $k_\parallel$-*filtering* effect which gives rise to the drastic difference between the actual spatial coherence length of indirect excitons and that inferred from far-field optical measurements is proposed and analyzed [5]. The effect originates from conservation of the in-plane wave vector $k_\parallel$ in the optical decay of the particles in outgoing bulk photons. The $k_\parallel$-filtering effect is consistent with the large coherence lengths recently observed for indirect excitons in coupled QWs. We also discuss how the screening of in-plane disorder by dipole-dipole interacting indirect excitons influences the first-order optical coherence length.

(v) Recently, sharp individual lines in the PL spectrum of indirect excitons have been observed for low optical excitations, by using a rather elaborate spectroscopic technique [6]. These emission lines are attributed to well-localized states, which can accommodate only one indirect exciton and are separated from the exciton continuum (delocalized states) by a binding energy of a few meV. With increasing optical excitation, the binding energy of the localized states effectively decreases, so that they eventually disappear at concentration of indirect excitons $\sim 10^{10}\,\mathrm{cm}^{-2}$. By deriving and solving a nonlinear Schrödinger equation for the localized states, we analyze *screening of short-range disorder* by dipole-dipole interacting excitons and predict a new *mesoscopic ring* of radius $\sim 10 - 100\,\mathrm{nm}$, that arises around a localized (impurity) state, in the density and near-field PL profiles of delocalized indirect excitons.

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Friday

Coulomb drag in the exciton regime in electron-hole bilayers

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Closely spaced two-dimensional bilayers composed of electrons in one layer and holes in the other layer allow studies of the transition from two Fermi systems to a Bose system when electrons and holes pair to form excitons. One result of exciton formation in these devices is expected to be a Bose-Einstein condensation of the excitons. Our approach to fabricating electron-hole bilayers is to use undoped GaAs/AlGaAs double quantum well heterostructures, and to generate the internal electric fields needed for carriers using gates on the top and bottom of the structure. The electrons in the upper quantum well have self-aligned contacts to the top gate. The holes in the lower quantum well overlap a gate approximately 0.4 micron below the original surface. Processing both sides of the bilayer is accomplished with a flip-chip technique developed at Sandia. With this structure, we can make independent contacts to the electron and hole layers, and densities in each layer can be varied from $4x10^{10}$ cm^{-2} to $1.5x10^{11}$ cm^{-2}. We report Coulomb drag measurements on bilayers with 20 nm and 30 nm $Al_{0.9}Ga_{0.1}As$ barriers. In the drag measurement, current is driven in the electron layer while voltage is measured in the hole layer. For Fermi liquids, Coulomb scattering leads to a T^2 dependence of the drag resistivity at zero magnetic field. We observe quadratic temperature dependence of the drag for the 30 nm barrier. When the barrier is reduced to 20 nm, the high temperature behavior remains quadratic, but below 1K there is a dramatic upturn in the drag resistivity. Increasing drag with decreasing temperature is very unusual, and signals the development of strong coupling between the layers. We compare our results to theoretical predictions of the drag resistivity for an exciton condensate [1,2]. The onset of strong coupling between the electrons and holes for the narrow barrier devices at low temperature suggests the formation of excitons in this system. This work has been supported by the Division of Materials Sciences and Engineering, Office of Basic Energy Sciences, U.S. Department of Energy. Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy under Contract No. DE-AC04-94AL85000.

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Transport experiments on electron-hole bilayers

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The possibility of excitonic phases in semiconductors was first raised in the 1960s[1]. At that time it was thought that since excitons are charge neutral objects, transport based experiments would not be of much relevance for such phases. Certain key experimental advances have radically changed this perspective. The advent of quantum well based structures and the ability to make independent contacts to closely spaced wells with steady state, controlled populations of electrons and holes have made a transport based approach possible. Of fundamental importance to transport based approaches to bilayers is a technique of measuring the interlayer interaction via the "drag voltage"[2].

We have made independently contacted bilayers in which the 2DEG and the 2DHG are separated by an $Al_{0.9}Ga_{0.1}As$ barrier 10-25nm wide, but with extremely low leakage. The 10nm barrier is smaller than the excitonic Bohr radius of GaAs (a_B ≈12nm) and the densities are sufficiently low such that the interlayer (electron-hole) interaction can dominate over the intralayer (electron-electron or hole-hole) interaction. Measurements of drag voltage over a wide range of densities[3], spanning matched (n=p) or unmatched (n<p or n>p) regimes show certain features that cannot be explained within the purview of a Fermi liquid picture. At low temperatures (T<1K), the "drag" voltage measured on the hole layer (with a current flowing in the electron layer) shows an upturn, followed by a downturn and then changes sign. The effect is either absent or present much more weakly for drag measured on the electron layer, even though the system is clearly in the linear response regime. This lack of symmetry is *very surprising* because it appears to contradict Onsager's reciprocity theorem as applied to four-terminal resistance measurements. The basis of this theorem is thermodynamic and it is not expected to be affected by the internal complexity of a system.

Secondly we find that the proximity of one layer (in 10nm devices) mutually induces an insulating temperature dependence ($d\rho/dT < 0$) in the single-layer resistance of the other layer, in the same temperature range where the anomalous drag is seen. Even when the individual layer mobilities are very high and $k_F l \sim 10 - 100$ in each layer, below T≈1K the layers acquire insulating character. If the first layer is fully depleted the sign of $d\rho/dT$ changes allowing us to unambiguously attribute this effect to interaction and not disorder. In both the experimental results mentioned here, it appears that the point of equal densities (n=p) is not special - rather contrary to initial expectations. It is possible that the small, residual anisotropy in the in-plane dispersion $E(k_{||})$ of the holes preventing strong dipolar pairing interaction. In which case it may be necessary to go to quantum well widths significantly less than ∼ 15-20nm, that is used in experiments at present.

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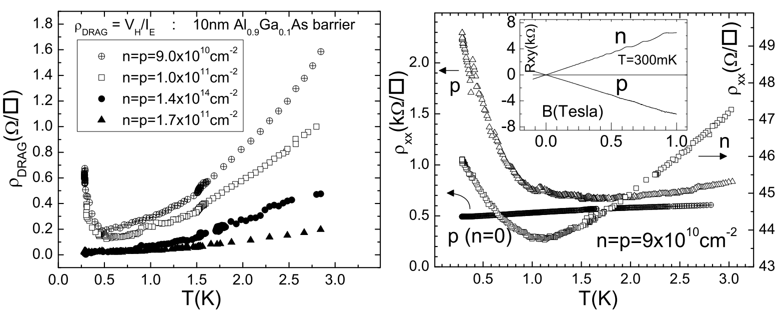

Figure 1: Coulomb drag (left) and single layer resistivities (right) in an electron-hole bilayer with 10nm $Al_{0.9}Ga_{0.1}As$ barrier. The drag voltage, when measured on the electron layer, did not show the upturn. At T=1K, the electron and hole mobilities at $9 \times 10^{10}cm^{-2}$ were $1.5 \times 10^6 cm^2V^{-1}s^{-1}$ and $1 \times 10^5 cm^2V^{-1}s^{-1}$

Strong correlated 2D dipole exciton system.

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We show by *ab initio* quantum Monte Carlo calculations that dipole excitons which are under experimental study now actually are strong interacting systems. This manifest itself in essential peculiarities in excitation spectra –existence of roton minimum, structure and condensate depletion which we discuss in the talk.

Generalized local density approximation for Kosterlitz-Thouless crossover of 2D dipole excitons in wide exciton trap is proposed.

Bose condensation of 2D dipole excitons and quantum crystallization in extended system and 2D trap are analyzed.

The ground-state phase diagram of 2D dipole exciton system is studied. In the gas phase the condensate fraction is calculated as the function of density. The collective excitation branch and appearance of roton minimum is analyzed.

Quantum phase transition of 2D dipole exciton system to new, crystal state controlled by the density of the system is considered. Possible experiments and 2D structures for observation of this new exciton phase are discussed.

2D composite exciton superfluidity in bilayer electron system is discussed the role of marginality of the system being analyzed.

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Accumulation of dark excitons in stress-induced potentials

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While it has long been known that the ground state of spatially indirect excitons is dark[1], its relevance to Bose-Einstein condensation (BEC) has been overlooked. In the past, signatures of excitonic BEC has been sought in the form of directional luminescence or coherence of the light emitted by excitons. In this contribution, we review our recent results on trapped dark excitons. In order to confine the particles, we apply the trapping method based on the stress-induced band-deformation, which can be used to create macroscopic and harmonic traps[2]. At moderate stress (or weak confining potential), the exciton luminescence (i.e., the ensemble of bright excitons) has a distribution dictated by the temperature and the shape of the trap[3]. However, at high enough stress, a distinct and well-localised dark region develops at the centre of the trapping potential. In the presentation, we will consider evidence that this dark region is an ensemble of optically inactive excitons, lying lower in energy than that of the bright excitons, and we will discuss how this new phase transition depends on various experimental parameters, such as, the strength of the potential, the temperature and the particle density. As shown in Fig.1, the phase transition occurs only at low temperatures, strong confinement, and at high densities, and this might imply the presence of a dark excitonic condensate. Further testing of the dark population is currently underway.

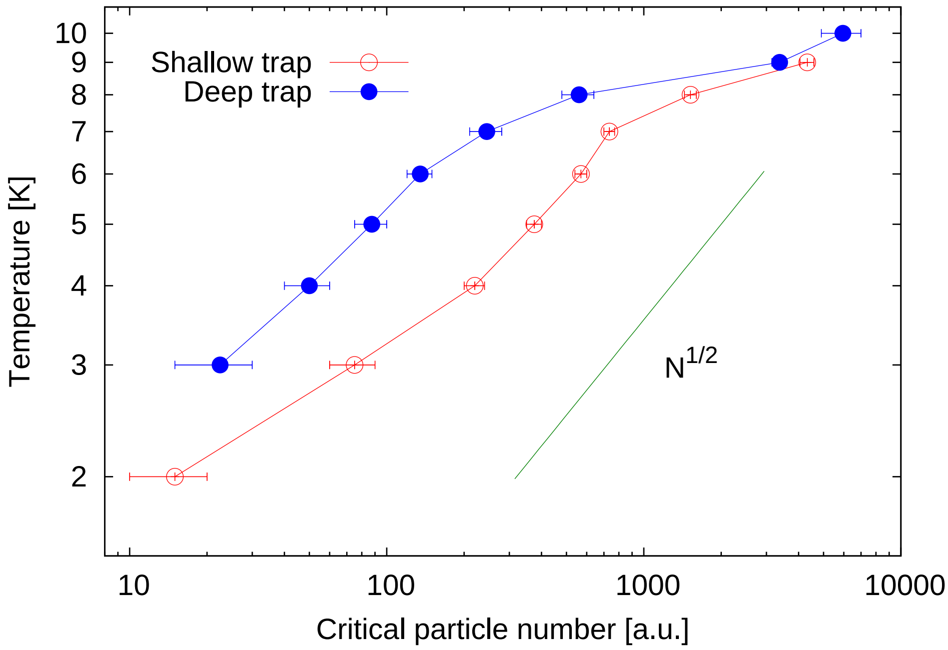

FIG. 1: The relationship between the critical excitation power and critical temperature of the phase transition in two cases, under strong (solid circles) and weak (open circles) confinement. For comparison, also shown is the square-root-like dependence for BEC dictated by the simple model of non-interacting bosons.

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Title to be confirmed

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Posters

Predicting the Linear Optical Response of J-Aggregate Microcavity Exciton-Polariton Devices

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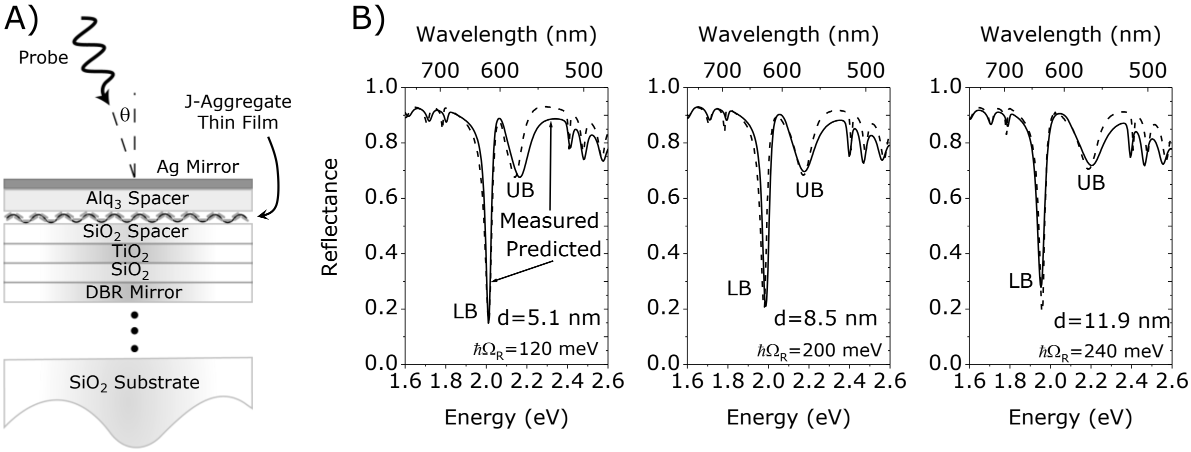
We use the transfer matrix numerical formalism to accurately predict the linear optical properties of strongly-coupled microcavity exciton-polariton devices containing thin films of J-aggregated cyanine dyes. Thin films of cyanine dye J-aggregates enable the observation of strong coupling between light and matter at room temperature due to their high absorption constant and narrow linewidth, which allowed for the first demonstration of exciton-polariton electroluminescence at room temperature [1-4]. Our model uses the spectrally-resolved complex index of refraction of the TDBC (5,6-dichloro-2-[3-[5,6-dichloro-1-ethyl-3-(3-sulfopropyl)-2(3H)-benzimidazolidene]-1-propenyl]-1-ethyl-3-(3-sulfopropyl) benzimidazolium hydroxide, inner salt, sodium salt) J-aggregate films [5]. The index of refraction is calculated by model-free quasi-Kramers-Kronig regression performed on the reflectance measurements of neat J-aggregate films on glass, enabling us to numerically engineer the properties of the complete microcavity devices (see Figure A) prior to fabrication. We demonstrate robustness of this numerical method by matching the experimentally obtained angular dispersion of light reflected from the strongly-coupled microcavity to the predictions of our model. Both numerically and experimentally we demonstrate that the Rabi splitting of exciton-polariton modes of strongly-coupled microcavities can be finely tuned by modifying the J-aggregate film thickness (see Figure B).



(A) J-aggregate microcavity exciton-polariton device structure. (B) Comparison of measured and predicted reflectance spectra for device shown. Upper and lower branch (UB and LB) polaritons are indicated.

Finally, we apply the model to estimate the linewidth of the lower branch exciton-polaritons in J-aggregate-based structures to be 8.4 meV. This is a key parameter in theoretical modeling of exciton-polariton dynamics and more than a factor of two smaller than linewidths assumed in previous studies [6-8].

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Low temperature behavior of excitons in an optically-induced trap

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We report on the behavior of a low-temperature gas of indirect excitons in an optically-induced exciton trap. We have recently proposed and demonstrated optically-induced trapping of indirect excitons in coupled quantum wells (CQW) [1]. An important advantage of the optically-induced exciton trapping is the possibility of controlling the trap in-situ by varying the laser intensity in space and time [2]. We exploit this opportunity and report studies of exciton kinetics in the optically-induced trap. Studies have demonstrated formation of the trap and collection of ~10^5 cold excitons to the trap over the course of 40 ns after the excitation is switched on [2], which meets the essential condition that trap loading time be smaller than the lifetime of the indirect excitons. For comparison, typical atomic optical traps have loading times for degenerate atomic gases that are on the order of a few tens of seconds, while the lifetimes of atoms in the trap are on the order of a few seconds [3, 4].

Experiments with indirect excitons have demonstrated that (i) the excitons travel to the trap center before recombination and the trap loading time is smaller than their lifetime and (ii) the excitons at the trap center are cold (because they are far from the hot area of the laser excitation). This leads to the accumulation of a cold and dense exciton gas at the trap center. The theoretical analysis of the dynamics of the degenerate Bose gas of excitons in the trap is in good agreement with the experimental data. Ongoing experiments are currently in progress to investigate optically-induced trapping of excitons at ultra-low temperatures.

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Control of Exciton Flux Through Tunable Potential Reliefs

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Indirect excitons in coupled quantum wells (CQW) present an opportunity for the shaping and control of exciton fluxes. The control is based on the fact that the indirect excitons are dipoles (their dipole moment d is close to the distance between the QW centers). Therefore an electric field F_z perpendicular to the QW plane results in the exciton energy shift $E = eF_zd$. The laterally modulated gate voltage $V_g(x,y)$ creates a laterally modulated electric field and, in turn, a lateral relief of the exciton energy $E(x,y) \propto V_g(x,y)d$. Control of $V_g(x,y)$ allows manipulation of the in-plane potential profile for excitons and, in turn, the exciton fluxes both in space and in time.

We present demonstration of control of exciton fluxes and potential energy reliefs for excitons on a time scale much shorter than the exciton lifetime. This opens pathways for studies of excitons in in-situ controlled traps, trap lattices, and other potentials. We demonstrate an excitonic integrated circuit with a variety of operational modes.[1]

Also we present the experimental and theoretical studies of the indirect excitons in a trap created by a laterally modulated gate voltage (Fig. 1a). We studied traps with both a lower exciton energy and a higher exciton energy in comparison to the exciton energy outside of the trap. In the elevated trap regime we observed a reduction of the effective exciton temperature. This is revealed by a strong enhancement of the occupation of the lower energy exciton states in the trap. The effective exciton temperature is reduced due to the evaporative cooling of excitons. The excitons with a higher energy escape the trap faster than the excitons with a lower energy resulting in the enhancement of the fraction of the low energy excitons, i.e. the reduction of the effective exciton temperature. Our data indicates that the evaporative cooling reduces the effective exciton temperature to close to the lattice temperature.[2]

We also observed sharp lines in the emission of the indirect excitons in the trap. Linewidths were measured as low as 0.18 meV, which is close to the limit of the spectrometer resolution. The sharp lines correspond to the emission of excitons in the strongly localized Lifshitz states. The emission of excitons delocalized over the trap is observed at a higher energy (Fig 1b). The maximum occupation of the localized states is found to be 1. The PL linewidth of the localized states increases with increasing exciton density and reaches about 0.3 meV at the density of delocalized excitons in the trap $n \approx 3\times10^9$ cm^{-2}. A much larger line broadening is observed for the delocalized states. The PL linewidth of the delocalized states increases from about 0.5 meV at $n \approx 10^8$ cm^{-2} to about 1.5 meV at $n \approx 7\times10^9$ cm^{-2}.

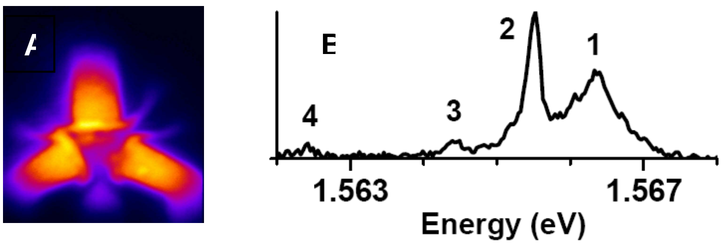

Fig. 1. Control of Exciton Flux and Sharp lines of Exciton Emission *(a) Output of the excitonic integrated ciruit in star switch mode. (b) Spectral emission of elevated trap. The numbers correspond to different exciton states.*

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Quantum theory of electron tunneling into intersubband cavity polariton states

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Recent absorption[1-2], photovoltaic[3] and electroluminescence[4] experiments on microcavities embedding quantum wells have shown strong coupling between a planar cavity photon mode and the transition between two conduction subbands, being the lowest one filled with a dense two-dimensional electron gas. A considerable research activity is currently flourishing along two interesting directions, namely the ultrastrong coupling cavity quantum electrodynamics[5] and the electrical injection of intersubband cavity polariton excitations [4,6,7].

Through an analytical non-perturbative theory[7], we show that the nature of an electron in the excited conduction subband can be profoundly modified by the strong interaction with the cavity vacuum field. For electron wavevectors larger than the Fermi one, the electron spectral function in the excited subband has a non-trivial structure reminiscent of a Fano resonance, resulting from the coupling between the bare electron and the continuum of the intersubband cavity polariton modes (with different photonic wavevectors). In the case of a spectrally narrow injector, these electron states can be selectively excited by resonant electron tunneling and can give rise to ultrahigh efficient intersubband electroluminescence. Our theory provides a deep and elegant insight into the fascinating link between semiconductor cavity quantum electrodynamics and electronic transport in the considered system, paving the way to exciting progress in fundamental quantum opto-electronics.

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Screening of short-range quantum well disorder by indirect excitons

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Recent advances in spectroscopic techniques have allowed the observation of sharp lines in the emission spectra of indirect excitons in coupled quantum wells (QWs) [1]. These emission lines are attributed to well-localized states i, which can accommodate only one indirect exciton and are separated from the exciton continuum (delocalized states) by a binding energy $\varepsilon_i^{(0)}$ of about $1-3\,\mathrm{meV}$. The latter values refer to rather low average densities, $n_{2\mathrm{d}}^{(0)} \leq 10^9\,\mathrm{cm}^{-2}$. With increasing optical excitation, i.e. $n_{2\mathrm{d}}^{(0)}$, the binding energy ε_i decreases, and the localized states eventually disappear at $n_{2\mathrm{d}}^{(0)} \sim 10^{10}\,\mathrm{cm}^{-2}$.

We report on screening of the short-range QW disorder by incoherent delocalized excitons. A localized state is described by the nonlinear Schrödinger equation:

$$-\frac{\hbar^2}{2m}\nabla^2\Psi_i + u_0 n_{2\mathrm{d}}^{(0)}\Psi_i + \frac{\mathrm{U_{imp}}(\mathrm{r}_\parallel)}{1+\alpha(T,T_0)}\,\Psi_i + \frac{u_0}{1+\alpha(T,T_0)}|\,\Psi_i|^2\Psi_i \quad = \quad \varepsilon_i\Psi_i\,, \tag{1}$$

where $\alpha(T,T_0) = [(u_0 n_{2\mathrm{d}}^{(0)})/(k_\mathrm{B}T_0)](e^{T_0/T}-1)$, $T_0 \propto n_{2\mathrm{d}}^{(0)}$ is the degeneracy temperature, $u_0 n_{2\mathrm{d}}^{(0)}$ is the mean-field energy due to dipole-dipole repulsive interaction between indirect excitons, $U_{\mathrm{imp}}(r_\parallel)$ is a bare (unscreened) short-range potential that gives rise to the state i with binding energy $\varepsilon_i^{(0)}$, and T is the temperature. In order to analyze how the wave function Ψ_i and binding energy ε_i change with increasing $n_{2\mathrm{d}}^{(0)}$, we have performed numerical statistical simulations of Eq. (1) for various model potentials $U_{\mathrm{imp}}(r_\parallel)$ (e.g., for $U_{\mathrm{imp}}(r_\parallel) = -V_0/\cosh^2(r_\parallel/a_{\mathrm{loc}})$ in parametric space $\{V_0, a_{\mathrm{loc}}\}$, see Fig. 1). The main results of our study are (i) an effective screening of $U_{\mathrm{imp}}(r_\parallel)$ and removal of the localized state i ($\varepsilon_i \to 0$) when $u_0 n_{2\mathrm{d}}^{(0)}$ becomes comparable with $\varepsilon_i^{(0)}$, (ii) a drastic increase of the screening effect with decreasing temperature T below T_0, and (iii) the prediction of a mesoscopic ring of radius $\sim 10-100\,\mathrm{nm}$ in the density profile $n_{2\mathrm{d}}(r_\parallel) = n_{2\mathrm{d}}^{(0)} + \delta n_{2\mathrm{d}}(r_\parallel)$ of delocalized indirect excitons around the localized (impurity) state i (see Fig. 1 (a), where $\delta n_{2\mathrm{d}}$ is plotted against the radial distance from the impurity).

The present work complements the study of the screening effect by dipole-dipole interacting excitons, previously developed in [2] for long-range-correlated disorder.

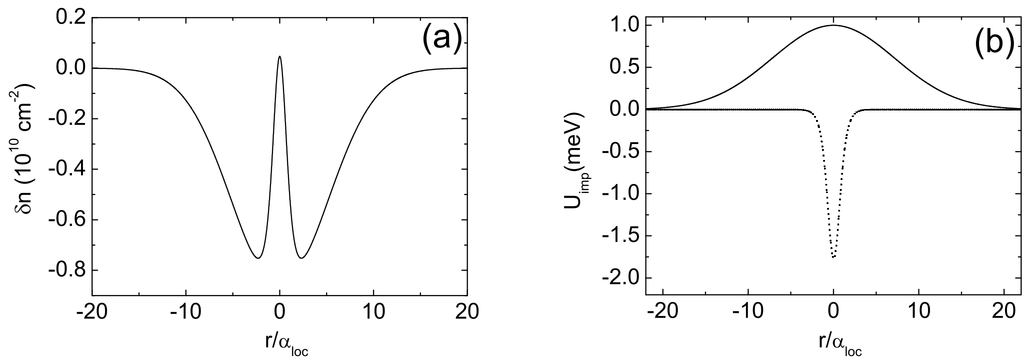

Figure 1: Screening of short-range disorder. (a) The spatial change of density $n_{2\mathrm{d}}$ of delocalized excitons near the localized state. (b) The input potential U_{imp} and wave function Ψ_i calculated with Eq. (1).

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Optical imaging of exciton-polaritons probability density in cylindrical traps

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We use optical spectroscopy for imaging the probability density of microcavity exciton-polaritons confined in a cylindrical trap. Composite half-matter half-light quasi-particles, the exciton-polaritons exhibit an extremely light effective mass, allowing to confine them inside traps of the size of several micrometers in size. Confined polaritons are therefore unique systems allowing a direct optical access to confined quasi-particles wavefunctions, in opposition to standard quantum confinement means in semiconductors, such as quantum dots.

The traps for polaritons are made of circular mesas, providing a local increased thickness of the micro-cavity length, therefore a lateral confinement for the photonic part of the polariton [1, 2]. The excitonic matter wave being strongly coupled to the confined photon modes, discrete confined levels are observed for both upper and lower polaritons.

Energies and spatial distributions of the confined polariton states are succesfully compared to the solutions of the time-independant Schrödinger equation for a particle confined in a cylindrical potential well, using the effective mass of the microcavity polariton.

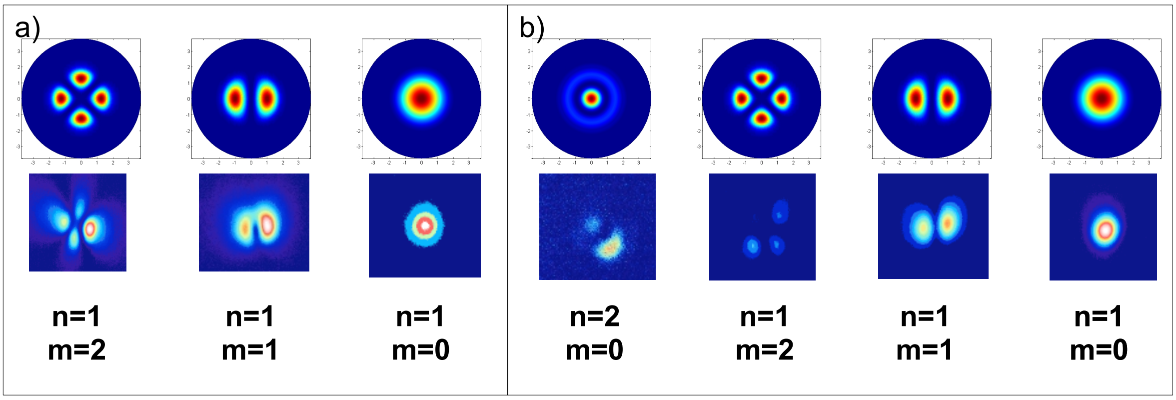

FIG. 1: Real space images of the levels of the a) upper b) lower polaritons confined in a 3 micrometers diameter trap. Top : solutions of the Schrödinger equation. Bottom : optical imaging of the level under resonnant excitation.

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Relaxation Dynamics of Confined Microcavity Polaritons

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Microcavity polaritons are the result of the strong coupling between excitons and electromagnetic modes in semiconductor microcavities. Under a certain density, these quasi-particles behave as bosons and are very good candidates for investigating quantum phenomena in solid-state systems. This lead to the observation of effects such as Bose-Einstein condensation (BEC) and polariton lasers [1] [2].

In micropillars, it appeared that one can reach spontaneous quantum degeneracy of microcavity polaritons at lower excitation densities than in planar microcavities. This suggests that trapping significantly enhances the relaxation process.

We investigate the effects of lateral confinement on the relaxation of microcavity polaritons using photoluminescence excitation and resonant time resolved photoluminescence. In the investigated sample, polaritons are trapped in mesas consisting in local cylindrical variations of the cavity length[3].

The photoluminescence of confined polaritons under resonant excitation is distributed over the lower energy states. This points out significant relaxation processes of confined polaritons. We attribute this relaxation to thermalization via phonons and observe a strong dependance on the mesa diameter. The very good agreement of theoretical predictions with experiment brings us to a global representation of polariton relaxation in presence of a trap.

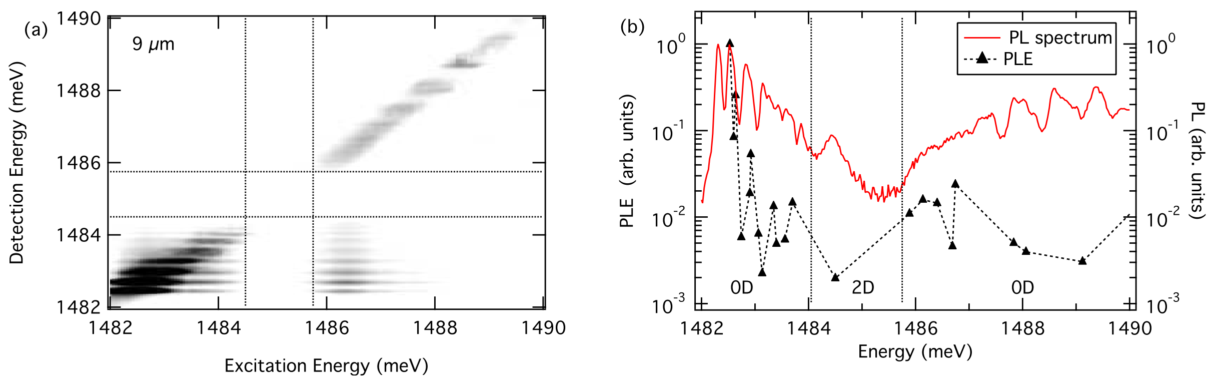

FIG. 1: PLE experiments on a 9 μm diameter mesa. (a) : image plot, (b) : spectrum and comparison with photoluminescence spectrum. The dotted lines separate planar from confined polariton energy ranges. The relaxation down to the lowest energy states and their relative intensities suggest an efficient thermalization process.

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Formation Dynamics of an Exciton-Polariton Condensate

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Since the achievement of Bose-Einstein Condensation (BEC) of exciton-polaritons in our CdTe microcavity [1], exciton-polariton condensation in semiconductor microcavities has been reported several times [2]. The main characteristics of this state of matter are the appearance of long range spatial correlations and the quasi Bose-Einstein distribution of polaritons. All these characteristics have been intensively studied and demonstrated in the steady state under non-resonant continuous wave optical excitation, but not much is known about their dynamical behaviour.
In this experimental work we have set out to investigate the dynamics of the redistribution of polaritons in momentum space as well as the dynamics of the formation and decay of the long-range spatial coherence. To achieve this goal we used femtosecond pulsed non-resonant excitation in conjunction with a streak camera. The characterisation of the dynamics in momentum space is performed by temporally resolving the far field emission from our microcavity, whereas the investigation of the dynamics of the long range spatial coherence is realised by means of an actively stabilised Michelson interferometer in a mirror - retroreflector configuration.
We evidence the stimulation of the condensate formation as a function of the excitation power and observe that the long range spatial coherence $g^{(1)}(\mathbf{r},-\mathbf{r})$ builds up simultaneously with the population that arrives at the lower polariton branch. Additionally the decoherence dynamics appears to be slower than the population decay.

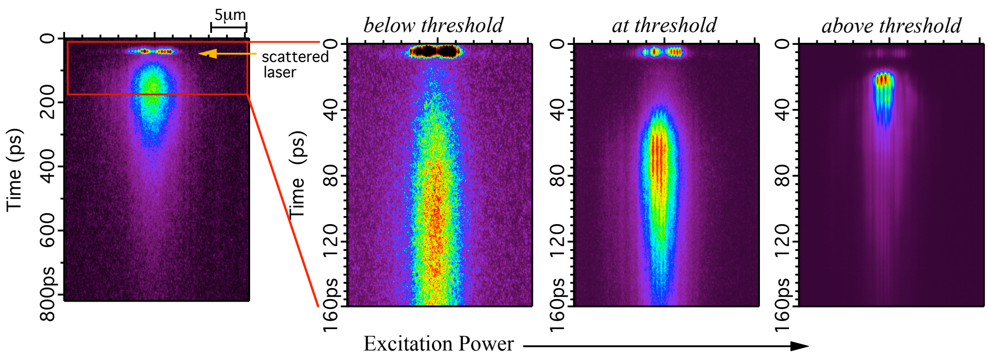

Figure: Temporally resolved interferograms for increasing excitation powers away from the autocorrelation point. The appearance of interference fringes at the threshold shows the transition from an incoherent to a coherent state of the polaritons. The "acceleration" of the dynamics is evidenced by the temporal shrinking of the response of the system.

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Polariton parametric oscillation in a single micropillar semiconductor cavity

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The strong coupling regime between excitons and photons in semiconductor microcavities gives rise to mixed, exiton-photon quasiparticles named polaritons which exhibit strong optical nonlinearities. Polariton stimulated parametric processes have been reported in various 2D cavity structures [1]. Quantum correlations are predicted between signal and idler beams thus making this system a potential source of non-classical photon pairs [2]. However, in most previous reports, the idler intensity is several orders of magnitude smaller than the signal and quantum correlations are difficult to evidence. This drawback can be overcome by confining the polaritons in all spatial directions. In the present work, we report on the first demonstration of stimulated parametric oscillations in single micropillars.

Micropillars were defined from a planar AlGaAs $\lambda/2$ cavity containing 12 GaAs quantum wells by electron beam lithography and reactive ion etching. Low temperature (10 K) micro- photoluminescence experiments have been performed on single micropillars. The inset of Fig 1 presents a typical photoluminescence spectrum from a 3.6 µm pillar under non resonant excitation. This spectrum exhibits the discrete emission lines expected in such zero dimensional cavities. When probing several pillars along the cavity wedge, anticrossing of each discrete line with the exciton demonstrate the strong coupling regime.

In square shaped micropillars the three lowest polariton modes are spectrally equidistant; polariton parametric scattering toward the first (M1) and the third (M3) modes can thus be achieved by resonantly pumping the second one (M2), since energy conservation is fulfilled.

Emission spectra obtained under resonant excitation of M2 are shown in Fig. 1. Above a marked threshold power of 50 mW, a pronounced non-linear increase of both M1 and M3 is observed. The emission intensity of both these modes increases by almost three orders of magnitude while multiplying the pump power by three. At threshold, the occupancy of M1 is measured to be close to unity, confirming that stimulated parametric scattering occurs. Promisingly, signal and idler beams are of comparable intensity.

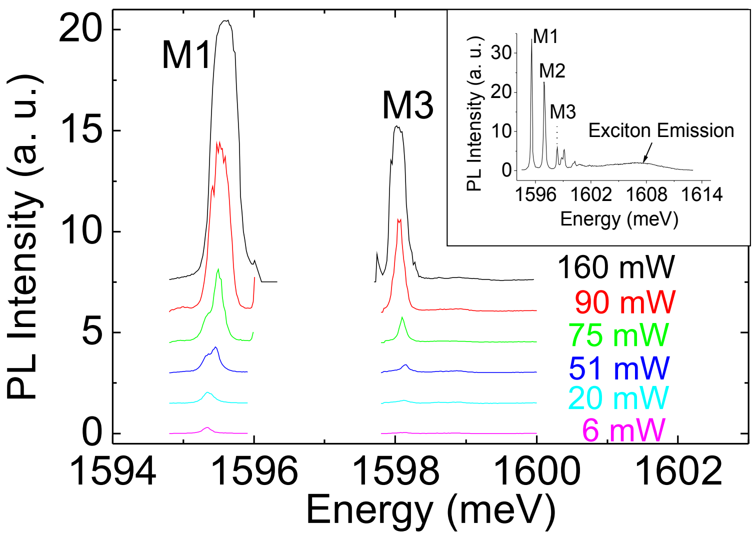

Fig 1: Emission spectrum from a 3.6 µm square pillar under excitation resonant to M2 at 10 K. Inset: Typical photoluminescence spectra from such a square pillar under non resonant excitation.

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