# Exchange Visit Grants: Scientific Report

**Francesca Maria Marchetti**

(Dated: August 5, 2009)

## I. PURPOSE OF THE VISIT

The aim of my six week visit to the Cavendish Laboratory, University of Cambridge, was to establish new collaborations and start up new projects on polariton superfluidity in different pumping regimes with several members of the host institution, such as Prof. Peter Littlewood (Theory of condensed Matter group), Dr Jonathan Keeling (Theory of Condensed Matter group), and Prof. Jeremy Baumberg (NanoPhotonics Centre). In addition I have coordinated my visit with the visit to Cambridge of Dr Marzena Szymanska (University of Warwick), with whom I have developed a project on persistent currents in polariton superfluids.

My visit has strongly benefit from the environment provided by the host institution, the Cavendish Laboratory, Cambridge. My past collaborations with several members of the Theory of Condensed Matter in the Cavendish Laboratory, including Prof. Peter Littlewood, Prof. Ben Simons, and Dr Jonathan Keeling have facilitated the interaction and will guarantee a secure outcome of the grant in terms of publications.

## II. DESCRIPTION OF THE WORK CARRIED OUT DURING THE VISIT AND MAIN RESULTS OBTAINED

### A. Stable vortex solutions in a polariton superfluid

During my 6 week visit to the Cavendish Laboratory in Cambridge, 2 weeks have been spent working together with Dr Marzena Szymanska (University of Warwick), who was also visiting the Cavendish laboratory, on a project on persistent currents in polariton superfluids in the optical parametric oscillator (OPO) regime.

Coherent resonant injection of parametrically pumped polariton condensates have been recently shown to exhibit a new form of non-equilibrium superfluid behaviour (Amo *et al.*, 2009a,b). In the optical parametric oscillator regime (Stevenson *et al.*, 2000), bosonic final state stimulation causes polariton pairs to coherently scatter from the pump state to the signal and idler states, which, at threshold, have a state occupancy of order one. The properties of the quantum fluids generated by OPO at idler and signal have been recently tested via a triggered optical parametric oscillator (TOPO) configuration (Amo *et al.*, 2009b). An additional weak pulsed probe laser beam has been used to create a traveling, long-living, coherent polaritons signal, continuously fed by the OPO. The traveling signal has been shown to display superfluid behaviour through linear dispersion and frictionless flow. However, generating long-lived quantised vortices and the possibility of metastable persistent flow in this configuration still remain missing in the superfluid 'checklist' (Keeling and Berloff, 2009).

Together with Dr Szymanska, in the past we already developed a numerical recipe to simulate mean-field two-component Gross-Pitaevskii equations for the coupled cavity and exciton fields with external pump and decay — see Ref. (Sanvitto *et al.*, 2009). This can be used to simulate the non-equilibrium polariton superfluid in the OPO regime. We have considered the case in which the non-equilibrium superfluid signal state is excited by a short probe laser pulse hosting a vortex with charge $m$. The idea is to stir the polariton superfluid only for a short time and observe its long lived rotation on time scales much longer than the duration of the pulse, the analogous of the *rotating drive* in trapped gases.

While in the past we have focused on a regime described as triggered parametric oscillator (TOPO), which has been observed experimentally (see Ref. (Sanvitto *et al.*, 2009)), in a new project we have been focusing on a new regime which has not yet been observed experimentally. This is the case in which the weak and short probe resonant with the signal transfer its angular momentum to the superfluid. After the probe is switched off, the signal experiences a transient period, when either the vortex drifts around or no vortex can be detected. After the transient, independently on the intensity and size of the probe, a vortex with a quantum of angular momentum stabilises into the signal and lasts as long as our simulations. The observation of such stable vortex solution, being linked to the persistence of currents, demonstrate the robustness of superfluid phenomena in the polariton OPO driven system.

Particular aspects I have been concentrated on during my visit to Cambridge are the stability of such vortex solutions to the addition of noise. Also I have established the absolute absence of correlation between the size of the stable vortex solution from the size of the vortex probe which generates it — see Fig. 1.

In addition, I observed that there are also cases where, during the transient period, the vortex at the signal changes vorticity, from $m = \pm 1$ to $m = \mp 1$ (see Fig. 2). Topological charge inversion has been already predicted to occur in confined atomic BECs at intermediate interactions strengths (García-Ripoll *et al.*, 2001). In the presence of an asymmetry which breaks rotation invariance, the vorticity is not a conserved quantity.

I expects these results to have a strong impact on the community of people working in this field. In particular there are already several experimental groups (Sheffield,

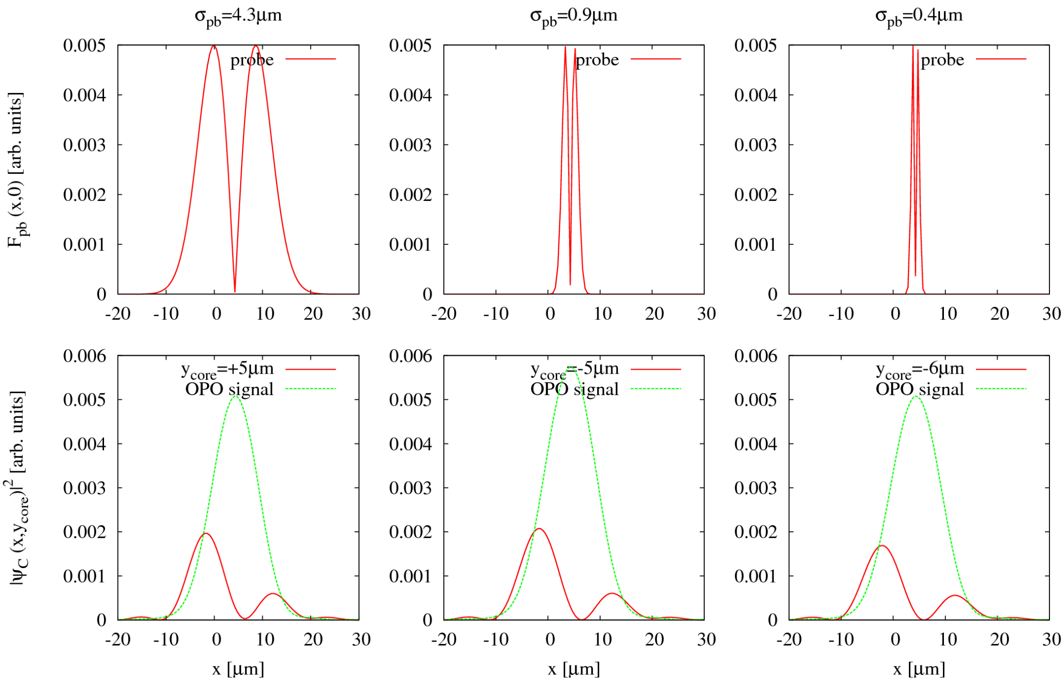


FIG. 1 Vortices of different sizes (first row) have been used to stir the OPO signal. The resulting stable vortex solutions obtained well after the probe has been switched off (second row) show that the vortex size is completely uncorrelated to the vortex of the probe used to stir the superfluid. Size of the OPO signal before the probe is switched on is shown for comparison (green dashed line).

Madrid, Lausanne, Stanford) dedicating their activity on the study of vortices in polariton superfluids.

### B. Polariton superfluid at room temperature

In order to have a polariton laser device operating at room temperature, wide band gap semiconductor structures based on group-III nitrides, such as GaN based cavities, can be used. The main advantage of using these structures over II-VI and III-V lies in the large exciton binding energy and a large coupling to the photon field, which makes them ideal systems for the realisation of functional devices operating at room temperature. Although the study of polaritons in group-III nitrides microcavities is still at its infancy, there are already reports (Christmann *et al.*, 2006) indicating the importance in the strong coupling regime of both exciton and photon inhomogeneous broadening. At the same time, there is already been reports of a room temperature Bose-Einstein condensate of polaritons in GaN cavity (Baumberg *et al.*, 2008; Christopoulos *et al.*, 2007), indicating the fast rate at which this field is progressing.

One of the reasons of my visit to Cambridge was the development of a theory of polariton condensation and lasing at elevated temperatures in GaN structures. In particular, during my visit I have been focusing on the role of photonic disorder in these structures, solving the Maxwell equation for an electric field confined between a typical configuration of the fluctuating cavity thickness, coupled to the Schrödinger equation for the exciton wavefunction. The difference in length and mass scales involved in this problem helps in finding the solution. Photon and exciton effective masses are very different, and one can therefore expects that, in the strong coupling regime, the kinetics is governed mainly by the photon component. Preliminary numerical simulations support the validity of this assumption. This project is still at its infancy, but promises interesting developments. In particular the other project I am planning to work on a longer timescale is the resonant polariton dynamics (OPO) of room temperature polaritons in GaN structures. The OPO regime for strongly localised polariton modes in these structures has not been studied before.

## III. FUTURE COLLABORATION WITH HOST INSTITUTION

During my visit to the Cavendish Laboratory in Cambridge I had the chance to visit several experimental groups, among which the group of Prof. Jeremy Baumberg, at the NanoPhotonics Centre. One project which I started looking at, and which I will develop in the future in collaboration with Prof. Jeremy Baumberg and Dr Jonathan Keeling (Theory of Condensed Matter, Cavendish Laboratory), is about **electrically tuned**

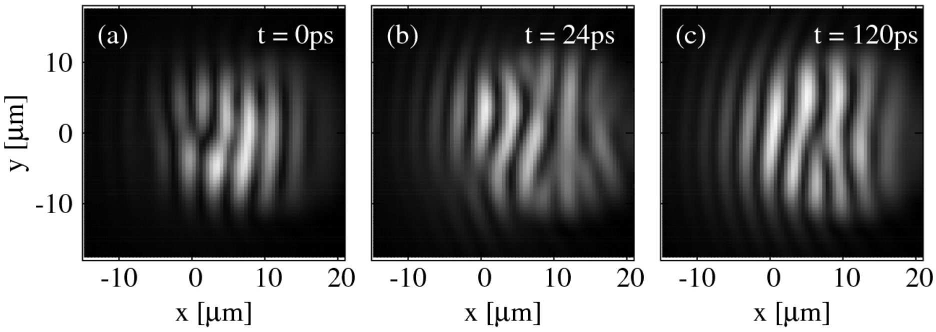


FIG. 2 These simulations show that during the transient period before the stable vortex solution equilibrates into the OPO signal, vorticity is not conserved. In particular if at $t = 0$ a vortex of charge $m = 1$ is imposed by the pulsed pump, during the evolution of the superfluid after the probe has been switched off, anti-vortices can appear at the edge of the superfluid, recombine with the initial vortex and leave a stable vortex solution with charge $m = -1$. The images show the interference fringes of the superfluid, where a vortex is characterised by a fork-like dislocation.

**polaritons**. The idea is to apply an electric field transverse to the growth direction of the cavity so that to polarise the excitons in the quantum well, which now experience a dipole-dipole interaction. The motivation for doing this is to increase the polariton-polariton interaction strength and therefore increase the parameter region for which polaritons can undergo Bose-Einstein condensation. In fact already previous experiments (see Refs. (Deng *et al.*, 2006; Kasprzak *et al.*, 2006)) have shown that thermalization processes due to polariton-polariton scattering can be dramatically amplified by increasing the value of the non-resonant pump power and by positively detuning the cavity energy above the excitonic energy. This corresponds respectively to an increase in the polariton density per unit area inside the cavity, and to an increase in their density of states.

However, while the transverse electric field does increase the polariton-polariton interaction, at the same time the oscillator strength between quantum well excitons and cavity photons is expected to get reduced because of Stark effect. Therefore I plan to establish the optimal bias for which the effect of the increase in the interaction strength is not washed out by the decrease of the Rabi splitting.

Another aspect of this project is related to the influence of direct and indirect excitons in the formation of polaritons in this structure. Direct excitons are expected to dominate a low bias, while at high bias indirect excitons are expected to have lower energy. For the particular structure used in experiments, a method based on an exact numerical solution of the Schrödinger equation on a given basis within the effective mass approximation can be used to evaluate the crossover from the direct to indirect exciton states. I plan to develop this part of the project also in collaboration of Dr Marzena Szymanska (University of Warwick).

I am planning to visit the Cavendish Laboratory again during the next academic year.

## IV. PROJECTED PUBLICATIONS

The project on stable vortex solutions in polariton OPO superfluids will bring shortly to a publication. With Dr Szymanska we still need to complete part of the analysis but we expect to submit a manuscript in within 3 months.

The project on electrically tuned polaritons mentioned in Sec. III will lead to two publications, but on a longer time scale, possibly by the middle of 2010.

I will acknowledge the support received from the European Science Foundation (ESF) in any of the publication mentioned above resulting from this grant, as I will also forward reprints to the ESF Secretariat as soon as available.

### References

Amo, A., J. Lefrere, S. Pigeon, C. Adrados, C. Ciuti, I. Carusotto, R. Houdre, E. Giacobino, and A. Bramati, 2009a, Nature physics, to be published .

Amo, A., D. Sanvitto, F. P. Laussy, D. Ballarini, E. del Valle, M. D. Martin, A. Lemaitre, J. Bloch, D. N. Krizhanovskii, M. S. Skolnick, C. Tejedor, and L. V. na, 2009b, Nature **457**, 291.

Baumberg, J. J., A. V. Kavokin, S. Christopoulos, A. J. D. Grundy, R. Butte, G. Christmann, D. D. Solnyshkov, G. Malpuech, G. B. H. von Hogersthal, E. Feltin, J.-F. Carlin, and N. Grandjean, 2008, Phys. Rev. Lett. **101**, 136409.

Christmann, G., R. Butte, E. Feltin, J.-F. Carlin, and N. Grandjean, 2006, Phys. Rev. B **73**, 153305.

Christopoulos, S., G. B. H. von Hogersthal, A. J. D. Grundy, P. G. Lagoudakis, A. V. Kavokin, J. J. Baumberg, G. Christmann, R. Butte, E. Feltin, J.-F. Carlin, and N. Grandjean, 2007, Phys. Rev. Lett. **98**, 126405.

Deng, H., D. Press, S. Götzinger, G. S. Solomon, R. Hey, K. H. Ploog, and Y. Yamamoto, 2006, Phys. Rev. Lett. **97**(14), 146402.

García-Ripoll, J. J., G. Molina-Terriza, V. M. Pérez-García, and L. Torner, 2001, Phys. Rev. Lett. **87**, 140403.

Kasprzak, J., M. Richard, S. Kundermann, A. Baas, P. Jeanbrun, J. M. J. Keeling, F. M. Marchetti, M. H. Szymańska, R. André, J. L. Staehli, V. Savona, P. B. Littlewood, *et al.*, 2006, Nature **443**.

Keeling, J., and N. G. Berloff, 2009, Nature **457**, 273.

Sanvitto, D., F. M. Marchetti, and *et al.*, 2009, eprint arXiv:0907.2371.

Stevenson, R. M., V. N. Astratov, M. S. Skolnick, D. M. Whittaker, M. Emam-Ismail, A. I. Tartakovskii, P. G. Savvidis, J. J. Baumberg, and J. S. Roberts, 2000, Phys. Rev. Lett. **85**(17), 3680.