



HAL
open science

Quantum degeneracy of microcavity polaritons

Augustin Baas, Jean-Philippe Karr, Marco Romanelli, Alberto Bramati,
Elisabeth Giacobino

► **To cite this version:**

Augustin Baas, Jean-Philippe Karr, Marco Romanelli, Alberto Bramati, Elisabeth Giacobino. Quantum degeneracy of microcavity polaritons. 2005. hal-00003867v1

HAL Id: hal-00003867

<https://hal.science/hal-00003867v1>

Preprint submitted on 11 Jan 2005 (v1), last revised 1 Mar 2006 (v2)

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Quantum degeneracy of microcavity polaritons

A. Baas, J.-Ph. Karr, M. Romanelli, A. Bramati, and E. Giacobino¹

¹*Laboratoire Kastler Brossel, Université Paris 6, École Normale Supérieure et CNRS,
UPMC Case 74, 4 place Jussieu, 75252 Paris Cedex 05, France*

We investigate experimentally one of the main features of a condensed phase, that is quantum degeneracy of a macroscopic fraction of the particles, in the case of polaritons in strong-coupling semiconductor microcavities. We show that resonant pumping allows to create a macroscopic population of polaritons in one quantum state, as expected. Furthermore we demonstrate that parametric polariton scattering results in the transfer of a macroscopic population of polariton from one single quantum state into another one. Finally we briefly outline a simple method which provides direct evidence of the first-order spatial coherence of the transferred population.

In the past few years, the possibility of condensation in solid-state systems has raised a growing interest [1]. Exciton polaritons in semiconductor microcavities appear as promising candidates since the demonstration of polariton pair scattering [2] which provides a mechanism allowing to populate very efficiently the lowest energy state, i.e. the $\mathbf{k} = \mathbf{0}$ state, where \mathbf{k} is the wave vector in the plane of the layers. The condensed phase in such systems differs in several ways from atomic Bose Einstein condensates, being intrinsically out of thermodynamical equilibrium. It has been described in terms of a polariton condensate [3], a polariton laser [4] or a superfluid [5]. However, whatever the theoretical frame used, a common necessary condition for such a condensation process is that a macroscopic fraction of the particles in the system are in one single quantum state. The aim of this paper is to give an unambiguous signature of this feature, using the fact that the coherence and polarization properties of the polariton field are transferred to the emitted light field, due to its part-matter, part-light nature. Therefore, quantum degeneracy of polaritons can be evidenced by proving that the emitted light is in a single-mode quantum state.

In an ideal planar semiconductor microcavity, the polariton eigenmodes are plane waves characterized by their energy, in-plane wave vector \mathbf{k} and polarization. Due to various effects limiting the transverse size of the polariton mode (among them disorder, the cavity wedge, and nonlinear effects), the polariton modes can generally be expressed as superpositions of plane waves with \mathbf{k} in a finite range Δk ; due to relaxation processes they also have a finite energy width. Subsequently, a reduction of the linewidth or angular divergence of the emitted light may indicate a reduction of the number of populated polariton modes. However, such properties, related to the first-order coherence, are not in themselves sufficient proofs of the single-mode nature of the polariton field. In the same way, a measurement of first-order temporal coherence does not allow to discriminate between the light from a single-mode laser and the light from a spectrally filtered thermal source [6]. A full characterization requires the measurement of second-order coher-

ence properties (like intensity correlations). Up to now, only the first-order temporal coherence of the microcavity emission has been extensively studied [7]. Second-order coherence in the time domain has been studied theoretically [8, 9, 10, 11] and experimentally through the measurement of the intensity autocorrelation function $g^{(2)}(\tau)$ of the emitted light [12].

Here we will focus on *spatial* second-order coherence. It has been shown recently that the measurement of intensity correlations in the transverse plane provides a criterion allowing to characterize unambiguously single-mode and multimode quantum states of light [13]. In this paper, we apply this criterion to the light emitted by a polariton population around $\mathbf{k} = \mathbf{0}$, created by polariton pair scattering under resonant pumping of the lower polariton branch by a single-mode cw laser. Our results show that the emitted light is in a single-mode quantum state, giving a proof of the *quantum degeneracy* of polaritons. We also demonstrate first-order spatial coherence through the observation of interference fringes in the emitted field. Our method is reminiscent of matter wave interference experiments in atomic condensates [14], although in our case only the photon fraction of the polariton field takes part in the interference.

We begin by briefly describing the characterization of single-mode and multimode beams [13]. Two possible methods can be considered:

(i) For a beam in a single-mode quantum state, a partial intensity measurement (i.e. only a part of the beam is sent to the photodetector) has the same effect as losses. This corresponds to the idea that in a single-mode quantum state, photons are randomly distributed in the transverse plane. Such a behavior can be tested by "cutting" the beam transversally with a razor blade and measuring the intensity noise as a function of intensity [15]. The noise normalized to the shot noise limit should vary linearly with the intensity -the slope is respectively positive, negative or equal to zero if the noise of the total beam is above, under or at the shot noise level. Any deviation from the linear behavior would prove the multimode character of the beam.

(ii) If two separate parts of the single-mode beam of

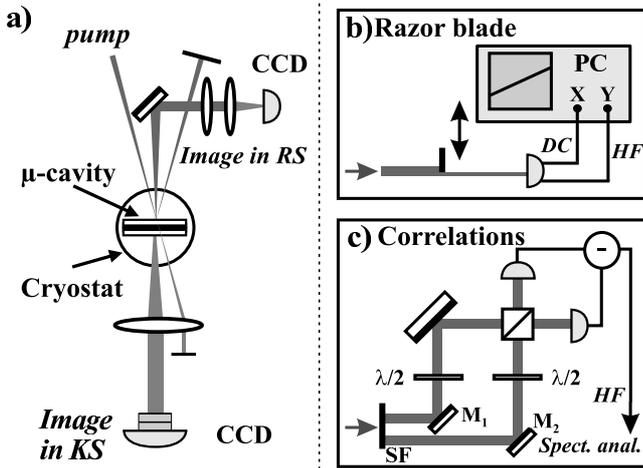


FIG. 1: a) Experimental setup. CCD camera for images in RS (KS) of the emitted light in reflection (transmission). b) "Razor blade" setup. HF (DC): high (low) frequency part of the signal. c) Intensity correlations set-up. Each of the mirrors M_1 and M_2 reflects the emission from one of the regions selected by the spatial filter (SF) in KS (see also Fig. 2 b).

equal intensities are sent to two identical photodetectors A and B , the noise of the difference of the photocurrents $N_A - N_B$ is the shot noise, whatever the quantum state of the beam -even for a beam with excess noise, when the noise measured by each detector is above the shot noise. There are no correlations at the quantum level between N_A and N_B , which again corresponds to the idea that photons are randomly distributed in the transverse plane. Any deviation from the shot noise level would prove the multimode character of the beam.

These methods only apply to the *transverse* single-mode or multimode nature of the beam. It is assumed that only one longitudinal cavity mode is present in the emission. For example, one can consider the case of a laser emitting on two consecutive longitudinal cavity modes, but with the same transverse distribution described by a TEM_{00} mode; it is clear that the above-described experiments do not allow to evidence the multimode nature of such a beam. However in microcavities the emission is obviously longitudinal single-mode, because other longitudinal modes are very far in energy. In the same way it is assumed that only one polarization state is present in the emission. In our case, this condition can be reached by using a σ^+ -polarized pump beam, since it was shown that the signal emission is then also σ^+ polarized [16].

In these experiments, a multimode beam can be identified unambiguously by a deviation from the expected behavior for a single-mode beam. However, no necessary and sufficient condition can be given for the identification of a single-mode quantum state, because the single-mode behavior has to be verified in *all* transverse bases. But a convincing indication can be given if the single-mode be-

havior is verified in a basis of transverse modes in which the field can be expected to be multimode [13]. Since the polariton modes are well approximated by plane waves defined by an in-plane wave vector \mathbf{k} , the plane waves are a relevant basis to demonstrate the eventual multimode character of the emission; in the following, all measurements are done in the far field.

The microcavity sample is a high quality factor 2λ cavity described in [17] with polariton linewidths in the 100-200 μeV range. The pump laser is a single-mode tunable cw Ti:Saphir with a linewidth of 1 MHz, spatially filtered through an optical fiber [18] and focused on a $100\mu\text{m}$ spot (full width at half maximum of the gaussian distribution) with a divergence of 0.6° . All experiments are carried out with one σ^+ polarized resonant pump beam and no probe beam. The left part of Fig. 1 shows the geometry of the experiment. Images of the nonlinear emission around $\mathbf{k} = \mathbf{0}$ are taken by CCD cameras in real-space (RS) (near field) and in \mathbf{k} -space (KS) (far-field).

We first consider the simplest case where the pump beam is at normal incidence and directly creates polaritons around $\mathbf{k} = \mathbf{0}$. The interest of investigating this configuration is to check the widely used assumption that a resonant pump field creates polaritons in a single quantum state, provided the spot size and the pump divergence obey certain conditions. The recent observation of complex transverse patterns in the emitted light in the nonlinear regime [18, 19] raises some doubts about the single-mode character of the polariton population. Transverse intensity correlation measurements allow to answer this question unambiguously. From a practical point of view, it is not easy to analyze the properties of the polariton emission since it is in the same direction as the much more intense reflected laser field. However, at high enough excitation density the polaritons are confined by nonlinear effects in a zone that is smaller than the excitation spot [18] (see the RS image of the excitation spot in Fig. 2 a). If only because of diffraction, the emitted field has a larger angular divergence than the reflected laser (see the KS image in Fig. 2 b). The reflected laser can then be filtered out and we perform the above-described intensity correlation measurements on the remaining part of the emitted field.

The curve in Fig. 3 a) shows the results of the "razor blade" experiment. The linear variation of the normalized noise as a function of intensity indicates the single-mode character of the emitted light ; the slope is positive because the beam has some excess noise.

This result was confirmed by the measurement of intensity correlations in the transverse plane. The experimental setup is shown in Fig.1 c). Two parts of the emitted beam are selected (as shown in Fig. 2 b) by placing a screen with two small holes in \mathbf{k} -space. The light transmitted by each of the holes is sent to a detector by removing the $\lambda/2$ waveplates and the high-frequency part of the photocurrent difference is sent to a spectrum

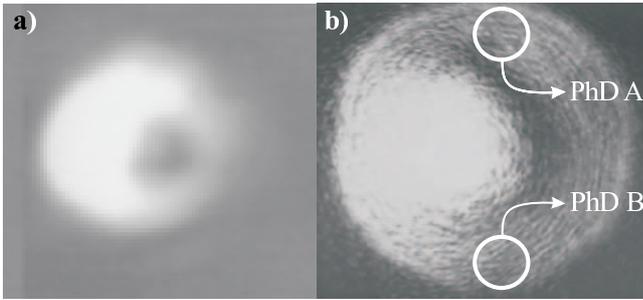


FIG. 2: Image of the non linear emission in RS (a) and in \mathbf{k} -space (b) in the degenerate geometry [18]. Cavity exciton detuning 0.3 meV and laser intensity 2.2 mW. In (a) the dark region in the laser spot corresponds to the polariton resonance. In (b) the polariton emission is seen around the (brighter) reflected laser in \mathbf{k} -space, showing a larger angular divergence. The principle of the intensity correlation measurement is schematically indicated.

analyzer. The polarizing cube, together with the $\lambda/2$ waveplates, allows to measure the shot noise reference by separating each beam into two parts of equal intensities incident on each detector and making the difference of the photocurrents [20]. An example of our results is shown in Fig. 3 b). The noise of the intensity difference is the shot noise level, whereas each beam has an excess noise of more than 30%. This experiment was repeated for different positions of the holes in \mathbf{k} -space, with identical results.

These results are a very strong indication that the emission around $\mathbf{k} = \mathbf{0}$ originates from one and the same polariton quantum state. In particular, it implies that non-degenerate processes such as the pair scattering $\{\mathbf{0}, \mathbf{0}\} \rightarrow \{\mathbf{k}, -\mathbf{k}\}$ play a negligible role and essentially validates the single-mode treatment adopted in [9, 18, 19]. The larger divergence of the nonlinear emission with respect to that of the pump beam can be explained by diffraction effects and is not associated with a polariton population in other modes.

We now consider a pump at the so-called "magic angle" a little above the parametric oscillation threshold, where a bright signal beam is emitted around $\mathbf{k} = \mathbf{0}$ [21]. Also in this configuration, complex transverse patterns have been observed in the emitted light around $\mathbf{k} = \mathbf{0}$ [17, 23], raising questions about its single-mode character. Again, intensity correlation measurements provide an unambiguous answer.

Fig. 3 a) shows the result of a "razor blade"-type experiment (Fig. 1 b) on the light emitted around $\mathbf{k} = \mathbf{0}$ in reflection, the reflected pump beam being carefully filtered out. The emitted beam is cut by a razor blade in \mathbf{k} -space. The variation of the normalized noise as a function of the intensity is linear within experimental accuracy, the positive slope meaning that the total beam has excess noise. This experiment demonstrates that only one signal-idler

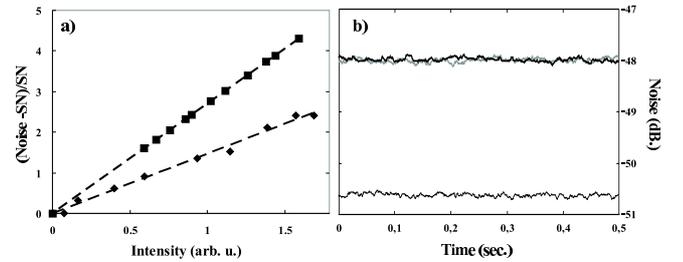


FIG. 3: a) Squares(diamonds): variations of the noise -HF signal- of the nonlinear emission around $\mathbf{k} = \mathbf{0}$ as a function of the detected intensity -DC signal-, in the degenerate (non-degenerate) geometry. The shot noise (SN) is subtracted from the total noise, and the result is normalized to the SN. Cavity-exciton detuning: respectively 0.3 and 1.2 meV. In the degenerate case, points at very low intensity are missing because the noise was too small compared to dark noise. b) Noise power as observed on the screen of the spectrum analyzer. Dark line: noise of the intensity difference, perfectly superimposed with the shot noise level (gray line). Dark noise (clear gray line) is 2.6 dB below the SN level.

pair oscillates, as can be expected from the analogy with optical parametric oscillators [24]. It validates the widely used model involving only three polariton \mathbf{k} states, which successfully accounts for most experimental observations [22]. In other words, polariton pair scattering makes it possible to create a macroscopic population of polariton in one single quantum state distinct from the pumped mode. It would be very interesting to make the same kind of measurement below threshold, since many signal-idler pairs are then involved and evidence for a multimode quantum state should be observed [25].

The single-mode nature of the signal polariton field implies phase coherence, i.e. first-order spatial coherence over the whole emission zone. We now present an original set-up revealing in a very direct and visual way the phase coherence of the signal field. The idea is to superimpose the light fields emitted by two separate spots of the sample, sufficiently small to have a significant divergence so that the emitted fields overlap in \mathbf{k} -space. This is analogous to Young's double slit experiment, where the slits are put directly on the surface of the light source.

As noted above, nonlinear effects can lead to various transverse patterns in the active region. Fig. 4 a) shows a RS image of the sample surface, after filtration in KS of the light emitted in a cone of 2° around the normal direction, which allows to get rid of the pump laser at the "magic angle" (about 12°). It can be seen that the signal field is emitted by two separate spots, a few microns in diameter and separated by $l \simeq 70 \mu\text{m}$.

The corresponding image in KS presents interference fringes (Fig. 4 b). We are confident that they are not due to a self-interference of the laser, because the laser light has been filtered out. We sent the emitted field through a monochromator and found no component at the laser

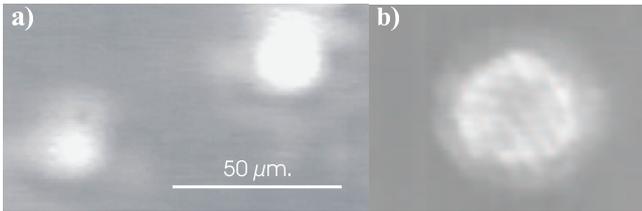


FIG. 4: Image of the light emitted in a cone of 2° around the normal direction a) in RS in reflection ; b) in \mathbf{k} -space in transmission. Cavity-exciton detuning: 1.3 meV. Laser intensity: 2.8 mW (around 1.5 times the threshold intensity).

wavelength. Moreover, the fringes are perpendicular to the line joining the two spots and the fringe separation is in full agreement with a simple two-slits type calculation: $i = \lambda f / l$, with f the focal of the lens. This experiment reveals a significant degree of first-order spatial coherence of the $\mathbf{k} = \mathbf{0}$ polaritons at a scale of $70 \mu\text{m}$. The fact that interference is observed in cw regime confirms, in addition, that a significant part of the beams emitted by the two spots originates from one and the same polariton mode (in spite of the complex shape avec the active region in RS). Indeed, two distinct modes would interfere during a time limited by the coherence time T_2 , in the same way as the emissions from two independent lasers [6].

This result was expected in view of the single-mode properties that we have discussed above. However, it also illustrates a direct method of measurement of first-order spatial coherence and gives an order of magnitude for the coherence length of the polaritons created by the parametric process, which can be compared to the coherence length of polaritons in the linear regime [26]. A systematic study as a function of pump intensity -specially around the parametric threshold- and cavity-exciton detuning would yield information about the mechanisms limiting the coherence length.

We have presented an experimental study of quantum degeneracy of microcavity polaritons, relying on the measurement of intensity correlations in the transverse plane. We have shown that (i) resonant pumping allows to create a macroscopic population of polaritons in a single quantum state; (ii) in the case of non-degenerate interaction, for which the coherence is not directly printed by the laser, the polariton pair scattering gives rise to a single-mode quantum state for the polariton population around ($k \simeq 0$). These results establish that a a very important step towards the realization of a condensed phase

in semiconductor microcavities has been achieved. The experimental methods that we have used are very promising for the characterization of quantum degeneracy [27], also under nonresonant pumping.

We acknowledge enlightening discussions with I. Carusotto, C. Ciuti, O. El Daif, C. Fabre, T. Guillet, N. Treps, and J. Tignon. We are very grateful to R. Houdré for providing us with the microcavity sample.

-
- [1] S. A. Moskalenko and D. W. Snoke, *Bose-Einstein Condensation of Excitons and Biexcitons and Coherent Non-linear Optics with Excitons* (Cambridge University Press, Cambridge, 2000).
 - [2] P. G. Savvidis *et al.*, Phys. Rev. Lett. **84**, 1547 (2000).
 - [3] J. Keeling *et al.*, Phys. Rev. Lett. **93**, 226403 (2004).
 - [4] Y. G. Rubo *et al.*, Phys. Rev. Lett. **91**, 156403 (2003).
 - [5] I. Carusotto and C. Ciuti, Phys. Rev. Lett. **93** 166401 (2004).
 - [6] L. Mandel and E. Wolf, *Optical Coherence and Quantum Optics* (Cambridge University Press, Cambridge, 1995).
 - [7] J. J. Baumberg *et al.*, Phys. Rev. B **62**, R16247 (2000); G. Messin *et al.*, Phys. Rev. Lett. **87**, 127403 (2001); S. Kunderman *et al.*, Phys. Rev. Lett. **91**, 156403 (2003); A. Huynh *et al.*, Phys. Rev. Lett. **90**, 106401 (2003).
 - [8] F. Tassone and Y. Yamamoto, Phys. Rev. A **62**, 063809 (2000).
 - [9] P. Schwendimann *et al.*, Phys. Rev. B **68**, 165324 (2003).
 - [10] J. Ph. Karr *et al.*, Phys. Rev. A **69**, 063807 (2004).
 - [11] D. Sarchi and V. Savona, cond-mat/04111084.
 - [12] H. Deng *et al.*, Science **298**, 199 (2002).
 - [13] M. Martinelli *et al.*, Phys. Rev. A **67**, 023808 (2003).
 - [14] I. Bloch *et al.*, Nature (London) **403**, 166 (2000).
 - [15] J.-Ph. Poizat *et al.*, J. Opt. Soc. Am. B **15**, 1757 (1998); J.-P. Hermier *et al.*, J. Opt. Soc. Am. B **16**, 2140 (1999).
 - [16] P. G. Lagoudakis *et al.*, Phys. Rev. B **65**, 161310 (2002)
 - [17] R. Houdré *et al.*, Phys. Rev. Lett. **85**, 2793 (2000).
 - [18] A. Baas *et al.*, Phys. Rev. A **69**, 023809 (2004).
 - [19] J. Ph. Karr *et al.*, Phys. Rev. A **69**, 031802(R) (2004).
 - [20] H.A. Bachor, *A Guide to Experiments in Quantum Optics*, Wiley, Weinheim, pp. 181-183 (1998).
 - [21] R. M. Stevenson *et al.*, Phys. Rev. Lett. **85**, 3680 (2000); A. I. Tartakovskii *et al.*, Phys. Rev. B **65**, 081308 (2002).
 - [22] C. Ciuti *et al.*, Phys. Rev. B **62**, R4825 (2000); C. Ciuti *et al.*, Semicond. Sci. Technol. **18**, S279 (2003).
 - [23] A. Baas *et al.*, Phys. Rev. B **70** 161307(R) (2004).
 - [24] C. Fabre *et al.*, C. R. Acad. Sci. Paris 1 IV, 553 (2000).
 - [25] W. Langbein *et al.*, Phys. Rev. B **70** 205301 (2004).
 - [26] A. I. Tartakovskii *et al.*, Phys. Stat. Sol. B **221**, 163 (2000).
 - [27] L. V. Butov *et al.*, Nature **417**, 47 (2003); C. W. Lai *et al.*, Science **303**, 503 (2004).