Quantum coherence in momentum space of light-matter condensates

C. Antón,1,2 G. Tosi,1 M. D. Martín,1,2 Z. Hatzopoulos,3,4 G. Konstantinidis,3
P. S. Eldridge,3 P. G. Savvidis,3,5 C. Tejedor,6,2,7 and L. Viña1,2,7,*

1Departamento de Física de Materiales, Universidad Autónoma de Madrid, Madrid 28049, Spain
2Instituto de Ciencia de Materiales “Nicolás Cabrera”, Universidad Autónoma de Madrid, Madrid 28049, Spain
3FORTH-IESL, P.O. Box 1385, 71110 Heraklion, Crete, Greece
4Department of Physics, University of Crete, 71003 Heraklion, Crete, Greece
5Department of Materials Science and Technology, University of Crete, 71003 Heraklion, Crete, Greece
6Department of Física Teórica de la Materia Condensada, Universidad Autónoma de Madrid, Madrid 28049, Spain
7Instituto de Física de la Materia Condensada, Universidad Autónoma de Madrid, Madrid 28049, Spain

(Dated: August 25, 2014)

We show that the use of momentum-space optical interferometry, which avoids any spatial overlap between two parts of a macroscopic quantum state, presents a unique way to study coherence phenomena in polariton condensates. In this way, we address the longstanding question in quantum mechanics: “Do two components of a condensate, which have never seen each other, possess a definitive phase?” [P. W. Anderson, Basic Notions of Condensed Matter Physics (Benjamin, 1984)].

I. INTRODUCTION

Cold atoms and exciton-polaritons in semiconductor microcavities are systems where their capability to constitute Bose-Einstein condensates (BECs) has been demonstrated in recent years.1–2 These BECs, due to their dual wave-particle nature, share many properties with classical waves as, for instance, interference phenomena.3–6, which are crucial to gain insight into their undulatory character.7–9 One of the main differences between atomic and polariton condensates resides in the particles lifetime: the finite lifetime of polaritons, in contrast with the infinite one of atoms, can be regarded as a complication. But making virtue of necessity, a short lifetime also implies a significant advantage: polaritons have a mixed exciton-photon character, their lifetime being determined by the escape of their photonic component out of the cavity. These photons are easily measured either in real- (near field spectroscopy) or momentum-space (far field spectroscopy)10, rendering full information about the polariton BECs wave-function and, in particular, about its coherence.11–13 Our goal is to profit from these measurements in momentum space to experimentally investigate something far from accessible in atomic condensates: the interference in momentum space produced by the correlation between two components of a condensate, which are, and have always been, spatially separated. Understanding coherence is important for a large number of disciplines spanning from classic optics to quantum information science and optical signal processing.14–17

Pitaevskii and Stringari made a theoretical proposal to investigate experimentally these interference effects in momentum space via the measurement of their dynamic structure factor.18 In related experiments, coherence between two spatially separated atomic BECs has been indirectly obtained using stimulated light scattering.19–20

In this work we perform a direct measurement of this correlation in polariton BECs, which moving in a symmetrical potential landscape, acquire a common relative phase, obtaining a positive answer to Anderson’s question,19–20 which opens new perspectives in the field of multi-component condensates.

II. EXPERIMENTAL RESULTS AND DISCUSSION

We confront this task in a quasi one-dimensional (1D) system made of a high-quality AlGaAs-based microcavity, where $20 \times 300 \mu m^2$ ridges have been sculpted. The sample, kept at 10 K, is excited with 2 ps-long light pulses from a Ti:Al$_2$O$_3$ laser. In order to create polaritons in two separated spatial regions, the laser beam is split in two, named $A$ and $B$, impinging simultaneously at positions distanced by $d_{AB} = 70 \mu m$. Additional experimental details are described in the Supplementary information.21 A crucial issue when optically creating polaritons is the excess energy of the excitation laser. There are two well explored alternatives: non-resonant excitation at very high energy22 and strictly resonant excitation.23 The latter situation generally produces macroscopic polariton states with a phase inherited from that of the laser, unless special care is taken in the experiment.22 The former case is appropriate to avoid phase heritage, but it does not provide the momentum distribution, shown below, required for our experiments. In order to avoid these difficulties, we opt for a different alterna-
tive, depicted in Fig. 1(a): the laser beams excite the sample at the energy of bare excitons and $k_x \sim 0$. The broad bands between 1.542 and 1.548 eV corresponds to excitonic emission bands; the sub-bands below 1.542 eV are the confined lower polariton branches. After energy relaxation, polariton condensates are created in a process that involves a non-reversable dressing of the excitons and therefore an erasure of the laser phase. Above a given

The phases are chosen to have inversion symmetry with respect to $x = 0$, because in our experiments we tune the intensities of the two lasers in order to get a symmetrical potential $V(x) = V(-x)$. In that respect, our condensates are related to each other through the symmetry of the excitation process.

Furthermore, our potential landscape renders an equal motion for $\psi_1^A$ and $\psi_1^B$, i.e. equal momenta $| (k_x)_j^A | = | (k_x)_j^B | = k_x$. These are precisely the suitable conditions to observe coherence between two components spatially separated by $d$, i.e. $\psi_j^A (x-d/2) = \psi_j^B (x+d/2) = \psi_0 (x)$, of a given condensate $\Psi_j^{coh}$. This coherence can be observed in k-space as we discuss now.

For the sake of clarity, we focus in the following discussion only on the left-propagating WPs. The corresponding order parameter in k-space can be written as:

$$\Psi_1^{coh} (k_x) = \psi_1^A (k_x) + e^{i\phi} \psi_1^B (k_x) = e^{-i k_x d/2} \psi_0 (k_x) + e^{i (\phi + k_x d/2)} \psi_0 (k_x)$$

with $\psi_0 (k_x)$ being the Fourier transform of $\psi_0 (x)$. This yields a momentum distribution

$$n_1^{coh} (k_x) = |\Psi_1^{coh} (k_x)|^2 = 2 [1 + \cos (k_x d + \phi)] |\psi_0 (k_x)|^2,$$

The coherence between the two components produces interference fringes with a period

$$\Delta k_x = 2\pi/d.$$

Our aim is to observe the existence of interferences in k-space coming from this macroscopic two-component condensate. Far-field detection allows the direct measurement of momentum distributions, i.e. it gives a direct determination of the existence, and the period, of these interference fringes. It must be taken also into account that the measured total polariton density is formed by a condensed population, $n^{coh}$, coexisting with a thermal one, therefore the interference patterns visibility, $\nu$, is lower than 1 (see Supplemental Material).

Our most important result is shown in Fig. 2(b): we indeed observe the interference fringes in k-space, described by Eq. (4) directly in the polariton emission. This certifies the correctness of our hypothesis that each couple of WPs ($\psi_1^A$, $\psi_1^B$) constitutes a two component condensate. Figure 2(a) shows the actual evolution in time of the four WPs schematically depicted in Fig. 1(a): our results clearly demonstrate that the distance $d$ between the two components of each condensate remains constant

$$\Psi_1^{coh} (x) = \psi_1^A (x) + e^{i\phi} \psi_1^B (x),$$

while those propagating to the right are described by

$$\Psi_2^{coh} (x) = e^{i\phi} \psi_2^A (x) + \psi_2^B (x).$$
with time during the first $\sim 70$ ps ($d = d_{AB}$), as evidenced by the dashed parallel arrows. Figure 2(a) contains also interesting real-space interferences when WPs $\psi_1^A$ and $\psi_1^B$ overlap in real space at 66 ps that we shall discuss in more detail below. A peculiarity of our experiments is that we observe the dynamics of the coherence; this allows us to determine that the two components of the condensate are phase locked since there is not any drift in the interference patterns.

As readily seen in Fig. 2(b), an initial acceleration of the four WPs, from rest, $k_x = 0$, to $k_x = \pm 1.6 \, \text{m}^{-1}$ during the first 40 ps, is followed by a uniform motion taking place from 40 ps to 70 ps. The interference pattern of each condensate is observed until $\sim 75$ ps, instant at which $\psi_1^A$ and $\psi_1^B$ disappear from the sample region imaged in the experiments. Then WPs $\psi_1^A$ and $\psi_2^A$ are progressively slowed by the presence of the barriers at the excitation spots ($V_A/V_B$ halts $\psi_1^B/\psi_2^A$). When these two WPs, which are the components of two different condensates $\Psi_1^{coh}$ and $\Psi_2^{coh}$, are stopped (at $\sim 100$ ps) another interference appears in k-space, but now at $k_x = 0$ as it corresponds to WPs at rest. This means that these two condensates also interfere with each other, being remarkable that $\Psi_1^{coh}$ and $\Psi_2^{coh}$ still preserve some kind of mutual coherence, supporting the functional form of Eqs. (1) and (2). For longer times, the two WPs move again, as can be observed in Figs. 2(a,b), becoming more difficult to track their trajectories.

Further insight into the quantum coherence is obtained by analyzing in detail the interferences occurring in momentum- and real-space. Accordingly, we present in Fig. 3 two-dimensional maps of the polariton emission at three consecutive, relevant times. We focus on the correspondence between the period of the interference patterns in each space (real and momentum) and the separation between the WPs in the complementary space. Figure 3(a) shows the momentum distribution $n(k_x, k_y)$, 35 ps after the impinging of the laser beams on the sample. The coherence of each $\Psi_2^{coh}$ is observed by the conspicuous interference patterns, $n_2^{coh}$, centered at $k_x = \pm 1.6 \, \text{m}^{-1}$. In both cases, the fringes period amounts to $\Delta k_x = 0.088(5) \, \text{m}^{-1}$ that, according to Eq. 5, should correspond to a distance between WPs of $d = 71(4) \, \mu\text{m}$. This is in good agreement with the experimental distance seen in Fig. 3(b): the two components of each condensate, $n_1^A$ and $n_2^B$, are separated by $d \approx 70 \, \mu\text{m}$ (see dashed arrows). Our findings are further supported by the Fourier transform map of $n(k_x, k_y)$ shown in Fig. 3(c): a well-defined Fourier component at $\Delta X = d = 70 \, \mu\text{m}$ is obtained, in accordance with the separation directly observed in real space.
Coherence in real space have been profusely studied in cold atoms, excitons and polariton condensates. Our experiments also show interferences in real space between two condensates, similar to those reported in atomic BEC. This is shown in Fig. 3(c) at 66 ps when WPς\(^2_A\) and ψ\(^1_B\) meet each other at \(x \sim 0\). The appearance of interference fringes in real space, \(n_{12}\), signals unambiguously to coherence between these two WPs. Since real and momentum spaces are reciprocal to each other, equivalent results for the interference patterns are expected. The complementary expression in real space to Eq. 5 reads now \(\Delta x = 2\pi/\kappa\), where \(\Delta x\) is the period of the fringes and \(\kappa\) the difference in momentum of the propagating WPs. The experimental period of the fringes, seen in the dashed-rectangle area in Fig. 3(c), \(\Delta x = 1.99(17) \mu m\), should correspond to \(\kappa = (k_x)_2 - (k_x)_1 = 3.2(2) \mu m^{-1}\). This is again borne out by our results, as shown in Fig. 3(d), where the emission in \(k\)-space shows clearly that WPs ψ\(^2_A\) and ψ\(^1_B\) are counter-propagating with \(k_x = \pm 1.6 \mu m^{-1}\), respectively. Figure 3(f) shows the Fourier transform of \(n_{12}\) in the region enclosed by the rectangle in Fig. 3(c). It reveals a strong \(\Delta K_x\) Fourier component at \(3.1 \mu m^{-1}\), in full agreement with the value of \(\kappa\) displayed in Fig. 3(d). Let us also emphasize that WPs first meet in real space at 66 ps, while interferences in momentum space are seen as early as \(\sim 10 ps\) demonstrating that the phase locking occurs before the WPs spatially overlap.

The third result that we present corresponds to the arrival at 108 ps of ψ\(^2_A\) and ψ\(^1_B\) to the excitation regions \(B\) and \(A\), respectively. Here, they run into the hills of the photogenerated potentials \(V_B\) and \(V_A\) that elastically convert their kinetic energy into potential energy. They slow down, halting, providing a new separation between WPs \(n_{22}\) and \(n_{11}\), \(d_{12} \sim 60 \mu m\) (see Fig. 3(h)). Their emission in momentum space, arising from \(k_x \sim 0\), evidences an interference pattern with \(\Delta k_x = 0.108(5) \mu m^{-1}\) (\(n_{12}\), see Fig. 3(g)). Once again, Eq. 5 predicts a separation \(d_{12} = 60(4) \mu m\) between \(n_{22}\) and \(n_{11}\), as observed in the experiments. For completeness, we also show in Fig. 3(i) the Fourier transform map of the density that exhibits an emerging component at \(\Delta X = d_{12} = 60 \mu m\). Further insight into this scaling behavior, relating distances in real space between WPs with the fringes...
period in momentum space, is presented in the Supplementary information\cite{supplemental_material}.  

III. CONCLUSIONS

In summary, the convenience of monitoring the evolution of exciton-polaritons in semiconductor microcavities, through the detection of emitted light, makes this system an ideal platform to study quantum coherence properties in real- as well as in momentum-space. Profiting from this fact, we have demonstrated the existence of quantum remote coherence between spatially separated polariton condensates whose phase is determined by the symmetry of the excitation conditions and therefore is constant in each realization of our multi-shot experiments. This issue is related to the superposition principle in quantum mechanics and it is crucial to understand how mutual coherence is acquired.

IV. ACKNOWLEDGEMENTS

We thank D. Steel and J.J. Baumberg for a critical reading of the manuscript. C.A. acknowledge financial support from a Spanish FPU scholarship. P.G.S. acknowledges Greek GSRT program “ARISTEIA” (1978) for financial support. The work was partially supported by the Spanish MEC MAT2011-22997, CAM (S-2009/ESP-1503) and FP7 ITN’s “Clermont4” (235114), “Spin-optronics” (237252) and “INDEX” (289968) projects.

\begin{thebibliography}{10}
\bibitem{davis} K. B. Davis, M. -O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle, Phys. Rev. Lett. \textbf{75}, 3969 (1995).
\bibitem{kasprzak} J. Kasprzak, 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, B. Deveaud, and L. S. Dang, Nature \textbf{443}, (2006).
\bibitem{andrea} M. R. Andrews, C. G. Townsend, H.-J. Miesner, D. S. Durfee, D. M. Kurn, and W. Ketterle, Science \textbf{275}, 637 (1997).
\bibitem{saha} D. S. Hall, M. R. Matthews, C. E. Wieman, and E. A. Cornell, Phys. Rev. Lett. \textbf{81}, 1543 (1998).
\bibitem{eislinger} T. Eislenger, I. Bloch, and T. W. Hänsch, J. Mod. Opt. \textbf{47}, 2725 (2000).
\bibitem{bloch} I. Bloch, Nature Phys. \textbf{1}, 23 (2005).
\bibitem{born} M. Born and E. Wolf, \textit{Principles of Optics: Electromagnetic Theory of Propagation, Interference and Diffraction of Light} (Cambridge University Press, 2000).
\bibitem{fick} Z. Fick and S. Swain, \textit{Quantum Interference and Coherence. Theory and Experiments} (Springer, 2005).
\bibitem{kavokin} A. Kavokin, Nature Photon. \textbf{7}, 591 (2013).
\bibitem{novotny} L. Novotny, \textit{Principles of Nano-Optics} (Cambridge University Press, 2006).
\bibitem{mandel} L. Mandel and E. Wolf, \textit{Optical Coherence and Quantum Optics} (Cambridge University Press, 1995).
\bibitem{pryde} G. J. Pryde, Nature Photon. \textbf{2}, 461 (2008).
\bibitem{pitae} L. Pitaevskii and S. Stringari, Phys. Rev. Lett. \textbf{83}, 4237 (1999).
\bibitem{saba} M. Saba, T. A. Pasquini, C. Sanner, Y. Shim, W. Ketterle, and D. E. Pritchard, Science \textbf{307}, 1945 (2005).
\bibitem{shim} Y. Shim, G. B. Jo, M. Saba, T. A. Pasquini, W. Ketterle, and D. E. Pritchard, Phys. Rev. Lett. \textbf{95}, 170402 (2005).
\bibitem{anderson} P. W. Anderson, \textit{Basic Notions of Condensed Matter Physics} (Benjamin, Menlo Park, California, 1984).
\bibitem{castin} Y. Castin and J. Dalibard, Phys. Rev. A \textbf{55}, 4330 (1997).
\bibitem{leggett} A. J. Leggett, \textit{Quantum Liquids} (Oxford University Press, Oxford, 2006).
\bibitem{pitae2} L. P. Pitaevskii and S. Stringari, \textit{Bose-Einstein Condensation} (Oxford University Press, 2003).
\bibitem{supplemental_material} See Supplemental Material at \url{http://link.aps.org/supplemental/XXX} for further details.
\bibitem{amo} A. Amo, J. Lefrère, S. Pigeon, C. Adrados, C. Ciuti, I. Carusotto, R. Houdré, E. Giacobino, and A. Bramati, Nature Phys. \textbf{5}, 805 (2009).
\bibitem{amo2} A. Amo, S. Pigeon, D. Sanvitto, V. G. Sala, R. Hivet, I. Carusotto, F. Pisanello, G. Léménager, R. Houdré, E. Giacobino, C. Ciuti, and A. Bramati, Science \textbf{332}, 1167 (2011).
\bibitem{wertz} E. Wertz, L. Ferrier, D. D. Solnyshkov, R. Johne, D. Sanvitto, A. Lemaitre, I. Sagnes, R. Grousson, A. V. Kavokin, P. Senellart, G. Malpuech, and J. Bloch, Nature Phys. \textbf{6}, 860 (2010).
\bibitem{WP} Since all WP have the same spreading, we employ the usual terminology simply labeling each WP by its central value $k_z$.
\bibitem{delvalle} E. del Valle, D. Sanvitto, A. Amo, F. P. Laussy, R. André, C. Tejedor, and L. Viña, Phys. Rev. Lett. \textbf{103}, 096404 (2009).
\bibitem{WP2} Since our samples are not strictly one-dimensional, we provide full images of the emission in two-dimensional spaces.
\bibitem{hodgman} S. S. Hodgman, R. G. Dall, A. G. Manning, K. G. H. Baldwin, and A. G. Truscott, Science \textbf{331}, 1046 (2011).
\bibitem{snoke2} D. Snoke, Science \textbf{298}, 1368 (2002).
\bibitem{high} A. A. High, J. R. Leonard, A. T. Hammack, M. M. Fogler, L. V. Butov, A. V. Kavokin, K. L. Campman, and A. C. Gossard, Nature \textbf{483}, 584 (2012).
\bibitem{balli} R. Balli, V. Hartwell, D. Snoke, L. Pfeiffer, and K. West, Science \textbf{316}, 1007 (2007).
\bibitem{roumpos} G. Roumpos, M. Lohse, W. H. Nitsche, J. Keeling, M. H. Szymanska, P. B. Littlewood, A. Löffler, S. Höfling, L. Worschech, A. Forchel, and Y. Yamamoto, Proc. Natl. Acad. Sci. USA \textbf{109}, 6467 (2012).
\bibitem{manni} F. Manni, K. G. Lagoudakis, R. Andre, M. Wouters, and B. Deveaud, Phys. Rev. Lett. \textbf{109}, 150409 (2012).
\bibitem{rahimi} A. Rahimi-Iman, A. V. Chernenko, J. Fischer, S. Brodbeck, M. Amthor, C. Schneider, A. Forchel, S. Höfling, S. Reitzenstein, and M. Kamp, Phys. Rev. B \textbf{86}, 155308 (2012).
\bibitem{spano} R. Spano, J. Cuadra, G. Tosi, C. Anton, C. A. Lingg, D. Sanvitto, M. D. Martin, L. Vina, P. R. Eastham, M. van der Poel, and J. M. Hvam, New J. Phys. \textbf{14}, 075018 (2012).
\end{thebibliography}
C. Antón, T. C. H. Liew, G. Tosi, M. D. Martín, T. Gao, Z. Hatzopoulos, P. S. Eldridge, P. G. Savvidis, and L. Viña, Phys. Rev. B 88, 035313 (2013).