Quantum hydrodynamics of a single particle

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Abstract
Semiconductor devices are strong competitors in the race for the development of quantum computational systems. In this work, we interface two semiconductor building blocks of different dimensionality and with complementary properties: (1) a quantum dot hosting a single exciton and acting as a nearly ideal single-photon emitter and (2) a quantum well in a 2D microcavity sustaining polaritons, which are known for their strong interactions and unique hydrodynamics properties including ultrafast real-time monitoring of their propagation and phase-mapping. In the present experiment we can thus observe how the injected single particles propagate and evolve inside the microcavity, giving rise to hydrodynamics features typical of macroscopic systems despite their intrinsic genuine quantum nature. In the presence of a structural defect, we observe the celebrated quantum interference of a single particle that produces fringes reminiscent of a wave propagation. While this behaviour could be theoretically expected, our imaging of such an interference pattern, together with a measurement of antibunching, constitutes the first demonstration of spatial mapping of the self-interference of a single quantum particle hitting an obstacle.

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Introduction
The generation, manipulation and detection of on-chip single photons is key to the development of photonic-based quantum information technologies1. Integrated optics (IO) devices working in the single-particle regime will enable the deployment of quantum information processing for both fundamental research and technological applications. IO chips should provide qubits generation, processing and readout. For instance, qubits generation can be implemented by semiconductor quantum dots (QDs)2,3 or parametric sources4,5. Superconducting single-photon detectors6 seem to be among the most promising candidates to date for integrated qubit detection7,8. Most of the optical circuits used for quantum information so far rely on linear properties of single photons propagation9 or on optical non-linearities of \(\chi^2\) or \(\chi^3\) materials10–12. By combining these elements, several functionalities such as quantum logic gates13,14, boson sampling15, quantum interference or quantum metrology16 have been demonstrated. However, present schemes for single qubits manipulation face real challenges, relying on complex cascades of linear optical elements or on weak nonlinear susceptibilities requiring long interaction paths. These features could result in severe limitations in the scalability and miniaturization of future devices.

Microcavity polaritons, the hybrid light-matter quasiparticles emerging from the strong coupling between a cavity mode and an excitonic transition, could represent a promising alternative to achieve quantum information processing in integrated optical circuits17. Their intrinsically...
interacting nature, inherited from their excitonic component, together with their long coherence time, inherited from their light component, make them strong candidates to perform nonlinear logic operations without losing information\textsuperscript{18, 19}. While collective mesoscopic phenomena involving microcavity polaritons—such as polariton lasing, superfluidity or optical parametric oscillation—have been extensively studied\textsuperscript{20}, there has been little exploration of their quantum, few-particle limit, i.e., involving non-Gaussian polariton states. The experimental demonstrations of polaritonic quantum behaviour have been mainly limited to Gaussian mixtures at best\textsuperscript{21–23}, with only recent progress towards the generation of non-Gaussian states, following the demonstration of polariton blockade\textsuperscript{24–26}. Taking the entirely different approach of exciting polaritons with quantum light\textsuperscript{27}, it was demonstrated experimentally that the creation and recombination of polaritons in a semiconductor microcavity can be done without damaging the quantum coherence of nonclassical states, which is a necessary condition for any quantum information processing\textsuperscript{28}.

In this work, we demonstrate how one can use single photons emitted by an external semiconductor QD to generate, inject and propagate individual microcavity polaritons—a fundamental milestone for the development of future polariton quantum devices. Moreover, with this experiment we show to be able to map the propagation of single polaritons in the two dimensional space during the propagation time, an thus bring down to its ultimate single-particle limit, the prominent and remarkable propagation of a polariton fluid. This is the first step towards several single-particle configurations in a solid-state, integrable, setup manipulating highly interacting single-polariton qubits. In our case, still with a single polariton, by imaging its propagation across an obstacle acting as a scattering center, we are able to observe the wavelike interferences that are produced by what is otherwise one polariton alone.

This observation represents an alternative version of the double-slit experiment, directly demonstrating the wave-particle duality for individual microcavity polaritons\textsuperscript{29, 30}. While wave-particle duality is somehow expected for quantum single particles, our experiment represents the first 2D mapping of such a behaviour. In our case, instead of a double slit or a single particle splitting, we observe the interference effect on a multiple path-scattering propagation of a single particle flying against an obstacle smaller than the wavepacket size, providing a direct imaging of the wave-particle duality of these light-matter excitations\textsuperscript{31}.

**Results**

A scheme of the experimental setup is shown in Fig. 1 (a). It is composed of three main parts: i) the generation of single photons, ii) the injection and propagation of single polaritons and iii) detection. The imaging and spectroscopy experiments were performed in both reflection and transmission configurations. The latter required a processing of the substrate to enable the transmission, and an optimization of the signal intensity by increasing the single-photon emission rate. A more detailed representation of the experimental setup can be found in the Supplementary Material. Despite its conceptual simplicity, our hybrid approach that couples a single photon source, providing the qubits, to polaritons in a high quality factor microcavity, propagating as single particles, presents considerable technical difficulties. first of all, the use of a tunable source of heralded single photons, i.e. Spontaneous Parametric Down Conversion (SPDC) in non-linear crys-

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**Fig. 1**  
(a) Schematic picture of the experiment: a pulsed laser pumps a QD to generate single photons that are injected inside a semiconductor microcavity. The image of the single polariton propagation is acquired in an EMCCD.  
(b) Second order correlation function of a QD emission when multiplexing the pump pulse-rate to 320 MHz. The antibunching value of $g^{(2)}(0) = 0.16 \pm 0.05$ is an unequivocal signature of single photon emission from these QDs.
tals, must be ruled out. This kind of source would imply a heralded measurement in order to be sure to measure the propagation of single photons, resulting in a very cumbersome implementation with common imaging systems. Additionally, the broad emission spectra of SPDC sources would be poorly coupled to the microcavity, whose high quality factor is necessary to confine the quantum state long enough to sustain polariton propagation. We decided then to use single QDs as a deterministic single photon source with an emission linewidth compatible with the narrow polariton resonance. However, most common QD systems (InGaAs QDs grown with the Stranski-Krastanov method) have a typical emission range incompatible with GaAs/AlGaAs microcavities. This makes necessary the use of GaAs QDs produced by Al droplet etching, that recently has shown to be capable of producing near ideal photon sources comparable with best commercial single photon emitters, showing values \( g^{(2)} (\tau = 0) \) below \( 10^{-4} \). The choice of QDs as single photon sources entails an additional obstacle to overcome: the necessity of keeping both systems, QD and microcavity, at cryogenic temperatures. Here we demonstrate that these issues can be overcome obtaining an alternative platform for the study of polariton systems in the single or few particle regime involving several qubits.

In the following experiments, single photons are generated from GaAs QDs fabricated by Al droplet etching and embedded in a low-Q cavity consisting of a \( \lambda/2 \) layer of Al\(_{0.4}\)Ga\(_{0.6}\)As with QDs sandwiched between two Bragg mirrors made of 9 and 2 pairs of Al\(_{0.95}\)Ga\(_{0.05}\)As (67 nm thick) and Al\(_{0.3}\)Ga\(_{0.7}\)As (55 nm thick)\(^{33,34} \). The QDs are pumped with a pulsed laser either at \( \lambda = 415 \) nm with a pulse duration of \( \sim 30 \) fs or at 760 nm with a pulse duration of \( \sim 5 \) ps. Thanks to a pair of cascaded Michelson and Morley interferometers, we can increase the laser repetition rate by a factor of four, from 80 MHz up to 320 MHz, in order to increase the number of photons per second (for more details on the photon-rate quadruplication, see the Supplementary Material). The QD size was optimized to obtain emission wavelengths around 775 nm. The generated photons are coupled to a single mode fiber and then used to pump the polaritonic device, a \( \lambda/2 \) microcavity, which is made of two Bragg mirrors of 40 and 32 pairs of Al\(_{0.96}\)Ga\(_{0.04}\)As (67 nm thick) and Al\(_{0.2}\)Ga\(_{0.8}\)As (55 nm thick) with a quantum well 7.2 nm wide embedded in the center. Both systems, QDs and the microcavity sample, are cooled down to cryogenic temperatures of 3.8K and 8.5 K, respectively. A comparison between the spectra of the microcavity and the quantum dot is shown in Fig. 2 (a, b), respectively, despite the mentioned technical difficult, we succeeded to grow QDs with a transition energy precisely in the energy range covered by the Lower Polariton Branch (LPB) of the microcavity-quantum well system\(^{35} \). By carefully tuning the single-photons injection angle, the QD emission can be resonantly coupled to the LPB. The quantum nature of the light is tested by measuring the second-order correlation function \( g^{(2)} (\tau = 0) \) with a Hanbury Brown and Twiss setup (HBT, Fig. 1 (b)), finding a value of \( g^{(2)} (0) = 0.16 \pm 0.05 \). The small residual difference from zero is attributed to the non-resonant excitation as well as the slow carrier relaxation in the QDs\(^{36} \). The real space images have been detected by an Enhanced Charged Coupled Device (EMCCD) camera coupled to a monochromator to allow energy resolved measurements.

Fig. 2 (c) shows the real-space image of the microcavity surface under single-photon excitation. The image shows two main features: a bright saturated circular spot and a weaker elongated spot. We assign the former to the reflected uncoupled single photons and the latter to the resonantly excited single polaritons that propagate inside the microcavity due to their externally imparted in-plane momentum. To prove this, we acquire an energy-resolved image (see Fig. 2 (d)). This image shows that, from all the peaks in the QD emission, the neutral exciton peak resonant with the LPB is the only one able to couple and propagate inside the sample, as evidenced by the faint but continuous vertical trace at the corresponding wavelength. The high Q factor of the cavity results in high energy selectivity and long propagation distances, close to 400 \( \mu \)m. To further prove that the propagation corresponds to a resonant polariton injection, the sample is moved to a point in which the LPB is not resonant with the QD emission, as shown in Fig. 2 (f). In this case, no single-polariton propagation is observed. By fitting the intensity profile of the propagating polaritons with an exponential decay and considering that single polaritons are injected with an in-plane momentum of \( 1:1 \) \( \mu \)m\(^{-1} \) (see Supplementary Material), we obtain a polariton lifetime \( \tau \sim 25 \) ps, which is in agreement with the lifetime that can be deduced from the polariton linewidth.

The reflection configuration is compelling for a proof-of-principle demonstration and as a first attempt to evidence the phenomenon, also allowing us to prove that only the single-photon excitonic peak couples to the microcavity and triggers a propagation inside while others get fully reflected. However, in reflection it is impossible to image the region around the point of injection. In order to get a more comprehensive picture of the single-polariton propagation, we modify our setup to perform experiments in a transmission configuration. To do that, the polariton sample was processed by wet etching to remove the ab-
sorbing bulk GaAs substrate in selected regions, and uncovering the microcavity. A comparison of a QD’s emission spectrum and a microcavity LPB dispersion corresponding to an etched region is shown in Fig. 3 (a) and Fig. 3 (b). The microcavity dispersion (panel a) is measured in transmission. Again, a QD with an excitonic peak (in this case a positively charged exciton) near the LPB is chosen to resonantly excite single polaritons. Moreover, to increase the amount of signal, the pulse repetition rate of the laser exciting the QD was quadruplicated, up to a final rate of 320 MHz. After this optimization, the microcavity sample is pumped with around 140 k single photons per second. To decrease the total recombination time of the exciton, in order to avoid temporal overlap of the generated photons, the pump wavelength was changed from 405 nm to 760 nm. Indeed, the QD decay time involves several processes, but in general, higher pump energies need more non-radiative processes, entailing longer decay times. Although different QDs were used to pump the cavity in reflection and transmission configurations, in all cases a $g^{(2)}$ measurement such as the one of Fig. 1 (b) was obtained.

Two cases were considered for the single-polariton propagation in transmission configuration: a “free propagation” along the microcavity (shown in Fig. 3 (c)), and propagation in the presence of an obstacle (shown in Fig. 3 (d)), given by a structural defect in the microcavity. Single-polariton propagation in Fig. 3 (c) and Fig. 3 (d) spreads slightly more than in Fig. 2 (c-e). This is obtained by modifying the excitation beam divergence, making it easier to image defects in the cavity. The polariton group velocity, estimated through the dispersion relation, is $v_g \approx 0.3 \mu m/ps^{-1}$. For a more complete description of the deduction of the group velocity, we refer to the Supplementary Material.

The second case, shown in Fig. 3 (d), is even more interesting. It shows the same single-polariton propagation but now across an obstacle formed by a structural defect highlighted by a red dot. The defect scatters the incoming single polaritons and substantially modifies the propagation pattern. Clearly, some interferences are formed as seen in Fig. 3 (d). While this would be the expected pattern for a conventional polariton fluid passing an obstacle, here it must be borne in mind that in the conditions of our experiment, these fringes arise from integrating photons emitted by polaritons that each travelled alone in the microcavity, given that they have been injected there by a strongly anti-
bunched single-photon source with a repetition rate to polariton lifetime ratio such that each polariton is separated from the previous and next one by more than 285 thousands times its lifetime. It is therefore surprising, from a classical perspective, that one polariton would simultaneously propagate through several distinct trajectories, as is required to produce destructive interferences. This is a variation of the famous double-slit experiment, in which the wavelike aspect is more fully manifest thanks to the interference pattern that we observe the possibility of mapping the polariton field everywhere in the real plane. Unlike the plethora of similar experiments performed with a screen at the end of the propagation\(^{39,44}\), in our case photons are emitted from polaritons by spontaneous emission, and since this follows an exponential law, they have the same probability to be emitted at any time of their propagation. In other words, polaritons can provide a full mapping of their spatial dynamics. In our case, the interference pattern is simply explained by the interference between a plane wave, representing the incoming single-polariton Fig. 4 (a), and a spherical wave, representing the scattered polariton Fig. 4 (b). The sum of these two fields amplitudes provide the interference pattern that we observe with an excellent quantitative agreement, as shown in Fig. 4 (c) as red lines on top of the experimental background.

**Discussion**

The apparent paradox of the double-slit experiment is nowadays familiar in quantum theory. Feynman called it “the only mystery” of quantum mechanics\(^{40}\). Still, its implications and deep underlying meaning do not cease to captivate one’s imagination. The polariton platform could contribute to this foundational and fundamental question. The wonders of quantum mechanics in our spatially mapped version of the double-slit experiment are even more salient from the fact that the fringes are visible ahead of the obstacle, meaning that even though the single polariton is not yet supposed to know that an obstacle lays ahead, its plane-wave forward motion amplitude of probability is already interfering with its scattered-backward spherical motion, thus suppressing the spontaneous emission from a polariton at any point of destructive interference even ahead of the obstacle.

Even if wave-particle duality for single particles is somehow expected in quantum mechanics, the access to the full spatial profile of the field opens new perspectives for deeper investigations of this key phenomena that, more than any other, questions the nature of physical reality. It makes it for instance an interesting testbed for Wheeler’s delayed-choice experiment and variations of it\(^{41}\), that question whether an observation can be conditioned on the past history of the particle. We have touched upon already how, in an interesting twist, the future of the particle is brought into question in our configuration. One could stretch the “particle” character of the polariton by imposing tighter constrains on its wavepacket size and localization and/or passing it through better designed potentials. This platform
should also be able to explore the violation of causal time-ordering\( \text{\cite{18}} \) in a quantum polariton switch. Also exciting is the possibility to involve multiple polaritons, and study nonlocal effects. In all cases, with the possibility of a reconstruction of the full polariton-field wavefunction, we expect that our first demonstration of a propagating single-polariton will give access to a wide range of fundamental quantum experiments in integrated optics. In conclusion, we have demonstrated the conversion of single photons from a semiconductor QD into propagating 2D microcavity polaritons, by resonant injection in a semiconductor planar microcavity, and we have observed their propagation in a still minimally controlled environment, i.e., in presence or absence of an obstacle on its way. The observation of a single polariton propagation makes one step further towards the design and implementation of several single-polaritons devices. At a fundamental level, we report the first observation of a polariton fluid that consists of a single particle and have confirmed its wave-particle duality by observing fringes that result from wave interference from states that each consists of a single polariton. In contrast to the numerous earlier reports on one of the most important and far-reaching experiments of Physics—the double-slit experiment—we have been able to provide the interference pattern in the full region of space where the phenomenon occurs. Further investigations of this phenomenon could allow to better understand the fundamental aspects and ontological meaning of quantum theory at large. From an application point of view, the fact that both the QD and polaritons are based on the same material combination opens the route to fully integrated solutions, where polaritons may mediate the interaction of photonic qubits emitted by QDs.

Methods

Microcavity Sample: We use a \( \lambda/2 \) cavity embedded between two DBRs formed by respectively 40 and 32 pairs of \( \text{Al}_{0.96}\text{Ga}_{0.04}\text{As} \) (67 nm thick) and \( \text{Al}_{0.2}\text{Ga}_{0.8}\text{As} \) (55 nm thick). A 7.2 nm wide GaAs quantum well is placed in the center of the cavity, at the maximum of the electric field. The sample substrate has been partially removed by wet etching process has been carefully calibrated to selectively attack the substrate and the number of pairs of the bottom DBR is not modified.

QDs Sample: GaAs QDs are fabricated by Al droplet etching and embedded in a low-Q cavity formed by a \( \lambda/2 \) layer embedding the Qds sandwiched between two DBRs formed by respectively 9 and 2 pairs of \( \text{Al}_{0.95}\text{Ga}_{0.05}\text{As} / \text{Al}_{0.2}\text{Ga}_{0.8}\text{As} \) with thickness of 67 nm and 55 nm.

Experimental realization: Both samples are kept at cryogenic temperatures; 3.8 K for the QDs and 8.5 K for the microcavity. In the reflection configuration, the QDs sample was pumped with a fs pulsed laser at 405 nm with a repetition rate of 80 MHz. In the transmission configuration, the excitation is done with a 780 nm ps pulsed laser, which has been multiplexed by using a cascade of Michelson and Morley interferometers to obtain a final repetition rate of 320 MHz. The emission from the QD is collected in a single-mode fiber optics and used to pump the microcavity sample in a configuration that allows a fine control of the in-plane linear momentum. For the detection, an image of the propagation plane is reconstructed in an Enhanced Charge Coupled Device (EMCCD).

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Conflict of interest

The authors declare that they have no conflict of interest.

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