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The future of quantum in polariton systems: opinion

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Abstract: A significant amount of control of exciton-polaritons has been achieved over the past decades, including their creation, localization in desired modes, coupling between modes, manipulation by control fields, and detection. As quantum particles maintain coherence (correlations) for some time and interact (causing the evolution of those correlations), exciton-polaritons underlie an emerging field of quantum polaritonics.

Quantum computers derive their power from their ability to support quantum superposition states or non-classical correlations such as entanglement. A variety of systems are proposed for their implementation, including cavity quantum electrodynamic systems, semiconductor quantum dots, or cold atoms. Exciton-polaritons share many similarities with these systems: they are constructed from cavities, are partly composed of excitons, and form analogues of Bose-Einstein condensates. Consequently, it is natural to speculate on their quantum applications. It is important to appreciate what we mean by "quantum". In the literature, particularly relating to exciton-polaritons, it is common to speak of quantum vortices, quantum fluids, or quantum something. While vortices may exhibit a quantized winding number, they exist also in classical optical wave fields. What are described as quantum fluids are more often than not well described by a mean-field wavefunction [1], which is defined by an amplitude and a phase. In the many cases where such a parametrization is accurate, it means we are not accessing the full Hilbert space of the system, which requires us to move away from the coherent states or polariton condensates that are typically studied. An often used argument is that something is ultimately composed of quantum particles and so is quantum. However, my computer is ultimately composed of quantum particles, yet it can not run Shor's or Grover's algorithm.

Quantum signatures of exciton-polaritons. Early theoretical works expected that the nonlinear interactions between polaritons would lead to entanglement [2–6]. In principle, if two polaritons scattered with each other, they would be entangled, however, in practice one never works with exactly two polaritons. When working with a distribution of particle numbers the quantum correlations that develop between interacting modes, e.g., those characterized by different wavevectors in planar microcavities, are better referred to as squeezing (referring to a squashing of the distribution in phase space when represented by the Wigner function). Only a limited squeezing [7,8] or quantum complementarity has been detected from interactions [9,10]. It was confirmed that if polaritons are excited by entangled photons generated outside the system, then they preserve this entanglement [11], so there is no doubt that they are quantum particles. The behaviour of single polaritons has also been well-characterized [12]. However, it has been challenging to generate strongly entangled states from the polariton-polariton interactions. This is likely due to the presence of other scattering processes, with disorder or acoustic phonons, that pollute the signals with uncorrelated polaritons.

Another illustration of the current limitations of the polariton system lies in the physics of single isolated modes. It is well-known that when polaritons are injected with a resonant laser and their intensity increases they will blueshift, due to interactions, out of resonance. This causes

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a sublinear increase in their intensity with laser power, known as the optical limiter effect. When studying this effect within a quantum optical theory, it was predicted that, if the interaction strength between two polaritons was strong enough to cause a blueshift beyond the linewidth, a polariton blockade effect would occur where a single polariton state was favoured [13] (analogous to photon blockade [14]). Unfortunately though, exciton-polaritons tend to be only weakly interacting (compared to their dissipation rate). State-of-the-art experiments detected the onset of the blockade [15,16], however, the deviation from a regular coherent state is small and insufficient for single particle applications [17]. This does not mean that polaritons are bad. Indeed, it was pointed out long ago that they typically require powers four orders of magnitude lower than other photonic systems to show nonlinear transitions [18] and classical polariton switches can operate with sub femto-Joule switching energy [19] down to the level where switching is caused by a single particle [20] (on average). The cross-Kerr modulation has been measured around 3mrad per polariton [21], which is better than other photonic systems (although not at the level attained with quantum dots or atomic emitters). Ideally though, polaritons could reach deeper into the quantum regime.

Reaching polariton quantum blockade. Mechanisms for improving the polariton blockade fall into two categories: either the polariton lifetime should be improved or the interaction strength should be improved. The traditional approach to improve the lifetime has been to use more layers in the dielectric mirrors to attain higher reflectivity [22]. Another recently popular approach has been to replace a mirror with a grating and search for a bound-state-in-continuum mode [23–26]. To improve the interaction strength between polaritons, one can seek to increase the size and consequently overlap of the underlying excitons. This is done with higher orbital Rydberg exciton states [27], which have been coupled to light to form polaritons [28,29]. Already composing polaritons of 2s excitons instead of 1s excitons results in a an enhancement of the polariton-polariton interaction strength by 4.6 times [30]. Higher order Rydberg exciton-polaritons are also under development [31], expected to realize quantum logic gates [32]. Another way to increase the size of excitons as well as their lifetime is to separate the electrons and holes in different semiconductor layers. Initially, these were known as indirect excitons, where the focus was on the long lifetime that allowed the observation of spontaneous coherence [33]. It was further found that such excitons could be coupled to regular direct exciton-polaritons when placed in a cavity [34], resulting in so-called dipolaritons [35] with a degree of tuning (and control [36]) affecting the enhancement of the interaction strength [37–39]. Following advances in materials science, it was realized that indirect excitons could be formed from the layers of 2D materials [40], leading to ten-fold enhancement of the interaction strength [41]. Theory has predicted further enhancement mediated by light [42]. Other notable methods of increasing the strength of polariton-polariton interactions include confining polaritons so that they are more likely to interact [13,43]. Enhanced squeezing was observed in micropillar cavities [8], compared to planar microcavities [7], however, it seems that confinement into sub-micron areas is needed for a significant polariton blockade. One interesting option is to use the confinement of excitons in the Moiré superlattice formed in twisted bilayers of different 2D materials. Moiré exciton blockade [44] and the strong coupling to light forming polaritons [45] have been achieved. Finally, several works have reported enhanced interactions when replacing neutral excitons with charged complexes [46–48] or coupling exciton-polaritons to electrons [49–51]. With so many ideas currently being investigated, the polariton quantum blockade seems fully achievable.

Avoiding the conventional blockade. Polaritons are typically driven by external lasers, so when considering a single polariton mode driven by a laser the polariton quantum blockade is the necessary target for achieving anything other than a classical-like coherent state. However, polariton physics does not need to be restricted to a single mode. A system may support different spatial modes as well as different spins or polarizations [52], and the different modes may be coupled together. This allows an effective blockade, even in the weakly nonlinear regime [53] due to the high sensitivity of quantum interferences to slight phase variations caused by nonlinearity [54]. This unconventional blockade [55,56] has not been experimentally demonstrated in the exciton-polariton system, however, it has been seen in other cavity/resonator systems [57,58]. A limitation of the unconventional blockade is that the antibunching only occurs in a narrow time window, due to the presence of an oscillation associated to the inter-mode coupling that should be fast compared to the system decay rate. However, a variety of alternate methods of getting an effective blockade even in the weakly nonlinear system have also been proposed. One simple theoretical method is based on an inverse parametric scattering process [59]. In traditional polariton parametric scattering [60,61] a pumped state is driven and one looks for the scattering of polaritons to so-called signal and idler states. In the proposed inverse process, the pumped state should be weakly driven with a laser and the signal state strongly driven. Whenever there are two particles in the pumped state they immediately scatter out, being stimulated by the strong signal state occupation. This allows an effective enhancement of the interaction strength proportional to the square root of the number of polaritons in the signal state [59]. A variety of other proposals also make use of interferences at multiple frequencies [62,65,66] or time modulated systems [63,64] for enhanced blockade.

Other non-classical polariton states. As quantum information protocols often require non-classical states as an initial resource, it is instructive to consider what states can be created from the polariton system aside antibunched ones. Here we should be careful with our definition of what is non-classical. The opposite of antibunched states, namely superbunched states were predicted in polariton cascades considering the statistics of the quantized particle number [67] and realized experimentally [68]. However, the superbunching behaviour can be described with a classical (positive) probability density function of different coherent states and so is not an example of a non-classical polariton state. Non-classical states should be characterized by non-classical probability density functions, such as negative Wigner functions, or non-classical correlations such as entanglement between different parts of the state. Theoretical proposals have been put forward for non-Gaussian states using using two particle pumping or loss to introduce Wigner function negativity [69] or Schrödinger cat states [70]. Other proposals make use of feedback [71]. Entangled states were long expected to arise from parametric scattering processes [2–6], possibly generalized to multimode cases [72], but are also theoretically predicted via a generalization of the unconventional blockade [73,74] or optimization of inverse parametric scattering schemes [75,76]

Quantum Polariton Computing. When designing a classical computer, one must first decide whether to operate with digital or analogue variables. The same choice must be made when designing a quantum computer, that is, we must choose between encoding information in discrete variables such as the spin or particle number, or continuous variables such as amplitude and phase. In quantum computing, in analogy to classical computing, schemes with discrete qubits are more prominent where the handling of errors is better developed. However, quantum computing can also be developed with continuous variables [77]. In the presence of polariton blockade, one could consider working in the basis of 0 or 1 polaritons in a given mode to define a qubit. Or, if we are sure there is a single polariton in the mode, perhaps its spin would suffice. However, in the absence of strong polariton blockade, it has been pointed out that we must appreciate that we do not have a fixed well-defined number of particles [78] and it is more appropriate to operate with their collective continuous variables. A complete scheme of universal quantum logic gates has been proposed based on qubits encoded in the fluctuations in the particle number on top of polariton condensates [79]. To limit the number of added polaritons, a strong nonlinearity is needed to induce an anharmonic spectrum in the particle number (Fock) space. While the requirements are then similar to those of polariton blockade, the fidelity of quantum logic gates was predicted to be higher for this form of encoding. A continuous variable quantum controlled-NOT gate has also been proposed based on exciton-polaritons [80], using inverse parametric scattering. As in the case of its use for blockade [59], the inverse parametric scattering scattering scheme avoids the need for strong nonlinearity. A limitation of the aforementioned schemes is that in a quantum circuit composed of multiple quantum logic gates, the entire operation needs to be completed before polaritons have the chance to escape the system. Although the polariton lifetime has increased from a few picoseconds in the earliest experiments to hundreds of picoseconds [22] in the state-of-the-art, this is still a significant limitation. The situation is rather different to the classical regime, where the intensity of a polariton signal can always be amplified by applying gain to the system [81]. In the quantum case, when a polariton is lost from the system it takes with it all the correlations with the remaining particles, and this information can not be replaced by adding a new polariton with the wrong correlations. In fact, it was explicitly shown that trying to compensate losses with a gain actually makes the situation worse for quantum logic gates [80]. Aside the polariton lifetime, it is important to consider the effect of the coherence time of the system, although this is usually much longer [82]. Alternative proposals for quantum logic gates have also been based on long-range dipolar exchange interactions [32]. Aside aiming to use polaritons for a quantum circuit model of quantum computing, we may consider alternative architectures. For example, the so-called one-way quantum computer replaces the need of quantum logic gates with the generation of a multipartite entangled state [83]. This architecture has been considered for continuous variables [84]. By considering a graph of polariton nodes and applying inverse parametric scattering to each node, a theoretical scheme of the required multimode entangled states was proposed [85, 88, 89], requiring only weak interactions. A conservative requirement for fault-tolerant continuous variable cluster state computation is a squeezing of 20.5dB [86]. This level seems achievable [87].

Quantum Neural Networks. Artificial neural networks are an alternative information processing architecture composed of a collection of nodes that receive input from their neighbours, develop a nonlinear response, and pass it to other neighbours. Different neural network architectures have been considered for polariton systems [90–93]. A particularly manageable proposal has followed a so-called reservoir computing geometry, where the collection of nodes is allowed to be mostly random and the entire network function is determined by the tuning of a single layer of weights applied to the output [94]. The proposal was realized successfully in experiments [95,96] and promises excellent energy efficiency [97] and an ability to correct classical noise [98]. Entering the quantum regime, quantum reservoir processors [99,100] have been proposed. While the classical counterparts excelled in recognizing classical patterns, the objective of the quantum reservoir processor is to recognize quantum patterns such as whether an incident state of light shows entanglement or not. Full quantum state tomography [101] of an incident state of light is also expected, with only local intensity measurements. Furthermore, the system can lead to a quantum advantage for solving classical computing tasks [102] or operated in reverse to act as a source of various quantum resource states [103,104]. More generally, exciton-polaritons can be seen as candidates for photonic Kernel machines [105].

Conclusion. We have discussed various quantum applications of exciton-polaritons. This has skipped a discussion of the many efforts of theorists toward modelling such systems (e.g., density matrix approaches [106–108], phase space approaches [109–111], renormalization techniques [112,113], and machine learning methods [114–117]) and many fundamental quantum effects (e.g., phase transitions [118–121], quantum quenches [122], power laws [123], the theory of exciting polaritons with quantum light [124], and quantum multistability [125]). This is far from a complete review of the field. Areas of applications such as quantum simulators [126] have yet to be specifically explored with polaritons, although the classical foundation of polaritons is well-developed and concepts in the wider area of quantum optics are appearing [127]. Even though quantum polaritonics represents a small fraction of the research in exciton-polaritons, which overwhelmingly focuses on classical effects, there are enough papers to define an emerging field. Other quantum systems are under more intense development, but this should only offer inspiration. The key milestones, such as quantum blockade, and niche applications have been identified for the near-term. It is too soon to put a limit on the long-term.

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