Emergent entanglement of microcavity polariton pairs

S. Portolan1,2, O. Di Stefano3, S. Savasta3, and V. Savona1

1Institute of Theoretical Physics, Ecole Polytechnique Fédérale de Lausanne EPFL, CH-1015 Lausanne, Switzerland
2CEA/CNRS/UJF Joint Team " Nanophysics and Semiconductors", Institut Néel, CNRS, BP 166, 25 rue des Martyrs, 38042 Grenoble Cedex 9, France
3Dipartimento di Fisica della Materia e Ingegneria Elettronica, Università di Messina Salita Sperone 31, I-98166 Messina, Italy

E-mail: stefano.portolan@grenoble.cnrs.fr

Abstract. We show theoretically that polariton pairs with a high degree of polarization entanglement can be produced through parametric scattering. In our proposed scheme, varying the polarizations of the two pumps, we have a complete control over the symmetries of the produced state (i.e. singlet or triplet output). Our microscopic model shows how a tomographic reconstruction, based on two-time correlation functions, can provide a quantitative assessment of the level of entanglement produced under realistic experimental conditions. Our study provides a suggestive perspective towards hybrid all-optical quantum devices where quantum information can be efficiently generated and controlled within the same structure. This result puts forward the robustness of pair correlations in solid-state devices, even when noise dominates one-body correlations.

The concept of entanglement has played a crucial role in the development of quantum physics. It can be described as the correlation between distinct subsystems which cannot be reproduced by any classical theory (i.e. quantum correlation). Scalable solid-state devices will make use of local electronic states to store quantum correlations [1]. Polaritons [2] on the other hand, as hybrid states of electronic excitations and light, are the most promising solution for generation and control of quantum correlations over longer range [3]. In particular, thanks to the Coulomb interaction acting on the electronic part of the polariton state, resonantly generated pump polaritons scatter into pairs of signal and idler polaritons, in a way that fulfills total energy and momentum conservation. The generated polariton pairs are ideally in an entangled state [4, 5]. The peculiar energy-momentum dispersion of microcavity polaritons has the advantage of allowing several configurations of parametric scattering, that can be easily selected by setting the frequency and angle of both the pump and the detected beams [6, 7]. Pumping with a specific circular polarization, no entanglement in polarization can be expected for only the co-circular parametric channel can be activated. On the other hand, when pumped linearly, the superposition of both circular polarizations can activate co-circular and counter-circular scattering which would create a superposition of singlet and triplet states which has an entanglement degree, in general, less than that of its single constituents. As a consequence, a complete control over the scattering channels, blocking and/or enhancing a channel with respect to the other, is of paramount importance for practical applications.
Here we show theoretically that polariton pairs with a high degree of polarization entanglement can be produced through parametric scattering [8]. We demonstrate that it can emerge in coincidence experiments, even at low excitation densities where the dynamics is dominated by incoherent photoluminescence. In our proposed scheme, varying the polarizations of the two pumps, we have a complete control over the symmetries of the produced state (i.e. singlet or triplet output). Our microscopic model [9] shows how a tomographic reconstruction [10], based on two-times correlation functions, can provide a quantitative assessment of the level of entanglement produced under realistic experimental conditions. In particular, we propose an operational method to measure the Entanglement of Formation (EOF) [11], out of a dominant time-dependent noise background, without any need for post-processing [12].

Third order nonlinear optical processes in quantum well excitons (with spin \(\sigma = \pm 1\)) can be described in terms of two distinct scattering channels: one involving only excitons (polaritons) with the same circular polarization (co-circular channel); and the other (counter-circular channel) due to the presence of both bound biexciton states and four-particle scattering states of zero angular momentum (\(J = 0\)) [13]. Moreover linearly polarized singlet pump excitation (i.e. \(\hat{c}_p = \cos \theta |x\rangle + \sin \theta |y\rangle = 2^{-1/2}(e^{i\theta}|-\rangle + e^{-i\theta}|+\rangle)\) cannot avoid the additional presence of the co-circular scattering channel which can lower polarization entanglement simply because, the matrix element of the \((J = 0)\) counter-circular scattering channel is smaller (about 1/3) than that for the co-polarized scattering channel, but certainly not negligible [14]. However, in the pump polarization scheme that we propose it is easy to see that the counter-circular channel cancels out, as already pointed out. This feature is unique to the present scheme, while all previously adopted pump configurations suffer from the presence of both singlet and triplet channels.

![Diagram](image)

**Figure 1.** (color online) (a) sketch of the proposed excitation geometry and of the lower polariton branch. The Gaussian pumps are linearly cross polarized (then the angle \(\theta\) will refer to the polarization of one of the two beams) with zero time delay. The specific polarization configuration with \(\theta = 0\), where \(\theta\) is the angle between \(\hat{c}_{p1}\) and the \(x\)-axis on the \(x-y\) plane, is depicted. (b) The simulated spectrally integrated polariton population in \(k\)-space. The parametric process builds up a circle passing through the two pumps (\(p_1\) and \(p_2\)), signal and idler polariton states are represented by any two points on the circle connected by a line passing through its center. For illustration the pair of signal-idler polariton modes chosen for entanglement detection are depicted as yellow crosses. The disc-shape contribution centered at the origin is the incoherent population background produced by phonon scattering.
The experimental set-up that we propose is a two-pump (linearly cross polarized) scheme under pulsed excitation, involving the lower polariton branch only (see Fig. (1) for details). The pumps ($p_1$ and $p_2$) are chosen with incidence angles below the magic angle [7] so that single-pump parametric scattering is negligible. For all the numerical simulations we will consider the sample investigated in Ref. [7]. This configuration is such that the counter-circular scattering channel (both bound biexciton and scattering states) is suppressed owing to destructive interference, while co-circular polarized signal-idler beams are generated. In the absence of the noisy environment, polariton pairs would be cast in the pure triplet entangled state $|+,−⟩−\exp(iθ)|−,−⟩$. On the opposite side, two-pump excitation with counter-circularly pump beams (here not adopted) is able to stop this channel giving rise to the entangled state $|+,−⟩−\exp(iθ)|−,−⟩$. The advantages of this configuration are manifold. First, detrimental processes for entanglement as the excitation induced dephasing results to be largely suppressed [14]. Spurious coherent processes, e.g. Resonant Rayleigh Scattering [15], are well separated in $k$-space from the signal and idler modes. In addition signal and idler close to the origin in $k$-space make negligible the longitudinal-transverse splitting of polaritons [16] (relevant at quite high in-plane wave vectors).

Following Ref. [10] the tomographic reconstruction of the two-polariton density matrix is equivalent, in the $σ = \{+,−\}$ polarization basis, to the two-time coincidence

$$\hat{ρ}_{σ}\tilde{σ},σ′\tilde{σ}′ = \frac{1}{N}\int_{t_{d}}^{T_{d}}\int_{t_{d}}^{T_{d}}(\hat{P}_{\tilde{k}_{σ}}^{†}(t_1)\hat{P}_{\tilde{k}_{σ}}^{†}(t_2)\hat{P}_{\tilde{k}_{\tilde{σ}},\tilde{σ}}(t_2)\hat{P}_{\tilde{k}_{\tilde{σ}},\tilde{σ}}(t_1)), \tag{1}$$

where $\hat{P}_{\tilde{k}_{σ}}^{†} (\hat{P}_{\tilde{k}_{\tilde{σ}},\tilde{σ}})$ creates a signal polariton at $\tilde{k}$ (an idler polariton at $\tilde{k}_{i} = \tilde{k}_{1} + \tilde{k}_{2} - \tilde{k}$), $N$ is a normalization constant and $T_{d}$ the detector window. We choose a very wide time window $T_{d} = 120 \text{ps}$, allowing feasible experiments with standard photodetectors. In order to model the density matrix eq. (1), we employ the dynamics controlled truncation scheme (DCTS), starting from the electron-hole Hamiltonian including two-body Coulomb interaction and radiation-matter coupling. In this approach nonlinear parametric processes within a third order optical response are microscopically calculated. The main environment channels, acoustic phonon interaction via deformation potential coupling [9, 17] and mirror losses, are taken into account in the Born-Markov approximation on the standard rate equations and then coupled to the coherent processes consistently within the DCTS-Langevin approach [9].

Among the various measures proposed in the literature we shall use the entanglement of formation $E(\hat{ρ})$ [11] for which an explicit formula as a function of the density matrix exists [20]. As Fig. 2 shows, there is a non-negligible region of the parameter space where, even in a realistic situation, high entanglement values are obtained. For increasing pump, EOF decays towards zero. This is a known consequence of the relative increase of signal and idler populations [18, 12] – dominating the diagonal elements of $\hat{ρ}$ – with respect to two-body correlations responsible of the non-diagonal parts, which our microscopic calculation is able to reproduce. Semiconductors heterostructures are complex systems in which other noise sources are expected. The simplest way to model this additional noise is via the introduction of a constant, temperature- and pump-independent, noise background $N_0$. This quantity also accounts for the noise background characterizing the photodetection system. In the inset of Fig. 2, the dependence of the EOF on $N_0$ is highlighted. In our simulation, the quantity $N_0$ causes EOF to vanish in the limit of low pump intensity. A value of $N_0$ of about $10^{-4}$ is realistic, as suggested by experiments [8, 19]. Different entanglement measures generally result in quantitatively different results for a given mixed state. However, they all provide upper bounds for the distillable entanglement , i.e. the rate at which mixed states can be converted into the “gold standard” singlet state. Small EOF means that a heavily resource-demanding distillation process is needed for any practical purpose. Fig. 2 shows how a relative small change in the lattice temperature has a sizeable impact on entanglement. As an example, for the pump intensity $I = 15I_0$, increasing the temperature
Figure 2. Dependence of the EOF on pumping intensity. The laser intensity $I$ is measured in units of $I_0 = 21$ photons $\mu m^{-2}$/pulse according to Ref. [7].

from $T = 1$ K to $T = 20$ K means to corrupt the state from $E(\hat{\rho}) \approx 0.88$ to $E(\hat{\rho}) \approx 0.24$, whose distillation is nearly four times more demanding. For a fixed pump intensity, Fig. 2 shows that, above a finite temperature threshold, the EOF vanishes independently of the pump intensity, i.e. the influence of the environment is so strong that quantum correlation cannot be kept anymore. In physical terms, at about 30 K the average phonon energy becomes comparable to the signal-pump and idler-pump energy differences, and the thermal production of signal-idler pairs is activated. The figure clearly shows that at low excitation density the detected intensity in the signal/idler channels arises mainly from PL. Nevertheless the obtained EOF for these intensities is very high, contrarily to intuition, but in agreement with recent results [12]. This result puts forward the robustness of pair correlations and entanglement that can be evidenced, even when noise is the dominant contribution to one-body correlations.

In conclusion we have shown that microcavity polaritons can be cast in an entangled state in a controlled way and we have given a ready-to-use realistic experimental configuration able to measure the EOF out of a dominant time-dependent noise background, without any need for post-processing.

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[20] Formally, the EOF is defined as the minimum average pure state entanglement over all possible pure state decompositions of the mixed density matrix. Easy speaking the minimum entanglement needed to construct the density matrix out of some pure states.