

Benchmarking photon-subtracted graph states of multimode light

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Quantum entanglement, one of the key resources for quantum information processing, can be deterministically generated in a scalable manner in continuous variable (CV) systems. However such CV entangled states typically display Gaussian statistics, which limits their use for quantum computing. It is experimentally feasible to overcome this problem by the mode-selective subtraction of photons from multimode Gaussian states, thus rendering them non-Gaussian [1]. Furthermore, photon subtraction is known to enhance the entanglement between a pair of modes.

In multimode setups, however, the theoretical properties of the resulting non-Gaussian states are still surrounded by open questions. In the present contribution we use techniques from quantum statistical mechanics [2] to obtain the multimode *Wigner function* for photon-subtracted states. This directly allows us to uncover a general condition for the negativity of the Wigner function, and to explore the state's entanglement properties.

As a key result, we use correlation functions to derive the general Wigner function of a non-displaced photon-subtracted state:

$$W_{-}(\beta) = \frac{1}{2}[(\beta, V^{-1}A_g V^{-1}\beta) - \text{tr}(V^{-1}A_g) + 2]W_G(\beta),$$

where $W_G(\beta)$ is the Wigner function of the initial Gaussian state from which the photon was subtracted, and V is its covariance matrix. All non-Gaussian features are introduced by the matrix A_g , that depends on the mode g in which the photon is subtracted, and which can be expressed analytically [3]. From the expression for $W_{-}(\beta)$ we directly deduce an elegant condition for the negativity of the Wigner function. Moreover, for pure states, we show that coherent subtraction of a photon can enhance entanglement between modes. We prove [4] that this entanglement can persist in *all* mode bases, contrary to the Gaussian case [5].

These methods also allow us to understand more details about specific classes of states. In particular, we will treat the case of photon subtraction from CV *graph states* (see Fig. 1 for an example). Such graph states can be implemented by generating gaussian entanglement between the optical modes of a multimode squeezed vacuum. These states display Gaussian statistics upon measurement of the field quadratures. Moreover, they form the backbone of measurement-based quantum computation, and can be produced in present-day experiments [6]. Photon subtraction can introduce non-Gaussian features in these states, hence making them appropriate for applications in quantum information processing.

In this contribution, we take a first step in exploring the physical properties of such experimentally achievable photon-subtracted CV graph states. By exploring the spread

of non-Gaussian features through the graph upon subtraction of a photon in one of its vertices, we pave the way for future experimental developments. This finally imposes the question how these results can be applied in the field of quantum computation.

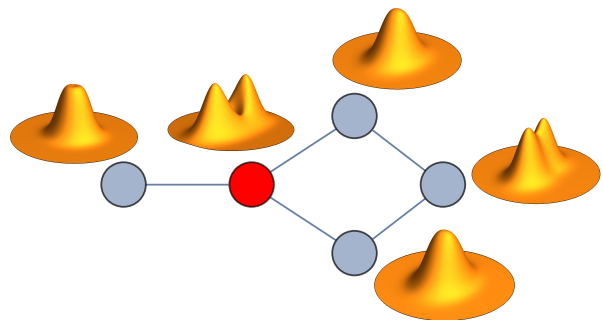


Figure 1: Single-mode Wigner functions for a five-mode graph state with a photon subtracted in the red vertex. In this case, non-Gaussian features spread throughout the whole network. However, we demonstrate that this will generally not be the case, and that vertices at more than two steps from the point of subtraction will remain completely unaffected.

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