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INVESTMENTS IN EDUCATION DEVELOPMENT

Non-Gaussian Ressources and The Optical Hybrid Approach of Quantum Information

Olivier Morin, Jianli Liu, Kun Huang, Virginia D'Auria, Claude Fabre, Julien Laurat
Laboratoire Kastler Brossel, Université P. et M. Curie, ENS, CNRS, 4 Place Jussieu, 75005 Paris, France

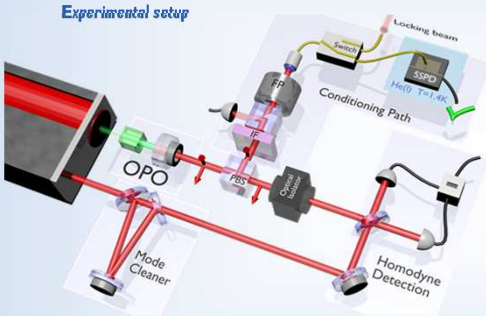
Laboratoire Kastler Brossel

A driving component for the development of diverse quantum information applications is the ability to efficiently engineer non-classical states of light. In quantum optics two strategies are possible: the discrete variables and the continuous variables. Although this two have been developed separately, the mixing of both - the optical hybrid approach – leads to new possibilities. We present the conditional preparation of high-purity single-photon Fock state [1] based on a continuous-wave type-II optical parametric oscillator [2] and coherent state superposition based on a type I OPO. We will then detail a witness uniquely suited for single-photon entanglement by using continuous variables tools. This kind of entanglement is a widely used resource in the context of long-distance quantum communication [3]. This operational witness is inspired by a Bell-type scenario which requires only local homodyne measurements [4].

Non Gaussian Resources generated via conditional preparation

Using a continuous-wave type-II optical parametric oscillator below threshold, we demonstrate a novel source of heralded single-photons with high-fidelity [2]. The generated state is characterized by homodyne detection and exhibits a 79% fidelity with a single-photon Fock state (91% after correction of detection loss). The low admixture of vacuum and the perfect spatiotemporal mode are critical requirements for their subsequent use in quantum information processing. Thanks to the OPO cavity, the spatial mode enables to reach high interference visibilities without the need of additional filtering. Moreover, the frequency-degenerate interaction makes the operation much simpler than previous realizations.

Experimental setup



A continuous-wave type-II optical parametric oscillator (OPO) is pumped (532nm) far below threshold [1]. The orthogonally-polarized signal and idler modes (1064nm) are separated by a polarizing beam-splitter (PBS). The idler mode is frequency filtered (Conditioning Path), in order to eliminate the non-degenerate modes from the OPO, and then detected by a superconducting single-photon detector (SSPD). Given a detection event, the heralded single-photon is characterized by quantum state tomography.

The signal from the homodyne detection is processed to obtain the quadrature measurements in the temporal mode of the OPO. Accumulated measurements give the marginal distribution of the state. The data are then processed using a maximum likelihood algorithm (MaxLik) to estimate the density matrix.

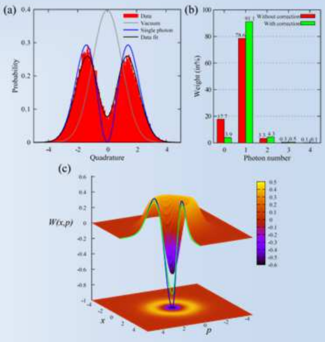
By using in the same scheme a type-I optical parametric oscillator (PPKT crystal) and tapping a small part of the output with a beam splitter, each detection event heralded a state closed to a coherent state superposition.

Single-photon with a type II OPO

(a) Measured quadrature obtained from 50000 acquisitions. The black solid line is a fit of the experimental data, while the blue solid line provides the distribution for a perfect single-photon state and the gray line for the vacuum.

(b) Diagonal elements of the density matrix of the generated state, with and without correction from detection losses.

(c) Corresponding Wigner function. The solid lines give the theoretical cross-section for a perfect single-photon and the experimental cross-section after correction.

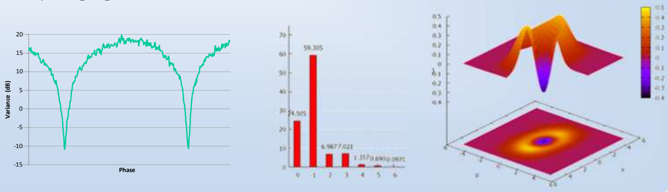


"Schrödinger's kitten" with a type I OPO

(a) Squeezing obtain with a pump power close to threshold

(b) Photon number distribution for the generated coherent state superposition

(c) Corresponding Wigner function



Witnessing single-photon entanglement with local homodyne measurements

A collaboration with Jean-Daniel Bancal, Pavel Sekatski, Melvyn Ho, Nicolas Gisin, Nicolas Sangouard
Group of Applied Physics, University of Geneva, 1211 Geneva 4, Switzerland

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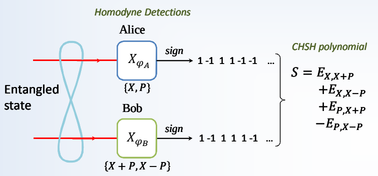
The proposed witness is the first one suited for single-photon entanglement which does not require any post-selection and assumption on the size of the Hilbert space. It relies on local phased-averaged homodyne detection only. Our results highlight the potential of hybrid methods, where discrete entanglement is characterized through continuous variable measurements.

A Bell-type senario

Many architectures rely on single-photon entanglement like $\frac{1}{\sqrt{2}}(|1\rangle_A|0\rangle_B+|0\rangle_A|1\rangle_B)$. In order mimmic a Bell test binary outcomes are obtained by sign binning the measurements of the quadratures. Alice & Bob make quadrature measurements amongst two basis, $\{X,P\}$ for Alice and $\{X+P,X-P\}$ for Bob, and compute a CHSH polynomial with the different probabilities outcomes

$$S=E_{X,X+P}+E_{X,X-P}+E_{P,X+P}-E_{P,X-P}$$

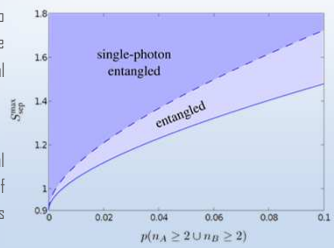


Separable bound

To conclude if the state is entangled or not it is necessary to bound the possible values for the CHSH polynomial with separable states. An upper bound S_{sep} can be estimated with the local photon-number $n>1$

$$p(n_A\geq 2\cup n_B\geq 2)\leq 2-p^A_{n\geq 2}-p^B_{n\geq 2}:=p^*$$

This bound can be optimized by including the knowledge of the local photon number probability 0 and 1 (which reduces the set of separable states). See [4] for more details. Moreover this bound is specific to entanglement in the qubit subspace.

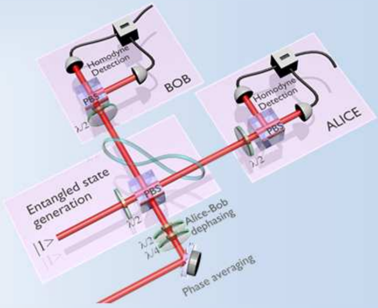


Experimental setup

A tunable single-photon entangled state is created by sending a heralded single-photon on a tunable beam-splitter based on a polarizing beam-splitter (PBS) and a half-wave plate (λ/2).

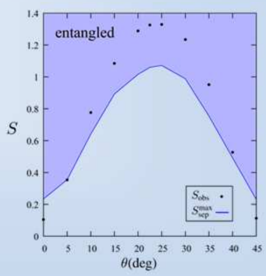
$$\cos(2\theta)|1\rangle_A|0\rangle_B+\sin(2\theta)|0\rangle_A|1\rangle_B$$

The proposed witness is then realized with two independent homodyne detections (Alice & Bob). The local oscillator is superposed to each modes via the first PBS. Its global phase is swept with a piezoelectric actuator in order to achieve a local phase averaging. The relative $\Delta\varphi$ is set with a combination of a half-wave plate and a quarter-wave plate (λ/4).



Experimental results

Observed CHSH values S_{obs} and separable bound S^{sep}_{max} as a function of beam-splitter angle. Note that the values of S^{sep}_{max} are lower than the ones presented in the first plot because the optimization here presented, uses the knowledge of the locally measured probabilities $p(n_A=j)$ $(p(n_B=j))$ for having $j=0,1$ photon in Alice's (Bob's) mode. This additional constraints leads to a tighter bound on S^{sep}_{max}.
Furthermore, the observed CHSH values are almost all larger than the separable bounds when dealing with entangled states (ie $\theta\neq 0°, 45°$). This shows the great robustness of the proposed witness.



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- [2] O. Morin *et al.*, *A high-fidelity single-photon source based on a type-II optical parametric oscillator*, Optics Letters **37**, 3738 (2012)
- [3] N. Sangouard et al., *Quantum repeaters based on atomic ensembles and linear optics*, Rev. Mod. Phys. 83, 33 (2011)
- [4] O. Morin *et al.*, *Witnessing trustworthy single-photon entanglement with local homodyne measurements*, PRL **110**, 130401 (2013)

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