Quantum non-Gaussian character of a heralded single-photon state

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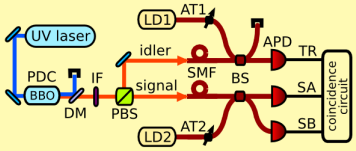
Abstract

We report on the experimental verification of quantum non-Gaussian character of a heralded single-photon state with a positive Wigner function. We unambiguously demonstrate that the generated state cannot be expressed as a mixture of Gaussian states. Sufficient information to witness the quantum non-Gaussian character is obtained from a standard photon anticorrelation measurement.

Experimental verification of quantum non-Gaussianity

Heralded single-photon source is based on parametric down-conversion process in 2 mm thick beta-barium borate (BBO) pumped by 50 mW cw multimode laser diode at 407 nm.



Photon pairs are separated from the pump by a dichroic mirror (DM) and spectrally limited by an interference filter (IF). The orthogonally polarized photons of a PDC pair are separated by a polarizing beam splitter (PBS) and coupled to single-mode optical fibers (SMF). Both outputs can be mixed with an attenuated (AT) laser diode (LD) signal at fiber beam splitters (BS) to emulate dark counts of detectors and a noise component of the state. The output modes are detected by single-photon detectors (APD) with efficiency of 50%. Electronic dark counts in coincidence basis were found to be completely negligible. The coincidence circuit (5 ns coincidence window) operates on output channels TR, SA, SB.

Each data set $[R_0, R_{1A,B}, R_2]$ yields the corresponding probabilities $[p_0, p_1]$, from which we have calculated $\Delta W = ap_0 + p_1 - W_G(a)$ and maximized the difference over all a. The resulting maximal criterion violation $\Delta W > 0$ in all cases and the bound $W_G(a)$ is always surpassed by many standard deviations [4],

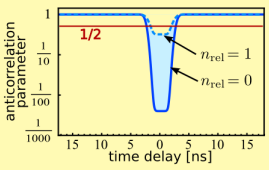
P [mW]	IF [nm]	p_0	p_1	$\Delta W\,[\times 10^{-6}]$
50	2	0.9124	0.0875	412 ± 1
50	10	0.8589	0.1410	1666 ± 3
20	10	0.8425	0.1574	2370 ± 2
50	–	0.7095	0.2901	14252 ± 17
5	–	0.7296	0.2704	11825 ± 15

Quantum non-Gaussianity under noisy conditions

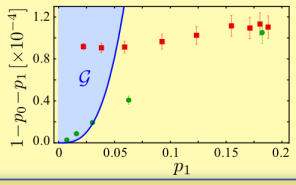
We have investigated the influence of background noise on the source properties. For this purpose we inject light from laser diodes LD1 and LD2 into trigger and signal detection blocks, respectively. Noise from LD2 emulates noise of the source while noise coming from LD1 effectively increases dark count rate of the trigger. With increasing noise in the both blocks we observe transition to the regime where $\Delta W < 0$,

$n_{\rm rel}$	p_0	p_1	$a_{\rm opt}$	$\Delta W\,[\times 10^{-6}]$
0.0	0.8195	0.1804	0.94018	3479 ± 7
0.1	0.9073	0.0926	0.98389	406 ± 3
0.2	0.9408	0.0591	0.99332	42 ± 2
1.0	0.9777	0.0222	0.99903	-84 ± 1

All the results exhibit strong photon anti-correlation effect [5] witnessed by $\frac{R_0 R_2}{R_{1A} R_{1B}} < 0.37$, including the case $n_{\rm rel} = 1$ for which $\Delta W < 0$:



Non-Gaussian character of the state is strongly affected by multiphoton content. We have studied its dependence on the noise amount added to the trigger channel only (green circles) and to both the channels simultaneously (red squares). All other parameters were fixed, P=50 mW and IF=10 nm.

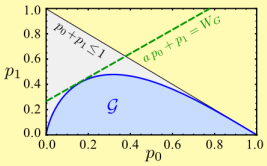


Motivation and theoretical background

Which mixed non-classical quantum states with positive non-Gaussian Wigner function do not admit explanation based solely on stochastic non-Gaussianity?

Negativity of Wigner function is equivalent to quantum non-Gaussian character of a pure state [1] but this relation does not simply extend to mixed states [2]. Its experimental verification also requires complete information on the state. Under lossy conditions, the negativity cannot be observed directly even for highly non-Gaussian states such as an arbitrary superposition of single photon and vacuum.

Recently, a criterion of the quantum non-Gaussianity has been theoretically proposed [3]. It is based on knowledge of probabilities of vacuum and single-photon states only, yet it can detect a wide class of states with positive Wigner function which are not mixtures of Gaussian states.



The boundary of Gaussian set $\mathcal{G}$ is given by the upper limit on the probability p_1 of single photon for a given probability p_0 of vacuum,

$$p_0 = \frac{e^{-d^2[1-\tanh(r)]}}{\cosh(r)} \qquad p_1 = \frac{d^2\, e^{-d^2[1-\tanh(r)]}}{\cosh^3(r)}$$

(r: squeezing parameter, $d^2 = \frac{e^{4r}-1}{4}$: displacement)

We define a non-Gaussianity witness $W(a) = ap_0 + p_1$. All points $[p_0, p_1]$ lying in the half-plane $ap_0 + p_1 > W_G(a)$, $W_G(a) = \max_{\rho \in \mathcal{G}} W(a)$, are certified by the witness to correspond to a state $\rho \notin \mathcal{G}$.

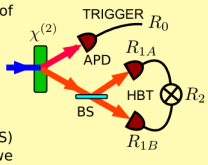
Using binary detectors (APD) and common Hanbury-Brown--Twiss correlation measurement, we are able to estimate probability of vacuum and lower bound of single-photon probability,

$$p_0 = 1 - \frac{R_{1A}+R_{1B}+R_2}{R_0}$$

$$p_1 = \frac{R_{1A}+R_{1B}}{R_0} - \frac{T^2+(1-T)^2}{2T(1-T)}\,\frac{R_2}{R_0} \le p_{1,\rm true}$$

(R_0: # of states, $R_{1A,B}$: single rates, R_2: coincidences)

We assume an arbitrary splitting ratio of the beam splitter (BS) and unity detection efficiency. For realistic detector, we underestimate the single-photon contribution further.

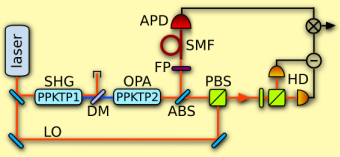


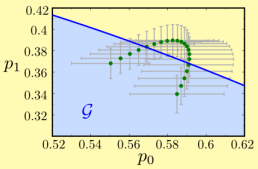
Conclusion

We have examined a source producing approximate single-photon states with positive Wigner function but exhibiting strong photon anti-correlation and we have unambiguously proved that the generated states cannot be expressed as mixtures of Gaussian states. In comparison to the witness based on negativity of the Wigner function, the present criterion can identify quantum non-Gaussianity of a much wider class of single photon sources. Consequently, the presented criterion is particularly useful for evaluation of single-photon sources where negativity of Wigner function cannot be observed.

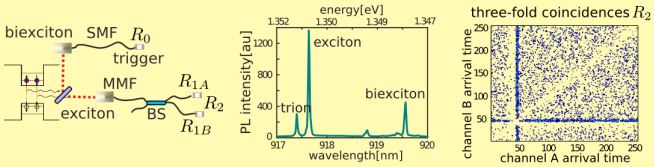
Outlook: Schrödinger cat and quantum dot

In collaboration with A. Tipsmark, R. Dong and U.L. Andersen, DTU Physics, Kgs. Lyngby: Approximate coherent cat state is prepared by subtracting a single-photon from squeezed vacuum and measured by means of balanced homodyne detection. Vacuum and single-photon contribution are estimated employing direct reconstruction from raw data. We have demonstrated statistically significant quantum non-Gaussianity even for states with positive Wigner function.





In collaboration with A. Predojevic, T. Huber, H. Jayakumar and G. Weihs, Uni of Innsbruck: The emission from InAs/GaAs quantum dot is spectrally filtered. Generated biexciton and exciton photons are coupled to single-mode (SMF) and multi-mode (MMF) fibers, respectively. Exciton emission is split in a multimode fibre beamsplitter to estimate vacuum and single-photon contributions. Non-Gaussian character is witnessed by $\Delta W > 0$.



References

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INVESTMENTS IN EDUCATION DEVELOPMENT