Review of the PhD thesis "Generation, Detection and Characterization of Photonic Quantum States" by Ivo Straka

The work of Ivo Straka addresses highly relevant experimental techniques related to fundamental concepts presently in the focus of research on the development of quantum technologies. The thesis adheres to the formal requirements generally expected for a PhD dissertation, including the length, the level of detail and proportions between the overview of existing knowledge and the achievements of the Candidate. It begins with an introduction of the essential concepts and methods required for understanding the experimental results and the conclusions drawn from them. The results and the contributions of the Candidate to them are clearly stated, supported by a transparent structuring of the bibliography. These results have been published in respected journals.

In my opinion, the most important subject of the thesis is the experimental study of non-Gaussianity. As the Candidate highlights in a concise summary, these states are presently believed to represent an important resource for quantum technologies. Interestingly, there are no widely-applied efficient techniques used for the detection (identification) of non-Gaussian photonic states. As far as I can judge, the Candidate has made key contributions to the pioneering experiments based on a recently proposed condition taking into account higher photon number detection events in a simple manner. Therefore, the results summarized in Chapter 3 of the thesis could alone be sufficient to fulfill the requirements of the PhD degree. Below, I provide a more detailed overview and comments to the work.

The thesis has clearly been prepared with a great care. The nicely polished text was a pleasure to read. The typesetting and the quality of figures and plots hint a strong dedication to perfection down to the last detail. After a brief overview of the important concepts, Chapter 2 focuses on the details of the two most important methods involved: namely the techniques to generate and detect quantum states of light. The extent of detail dedicated to the problematics of detection and analysis of

statistics in the presence of noises is sufficient for understanding the rest of the thesis. However, the treatment of SPDC processes neglects the presence of higher order photon number contributions. This is slightly surprising, since these contributions are strong limiting factors for applications. Later in Sec. 3.2.4 the Candidate actually deals with the higher photon numbers, even includes a formula with the correct photon number distribution. Therefore, this subject would have worth at least a single paragraph in the introduction, stating also the proper quantum state.

Chapter 3 is dedicated to the main results of the thesis, namely the experimental characterization of quantum non-Gaussianity (QNG). After summarizing the concept and importance of non-Gaussianity, the recently proposed QNG witness and a measure of non-Gaussianity based on it is introduced. The measurement results in Sec. 3.2 seem to be very convincing, and according to what is expected from the theory. Perhaps, Fig 3.2 could be improved by indicating the used values of τ, e.g. by specifying the spacing and range if equidistantly chosen. A slight shortcoming of this section is Fig. 3.1, which I find a bit vague: precise definitions are missing for several items. For example, the border for QNG sounds like it's based on some witness measure, however, it is not given what witness it could be. The QNG witness Eq. (3.1) doesn't seem to be applicable to this Figure, since it makes use of higher order photon contributions, whereas the figure appears to represent a set of states equivalent to something like a Bloch sphere defined by the Fock states $|0\rangle$ and $|1\rangle$. The dashed lines are supposed to correspond to the "trajectory" of certain states, but no mention of which states these are, and whether they are relevant to the work in this thesis or not. It is also not clear, whether the shape of the different sets refer to their properties such as convexity? Besides witnessing QNG, the Candidate also gives figures for QNG depth. I was unable to convincingly decide, whether actual measurements were made to determine the value of attenuation T corresponding to the true QNG depth, or only the (approximate) lower bound given by Eq. (3.3) was used. Perhaps, introducing something like QNG negativity would have helped to distinguish between experiments that directly measure QNG depth from those estimating it from the lower bound. The distinction between the two cases might be important, since it's not certain that the approximations leading to Eq. (3.3) hold for real-world quantum states such as those from the SPDC process.

Section 3.3 is dedicated to the QNG characterization of multi-photon states. The experiment presented uses time-multiplexing to realize a multi-mode emitter using a single non-linear source in a pulsed regime. The emitter thus emits into time-bin modes, which are effectively traced out by discarding the time-bin information at measurement. This is a clever and simple solution that allows the simulation of sources with higher average number of photons. The experiment appears to be

performed correctly, the errors are low enough to make conclusions based on the theoretical model. Unfortunately, the thesis concentrates exclusively on the experimental parts of Ref. [A2], leaving out possibly relevant details of the theoretical models and concepts. I would be very curious, for example how the "mixing" of the single photon states are performed: whether one formally considers two photons – one in each mode – equivalent to a $|2\rangle$ state, or there is no mixing in this sense and one looks at the statistics of a multi-mode state like in Ref. [30]? Another thing I came across accidentally in Ref. [A2] is a definition of a matrix T_{nm} that is supposed to be the conditional probability $\mathcal{P}(n|m)$ expressing the probability of detecting n photons, given the input contained m of them. Ref. [A2] gives an explicit formula for these conditional probabilities (calculated also in a work cited as Ref. [30] in the thesis). I would expect that such a conditional probability obeys a normalization $\sum_n T_{nm} = 1$, however, this doesn't seem to be the case. Perhaps some approximation has been used in the derivation of that formula? If so, it would be necessary to check how well the conditions for the approximation are met, otherwise it is hard to make definite conclusions regarding quantum non-Gaussianity. The remarks regarding "depth" above apply here as well. It appears to me that only the lower bound was used, yet there's no mention whether it holds also for the higher order criteria as well.

Section 3.4 considers the experimental study of genuine quantum non-Gaussianity (GQNG). For witnessing GQNG a similar concept is used as in Sec. 3.2. Three states are studied theoretically: $|3\rangle$, a three photon "mixture" and ρ_G given in Eq. (3.6). The description of the experiment is rather brief, it is even not quite clear which case is studied. I assume that it is the 3 photon "mixture." The GQNG criteria is studied in the presence of noise, which makes the experiment rather interesting. The interpretation of the results is also rather brief. In particular, I feel that Fig. 3.12 would deserve some explanation. For example, it seems that states produced with higher number of heralded photons, say ν, did not satisfy the GQNG criteria of Eq. (3.5) for $n < \nu$. I wonder if this is an expected behaviour, and if so what is its meaning?

Finally, Chapter 4 turns to a substantially different context. In contrast to the previous chapters which focused on various aspects of quantumness (e.g. non-classicality, non-Gaussianity), here the experimental generation of arbitrary "classical" photon statistics is described. The basic principle is the temporal modulation of the intensity of a coherent source to achieve a certain power distribution $P(W)$. The temporal control is achieved using an AOM controlled by an appropriate signal to obtain a desired output. The experimentally obtained photon statistics correspond well to the target distributions, making this a very nice series of experiments. I some-

how suspect that there are many technicalities regarding the detection that are not detailed. For example, I couldn't figure out how multi-photon, $|n\rangle$, probabilities are exactly identified? Am I correct to interpret the result such that the task is to find probabilities P_j such that on the density matrix (in the Fock basis) $\rho = \sum_j P_j |\alpha_j\rangle\langle\alpha_j|$ has on its diagonal a distribution as close as possible to p_j? And that the coherent states α_j are generated by attenuation of the initial signal, and P_j corresponds to the time duration of the given level of attenuation? Clearly, this optimization procedure is possible (it is a convex optimization problem), yet it is not rigorously proven that any distribution could be approximated with arbitrary precision. The experimental results for generating pseudo thermal states are presented on Figs. 4.2. Pseudo-thermal states are generally assumed to be easy to generate, however, the present experiments display precise control over the average photon number of the generated distribution. What I find strange is that the $g^{(2)}$ functions measured using a HBT technique fit very well with the values expected from true thermal distribution, suggesting that not only the diagonals, but also the coherences are correctly reproduced by this method. Is this generally true, or it is just a coincidence for thermal light? The subsection in Sec. 4.5 (unfortunately these are left unnumbered my mistake) on photon-number correlations doesn't answer this question. It reports two kinds of correlation measures, standard $g^{(2)}$ and another used in Ref. [159]. I guess that the standard method refers to Hanbury-Brown–Twiss interference. It is not mentioned why the correlations were addressed using the method of Ref. [159] if there were means to obtain $g^{(2)}$, and why numbers are quoted only for that one, and not for HBT?

In summary, the thesis describes interesting and relevant experimental work, fulfilling the criteria required for a PhD degree. The questions raised above were formulated mainly to satisfy my curiosity and to stimulate a fruitful discussion, rather than for the purpose of raising doubts about the quality of the work.

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