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REPORT ON THE DOCTORAL THESIS "ENTANGLEMENT SOURCES AND TESTING THE FOUNDATIONS OF QUANTUM THEORY" BY MOHAMED NAWAREG

The thesis "Entanglement Sources and Testing the Foundations of Quantum Theory" written by Mr Mohamed Nawareg under supervision of prof. Marek Żukowski from University of Gdańsk and prof. Mohamed Bourennane from Stockholm University deals with an interesting and timely problem of constructing optical sources of quantum entanglement and utilizing them to test the foundations of quantum theory. These efforts contribute to our deeper understanding of quantum mechanics, which the fundamental physical theory of the microworld, and also lead to new applications in information technologies, such as secret communication with security guaranteed by fundamental physical principles, or certified generation of randomness. In his dissertation, Mr Nawareg made a number of noteworthy contributions to the field of quantum information science and presented original results that warrant in my opinion recommending a public defence of the submitted thesis.

After presenting motivation and thesis overview in Sec. 1 of the dissertation, the author introduces in Sec. 2 basic concepts and tools that are used in subsequent parts of the thesis. This introductory part sets the scene and familiarizes the reader with notation, but the presentation may be difficult to follow for a person without a background in quantum physics. For example, the density matrix is defined in Eq. (2.2) without an explanation why a weighted sum of projections on pure states is the right way to describe statistical mixedness. While one can understand author's desire to introduce the fundamental concept in his research – namely entanglement – as early as possible, it might have been more appropriate to define it after a more detailed discussion of the qubit and photon polarization as its pratical realization in Sections 2.4 and 2.5. Without this, for example the remark that "any measurement on subsystem *a* or *b* gives a purely random result" made at the end of Sec. 2.3.1 may seem a bit cryptic. Annihilation operators used in Eq. (2.11) and later are not related to single-photon states introduced earlier. It would be also worth to mention that a unitary beam-splitter transformation derived in Eq. (2.14) required assumption that the optical element is lossless. For a reader unfamiliar with nonlinear optics, it would also be helpful to expand acronyms such as “BIBO” in the caption of Fig. 2.6.

These shortcomings may be a result of author’s intention to keep Sec. 2 concise. One should emphasize that subsequent parts of the thesis, presenting original results, do not leave the reader with such ambiguities. In Sec. 3 the author gives a nice overview of entanglement sources based on spontaneous parametric down-conversion, illustrating concepts and experimental configurations with clear diagrams. My only comment here is that while momentum conservation in parametric down-conversion is approximate due to the finite length of the nonlinear medium, energy is conserved to a very good approximation due to the off-resonant nature of the down-conversion process. After presenting previous approaches, the author describes his own efforts to build a source of polarization entangled photon pairs in Mach-Zehnder and Sagnac configurations. Detailed descriptions of the setups and a thorough discussion of their properties confirms that the author has mastered experimental construction of sources of photonic entanglement. In particular, it should be mentioned that alignment of Sagnac-type setups contains usually an element of a challenge, as moving or tilting any optical element modifies simultaneously both interferometer paths. Therefore building such setups requires a prior thought what algorithm will ensure convergence of the alignment procedure. In return, Sagnac configurations offer phase stability, lack of which is a notorious problem in the case of Mach-Zehnder interferometers. Successful operation of the constructed setup is confirmed by measurements of polarization correlations between generated photons. The results are convincing, although a bit more effort could have gone into their presentation (points with error bars instead of lines connecting individual experimental points, added sinusoidal fits, etc.) The author then proceeds to demonstrating Hong-Ou-Mandel interference between photons generated in two independent down-conversion processes. This objective is more challenging due to lower rates of quadruple coincidence events compared to two-fold coincidences in polarization correlations. When introducing the Hong-Ou-Mandel effect, it would be useful to clarify what defines the width of the Hong-Ou-Mandel dip shown e.g. in Fig. 3.11. The experimental results are presented clearly, including error bars. One might wonder how the results would change if interference filters were placed only in heralding arms or directly in front of detectors, but such a discussion might stray away too far from the main theme of the thesis.

Chapter 4 addresses the problem of experimental detection of entanglement. The author discusses briefly various approaches to confirm entanglement generation. Then he proceeds to describe and to demonstrate a new method based on witnesses that are independent of the specifics of measuring devices. Such a strategy is very valuable, as it removes the need to calibrate measurements and subsequently to trust the operation of measuring devices. The experiment is rather challenging, as it uses three photon pairs generated in independent down-conversion processes, synchronized by using as a pump frequency-doubled pulses from a mode-locked Ti:sapphire laser. The results are presented in great detail, and generation of mixed Werner states with a varying weight of the singlet fraction allowed the author to demonstrate the transition from a separable to an entangled state.

In Chapter 5 the author presents results concerning generalized Bell's inequalities. The chapter begins with an accessible review of assumptions underlying local realistic theories. My only comment here is that the use of carets to denote observables in the second sentence of Sec. 5.2.1 may be somewhat confusing, as these symbols were previously used to denote quantum mechanical operators, while local realistic theories go beyond this description. Author's original contribution is the derivation of new, lower-order Bell's inequalities. Calculations are presented step-by-step and can be followed easily. The results can have interesting consequences for detecting genuine multipartite entanglement and discriminating it against entanglement present when the composite systems is split into fewer partitions. Finally, Chapter 6 probes further foundations of the quantum theory with an effort to explain the allowed range of quantum correlations by the exclusivity principle. The theoretical concept is illustrated with experimental data combining measurements carried out by the author and the University of Rome group. Here the description of the experimental results is rather concise, for example it is not clear how the fidelity of the experimentally generated state has been determined. Also, for a reader unaccustomed with the Rome setup it would be helpful to explain the notation of orbital angular momentum states $|m\rangle$, either in the main text or in Appendix B.

Typesetting of the thesis has been done carefully, the list below contains noticed typos:

- Eq. (2.14): a missing imaginary unit in the overall exponential factor.
- Page 27 and later: "downconversion" instead of "downconvertion"
- Page 30: second should be denoted with small "s" rather than capital "S"
- Eq. (3.17): second line can be simplified to $\cos^2(4\theta)$
- Page 49, first line of the last paragraph: "free will" instead of "free well"
- Page 50, last line of Sec. 5.1: "Einstein" instead of "Einstien"
- Ref. [34], "Jozsa" instead of "JOZSA"

Concluding, the submitted thesis describes several original contributions to the field of quantum information science. Some of the presented results have been included in two articles that appeared in *Scientific Reports* and *Physical Review A* and there is clearly material for more publications. In my opinion these achievements entirely fulfil requirements for a doctoral dissertation.