REVIEW

of dissertation

for obtaining the scientific degree "Doctor"

in the professional research field 4.1. Physical sciences (Physics of atoms and molecules)

in defense procedure at the Faculty of Physics

at Sofia University "St. Kliment Ohridski"

The review was prepared by Assoc. Prof. Boyan Tonev Torosov, Institute of Solid State Physics, Bulgarian Academy of Sciences, as a member of the scientific jury according to Order № RD 38-372 / 03.06.2024 of the Rector of Sofia University.

Dissertation title: Quantum Process Tomography: High Fidelity Methods

Author of the dissertation: Stancho G. Stanchev

I. General description of the submitted materials

1. Description of the submitted documents

The candidate Stancho G. Stanchev has presented a dissertation and a thesis summary, as well as the mandatory tables for the Faculty of Physics from the Regulations on the terms and conditions for acquiring scientific degrees and holding academic positions at Sofia University – St. Kliment Ohridski. There are also additional documents (such as curriculum vitae, diploma for master degree, statement of authorship, anti-plagiarism statement, and reference for fulfillment of the minimum requirements), supporting the achievements of the candidate.

The documents submitted for the defense by the candidate comply with the requirements of the Development of Academic Staff in the Republic of Bulgaria Act and the Regulations for its application and the Rules of Procedure and the Regulations on the Terms and Conditions for Acquisition of Scientific Degrees and Academic Positions at Sofia University – St. Kliment Ohridski.

2. Data for the applicant

Stancho Stanchev graduated as a Master in Electrical Engineering from the Technical University of Varna in 1999. After that, he worked for several companies as a technician, technologist, and technical organizer until 2020, when he started his PhD studies at Sofia University – St. Kliment Ohridski, within the group of Quantum Optics and Quantum Information, supervised by prof. Nikolay V. Vitanov. His work during the PhD studies has been mainly focused on developing high fidelity methods for quantum process tomography.

3. General description of the candidate's scientific achievements

The primary focus of the dissertation is the development of novel methods for process tomography, which allow for the characterization of a quantum channel with high precision and accuracy. The research was conducted under the supervision of prof. Nikolay V. Vitanov. The dissertation is based on three scientific publications, all of which have been published in high-impact journals. Being the first author, I assume that the contribution of the candidate in all three publications is essential. Therefore, the dissertation complies with the minimal requirements for acquisition of the scientific degree Doctor. Furthermore, the scientific publications in the dissertation do not repeat those from previous procedures for acquiring a scientific title and academic position. Finally, according to the anti-plagiarism statement, there is no proven plagiarism in the submitted dissertation and the Summary.

4. Analysis of the basic and applied scientific achievements of the candidate as evident from the documents for participation in the procedure

The main scientific and applied contributions of the present dissertation are in the field of quantum tomography, with applications in quantum computing. In particular, using a multi-pass approach and applying a sequence of the same quantum channel, applied multiple times, one can improve the traditional methods for quantum process tomography.

The dissertation is presented in seven chapters:

The first chapter is a short introduction that motivates the research, conducted in the Dissertation and gives a brief overview of its structure.

Chapter 2 introduces the reader to some aspects of quantum information theory, used later in the dissertation. In particular, the formalism of open quantum systems is explained and the representations of completely-positive-trace-preserving maps are examined.

Chapter 3 studies the topic of device characterization. Some standard approaches are described, such as randomized benchmarking, quantum process tomography, and gate set tomography.

In Chapter 4 the method of multi-pass quantum process tomography is developed.

In Chapter 5 the multi-pass propagators for systems with Majorana or Morris-Shore symmetry have been found.

Chapter 6 applies the results from the previous chapter to address the problem of characterization of Raman qubit gates.

Chapter 7 presents the conclusions.

The contribution results from this dissertation can be classified as enrichment of existing knowledge and application of scientific achievements in practice.

Quantum device characterization, which is the main subject of this dissertation, refers to the process of measuring, analyzing, and understanding the properties and behavior of quantum computers. In essence, the goal is to study the characteristics of the quantum processors, such as coherence times, gate fidelities, noise sources. Quantum device characterization is an essential process in the development and implementation of quantum computing, enabling the advancement of practical quantum systems. In particular, a number of techniques have been developed for that goal, such as randomized benchmarking, quantum state tomography, quantum process tomography, gate set tomography, classical shadows, neural-shadow tomography, etc. In the present dissertation, a novel method for process tomography has been developed, based on the multiple-time application of a quantum channel. This technique is shown to improve the precision and accuracy of standard quantum process tomography.

The dissertation starts with three introductory chapters, where first some motivation is given on why this research has been conducted, and after that a very extensive and well written overview is presented, which covers the topics of quantum-information basics, open-quantum-system formalism, and quantum-characterization methods.

Chapter 4 introduces the technique of Multipass Quantum Process Tomography, which is shown to greatly improve the precision and accuracy of standard quantum process tomography. This approach can be used as a complement to other methods, too, such as the ancilla-assisted process tomography. The technique has been applied to the sqrt(X) and CNOT gates, using either a noisy simulator or a real IBM quantum processor..

In Chapter 5, the multipass propagators of quantum systems with Wigner-Majorana or Morris-Shore symmetry have been derived. These results may find a number of applications, such as in the development of quantum-control methods for multistate systems, or for the estimation of the efficiency of different dynamical-decoupling sequences for qubits and qudits.

Chapter 6 builds on the results from the previous chapter and presents a tomographic method designed for the characterization of high-fidelity Raman qubit gates, which obey the Morris-Shore transformation. The proposed method makes use of coherent amplification of the gate errors by repeating the same gate numerous times. By examining the multi-pass probabilities, we establish their dependence on four key parameters: pulse area error, detuning error, filling ratio, and the number of pulses (passes).

The conclusions of the dissertation work are summarized in Chapter 7. The publications used, the contributions, as well as the conference presentations of the author, are summarized in the Appendix.

5. Critical remarks and recommendations

The dissertation is very well written and easy to follow. I particularly liked the adopted LaTeX style, the used LaTeX packages, and the formatting of the figures. All these made the reading seamless and enjoyable. Also, I think the introductory chapters 1-3 might be very useful for any reader that wants to gain initial knowledge about the topic of device characterization. The candidate has made a clear effort to present a complicated topic in an accessible manner and this deserves recognition.

I have the following questions/comments on the dissertation:

- On p. 9, postulate 2, the time-dependent Schrodinger equation is introduced and the author explains that it describes the evolution of an isolated (closed) system. However, if Eq. (2.3) is only valid for an isolated system, then why is the Hamiltonian time-dependent?
- The expressions for p below Eqs. (2.151) and (2.156) seem wrong. Shouldn't p be a real number between 0 and 1?
- The name of Chapter 3 is "Quantum Characterization, Verification and Validation". However, it only discusses characterization, and doesn't explain anything about the "verification and validation" part. In particular, it's not even clear what is the difference between verification and validation.
- In Chapter 4 (Sec. 4.6), some data is presented on the constructed Pauli Transfer Matrices, using either a noisy simulator or a real device. It seems that the first row of these matrices always contains only zeros, except for the first element which is one. Does that mean that no leakage is present in the system or that the method cannot be applied for trace-decreasing maps?

6. Personal impressions of the candidate

I have known the candidate since he joined the Quantum-Optics-and-Quantum-Information group of Prof. Nikolay V. Vitanov. My impressions are that he is very motivated and hard-working. He is also very proactive, looking for discussions with his colleagues, but also ready to listen to feedback and advice. Also, he is quite open to quickly adopting new cutting-edge technologies which would help him with his work.

7. Conclusion

After getting acquainted with the presented dissertation, summary and other materials, and based on the analysis of their significance and the contained in them research and applied contributions, I **confirm** that the scientific achievements in the dissertation meet the requirements of Development of Academic Staff in the Republic of Bulgaria Act and the Regulations for its application and the relevant Regulations of Sofia University "St. Kliment Ohridski for obtaining the scientific degree Doctor. In particular, the candidate exceeds the minimum national requirements in the professional field and no plagiarism has been established in the dissertation, summary and scientific papers submitted at the competition.

I give my **positive** assessment of the dissertation.

II. OVERALL CONCLUSION

Based on the above, I recommend the scientific jury to award the educational and scientific degree Doctor in the professional field 4.1 Physical Sciences to Stancho G. Stanchev.

30 Aug 2024 Reviewer signature: ....

(Assoc. Prof. Dr. Boyan Torosov)