REVIEW
of the PhD thesis
for obtaining the educational and scientific degree "Doctor" in Physical sciences,
at the Faculty of Physics of Sofia University St. Kliment Ohridski

The review is prepared by: Prof. Stéphane Guérin, University of Bourgogne, Dijon, France

Topic of the dissertation: "***Quantum Process Tomography: High Fidelity Methods***"

Author of the dissertation: **Stancho Georgiev Stanchev**

03.09.2023 – Dijon (France)

General characteristics of the candidate's scientific achievements

The present thesis is about the general field of quantum process tomography using high fidelity methods. Quantum tomography is of great importance in quantum technology and quantum computation in particular, since it plays a pivotal role in characterizing the implementation of quantum logical gates, in order to verify and validate them.
The work mainly focusses on the so-called "multi-pass technique" which consists of performing quantum tomography on multiple identical applications of the same quantum gate before measurement. This leads to an accumulative effect, which, from a fast post-processing procedure that derived the individual process from the multi-pass process, is shown to enhance both the precision (i.e. via a narrow histogram of measured gate errors) and the accuracy (i.e. via centering the histogram to the true gate error) of a single gate. The inaccuracy is proportional to the state preparation and measurement (SPAM) and readout errors, while the imprecision is associated with random errors, typically the shot noise errors. It is known that the imprecision can be reduced by increasing the number of shots. The present technique allows one in addition to mitigate the SPAM and readout errors, i.e. to improve the accuracy. The important result is that this technique offers a remarkable accuracy with a relatively low number of experiments compared to standard methods.
The theoretical results (simulations) are demonstrated experimentally on the IBM quantum computer in a very convincing manner.
These results have been very recently published in a high-level journal of the Nature Publishing Group (Scientific Reports - DOI: 10.1038/s41598-024-68353-3).
The thesis contains related results concerning the determination of analytic formulae for coherent interaction of multistate quantum systems with pulse train featuring specific symmetry linking single-pass and multi-pass processes. This is applied to the characterization of high-fidelity Raman qubit gates. These have been published into Physical Review A and Journal of Physics B, two high-reputation journals.

The manuscript is organized as follows:

Chapter 2 presents a summary of quantum information theory, including open quantum systems under the Markovian conditions. Chapter 3 provides a very solid state-of-the-art review of methods for characterizing and validating quantum processes, i.e. quantum tomography. These two Chapters are very informative and written in a very pedagogical way for readers not familiar about details of quantum tomography. They also prepare very well the subsequent chapters which contain the original results of the thesis.
Chapter 4 presents the development of the main results: the multi-pass tomographic method, which achieves increased accuracy and precision. Convincing simulations and demonstrations on the IBM quantum machine are presented. In Chapter 5, multi-pass propagators in coherently driven multilevel systems (of Morris-Shore and Wigner-Majorana symmetry) are determined. Chapter 6 applies the preceding results to the characterization of Raman qubits gates and the tomography of a gate under Morris-Shore dynamics.
Chapter 7 concludes the work and presents possible obstructions of the method:
- pulses not identical, but without any quantified analysis,
- repetition time below the coherent time of the qubit,

and potential generalizations, such as:
- development of quantum control methods for multistate systems,
- broader applications of the multi-pass method to qutrits and qudits in general,
- extension to arbitrary pulse shape for the Raman gate.

Critical remarks, questions and recommendations

The PhD thesis is written in a very good English, it is very well organized and presented. I can just mention some typos in referring to chapters or sections due to an incomplete transcription from the related articles on which three chapters have been based (see in particular Chapters 5 and 6).
The state-of-the-art about quantum information and more notably quantum tomography is originally presented showing the solid knowledge of the candidate about these techniques.
The thesis has resulted in three published peer-reviewed papers of very high quality (Scientific Reports, Physical Review A and Journal of Physics B). Stancho Stanchev is the first author of all these papers, which expresses the recognition of his significant contribution. These publications demonstrate the high quality of the thesis. In addition, the candidate has presented 6 communications (oral presentations and posters) in international conferences related to his PhD thesis. During his thesis work, Stancho Stanchev has visited the prestigious Niels Bohr Institute and Aarhus University where he had stimulating conversations with Professor Klaus Molmer, a high-reputation professor in physics.

I have the following questions to be addressed during the defense:

- It is mentioned that the Qiskit MitigatedProcessTomography module for the IBM quantum computer can mitigate readout errors. It should be clarified how this module is used in combination with the present multi-pass technique or if the latter technique is sufficient to mitigate these errors without using the module. In this case, how compare the module with the present method?

- How scales the enhancement of the accuracy with respect to the number of applied gates?

- Other methods, as the one discussed in [Cho+12], use gate application of a sequence of identical repetitions. How does it compare to the present method?

- It is mentioned that the muli-pass method might be applied for accurate description of dynamical decoupling and quantum sensing with qudits. Could this be explained with more details?

- It is mentioned that an obstruction of the method concerns the repetition time that should be below the coherent time of the qubit. Would it be possible to access the characterization of the qubit decoherence by the multi-pass method?

Conclusions

I am convinced that the theoretical results and demonstrations on the IBM quantum computer presented in the thesis will have a strong impact in the field of quantum information, in particular for quantum tomography, as they can be applied for a large variety of systems (qudit, platforms, control, …). The dissertation, the abstract and the quality of the scientific publications of Mr. Stanchev cover the requirements of the Faculty of Physics of Sofia University St. Kliment Ohridski. I thus support the award of the educational and scientific degree "Doctor".

Prof. Stéphane Guérin