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Jury Member Report – Doctor of Philosophy thesis.

Name of Candidate: Oksana Borzenkova

PhD Program: Computational and Data Science and Engineering

Title of Thesis: Linear optical realization of variational quantum algorithms

Supervisor: Professor Jacob Biamonte
Co-supervisor: Dr. Stanislav Straupe

Name of the Reviewer:

I confirm the absence of any conflict of interest	**Date: 20-11-2024**

The purpose of this report is to obtain an independent review from the members of PhD defense Jury before the thesis defense. The members of PhD defense Jury are asked to submit signed copy of the report at least 30 days prior the thesis defense. The Reviewers are asked to bring a copy of the completed report to the thesis defense and to discuss the contents of each report with each other before the thesis defense.

If the reviewers have any queries about the thesis which they wish to raise in advance, please contact the Chair of the Jury.

Reviewer's Report

Reviewers report should contain the following items:

- Brief evaluation of the thesis quality and overall structure of the dissertation.
- The relevance of the topic of dissertation work to its actual content
- The relevance of the methods used in the dissertation
- The scientific significance of the results obtained and their compliance with the international level and current state of the art
- The relevance of the obtained results to applications (if applicable)
- The quality of publications
- The summary of issues to be addressed before/during the thesis defense

The thesis of Oksana Borzenkova contains a comprehensive study and original research results on the implementation of variational quantum algorithms on a linear optical photonic platform. It addresses the highly topical subject of noisy intermediate-scale quantum (NISQ) computation, exploring the feasibility of solving practical problems using current or near-future quantum computational devices. It presents the

implementation of a variational quantum eigensolver algorithm for the Schwinger Hamiltonian on two-qubit linear optical processors, based on polarization and dual-rail quantum information encoding. This represents a simulation of a complex quantum system model related to quantum field theory, using another well-controlled quantum system, allowing the determination of its ground state energy and the properties of phase transitions. The research presents a full-stack quantum computation, combining the initial problem in terms of the Hamiltonian under study, its mapping to a qubit system, the quantum algorithm, and its implementation, which combines quantum computation on a real linear optical quantum processor and classical computation on a PC. The dependency of the calculation results on the impact of noise has been studied, and it was found that some results are robust to certain noises, and the impact of some other noises can be partially mitigated.

Additionally, the research addresses the cornerstone of the linear optical quantum computational platform limiting its scalability: the development of efficient multiphoton emitters. Various configurations of the sources have been experimentally studied, and state-of-the-art results have been obtained.

The topic of the dissertation fully relates to its content, the techniques and equipment used in the experiment are at the state-of-the-art level. Obtained results are significantly strong, and experimental results are supported by numerical calculations in good agreement with them. Technical characteristics of the developed devices such as the programmable linear optical circuit and multi-photon sources are at the international level, and some of them even surpass it.

The results contained in the dissertation are published in high-impact international scientific journals: Applied Physics Letters and Optics Letters. The high quality of these publications is unquestionable.

The results can be applied to the development of new NISQ computational systems, pushing us towards practical quantum computations.

At the same time, I need to note **the text is very poorly structured**. Formally, the thesis contains all the necessary parts: three original chapters, a review of the literature, an abstract, an introduction, a conclusion, and a bibliography. However, different parts of the text are weakly connected to each other. It almost has no internal logic, different parts are weakly linked to each other and have significant overlap. The Introduction chapter does not present the statement of the topic and focus, the student's vision and motivation for research, its location in a broad scientific context, research aims and tasks, and thesis structure. The review and original parts are mixed, and there are no cross-references between them. Two original chapters almost fully copy the text of the student's publications. The Bibliography chapter contains 221 randomly sorted sources, presented in different formats with some typos. Quite a lot of citation links in the text point to wrong sources. Despite the huge list of soutces related to the topic, there is no real literature analysis, no comparison between the original and already known results.

The **text quality is also very weak**. Different parts of the text have different designations of the same mathematical elements. Many designations have no definitions. Many abbreviations have no explanations when they first appear in the text, and sometimes the explanations can be found far below in the text. Many figures are not referred to and described in the text. There are some typos and mistakes in the text and equation formatting. In addition, some paragraphs of the review parts were fully copied from the cited sources and presented without quotes. Many figures presented in the text were copied from other sources, which was not mentioned in the figure captions.

In the following, I would like to summarize the questions and that I feel important to raise with respect to the results without doubting the quality, importance, and correctness of them.

1. Do variational quantum algorithms provide a quantum advantage? What scale of the quantum computation system will be enough for it?
2. All the presented implementations of quantum algorithms on the linear optical platform are based on principally non-scalable two-qubit gates. How can the obtained results be applied to scalable architectures?
3. In Chapter 4, photon distinguishability was considered as the main source of errors since it decreases the visibility of HOM interference (82% using the optical circuit). At the same time, it was mentioned that the HOM interference in a fiber beam splitter was 98%, which means the main source of errors is not photon distinguishability but the optical circuit's imperfection. Is it correct to mitigate one imperfection by considering the variation of another one? Why was photon distinguishability varied by polarization, and not by the time delay? Can this polarization change affect the phases and splitting ratios of the optical circuit?
4. How does eq (4.10) for unitary matrix fidelity reflect the real quality of the optical circuit, since it does not include the phases of the unitary matrix elements? Does the high value of this fidelity (99.18%) mean that not only the splitting ratios but also the passive phases of the produced circuit fit well with the desired one? In the conclusion, it was mentioned that the fidelity of the two-qubit entangling CNOT gate is 94.4%. How was this value obtained? How does it fit with the 82% HOM-interference visibility?
5. The multi-photon source, presented in Fig. 5.2, has 8 outputs. The caption of the figure is “Experimental setup with six photons”. In the table presented in Fig. 5.3, no more than 4-photon coincidence is presented. So, how many photons can this source produce? Does it use different crystals in different parts? Why?

Issues that need to be addressed:

1. The introductory chapter does not contain any necessary elements, such as a statement of topic and focus, the student’s vision and motivation for research, its location in a broad scientific context, research aims and tasks, and thesis structure.
2. The abstract does not contain any information related to the third original chapter.
3. All the parts of the text related to the literature review should be combined in one chapter, structured, and then referred to in the other parts of the text.
4. All literal borrowings from sources must be paraphrased; all borrowed figures should be provided with links to the sources.
5. All abbreviations and designations should be defined and explained in the text.
6. The bibliography should be sorted, formatted, and wrong citation links should be fixed.
7. All the obtained results should be directly compared with the literature. Scientific novelty should be highlighted.

8. The Schwinger model, studied in the research, has a very brief explanation. The physics of the studying system is unclear, as is its mapping to the qubit system. The motivation for studying this model is also unclear.
9. Section 4.5.3 related to the VQE test by finding the molecular ground state also has a very brief explanation and unclear motivation. Also, there is confusion between polarization and dual-rail encoding in this section.
10. The original part of Chapter 5 related to home-made multi-photon sources is described too briefly. No experimental details are provided. Very little information about source parameters is presented. Almost no comparison with other sources known from the literature. No conclusion.
11. All the other experiments also have quite a brief description. More technical details can be provided.

In conclusion, the dissertation of Oksana Borzenkova contains strong scientific results, showing the authors skills both in experimental an in theoretical quantum optics and quantum computation. However, the presentation of this results is very weak and the text should be significantly improved, addressing all the listed issues.

Provisional Recommendation

☐ *I recommend that the candidate should defend the thesis by means of a formal thesis defense*

☒ *I recommend that the candidate should defend the thesis by means of a formal thesis defense only after appropriate changes would be introduced in candidate's thesis according to the recommendations of the present report*

☐ *The thesis is not acceptable and I recommend that the candidate be exempt from the formal thesis defense*