REVIEW

of a dissertation

for the acquisition of an educational and scientific degree "doctor" in professional field 4.1 Physical sciences, according to the procedure for defense at the Faculty of Physics (FzF) of the Sofia University "St. Kliment Ohridski" (SU)

The review was prepared by Assoc. Prof. Petar Aleksandrov Ivanov, SU "St. Kliment Ohridski", Faculty of Physics, in his capacity as a member of the scientific jury according to Order RD 38-272/03.06.2024 of the Rector of Sofia University.

Dissertation topic: "Precision Methods for Tomography of Quantum Processes".

Author of the dissertation: Stancho Georgiev Stanchev

Applicant details.

Stancho G. Stanchev received a master's degree in Electrical Engineering at the Technical University of Varna in the period 1994-1999. In the period 2002-2008 he worked as a Service Technician and designer of electrical installations in industrial enterprises. In the period 2008-2020, he was a technical organizer in the wind industry. Since 2020, he is a doctoral student in the group of Prof. N. Vitanov.

General description of the candidate's scientific achievements.

Quantum informatics is one of the fastest growing fields of modern physics, which is both fundamental and purely practical in nature. A quantum computer is an analogue of a classical computer that obeys the laws of quantum physics. A core element of a quantum computer is a qubit, a two-state system that carries quantum information. Changing the state of the qubit is done by applying a quantum gate, which is a fundamental element in quantum circuits and algorithms. Quantum process tomography plays an important role in characterizing the accuracy of quantum gates and quantum circuits.

The dissertation of Stancho G. Stanchev is devoted to the development of quantum tomography techniques for characterizing the accuracy of single-qubit and two-qubit quantum gates. In the dissertation, a new multi-process quantum tomography is proposed and experimentally demonstrated, which characterizes the precision of quantum gates more accurately than existing methods. The experimental demonstration of the proposed tomography technique uses IBM Quantum processors. Another main results of the thesis is the development of methods for the amplification and measurement of coherent errors of single-qubit gates, by applying repetitive interactions.

General overview of the dissertation work

Chapter Two examines basic principles in quantum information theory. Based on the fundamental rules in quantum mechanics, a quantum information processing diagram is presented, which includes: (1) preparation of the initial state. (2) Time evolution of the quantum state. (3) Measuring the probabilities of the system being in a given state. Quantum evolution is represented by unitary operators (gates), which play a key role in modern quantum technologies. Gates can be single-qubit gates that act on a single qubit, such as a Hadamard gate, a phase gate, etc., or multi-qubit gates that act on more than one qubit. An example of such gates is CNOT gate, CPHASE gate, SWAP gate and others. Of great importance in quantum information is the characterization of the precision of the quantum gate, that is, how close the experimentally realized gate is to the target gate. Quantum tomography aims to determine each of the matrix elements of the quantum gate and thereby measure fidelity. Obviously, quantum systems are not completely isolated due to interactions with the environment. The second chapter examines the basic principles and equations of open quantum systems. The states of such systems are described by a density matrix, and the evolution in time by means of the Lindblad equation and Kraus operators. Quantum evolution can generally be represented by a completely positive and trace-preserving map (CPTP map). It is important to note that the representation by Kraus operators is not the only one, and there are other CPTP representations of processes, such as those of Stinespring, Choi-Jamiolkowski, Pauli transfer matrix representation (PTM) and others . In the present dissertation, PTM representation is mainly used, which can be expressed by Kraus operators and Pauli basis operators. A PTM representation is in the so-called Hilbert-Schmidt space of dimension d^2. In this representation of the density matrix is vectorized (supervector), the PTM matrix is a superoperator that transforms the initial state to a new state. If we have a series of processes, then the complete process is represented as a matrix product of the individual processes, which is an important convenience of the PTM representation. Table 2.1 of the dissertation presents a relationship between the different CPTP representations, which is implemented through basis transformation operators.

The third chapter of the dissertation is devoted to quantum state tomography. First, qubit state tomography is considered. The density matrix can be represented in the basis set by the Pauli matrices. The coefficients in the expansion are the average values of the Pauli matrices in the given state. Measurements are usually performed in the Z basis (Computational basis). If we want to make an X or Y measurement, an additional rotation (fiducial operations) must be applied, which transforms the qubit state into the Z basis, so that the measurement in the Z basis gives information about the X and Y basis states. Standard quantum process tomography (SQPT) is based on the following steps: The system is prepared in a certain state that is considered accurate. The second stage is the application of the unknown process (gate) on the d^2 orthonormal prepared state. In the last stage, d^2 projective measurements are carried out. State Preparation and Measurement (SPAM) gates are assumed to be known and accurate. Experiments are repeated many times so that sufficient statistics can be gathered and the corresponding probabilities can be determined. In the limit of a large number of repetitions (shots), the probabilities that count d^4 are directly related to the unknown process and preparatory states. Once the probability matrix is measured, the unknown process is reconstructed by linear inversion. As a final step, a maximum likelihood estimation (Maximum Likelihood Estimation) is made to find the physical process corresponding to the PTM matrix.

Diamond norm and process infidelity are used as an indicator of the error of the measured process relative to the ideal process. Standard SQPT tomography relies on the accuracy of measurement (SPAM) gates and readout information, which can generally be inaccurate, leading to systematic errors. When multiple scans of the same process are performed, different results with a distribution close to Gaussian are obtained. The dissertation presents a simulation with 50 tomography scans, where a diamond standard was used as an error indicator. The deviation of the mean from the exact value is called imprecision, while the width of the Gaussian distribution is called imprecision, which decreases as the number of shots increases.

The fourth chapter of the dissertation is groundbreaking and is based on the PhD student's third publication. Multi-process Quantum Tomography (MQPT) is proposed, which is based on repeated applied gating. This results in the amplification of single-process errors into multi-process errors, which are then measured with high accuracy and precision by SQPT. Essentially, the method involves measuring the PTM of the multiprocess using standard quantum tomography, then processing to derive the PTM of the single process. The thesis presents an IBM Quantum simulation using IBM_QASM_SIMULATOR. The discrepancy between the actual process and the ideal (target) is defined by the error matrix. The purpose of multi-process quantum tomography is to measure the diamond norm, which is an indicator of process errors, but also to find the individual elements of the error matrix. Essentially, MQPT involves a first stage where N sequential processes are applied. The goal is to amplify the gate error and thereby improve the precision and accuracy of the derived unitary process. In the second stage, the single process is extracted from the measured multi-process. Two approaches are proposed in the dissertation: (1) iterative method (2) linear approximation.

In the iterative approach, it represents a loop where each iteration corrects the error matrix. The dissertation presents a demonstration of the effectiveness of the method for one-part and two-part gates using IBM Quantum IBMQ_SIMULATOR simulation.

The linear approach is considered for involutive gates and for arbitrary target gates. Essentially, the method reduces to a Sylvester equation for the error matrix. Finding the error matrix then allows the unit process to be found.

The proposed MQPT is experimentally demonstrated on a CNOT gate, which is a basic two-part gate of an IBMQ_MANILA processor. The results of MQPT are compared with the results obtained from SQPT. 10 scans with 400 shots were performed for both SQPT and MQPT. A comparison of different tomography approaches is shown in Figure 4.5. Infidelity results are also shown, using the IBM calibration data, which determines the CNOT mean gate error, as the measurement reference. The result shows that SQPT overestimates the errors, while both MQPT methods give significantly lower values, which is an important advantage of the proposed method.

The fifth chapter of the dissertation examines coherent interaction of quantum systems with a series of pulses. The quantum systems considered have Wigner-Majorana (WM) and Morris-Shor (MS) symmetries. These symmetries allow the dynamics of a multilevel system to be reduced to a two-state problem. The Hamiltonian of a system with WM symmetry has a tridiagonal form, where the matrix elements must fulfill certain conditions. The Morris–Shore transformation allows a multistate system consisting of two connected sets of degenerate levels to be transformed into a set of independent two-state systems and a set of separated dark states. The requirement of the MS transformation is that all Rabi frequencies have the same time dependence and the same frequency differences (detunings). The unitary propagator for a two-state system can be expressed in terms of the Cayley-Klein parameters. After performing the inverse transformation, an expression for the unitary propagator of the original system can be found. In the dissertation, expressions are found for the unitary propagator when there are N iterations of the interaction described by the Hamiltonian having WM or MS symmetry. These analytical expressions are the main result in this chapter.

The sixth chapter of the dissertation is devoted to the characterization of high-precision Raman qubit gates. A Raman system is a three-level system where the two main metastable levels interact with a third level, which in most cases is a short-lived level. In the case where the Rabi frequencies have the same time dependence, the Raman system can be reduced to an effective system with two states and one dark state. In this case, one can find an expression for the unitary propagator in the original basis. Under certain conditions, the dynamics of the system can be limited to only the two fundamental levels that form a qubit. In this case, the unitary propagator is a single qubit gate. The aim of this chapter is to develop a tomographic method for determining the coherence errors of gates in Raman-coupled qubits. The main idea is to use constructive interference created by repeated interactions, which leads to an increase in errors. These values can be measured, from which single gate errors can be determined. This relationship is based on the relationship between the N-process Cayley-Klein parameters and the single-process Cayley-Klein parameters, respectively. Detuning error (detuning error) and pulse area error (pulse area error) are considered. The Cayley-Klein parameters are expressed in terms of three parameters that characterize the coherent errors in the gate. Finally, a technique for determining gate errors is proposed. The Rabi model is considered first. In a close resonance approximation, a sequence of measurements is proposed that determine the errors in the Raman qubit gate. The tomographic technique is also considered for other models with time-dependent Rabi frequencies.

The last **seventh chapter** presents the conclusion of the dissertation work.

Publications and significance of results

The dissertation is based on **3 scientific publications** in journals with an impact factor.

The nature of the initial works and their number fully satisfy the requirements of the Department of Physics, Sofia University"St. Kliment Ohridski" to receive the scientific degree "doctor".

Critical remarks

The dissertation is written in very good English and the presentation of the results is clear. Before each chapter there is a short introduction and finally conclusions are presented. Basically the only complaint I have is that some parts of the introductory chapter could be shortened. Also, for the convenience of the reader, it would be good to introduce the IBM Quantum qubit with more details.

I have the following questions for the dissertation student related to the dissertation:

1. The thesis mentions that the average error of the IBM Quantum CNOT gate is 6x10-3. How is this value measured?

2. How is IBM Quantum read out? It is mentioned in the thesis that this is one source of error. How can this error be reduced?

3. Where can one observe a real quantum system with more than three levels that possesses Wigner-Majorana symmetry?

Personal impressions of the candidate

I have known Stancho G. Stanchev personally since he started as a doctoral student in the group of Prof. Nikolay Vitanov. My personal impressions are of a highly motivated scientist who works with desire and inspiration in the field of quantum information. The submitted dissertation work shows that Stancho G. Stanchev has really penetrated deeply into this rapidly developing field.

Conclusion

After having familiarized myself with the submitted dissertation, the Abstract and the other materials, I confirm that the scientific achievements meet the requirements of ZRASRB and the Regulations for its application and the relevant Regulations of SU "St. Kliment Ohridski" for acquiring the educational and scientific degree "doctor". In particular, the candidate satisfies the minimum national requirements in the professional direction and no plagiarism has been found in the dissertation and the Author's Abstract submitted for the competition.

GENERAL CONCLUSION

Based on the above, I recommend the scientific jury to award the educational and initial degree doctor in professional direction 4.1 Physical Sciences; Physics of Atoms and Molecules by Stancho Georgiev Stanchev.

29.08.2024

Prepared the review:

Assoc. Prof. Peter Ivanov

Peter Ivanov

Digitally signed by Peter Ivanov
DN: cn=Peter Ivanov, o=Sofia University, ou, email=pivanov@phys.uni-sofia.bg, c=BG
Date: 2024.08.29 11:32:04 +03'00'