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**Investigation of the nature of decoherence in experimental quantum gates using a quantum noise model based on the analysis of Markov dynamics of quantum processes**

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Quantum decoherence of quantum systems is an important challenge on the way to creating reliable quantum computers. The loss of a fragile quantum state due to interaction with the environment introduces errors in calculations and limits the time during which a quantum processor can operate efficiently. To overcome this problem, a deep understanding of the nature of quantum noise is needed. In this paper, we solve precisely this problem by investigating decoherence on a modern ion processor using experimental data and a range of different techniques. Our goal is to develop realistic and at the same time cost–effective models that will predict the behavior of quantum processors and optimize algorithms to minimize the impact of noise.

To achieve this research goal, we apply two complementary approaches to decoherence modeling. The first approach is based on the representation of experimental quantum channels as a sequence of simple, well-studied standard quantum channels following an ideal quantum gate. This allows us to "disassemble" a complex experimental channel into simpler components. In this paper, this method is used for three types of quantum gates: *Rx, Ry, Rxx.*

The second approach to decoherence modeling, which is more fundamental, uses the apparatus of open quantum systems. He connects the ideal description of quantum gates (through unitary operators) with the real dynamics of qubits, taking into account their interaction with the environment. To describe Markov dynamics, we use the Gorini-Kosakovsky-Sudarshan-Lindblad equation, which is based on the evolution generator superoperator and has the form:

(1)

где – the density matrix, *H* – the Hamiltonian, – the time differentiation, – the noise operators of the dissipative part.

This approach allows us to theoretically describe the decoherence processes based on the physical parameters of the system.

The developed model is intended for the analysis and characterization of quantum gates on a quantum processor. In particular, the model allows us to reconstruct the Markov evolution generator (also called a dissipator), which describes the imperfect behavior of the gate due to decoherence and noise. In addition, the model allows us to determine the correction to the ideal Hamiltonian, taking into account the real conditions of the gate implementation. The principle of operation of the model is to approximate the input quantum channel (superoperator) describing the gate with a Markov approximation of the form:

(2)

where – gate execution time, 𝐇 *–* the unitary evolution generator corresponding to the implementation of the ideal gate (the ideal gate channel has the form ), – the correction to the unitary generator and is the dissipator.

To analyze the obtained dissipator, it was presented as a superposition of superoperators corresponding to the action of standard quantum channels: depolarizing, dephasing, and damping. This makes it possible to interpret dissipative processes in terms of known types of quantum noise.

The results of processing experimental data for the first model are presented in Table 1 and Table 2, demonstrating the extent to which the use of standard quantum channels has improved fidelity (reproduction accuracy) between experimental and ideal gates. Fidelity, used as a quantitative measure of similarity, is defined by the expression: .

Table 1. Fidelity of reproduction for a two-qubit *Rxx* gate.

| Gate *Rxx* | *F* | *F0* |
| --- | --- | --- |
| 2-qubit depolarization | 0,909 | 0,825 |
| x2 1-qubit depolarization | 0,966 |
| x2 1-qubit damping | 0,873 |

Table 2. Fidelity of reproduction for single-qubit gates depending on the channel.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| Gate name |  |  |  |  |
| *Rx* | 0,894 | 0,978 | 0,941 | 0,907 |
| *Ry* | 0,973 | 0,998 | 0,955 | 0,960 |

The results obtained demonstrate that the depolarizing channel is the most appropriate and adequate model for describing dissipative processes in the system under consideration within the framework of the first model. The use of a depolarizing channel significantly increased fidelity by 9% and 7% for single-qubit gates, and by 10% and 17% for double-qubit gates, indicating a significant improvement in the quality of quantum operations.

For the second model, aimed at a more detailed study of dissipation, a table of coefficients of decomposition of the final dissipator into the basis of superoperators (formula (2)) corresponding to standard quantum channels is presented. The representation of the coefficients in the form of triples (each triple is divided by the maximum of these three numbers for the simplest comparison) facilitates the interpretation of the contribution of each standard channel to the total dissipation.

(2)

Table 3. Maximum fidelity between the experimental dissipator and the desired linear combination of standard channel dissipators

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| test №, system dimension |  |  |  |  |
| test 1, d = 2 | 0,033 | 1 | 0,497 | 0,980 |
| test 2, d = 2 | 0 | 1 | 0,002 | 0,999 |
| test 1, d = 4 | 0,083 | 1 | 0,145 | 0,764 |
| test 2, d = 4 | 0,112 | 1 | 0,337 | 0,685 |

The results obtained indicate that depolarization prevails in real quantum noises and, for example, for single-qubit operations, the depolarizing channel is a very good approximation of the noise existing in the processor as a whole, which also corresponds to the result obtained in the first method.

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**Literature**

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