Abstract

論文の内容の要旨

論文題目　Theory of quantum error correction in near-term quantum devices
(近未来で実現される量子デバイスにおける量子誤り訂正の理論)

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- **Total summary**

In this thesis, we investigated a theory of quantum error correction (QEC) in near-term quantum devices. Due to the recent development of quantum technologies, QEC with several tens of qubits is expected to be demonstrated in the next few years. On the other hand, since such a large quantum system cannot be tracked with current classical computers, several problems about practical QEC experiments emerge as quantum devices are scaled up. We provided solutions to the following two essential problems among them.

First, we extended a simulatability of quantum error correcting code under coherent noise using free-fermionic dynamics. This extension enables an efficient and accurate evaluation of an effective physical error probability suppressed with QEC under practical errors. Since this probability should be known before we design quantum devices for QEC, this result provides vital information for experiments.

Second, we proposed a general framework to use machine learning as a part of decoding algorithm in QEC. QEC requires a fast and high-performance classical decoder for its implementation. Using machine learning for decoding is one of the most promising solutions to this. However, what part of a decoding algorithm should

be delegated to machine learning in order to achieve the near-optimal performance has not been discussed. We constructed a general framework to discuss it, and showed fundamental relations between the decoding problem and the task of machine learning. Furthermore, we proposed a criterion for achieving high performance. Then, we confirmed that the performance of the machine-learning-based decoder constructed with this guiding principle is superior to the known decoders in various situations.

- **Background**

Quantum computation is a computational framework to utilize properties of quantum mechanics for computation. Since quantum computer is believed to enable exponentially faster processing than classical computer in several tasks, massive efforts have been paid for building quantum computer. When we build quantum computer in a scalable manner, the most difficult obstacle is unavoidable physical errors caused by noise from environment and by imperfection in experimental controls. An applicable size of computational tasks is limited by an achievable physical error probability. Quantum error correction (QEC) provides solutions to this problem. According to the theory of QEC, we can construct a few clean logical qubits from several tens of noisy physical qubits if each qubit has a physical error probability smaller than a threshold value. Thanks to the recent development of quantum technologies, quantum devices have been scaled up with a small physical error, and this requirement for QEC is expected to be satisfied in the next few years. When we start to build quantum devices in such a large scale, it is expected that we encounter several new problems which originate from the fact that such a large quantum system cannot be tracked with current classical computers. In this thesis, we focused on two of the most essential problems among them. The first is that we cannot efficiently evaluate the effective error probability after suppression achieved with a QEC. The other is that a fast, versatile, and reliable decoding algorithm is still lacking.

- **Efficient simulation of quantum error correction under coherent noise based on non-unitary free-fermionic formalism**

According to the theory of QEC, we can perform quantum computation with an arbitrary accuracy by increasing the number of physical qubits for constructing a logical qubit. We call the effective error probability of a logical qubit as a logical error probability. A logical error probability for a given setting of

QEC is the most vital information when we design quantum devices for QEC. We can efficiently calculate a logical error probability by sampling the results of QEC if we can efficiently simulate the noisy quantum circuits of the chosen quantum error correcting code. The value of a logical error probability depends on various factors of QEC, such as the assumed noise model. Since an efficient simulation of quantum circuits under an arbitrary noise model is known to be computationally hard in general, what family of noisy quantum circuits can be efficiently simulated has been a focus of theoretical study. By virtue of the Gottesman-Knill theorem, we can efficiently simulate an arbitrary quantum circuit that consists of probabilistic Clifford operations and Pauli measurements. Since the circuits of quantum error correcting codes can be usually represented with Clifford operations and Pauli measurements, we can efficiently simulate them under Clifford noise, and can calculate the logical error probability. For example, incoherent noise, which is caused by decoherence of qubits, can be considered as Clifford noises. On the other hand, coherent noise, which is caused by experimental imperfection such as inaccurate calibration, cannot be represented as probabilistic Clifford operations. Thus, an efficient and accurate scheme for calculating a logical error probability under coherent noise has been lacking.

In this part, we show that the logical error probability under coherent noise in the case of a surface code, which is the most promising candidate of quantum error correcting codes, can be efficiently and accurately calculated. The key of our idea is to use non-unitary free-fermionic formalism for an efficient simulation of quantum circuits under coherent noise. It is known in the field of the condensed matter physics that dynamics of free fermions can be efficiently simulated. We expect that if we can map the quantum circuits of a quantum error correcting code under coherent noise to dynamics of free fermions, we can efficiently simulate the noisy quantum circuit by simulating the mapped free-fermionic dynamics. We first showed that one-dimensional (1D) repetition code, which is a 1D analog of the surface code, under coherent noise can be straightforwardly mapped to a free-fermionic dynamics. Then, we showed that the surface code under coherent noise can also be mapped to a dynamics of free fermions. We also numerically calculated the effect of the coherence in noise on logical error probabilities in the 1D repetition code. In particular, we found that the tolerable physical error probability to perform QEC becomes one-third when noise is fully coherent compared to the case under incoherent noise. We also estimated the effect of the coherence in noise on the logical error probability using leading-order analysis, based on an ansatz that the effect of the coherence in noise can be attributed to an increase of an effective physical error probability under incoherent noise. We confirmed that our accurate numerical results agree well with the approximation based on the ansatz.

- **General framework for constructing near-optimal machine-learning-based decoder of the topological stabilizer codes**

One of the most important factors that determine the performance of QEC is a decoding algorithm. Unfortunately, it is known that there is no efficient and optimal decoding algorithm for QEC in general. Thus, an efficient and near-optimal decoding algorithm which is applicable to any practical noise model is demanded in order to demonstrate QEC in near-term quantum devices. Though various decoding algorithms have been proposed, they sacrifice either of accuracy, efficiency, or applicability to various noise model. An idea of using machine learning as a part of decoding algorithm is expected to solve this problem. This is because once we appropriately train the prediction model, it is expected that the trained model can efficiently carry out the task of the decoding. Though several decoding algorithms using machine learning were proposed, they only mapped the decoding problem to the scheme of machine learning straightforwardly, and numerically showed that their performances can be comparable to those of known deterministic decoding algorithms. There is no comprehensive understanding about how we should use machine learning as a part of decoding algorithm.

In this part, we clarify what part of the decoding algorithm should be delegated to the machine learning in order to guarantee that the whole decoding algorithm becomes optimal in any noise model when the prediction model is correctly trained. In order to discuss the condition analytically, we introduce a general framework of machine-learning-based decoder such that all the existing works about machine-learning-based decoder can be treated as specific cases of this framework. Furthermore, based on this framework, we proposed a criterion which should be minimized to construct a near-optimal decoding algorithm when we use machine learning as a part of the algorithm. We numerically showed that the performance of the machine-learning-based decoder constructed with this guiding principle is superior to all the existing machine-learning-based decoders. We also confirmed that the performance of the proposed decoder is close to the optimal one not only in the surface code but also in the color codes, which are another family of topological codes.