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学位（専攻分野）	博士（情報学）
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学位論文題目	Symmetry breaking and its applications to quantum information processing
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（様式３）

博士論文の要旨

氏　　名　櫻井　彰忠

論文題目 Symmetry breaking and its applications to quantum information processing

The recent developments in quantum technology enable us to realize and control isolated quantum systems with multiple particles and spins with high precision. These systems are called the Noisy Intermediate-Scale Quantum (NISQ) devices and consist of tens to hundreds of qubits. Although the size of these devices suggests computational power superior to their classical counterparts, errors associated with system imperfections seem to be an obstacle to performing advanced quantum processing tasks. It is an open fundamental question of how such devices could harness this expected computational power if that is possible.

In this thesis, we address this question with two different approaches. In these approaches, we will focus on Floquet systems, which are periodically driven quantum systems that have been experimentally demonstrated in many physical systems. Floquet systems are expected to exhibit new phenomena that cannot be seen in equilibrium quantum systems and could be exploited for quantum processors. In particular, we use discrete-time crystals (DTCs), which break the discrete-time translational symmetry (DTTS).

In Chapter2, we briefly explain DTTS breaking and DTCs in Floquet spin networks and provide the physical concepts and mathematical tools for the following chapters. We primarily consider 2T-DTCs, which are widely applied to other theoretical models and experimentally demonstrated with several NISQ devices. To simplify the discussion, we introduce its minimum model and carefully derive its 2T-effective Hamiltonian, essential for analyzing DTCs. Using this Hamiltonian, we show the Z2-Ising symmetry plays an essential role in 2T-DTCs. After that, we explain two different approaches, MBL-DTCs, and pre-thermal-DTCs to understand the stability of the sub-harmonic oscillation on the spin networks, which is a signal of the DTTS breaking. Further, to understand the DTC and its phase transition, we introduce a mapping between the Ising model and the effective Hamiltonian, which governs stroboscopic dynamics. At the end of the chapter, we review two crucial experiments on DTTS breaking and realizing DTCs using trapped ions and NV centers.

The first part of the thesis proposes two new quantum phases that break the DTTS using a spin network. Chapter 3 shows how regional driving can break the DTTS regionally. Due to this regionally broken DTTS, two different phases of matter can coexist in one quantum system, despite the interactions throughout the quantum system. We named this novel quantum state "chimeric time crystal" as an analogy to the classical chimeric state. We investigate the chimera time crystal from a microscopic perspective by employing its entanglement entropy at stroboscopic times. We found that while a network exhibits the chimera phase, the entanglement growth is highly suppressed despite long-range interaction. Our results could contribute to the design of the quantum simulator and quantum memories using Floquet systems.

In DTCs, besides the Z2-Ising symmetry, the spin network has the U(1)-symmetry at stroboscopic times. Chapter 4 introduces a new DTC model breaking the local U(1)-symmetry. We show that as long as the global U(1)-symmetry is preserved, the network can exhibit DTCs for specific initial states. We analyze this model with and without environmental effects and show that the network can exhibit sub-harmonic oscillation with sufficiently long periods, even when the environmental effects being present.

Next, we discuss our discovery that breaking the local U(1)-symmetry in the network induces the time crystal growth that does not appear in the conventional model. We show that time crystal growth can be stabilized due to the environmental effect. To understand its mechanism, we analyze the spectrum of the 2T-effective Liouvilllian operator, which governs the stroboscopic dynamics of the dissipative systems. The analysis shows that the time scale of time crystal growth can be estimated by the Liouvillian gap. Further, we investigate negativity (a measure of entanglement commonly used in open systems) of the spin network to understand crystal growth from the microscopic perspective. Our new model allows us to understand the dynamical quantum phases of matter coupled to the environment.

The second part of the thesis proposes a new quantum processor using such dynamically driven systems. Our model is a quantum neural network (QNN) based on two classical computational models, reservoir computation and extreme learning machine. It mainly consists of a classical input layer, a quantum layer, and a classical output layer. The quantum layer is a quantum reservoir providing a huge neural network. The classical input is to pre-process the classical data and then efficiently encodes the data into the quantum reservoir as its initial state. We employ a DTC for the quantum reservoir. To connect the quantum layer to the classical output layer, we insert M-layer, which is a measurement layer to convert the quantum output information to the classical information. The learning process optimizes the classical network between the M-layer and the output layer.

We then apply this new QNN model to classification problems. In particular, we extensively investigate how this model enables pattern recognition of handwritten digits using the MNIST data set and demonstrate that the accuracy reaches 98% with only 14 qubits. We efficiently encode images into quantum states using classical data compression with only single-qubit operations. Unlike the variational quantum algorithms, our model does not require optimization on the quantum system. This dramatically simplifies the quantum device and its control, and it contributes a significant speed-up of the learning processes. Using DTCs as the quantum layer, we reveal the essential relationship between the quantum neural network's performance and the system's symmetry.

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Results of the doctoral thesis screening

博士論文審査結果

Name in Full
氏 名　櫻井　彰忠

Title
論文題目　Symmetry breaking and its applications to quantum information processing

The thesis titled "Symmetry breaking and its applications to quantum information processing" has six chapters. The first chapter has the introduction for the thesis to explain the motivation of his PhD research and provides the technical basis of quantum information, Floquet systems, symmetry breaking, quantum phase of matter, and machine learning to understand the following chapters.

The second chapter starts with a description of the discrete-time translational symmetry (DTTS) breaking and discrete time crystals (DTCs) in Floquet spin networks. Using the minimum model of the DTCs, the role of the Z2-Ising symmetry is discussed. The DTC and its phase transition are also discussed by introducing a mapping between the Ising model and the effective Hamiltonian. At the end of chapter, the recent experimental development to realize DTCs was summarized.

Chapter 3 shows how regional driving can break the DTTS regionally, and then applying this regionally broken DTTS, it shows that two different phases of matter can coexist in one quantum system. To derive and explain this novel quantum phase of matter, in his thesis he analytically derived the effective Hamiltonian and applied two complementary approaches: the analytic characterization of the effective Hamiltonian and the numerical calculation of the quantum dynamics. Further, the quantum informatic properties in this phase of matter are investigated by calculating the entanglement entropy at the stroboscopic times and the analysis discovers that the suppression of the entanglement growth despite the long-range interaction in the spin network.

Chapter 4 introduces a new DTC model with the local U(1)-symmetry breaking, which indicates that the preservation of the global U(1)-symmetry is sufficient for the network to exhibit DTCs for specific initial states. In this chapter, two different cases with and without environmental effects are discussed and it is shown that even with dephasing the network can exhibit sub-harmonic oscillation with sufficiently long periods. The stability of the DTC phase has been analytically discussed. Further, it describes his discovery of time crystal growth. Breaking the local U(1)-symmetry in the spin network induces the growth of time crystal which can be stabilized by the environmental effects. This phenomenon is then explained by the analysis of the 2T-effective Liouvillian.

In Chapter 5, a new quantum processor using such dynamically driven systems is proposed. This is a new quantum neural network (QNN) model with a quantum reservoir. It is then numerically tested by its performance for classification problems. The thesis provides the performance evaluation for a few classification problems. In particular, it numerically demonstrates its performance for the pattern recognition problem of hand written digits using MNIST data set. The accuracy rate of 98% has been achieved with only 14 qubits.

Chapter 6 summarizes the results in the thesis.

In the final evaluation, the candidate presented his thesis in the order described above and appropriately answered to the questions raised by the evaluation committee. After the evaluation, the committee discussed his thesis and the presentation and concluded that his PhD research is high quality and significant in both its novelty and originality.

To conclude, his thesis focus on symmetry braking to deepen our understanding of quantum phase of matter in periodically driven systems and applies it to design novel applications for quantum information processing. During his PhD, he published four journal papers and several oral presentations in the international workshops. He has a significant contribution in the fields of quantum physics and quantum information processing. The evaluation committee concluded that his thesis deserves a PhD.