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変革を駆動する先端物理・数学プログラム（FoPM）

国外連携機関長期研修　報告書

氏　　名	矢萩　慎一朗
所属部局	理学系研究科　　物理学専攻
受入先	QunaSys　リサーチ事業部
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During this internship, I leveraged my academic background in theoretical particle physics to study the simulation of experimental and theoretical models using quantum computers. Specifically, we conducted reviews of relevant research papers and utilized Python to implement quantum circuits equivalent to those described in the literature, successfully reproducing their results. Furthermore, we explored methods for more efficient simulations and presented our findings on these topics.

Quantum computing technology has advanced dramatically in recent years, enabling qubit-based computation by realizing two-level systems through various methodologies. While current physical simulations on quantum computers often rely on simplified toy models due to limitations in the number of qubit and gate fidelity, it is expected that quantum computers capable of simulating practical, large-scale systems will be realized within the next few years.

Since particles in the real world exhibit quantum behavior, quantum computers are expected to perform certain calculations more efficiently than classical computers. In particle physics experiments, the sequential processing of vast amounts of observed data is required and quantum computing holds the potential for more precise and fast data analysis.

The following are the papers that I reviewed in particular detail.

In accelerator experiments designed to observe elementary particles, the phenomenon where particles continuously branch is known as a parton shower. Generally, these experiments measure the energy and momentum of particle bundles called jets. The paper [1] investigates a method to map this information into quantum states and utilize quantum machine learning to identify the original particle that initiated the jet. The paper employs two types of machine learning: Quantum Autoencoders (QAE) and Variational Quantum Circuits (VQC). The former involves supervised learning, where combinations of particle types and trajectories are provided as a labeled dataset, while the latter involves unsupervised learning, which classifies trajectories based on inherent features without requiring a labeled dataset. Future applications are expected to include filtering jets produced by specific particles of interest, such as the Higgs boson or W and Z bosons, from massive datasets, as well as detecting unknown particles.

The paper [2] simulates the collision of wave packets that composed of various overlapping momenta using quantum computers. Generally, by mapping an initial state and a Hamiltonian onto a quantum circuit, one can calculate time-evolution using the method called Trotter decomposition. In spin models like the Ising model, the degree of freedom of a single spin (up or down) can be directly represented by a single qubit. A wave packet is realized as a superposition of plane waves of various momenta with specific weights, typically following a Gaussian distribution centered around a momentum k_0. Given a specific Hamiltonian, a ground state can be obtained from a superposition of plane waves by preparing a quantum circuit with tunable parameters and using Variational Quantum Eigensolver (VQE), which is the process to minimize the energy using classical machine learning. By simulating the collision of ground states centered at different momenta, one can investigate the production of excited states, which corresponds to the fundamental scattering phenomena in the jet production process. The paper demonstrates that for relatively simple systems, such as the 1D Ising model or the Schwinger model, the creation of excited states via collision occurs only when the energy exceeds a certain threshold via quantum computers.

The paper [3] explores methods for simulating SU(n) lattice gauge theory on quantum computers. Generally, in pure gauge theory without matter terms, states are represented by assigning representations of the gauge group to each link of the lattice. Since there are infinitely many representations for SU(n), some form of truncation is necessary to map these states onto a quantum circuit. This paper represents states by restricting them to a finite set with low electric energy. Calculating time-evolution requires the Clebsch-Gordan coefficients, which appear in the products of representations and are computed classically. In general, since the number of states increases exponentially with

the system size, implementing the transitions between each state remains the most gate-intensive part of the quantum circuit. Currently, simulations for systems of 2×2 (2-dimensional) or 2×2×2 (3-dimensinal) are feasible, yielding results that align with classical diagonalization methods.
As described above, the application of quantum computers to various simulations in the field of particle physics is being actively researched. In these studies, Python is predominantly used for circuit design and computation, whether via simulators or actual quantum hardware. Packages such as Qiskit are instrumental for describing quantum circuits, and services provided by IBM allow for execution on real quantum devices. While current limitations in the number of qubit and error correction make it difficult to outperform classical simulators, the physical trends such as particle classification from jets and the presence of excitations can be reproduced. During my internship, I implemented quantum circuits based on these papers and successfully reproduced their results using simulators. We also researched methods to improve circuit efficiency in terms of qubit and gate counts for future large-scale execution, focusing on techniques for more effective information mapping and the use of symmetries to simplify time-evolution calculations.

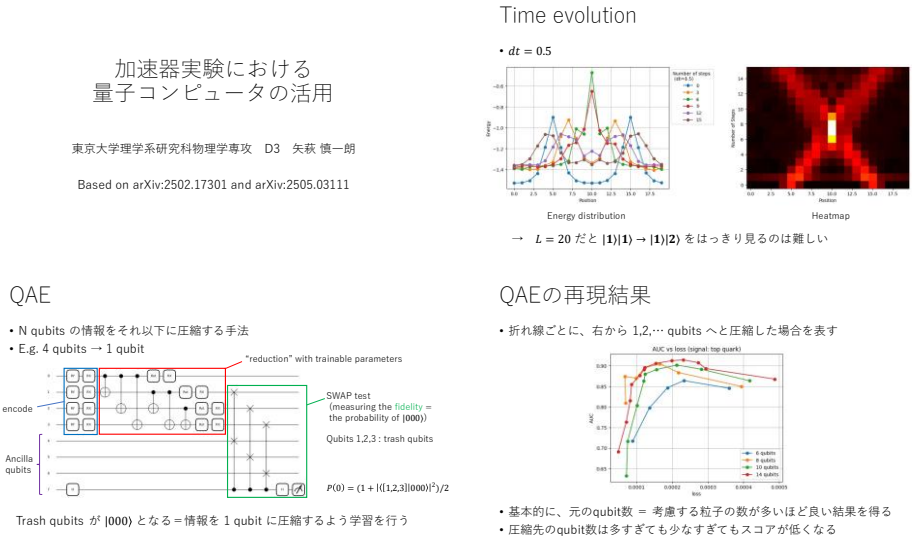


Figure 1　Selected slides from the presentation

References

[1] A. Bal, M. Klute, B. Maier, M. Oughton, E. Pezone and M. Spannowsky, “One particle - one qubit: Particle physics data encoding for quantum machine learning”, Phys. Rev. D **112** (2025) no.7, 076004.
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[3] P. Balaji, C. Conefrey-Shinozaki, P. Draper, J. K. Elhaderi, D. Gupta, L. Hidalgo, A. Lytle and E. Rinaldi, “Quantum circuits for SU(3) lattice gauge theory”, Phys. Rev. D **112** (2025) no.5, 054511.