【Grant-in-Aid for Transformative Research Areas（B）】

Unveiling the Quantum Information Structure of Many-Body Systems: Decoding New Physics from Fine Microscopic Details

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Purpose and Background of the Research

●Outline of the Research

In the quantum world, many interacting particles can produce complex properties that cannot be understood from individual particles alone. Such quantum many-body systems underlie quantum computers, quantum materials, and quantum heat engines, but the hidden order of information inside them remains poorly understood. In this research area, we view quantum many-body systems as places where information is encoded, spreads, is transformed, and is controlled. By focusing on quantum entanglement, heat, computational complexity, information propagation, and control costs, we aim to reveal the hidden information structure of quantum many-body systems.

The project proceeds in four directions: information structures of quantum states (A01), quantum transformations (A02), quantum control (A03), and computational physics for exploring such structures (A04).

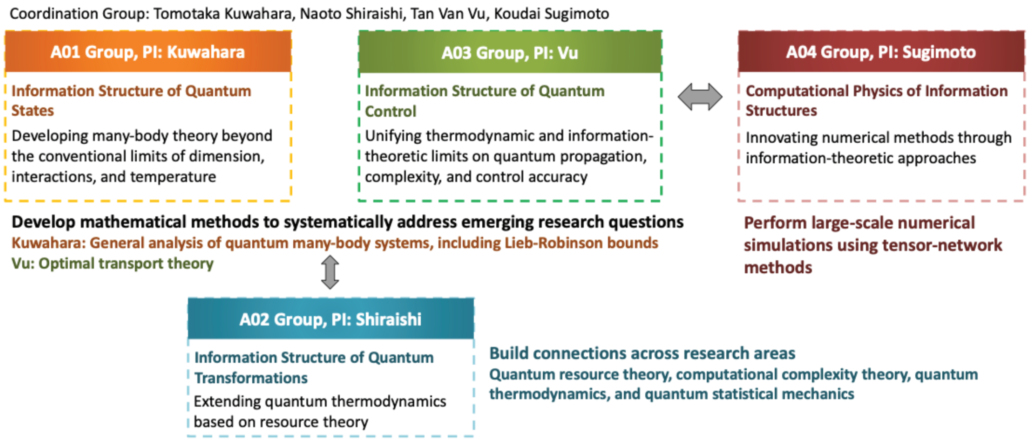

Figure 1. Image of the Whole Project

●Toward a New Quantum Many-Body Theory Beyond Conventional Limits

Conventional theories have mainly focused on tractable quantum systems. However, real quantum materials and future quantum technologies require theories for more complex regimes, such as high dimensions, low temperatures, strong correlations, and nonequilibrium dynamics.
By integrating quantum information, quantum thermodynamics, optimal transport theory, and computational physics, this project aims to reveal universal information structures hidden in complex quantum many-body systems.

●Research Goals of Each Group

A01: Reveals universal structures of entanglement and information propagation in high-dimensional, low-temperature, and strongly correlated quantum many-body systems, with a focus on the entanglement spectrum.

A02: Clarifies the fundamental limits of transforming quantum states by combining quantum thermodynamics, resource theory, and computational complexity.

A03: Formulates universal trade-offs among speed, accuracy, and energy cost in quantum control using optimal transport and information theory.

A04: Develops large-scale numerical methods, such as tensor networks, to study finite-temperature and nonequilibrium quantum many-body systems and connect theory with experiment.

Expected Research Achievements

● Breakthroughs through Interdisciplinary Collaboration

This research area tackles unresolved problems that are difficult to solve within a single field. By combining theoretical and numerical methods across the groups, we aim to reveal information structures common to quantum many-body systems, including information propagation, thermodynamic cost, localization, and computational complexity.

1. Information propagation beyond Lieb-Robinson bounds: We develop a new “post-Lieb-Robinson” theory that treats not only how fast quantum information can spread, but also how much information can be transmitted over a given distance and time scale. This approach reframes information propagation in quantum systems from a simple question of whether information can reach a region to a quantitative theory of how information is distributed and transported. It also aims to reveal new structures in time-dependent quantum dynamics that are absent in time-independent systems.
2. Thermodynamics of quantum computation: As quantum computers become larger, the energy cost of cooling and control becomes essential. We combine quantum thermodynamics and resource theory to clarify fundamental limits on energy, accuracy, and speed in quantum information processing.
3. Information-theoretic understanding of many-body Wannier-Stark localization: We study how strong external fields suppress the spreading of quantum information and energy. By combining theory and numerical simulations, we aim to build a new theory of localization in driven quantum many-body systems.
4. Quantum circuit complexity of error spaces: We clarify the unavoidable computational cost required to approximate quantum states and dynamics with small errors. This provides a theoretical basis for distinguishing what is efficiently computable from what is fundamentally difficult in quantum many-body simulations.

● Future Impact

Information-theoretic methods are expanding beyond quantum physics into AI, complex systems science, computational science, and industry. This research area will elucidate the information structure of quantum many-body systems from first principles, strengthen the foundations of quantum computing and quantum materials research, and create new currents in quantum science and information theory.

Website(s)	https://kuwahara-quantum.com/en/