Research area in Strategic Objective *"Creation of innovative quantum control technology through integrating quantum information and quantum materials"*

Quantum Cooperation between Materials and Information

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Overview

In this research area, intending to create innovative quantum control technology, we promote original and challenging research that transforms quantum materials properties into technology based on the viewpoint of quantum information. Through the cooperation of quantum materials science and quantum information, we conduct research and development to understand, functionalize, and control quantum materials, the node of the two research fields. We will create new foundations for the future of quantum control technology by pioneering new concepts and techniques. We will foster young researchers who will globally lead quantum science and technology by demonstrating their abilities supported by their rich conceptual power and insight, material synthesis, microfabrication techniques, measurement techniques, theory, and computational techniques.

We promote research from two perspectives: "control and functionalization of quantum many-body systems" and "application of new phenomena and states to quantum devices and quantum materials." Specifically, we will focus on pioneering new control methods of quantum states in quantum materials based on quantum information, proposing and demonstrating new principles for quantum bits, quantum sensors, and quantum simulations, and presenting and proving quantum algorithms with future-feasible physical systems in mind. We aim to integrate quantum materials science and quantum information beyond the conventional framework to build a cooperative development of the two research fields through these efforts.

Our research area promotes quantum science and technology in collaboration with materials science, information science, mathematical science, nanostructures science, and so on. We aim for discontinuous innovation through quantum control technology that can trigger a revolution in intellectual production and meet social needs, such as ensuring the safety and security of our country and citizens.

Research Supervisor's Policy on Call for Application, Selection, and Management of the Research Area

1. Background

Quantum science and technology is an innovation that will revolutionize the society of Japan and the world in the future, and competition in research and development is intensifying both domestically and internationally. The quantum revolution resulting from its growth is expected to meet various social needs, such as drastic improvement in intellectual production, the realization of a healthy and long-lived society through innovative medical care and health management, and the assurance of the safety and security of our country and citizens through communication and encryption technologies.

On the other hand, the subtleties and complexities of quantum states and their controls are unknown to human beings. Therefore, it is difficult for us to truly enjoy the unique properties of quantum states if we simply continue to develop technologies based on the existing ones; many breakthroughs in quantum control technology are indispensable. For example, while multiple methods are in a parallel development in the intense competition of quantum bits, it is believed that there is no conclusion yet on the type of quantum bits that will prevail in the future. At present, not all element technologies for realizing a large-scale quantum computer are available, and basic research on experimental, theoretical, and software aspects is still required. In this respect, quantum control technology is yet an unexplored area, a challenging field that can potentially change existing methodologies and worldviews with a single new idea.

Our research area promotes research to create ideas that can become fundamental technologies of the future, aiming to change the game from Japan through the cooperation of quantum materials science and quantum information.

2. Principle of invitation project and selection

(1) Basic principle

This PRESTO provides up-and-coming young researchers with the opportunity to promote cooperative research on materials and information from a quantum perspective to create new quantum control technology that will lead the next 10 to 20 years. As the name "quantum materials" implies, topology and quantum many-body phenomena involving many degrees of freedom give birth to abundant quantum phenomena. However, these fertile properties are unallocated to quantum control technology, and from this perspective, they remain unexplored. Creating new research fields at the intersection of quantum materials science and quantum information connotes tremendous values as an

effort to increase options of element technologies for large-scale quantum information processing and as a trigger for a global game-changer. We invite research proposals that expand the wings of imagination beyond stereotypes and view quantum materials as a field of quantum information, transforming this rich resource into technology. Conversely, we also welcome research proposals that bring an unprecedented perspective by starting from quantum information and promoting research with future-feasible physical systems in mind.

(2) Examples of specific proposals

Specifically, we seek ambitious research proposals on two topics: (1) control and functionalization of quantum many-body systems and (2) application of new phenomena and states to quantum devices and quantum materials. Quantum many-body systems with unique ground states and peculiar excited states often arise in quantum materials due to the topological properties and the entanglement of many degrees of freedom, such as charge, spin, and orbital. We welcome proposals to explore and elucidate new phenomena, new states, and new quasiparticles in such quantum many-body systems and develop them into quantum control technologies. We also accept proposals for quantum simulation of novel quantum materials phenomena and their improved controls and on the design, synthesis, and functionalization of materials expecting new phenomena to emerge. Furthermore, we encourage proposals on new quantum devices to transform the properties of new phenomena and states arising in quantum many-body systems into sensing, information processing, and other functions.

Some of the following research examples are also themes already being addressed worldwide. When you make such a proposal, please clarify your current status in the world and indicate the potential for academic development by asking yourself, “Why do I need to work on it now?” and “What new trends will be created in the world in the ten years after the PRESTO research period ends?” We also hope to receive other proposals for novel and challenging methods and ideas that will surprise the referees.

A) Control and functionalization of quantum many-body systems

- Design and synthesize new materials and substances (topological insulators, quantum spin liquids, quantum liquid crystals, etc.) that are expected to exhibit new quantum materials phenomena, and explore and demonstrate their application to quantum control technology
- Decoherence and dissipative engineering in quantum many-body systems

- Pioneering new quantum control techniques (quantum pumps, Floquet states, time crystals, etc.) realized by a non-equilibrium periodic driving
- Pioneering functions of nonlinear optical effects (e.g., shift currents) related to quantum phases
- Quantum algorithms, quantum-inspired algorithms, quantum machine learning, etc. with future-feasible physical systems in mind
- Development of methods to understand and control quantum many-body systems from the perspective of quantum entanglement

B) Application of new phenomena and states to quantum devices and quantum materials

- Propose and demonstrate new principle quantum bits and quantum sensors utilizing various topological structures and elementary excitations (Majorana particles, magnons, phonons, skyrmions, melons, etc.) that occur in quantum materials
- Advancement of solid-state qubits and quantum sensors infrastructure, including quantum dots, superconducting circuits, and diamond NV centers, and their applications
- Advanced, miniaturized, and chip-configured cold-atom systems, ion traps, optical circuits, etc., and their application to quantum simulations

(3) Selection policies

This research area does not accept research that straightforwardly extends existing research or combines or improves previous research. We expect original and innovative ideas and concepts that thoroughly reveal the proposal's value from the viewpoint of quantum control technology, its potential to bring about innovations, and the resulting universality as innovative functions or scientific value. Proposers should indicate international research trends and clarify the superiority and originality of their research proposals compared to conventional research. Furthermore, we expect ambitious research proposals that will pioneer new academic streams, describe the extent to which the study can be promoted within the PRESTO period, and offer prospects for applications that will contribute to solving social issues in the future.

Challenging proposals from those working exclusively in quantum materials science or quantum information are also welcome. We highly encourage researchers in quantum materials science to demonstrate new ideas from the viewpoint of quantum information or researchers in quantum information to invent new ideas from quantum materials science. Therefore, preliminary experiments to ensure the plan's feasibility are unnecessary at the proposal submission. However, even if the

proposal is still in the conceptual stage, we strongly request a logical demonstration of the feasibility of the research plan.

For research proposals on materials development, we expect proposals that go beyond the conventional approach of searching materials properties to demonstrate quantum control technology.

For research proposals on measurement, control, and evaluation, we expect innovative proposals that will yield new quantum control technologies through the development and advancement of new methods using quantum states.

For research proposals related to theory and computation, we do not expect research that advances knowledge only one or two steps forward within existing fields. Instead, we seek research that incorporates qualitatively new ingredients, opens up new areas, and results in a cross-disciplinary outcome. We also ask for a clear explanation of how the research proposal will guide the future development of quantum control technology.

3. Research periods and research funds

In principle, the research period will not exceed three and a half years, and the total research budget will not exceed 40 million yen (excluding indirect expense).

4. Principle of research-area management

In this research area, the research supervisor and advisors will work together to provide an environment where the PRESTO researchers can spend three and a half years working on their original research without being preoccupied with short-term outcomes. In addition, we strongly encourage collaborative and cross-disciplinary research exchanges by creating an atmosphere in which new research seeds can be discovered and nurtured through interactions with researchers in different fields in the related CREST and PRESTO research areas. We promote joint research with foreign countries and collaboration with associated communities domestically and internationally to conduct the research efficiently.