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

Unveiling, Design, and Development of Asymmetric Quantum Matters（Asymmetric Quantum Matters）

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Purpose and Background of the Research

●Outline of the Research

In this research area, we utilize the concept of multipole triggered by asymmetric electronic states in solid crystals to develop innovative functional properties and to understand electromagnetic effects such as cross-correlation response and non-reciprocal conduction. Recent advancements in quantum beam techniques and high-resolution physical property measurements enable us to unveil the order of multipoles and quantify the susceptibility to external fields. Based on the obtained insight, we construct new theoretical models of the cross-correlation mechanism and design new asymmetric quantum matters. Moreover, we extend the concept to molecular clusters, artificial materials, and broader targets, for leading the evolution of next-generation material science and seeking to frame the “asymmetronics”.

Figure 1. Overview of this research area.

●Development of new cross-correlation functions

In solid crystals, the asymmetry of electronic states is the origin of various functional properties. For example, electric polarization and ferroelectricity appear when the spatial inversion symmetry breaks, whereas ferromagnetism occurs when the time reversal symmetry breaks. Furthermore, when both spatial and time reversal symmetries are broken, a unique function "cross-correlation” emerges, wherein electricity and magnetism are closely correlated.

Recent research has shown that this cross-correlation can be understood by using a quantum "multipole”, which contains both the charge and spin of electrons. This concept is very useful for describing the functional properties. If spatial inversion symmetry is conserved, only diagonal responses like magnetization to a magnetic field will occur.

However, in an asymmetric state where the spatial inversion symmetry is broken, odd-parity multipole becomes active to induce off-diagonal responses and nontrivial cross-correlation functions. The advantage of the concept is that it is possible to explore new cross-correlation functions without any restriction in addition to the reflection and rotation symmetries considered before. This new tool gives us a significant breakthrough in materials science.

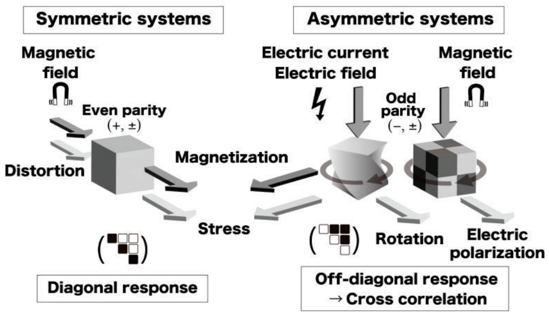

Figure 2. In a system with space inversion symmetry (left), a diagonal response to an external field appears. On the other hand, in asymmetric systems where space inversion symmetry is broken (right), a variety of cross-correlations are expected to occur due to off-diagonal responses.

●Asymmetric quantum matters × microfabrication techniques

Our research focuses on measuring the anisotropy in asymmetric quantum matters arising from the order of multipoles to develop new functions of cross-correlation. To enhance the response by single-domain formation and high current density, we employ the focused ion beam (FIB) technique commonly used in the semiconductor industry. Figure 3 displays our sample used for precise measurements to capture physical properties such as domain formation, non-reciprocal conductivity, and non-linear response that accompany the formation of order. Our findings lead to a better understanding of previously unknown physical properties, which can inspire innovative new material functions.

Figure 3. Single-crystalline sample micro-fabricated by FIB to measure transport properties.

Expected Research Achievements

●Unveiling order and fluctuations of multipoles to design and develop new asymmetric quantum matters

We focus on asymmetric quantum matters in which order of multipoles could produce a variety of functional properties. Utilizing a combination of advanced quantum beam, microfabrication technology, high-resolution macroscopic measurements, theoretical calculation and materials informatics, and materials synthesis, we explore new researches on detection, design, and development. Our goal is to develop next-generation materials science that spreads to a wide range of research fields.

(1) Research using advanced quantum beam analysis techniques to investigate the electronic states and the order parameters of multipoles. (A01)

(2) Experimental research that will lead to technological innovation, such as providing new functions of matters and realizing a huge response by microfabrication. (A02)

(3) Theoretical research that constructs basic theories based on multipoles and promotes its application. (B01)

(4) Development of new materials and functional properties. A wide range of materials are objects based on a scale-seamless perspective. (C01&C02)

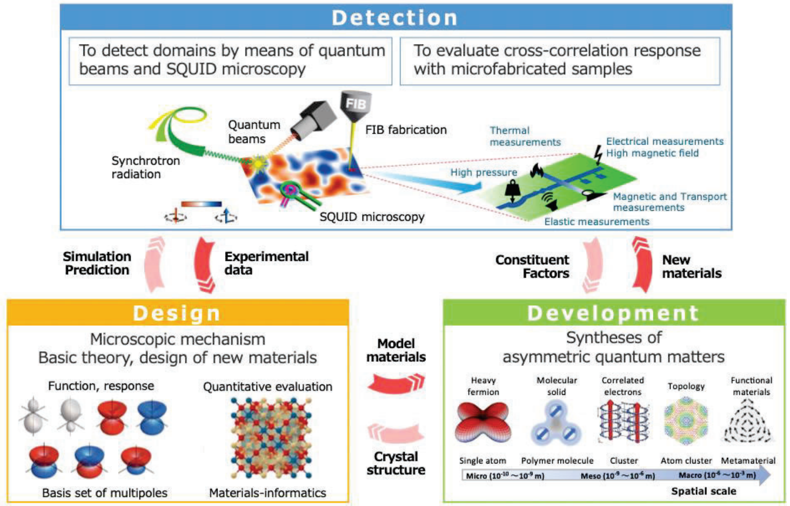

Figure 4. Intimate collaborations between the planned researches in this research area.

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