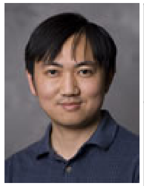
【Grant-in-Aid for Scientific Research (S)】

Cooperative Effects between Moiré Magnetism and 2D Superconductivity



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Project Information	Project Number : 25H00413　　Project Period (FY) : 2025-2029 Keywords : Moiré Magnetism, Superconductivity, Majorana particle, Spin injection, Josephson junction

Purpose and Background of the Research

●Outline of the Research

2D materials, which have an ideal two-dimensional (2D) structure, exhibit unique physical phenomena, often surpassing the physical properties of bulk materials. The physical properties of 2D materials are diverse, including metals, semiconductors, insulators, magnets, and superconductors. Combining these 2D materials with different physical properties makes it possible to create unique heterostructures, enabling the exploration of new physical phenomena and the development of next-generation devices. It has also been revealed that when two or more 2D materials are twisted relative to each other, a moiré superlattice is formed due to the lattice mismatch and twist angle of the adjacent 2D materials, and the long-period potential of the moiré superlattice significantly modulates the physical properties of 2D materials and 2D material heterostructures.

In the previous project "Grant-in-Aid for Scientific Research (A): Superconducting and magnetic properties of van der Waals heterostructure (Principal Investigator: Yong P. Chen)," the principal investigator's team of this study fabricated a heterostructure of 2D antiferromagnets CrI_3 and $CrCl_3$, and observed interface ferromagnetism and controlled it by gate voltage [Nat. Commun. 13, 7348 (2022)]. In addition, two 2D antiferromagnets CrI_3 were twisted relative to each other and stacked, and experimentally observed "moiré magnetism" (Fig. 1) caused by a moiré superlattice [Nat. Electron. 6, 434 (2023)]. These results suggest the creation and control of new magnetic states through 2D magnetic heterostructures and twisted moiré superlattices, and it is expected that innovative spintronics functionalities unique to the "heterostructure of twisted 2D magnetic materials and 2D superconductors" (Fig. 2) that cannot be obtained with a "simple heterostructure of 2D magnetic materials and 2D superconductors" emerge.

Therefore, in this research project, we focus on the "Cooperative effects between moiré magnetism and 2D superconductivity".

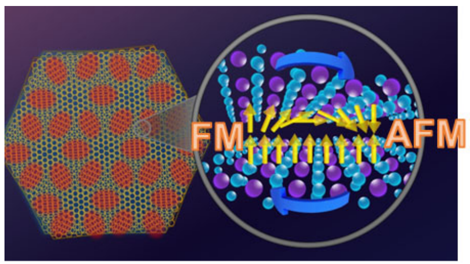

Figure 1. Conceptual drawing of "moiré magnetism".

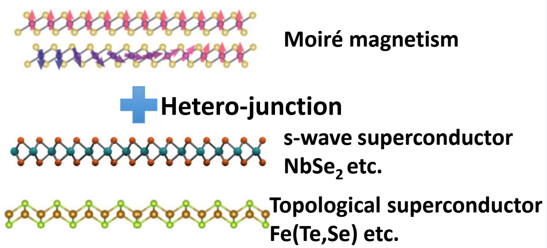

Figure 2. This research focuses on the "heterostructure of twisted 2D magnets and 2D superconductors"

Expected Research Achievements

●Observation of Majorana particle

In twisted 2D magnets, the magnetic order changes spatially due to the moiré superlattice, so it is hypothesized that majorana particles could form at different magnetic orders or at different moiré superlattice positions depending on the superconductor to which they are joined. (Fig. 3) Using STM, we will detect the zero-energy state, which is one of the characteristics of majorana particles, and clarify how the detection position of the zero-energy state changes due to an external magnetic field.

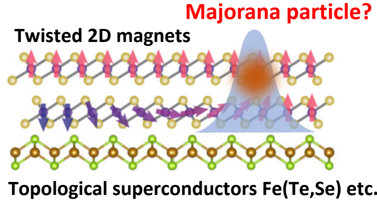

Figure 3. Schematic of majorana particle formation.

●Modulation and control of high-temperature superconducting properties by magnetic order and magnetic excitation

We will fabricate heterostructures of 2D high-temperature superconductors and twisted/2D magnets (Fig. 4), and systematically investigate the changes in superconducting properties (transition temperature, critical magnetic field, critical current) due to the interface electron exchange interaction and proximity effect.

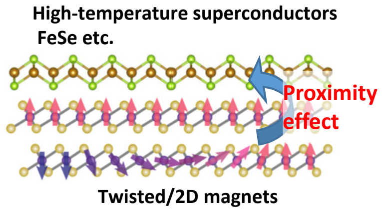

Figure 4. Conceptual diagram of the proximity effect on superconducting order.

●Effect of spin injection on superconducting properties

Using the spin pumping method (spin injection method using microwave excitation), we will inject spins from a magnetic material into a superconductor (Fig. 5), and systematically investigate the changes in superconducting properties (critical magnetic field, critical current, etc.) due to spin injection. We systematically investigate the change in the spin injection efficiency on the electronic and magnetic phase diagram, which is known from previous studies such as inelastic neutron scattering experiments.

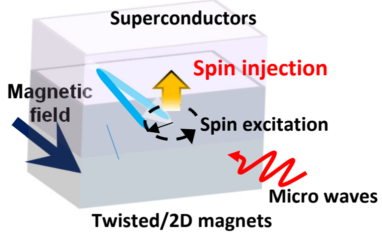

Figure 5. Schematic of spin injection experiment using spin pumping.

●Magnetic order, magnetization dynamics and Josephson dynamics in Josephson junctions

We will fabricate a superconductor | twisted magnet | superconductor Josephson junction (Fig. 6) and aim to detect 2D magnetism due to Josephson dynamics by measuring the current-voltage characteristics. Furthermore, we will study electrical transport phenomena arising from the cooperation of Josephson dynamics and spin dynamics. We will evaluate the effects of external magnetic fields and textured magnetization of magnetic materials on Josephson dynamics.

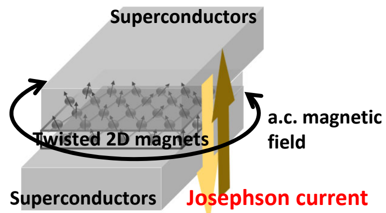

Figure 6. Schematic diagram of Josephson junction experiment.

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