Quantum teleportation in spin liquid – Toward the realization of topological quantum computation

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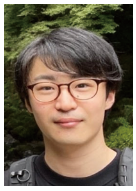


Abstract

We have theoretically elucidated the phenomenon of quantum teleportation utilizing the quantum entanglement of Majorana particles that exist within a magnetic state known as a quantum spin liquid. Majorana particles, originally proposed in the field of elementary particles, possess a unique property where the particle is identical to its own antiparticle. Recently, it has been theoretically predicted that particles with similar properties to Majorana particles appear in the spin-liquid state of a magnetic insulator called a Kitaev material. Due to their strong quantum entanglement, these particles are expected to be applicable to fault-tolerant quantum computation. However, to this date, there has been no known experimental method to verify the strong quantum entanglement of Majorana particles in Kitaev materials. In this study, we clarified that a quantum teleportation phenomenon occurs, whereby two spatially well separated electron spins exchange information via the quantum entanglement of Majorana particles in the material. Additionally, we demonstrated that this phenomenon can be detected electrically.

Background & Results

In this study, we developed a method to observe the quantum entangled state of Majorana particles in Kitaev materials. It is found that by conducting electrical conductivity measurements, Majorana particles in specific magnetic insulators such as a candidate material ruthenium tri-chloride can be detected. Furthermore, since Majorana particles bound to point defects are resilient to environmental noise, they can serve as components for qubits, marking a significant step toward the realization of a topological quantum computer.

Significance of the research and Future perspective

The theoretical proposal that Majorana particles could emerge in magnetic insulators known as Kitaev materials was put forth in 2006. With the discovery of specific candidate materials in 2009, the search for Majorana particles in magnetic materials have been extensively studied. Recent studies on the candidate material ruthenium tri-chloride have provided indirect evidences supporting the existence of Majorana particles. These particles are also anticipated to play a key role as a wildcard in realizing a topological quantum computer. Conventional quantum computers are generally highly sensitive to noise from environment, making the protection of quantum information from noise a critical challenge. In contrast, topological quantum computers using Majorana particles inherently possess mechanisms for protecting quantum information, potentially overcoming this issue at its core. Therefore, discovering Majorana particles in materials would mark a significant turning point toward developing ideal quantum computers in the future.

In this study, we theoretically examined a model in which Majorana particles emerge when multiple point-like lattice defects are present in a magnetic insulator under an external magnetic field, utilizing the property that entangled Majorana particles are bound to point defects on the lattice. As a result, we clarified that a quantum teleportation phenomenon reflecting the quantum entanglement of Majorana particles strongly bound to point defects occurs between electron spins adjacent to these defects and examined quantitatively that this teleportation does not depend on the relative distance. Furthermore, we used numerical simulations to demonstrate that the quantum teleportation phenomenon of electron spins can be detected by measuring electrical conductivity with a scanning tunneling microscope. Using this method enables experimental verification of Majorana particle quantum teleportation in Kitaev materials, representing a step forward toward realizing topological quantum computation.

Figure 1

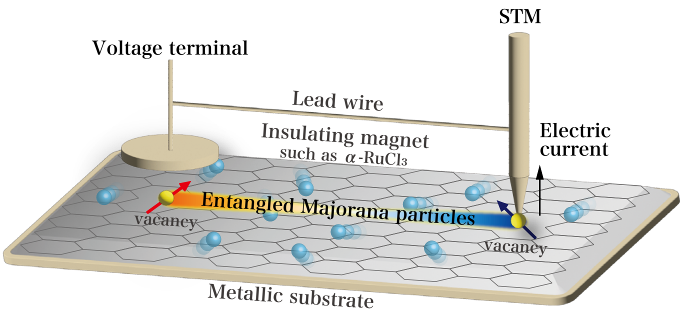

Figure 2

Patent

Treatise Takahashi, Masahiro; Yamada, Masahiko; Fujimoto, Satoshi et al. Nonlocal spin correlation as a signature of Ising anyons trapped in vacancies of the Kitaev spin liquid. Physical Review Letters. 2023, 131, 236701-1-6. doi: 10.1103/PhysRevLett.131.236701

URL

Keyword quantum teleportation, topological quantum computation, spin liquid, Majorana particles