Experimentally Tunable QED and Fractional Matter in Quantum Spin Ice

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Quantum spin ice (QSI) represents a class of three-dimensional quantum spin liquids where emergent gauge theories describe low-energy excitations. Recent advances have enabled both theoretical control over the emergent quantum electrodynamics (eQED) in dipolar-octupolar QSI and experimental verification of fractionalized spinon excitations in $Ce_2Sn_2O_7$. In this report, we summarize two key developments: (1) the demonstration of tunable emergent photon properties using external magnetic fields, and (2) neutron spectroscopy evidence for spinon-gauge field interactions in a three-dimensional spin liquid. These results provide new pathways for studying emergent gauge fields in condensed matter systems and open potential applications in quantum information science.

1. Introduction

Quantum spin ice (QSI) is a paradigmatic example of a three-dimensional quantum spin liquid, where long-range entanglement and emergent gauge theories play a central role in describing its low-energy excitations. These systems realize a U(1) quantum electrodynamics (QED) phase, featuring emergent photons, spinons, and visons. Understanding and controlling the properties of QSI has profound implications for condensed matter physics and quantum information science.

In this report, I summarize two recent advancements in QSI research: (1) the theoretical proposal of an experimentally tunable emergent QED in dipolar-octupolar QSI, and (2) the observation of fractional matter excitations coupled to an emergent gauge field in $Ce_2Sn_2O_7$. These results highlight the interplay between gauge fields and fractionalized excitations, providing new avenues for exploring exotic quantum phases.

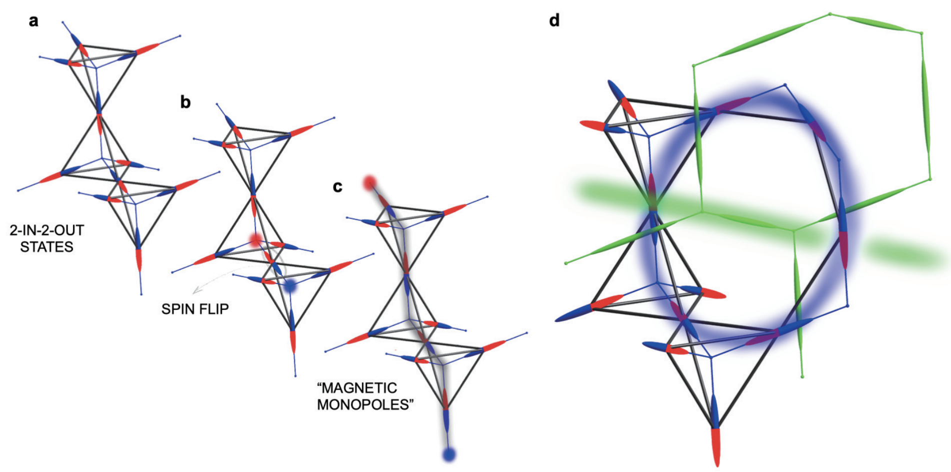

図 1　Magnetic monopoles in quantum spin ice.

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2. Research Overview

2.1. Experimentally Tunable Emergent QED in Dipolar-Octupolar QSI

Recent theoretical work has demonstrated that an external magnetic field can be used to tune the emergent speed of light and control the fine structure constant of the emergent QED in dipolar-octupolar QSI. This effect, analogous to the electro-optic Kerr effect, allows for differential tuning of the two photon polarizations. In particular, applying a magnetic field along different crystalline axes induces novel field-driven phase transitions, including a transition between 0-flux and π-flux QSI phases, as well as mixed-flux configurations.

These findings provide an experimental pathway to engineering eQED dynamics in candidate materials such as $Ce_2Zr_2O_7$, $Ce_2Sn_2O_7$, and $Ce_2Hf_2O_7$. The tunability of these systems opens possibilities for observing unconventional gauge field dynamics and designing artificial quantum electrodynamics analogs in condensed matter settings.

2.2. Fractional Matter Coupled to an Emergent Gauge Field in $Ce_2Sn_2O_7$

Neutron spectroscopy experiments on $Ce_2Sn_2O_7$ have provided strong spectroscopic evidence for fractionalized excitations in a three-dimensional quantum spin liquid. High-resolution backscattering neutron spectroscopy reveals a gapped spectrum with multiple peaks corresponding to pair production and propagation of fractional spinons strongly coupled to an emergent gauge field. This signature matches the theoretical predictions for the π-flux phase of quantum spin ice, reinforcing the validity of QED-based descriptions of spin liquid phases.

These results mark a significant step toward experimentally verifying emergent gauge theories in real materials. The observed spectral features provide a direct link between spinon dynamics and gauge field fluctuations, establishing $Ce_2Sn_2O_7$ as a promising platform for further studies of quantum spin ice.

3. Conclusion and Future Directions

These findings advance our understanding of emergent gauge fields and fractionalized matter in QSI. Future research will focus on:

(1) Extending experimental techniques to probe spinon dynamics at even finer energy resolutions.

(2) Investigating other QSI candidates to determine the universality of these phenomena.

(3) Exploring potential applications in quantum information science, where emergent gauge theories could be harnessed for robust quantum computation.

The ability to tune emergent QED and directly observe fractionalized excitations in QSI represents a major milestone in the study of quantum matter, opening new avenues for both fundamental physics and technological applications.

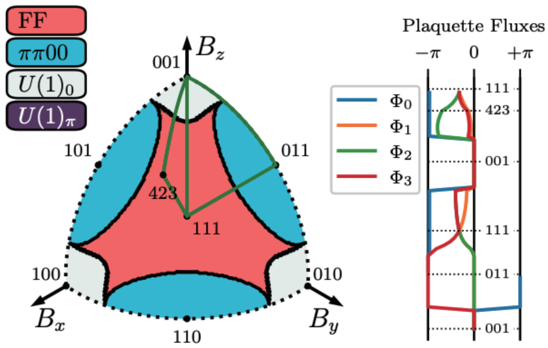

図２ Phase diagram of the frustrated flux phase.

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