Condensed Matter Theory Laboratory
Chief Scientist: Akira Furusaki (D.Sci.)

(0) Research field

CPR Subcommittee: Physics

Keywords: topological phases, strongly correlated electron systems, frustrated magnets, phase transitions

(1) Long-term goal of laboratory and research background

Many-electron systems having infinite degrees of freedom exhibit rich physical phenomena: they can have phases with spontaneously broken symmetry and transitions among these phases. A typical example is offered by magnetism and superconductivity in strongly-correlated electron systems, such as transition metal oxides and molecular conductors, which are the main research subjects of our laboratory. Our recent research subjects include unconventional ordered states and spin liquids in strongly frustrated quantum magnets and other new kinds of quantum phases like topological insulators and topological superconductors, or symmetry protected topological phases.

(2) Current research activities (FY2020) and plan (until Mar. 2025)

(A) Topological phases of matter

We have studied topological phases of matter such as topological insulators and superconductors. In the past year, we have studied Majorana zero modes bound in a vortex in a topological superconductor with s-wave superconducting order. In the presence of n-fold rotation symmetry (n=2, 4, 6) there can exist two Majorana zero modes with different rotation eigenvalues. We have also studied one-dimensional interacting electron systems with spin-orbit coupling under magnetic field and discussed Majorana bound states near the edges of a quantum wire in the Ising antiferromagnetic quasi-long-range ordered phase.

Future plan, 1) We will study Majorana zero modes in topological crystalline superconductors. 2) We develop a theory of fragile topological insulators.

(B) Frustrated magnets

We investigated the degeneracy of the ground state on the magnetization plateaus in a spin-1/2 kagome-lattice antiferromagnet, using adiabatic flux insertion and symmetry-based 't Hooft anomaly analysis. The flux insertion argument shows an exact lower bound on the ground state degeneracy at magnetizations 1/9, 1/3, 5/9, and 7/9 in the presence of U(1) spin rotation and translational symmetry. This result shows that the lower bound at 1/3 magnetization is one. We search for the possible ‘t Hooft anomaly that can forbid a unique gapped ground state in the 1/3 magnetization plateau. Since the anomaly is not affected by the spatial anisotropy in general, we mapped the system to weakly coupled triangular spin tubes in the one-dimensional limit. In the 1/3 plateau state of the S=1/2 triangular spin tube, the anomaly between the $Z_3 \times Z_3$ symmetry and the translational symmetry indicates that there cannot exist a unique gapped ground state. In contrast, the kagome antiferromagnet can have a unique gaped ground state because one of the Z_3 symmetries in the unit cell is explicitly broken.

Future plan, 1) To derive a low-energy effective model of the quantum lattice model, we investigate a numerical method to block-diagonalize the Hamiltonian of a finite system. Combining this result with a numerical series expansion method, we develop a new method for deriving the effective Hamiltonian in a non-perturbative manner.

(C) Theory of magnetic excitations and magnetoelasticity in quantum spin ice systems

A class of insulating magnetic rare-earth pyrochlores $R_2T_2O_7$ (R : rare-earth elements, T : transition-metal elements), dubbed quantum spin ice, has been studied extensively as a laboratory for the emergent U(1) quantum spin liquid that accommodates fictitious quantum electrodynamics with the monopoles of magnetic moments playing the role of electric charges in real quantum electrodynamics. In particular, the possibility of a quantum phase transition between the U(1) quantum spin liquid and electric quadrupole ordered phases in $Tb_2Ti_2O_7$ and the ferromagnetic phase with a Bose condensation of the monopoles have been experimentally reported. These systems are considered to be so close to the U(1) quantum spin liquid phase, that conventional theoretical approaches cannot readily explain their magnetic excitation and magnetoelastic properties. We have thus extended the lattice gauge theory for U(1) quantum spin liquids so as to describe classically ordered phases quantitatively, and provided a quantitative theoretical explanation of the magnetic excitation spectra in $Yb_2Ti_2O_7$. Furthermore, we have incorporated a coupling between the rare-earth quadrupole moments and the strain into the quantum spin ice model, and explained experimental results of ultrasonic measurements on $Tb_2Ti_2O_7$.

Future plan, We will apply the above theoretical framework to generic quantum spin ice systems including Ce and Pr systems. On this basis, we will theoretically explore the possibility of realizing the U(1) quantum spin liquid, describe quantum phase transitions from the U(1) quantum spin liquid to classically ordered phases, and propose routes to experimental verifications.

(C) Spin transport phenomena in antiferromagnets

Quantum transport phenomena which involve electronic spin degree of freedom are one of the central topics in modern solid state physics; Their studies have developed in different fields, e.g, spintronics and strongly correlated electron systems. We have been investigating the possibility of realizing spin transport such as spin-current conduction and anomalous Hall effect in conventional antiferromagnets without a net ferromagnetic moment, called collinear-type, in which the up- and down-spin moments order antiparallel to each other. This year we proposed the anomalous Hall effect in organic antiferromagnets; we also studied the strong correlation effect by treating it exactly within a numerical simulation. Furthermore, we proposed a mechanism of spin-current generation in well-known transition metal oxide system, i.e., the perovskites.

Future plan, 1) We will investigate the anomalous Hall effect in perovskite-type transition metal oxides. 2) We will develop a scheme to derive the spin-orbit coupling in effective models and apply it to different organic magnetic materials.

(3) Members

(Chief Scientist)
Akira Furusaki
(Senior Research Scientist)
Tsutomu Momoi, Shigeki Onoda,
Hitoshi Seo
(Special Postdoctoral Researcher)
Shunsuke Furuya
(Postdoctral Researcher)
Shuntaro Sumita
(Trainee)
Takuya Furusawa, Mateo Fontaine

(4) Representative research achievements

1. "Majorana end states in an interacting quantum wire", Ren-Bo Wang, Akira Furusaki, and Oleg A. Starykh, **Phys. Rev. B 102**, 165147 (2020).

2. "Double Majorana vortex zero modes in superconducting topological crystalline insulators with surface rotation anomaly", Shingo Kobayashi and Akira Furusaki, **Phys. Rev. B 102**, 180505(R) (2020).

3. "Roles of easy-plane and easy-axis XXZ anisotropy and bond alternation on a frustrated ferromagnetic spin-1/2 chain", Hiroshi Ueda and Shigeki Onoda, **Phys. Rev. B 101**, 224439 (2020).

4. "Perovskite as a spin current generator", Makoto Naka, Yukitoshi Motome, and Hitoshi Seo, **Phys. Rev. B 103**, 125114 (2021).

5. "Parafermionization, bosonization, and critical parafermionic theories", Yuan Yao and Akira Furusaki, **J. High Energy Phys. 2021**, 285 (2021).

Supplementary

Laboratory Homepage

https://www.riken.jp/en/research/labs/chief/condens_matter_theor/index.html
http://www2.riken.jp/lab-www/cond-mat-theory/index-e.html