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 various phases with rich physical phenomena: phases with spontaneous symmetry breaking and those with nontrivial topological properties. Typical examples of symmetry breaking include magnetism and superconductivity in strongly correlated electron systems such as transition metal oxides and molecular conductors. 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 (FY2021) and plan (until Mar. 2025)

(A) Topological phases of matter

We have studied topological phases of matter such as topological insulators and superconductors and other symmetry protected topological phases. In the past year, (1) we have constructed a series of toy models of three-dimensional fragile topological insulators with spin-rotation symmetry and time-reversal symmetry of spinless fermions (i.e., negligible spin-orbit coupling). The topological states of our models are fragile in that topological distinction can be lost when topologically trivial bands are additionally introduced. We have discussed the stability of symmetry-protected gapless surface modes. (2) In addition, we have revisited fractional Josephson effect in a superconductor/normal-metal/superconductor junction where the superconductors are in the topological phase. We have shown that the Majorana zeromodes localized at the two interfaces of a superconducting electrode and a normal metal are coupled through discrete levels in the normal metal, leading to resonant enhancement of 4π-periodic (fractional) dc Josephson current. (3) We have generalized the Lieb-Schultz-Mattis theorem for the ground state of one-dimensional many-body systems to higher-dimensional many-body systems with inversion or rotation symmetry.

Future plan, 1) We will study Majorana zero modes in topological crystalline superconductors. 2) We will consider higher-order topology of symmetry protected topological phases.

(B) Frustrated magnets

1) In collaboration with the experimentalists, we performed heat capacity measurements in magnetic fields in the chromium spinel oxide $HgCr_2O$ and the two-dimensional dimer system $SrCu_2(BO_3)_4$, which are candidate materials for the appearance of spin-nematic phases. The presence of a new quantum phase was confirmed in the magnetic field regime, where our theory predicted the formation of the spin-nematic phase. To understand the experimental data, we theoretically analyzed the behavior of the heat capacity and the nuclear magnetic relaxation rate in the vicinity of the spin-nematic phase using Bose gas theory. 2) We developed a method to derive non-perturbatively low-energy effective models of quantum lattice models, including frustrated magnetics. We used numerical methods for block diagonalization of finite-size system Hamiltonians to obtain the interactions and to estimate their strengths non-perturbatively by numerical series expansion methods.

Future plan, 1) We will extend the treatment of dynamical physical quantities using Bose gas theory to the inside of spin-nematic phases. Using the Hartree-Fock approximation, we incorporate interaction effects to analyze the temperature dependence of the dynamical structure factor $S(k,\omega)$ and the nuclear magnetic relaxation rate. 2) The newly developed derivation of the non-perturbative effective model will be applied to frustrated magnetic materials and the Kitaev model to investigate the non-perturbative evaluation of low-energy degrees of freedom.

(C) Theory of magnetic 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, experimental observations suggest a quantum phase transition between the U(1) spin liquid and electric quadrupole ordered phases in $Tb_2Ti_2O_7$. The magnetoelastic properties have provided a clue to understand the quadrupole order and disorder transition in this and related systems. Now, our previous high-temperature RPA analysis of the magnetoelastic properties of $Tb_2Ti_2O_7$ on the basis of localized f-electrons mutually coupled via superexchange and magnetic dipole-dipole interactions and also linearly coupled to strains was extended to study a lower-temperature quantum spin ice regime, finding out the phase transition to quadrupole-ordered phase in agreement with 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.

(D) Spin-charge cross correlation in organic/inorganic antiferromagnets

Quantum phenomena which involve the electronic spin degree of freedom are one of the central topics in modern solid-state physics; Their studies have developed in fields such as spintronics and strongly correlated electron systems. We have been investigating the possibility of exotic properties such as nontrivial spin-split band structure, spin-current conduction, and anomalous Hall effect, realized in collinear-type antiferromagnets without a net ferromagnetic moment in which the up- and down-spin moments order antiparallel to each other. This year we presented a numerical study of strong correlation effect in the spin-split bands in organic antiferromagnets. Furthermore, we studied the anomalous Hall effect in perovskite-type transition metal oxides and identified the conditions for its appearance under different antiferromagnetic patterns.

Future plan, 1) We will seek for the possibility of exotic superconductivity under the spin-split band structure. 2) We will investigate contributions to the anomalous Hall effect by different mechanisms under collinear, coplanar, and non-coplanar spin structures in a unified manner.

(3) Members

(Chief Scientist)
Akira Furusaki
(Senior Research Scientist)
Tsutomu Momoi, Shigeki Onoda,
Hitoshi Seo
(Special Postdoctoral Researcher)
Yuan Yao
(Postdoctral Researcher)
Shuntaro Sumita, Kazuki Yokomizo
(Trainee)
Takuya Furusawa

(4) Representative research achievements

1. "Fragile topological insulators protected by rotation symmetry without spin-orbit coupling", Shingo Kobayashi and Akira Furusaki, **Phys. Rev. B 104**, 195114 (2021).

2. "Superconductor/normal-metal/superconductor junction of topological superconductors revisited: Fractional Josephson current, fermion parity, and oscillating wave functions", Shuntaro Sumita and Akira Furusaki, **Phys. Rev. B 104**, 205431 (2021).

3. "Geometric approach to Lieb-Schultz-Mattis theorem without translation symmetry under inversion or rotation symmetry", Yuan Yao and Akira Furusaki, **Phys. Rev. B 106**, 045125 (2022).

4. "Quantum phase of the chromium spinel oxide $HgCr_2O_4$ in high magnetic fields", Shojiro Kimura, Shusaku Imajo, Masaki Gen, Tsutomu Momoi, Masayuki Hagiwara, Hiroaki Ueda, and Yoshimitsu Kohama, Phys. Rev. B **105**, L180405 (2022).

5. "Antiferromagnetic State in κ-type Molecular Conductors: Spin Splitting and Mott Gap", Hitoshi Seo and Makoto Naka, **J. Phys. Soc. Jpn. 90,** 064713 (2021).

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