

論文の内容の要旨

Symmetry-Protected Topological Phases of Quantum Particles with Integer Spin (整数スピンを持つ粒子の対称性に保護されたトポロジカル相)

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Symmetry-protected topological (SPT) phases have been gaining much attention. Gapped SPT phases refer to the quantum phases of those unique gapped ground states that can never be smoothly connected to trivial product states while preserving certain symmetry. An example is the Haldane phase, which is a (1+1)D gapped SPT phase protected by the $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry. In quantum critical systems, it was recently realized that the concept of gapless SPT phases can also be developed. In this thesis, I focus on SPT phases in many-body spinful boson systems and spin systems. In fact, boson and spin degrees of freedom (DOF) have no intrinsic difference from each other, because they are both bosonic: In both cases, operators on DOF at different spatial locations commute with each other.

In the first three chapters, I will give an introduction to bosonic SPT phases. Chapter 2 discusses how to understand and classify (1+1)D SPT phases, including both gapped and gapless cases. Chapter 3 is about higher dimensional gapped SPT phases. In particular, weak SPT phases, Lieb-Shultz-Mattis (LSM) anomaly, and crystalline SPT phases will be discussed.

In Chapter 4, we theoretically demonstrate that gapped SPT phases can be realized with ultracold spinful bosonic atoms loaded on the lattices which have a flat band at the bottom of the band structure. Ground states of such systems are not conventional Mott insulators in the sense that the ground states possess not only spin fluctuations but also non-negligible charge fluctuations. The SPT phases in such systems are determined by both spin and charge fluctuations at zero temperature. We find that the many-body ground states of such systems can be exactly obtained in some special cases, and these exact ground states turn out to serve as representative states of the SPT phases. As a concrete example, we demonstrate that spin-1 bosons on a sawtooth chain can be in a Haldane phase, and this SPT phase is a result of spin fluctuations. We also show that spin-3 bosons on a kagome lattice can be in an SPT phase protected by D_2 point group symmetry, but this SPT phase is, however, a result of charge fluctuations.

Chapter 5 focuses more on the gapless phases. In quantum spin-1 chains, there is a nonlocal unitary transformation, known as the Kennedy-Tasaki transformation U_{KT} , that defines a duality between the Haldane phase and the $\mathbb{Z}_2 \times \mathbb{Z}_2$ symmetry-breaking phase. We find that U_{KT} also defines a duality between an SPT Ising critical phase and a trivial Ising critical phase, which provides a "hidden symmetry breaking" interpretation for the topological criticality. Moreover, since the duality relates different phases of matter, we argue that a model with self-duality (i.e., invariant under U_{KT}) is natural to be at a critical or multicritical point. We study concrete examples to demonstrate this argument. In particular, when H is the Hamiltonian of the spin-1 antiferromagnetic Heisenberg chain, we prove that the self-dual model $H + U_{KT} H U_{KT}$ is exactly equivalent to a gapless spin-1/2 XY chain, which also implies an emergent LSM anomaly. On the other hand, we show that the SPT and trivial Ising criticalities that are dual to each other meet at a multicritical point which is indeed self-dual. Our discussions can be generalized to other symmetries beyond the spin-1 chains.