Abstract

Skyrmions are three-dimensional spin structures in magnetism that have captured significant attention owing to their unique topological properties and exceptional stability. These textures arise from the intricate twisting of magnetization in real space, characterized by a topological invariant—a property that makes them robust against continuous deformations and resistant to perturbations. This stability distinguishes skyrmions from conventional magnetic structures, positioning them as promising candidates for advanced applications such as spintronics and data storage. However, the concept of a topological invariant is challenging to generalize to quantum systems, where the orientation of a quantum spin is typically not well-defined. Despite this, skyrmions open exciting avenues for exploring fundamental physics and driving innovations in both classical and quantum technologies. This thesis explores the properties of quantum skyrmions in relation to quantum phase transitions, entanglement dynamics, and their potential applications in quantum thermodynamics. The first part of the study models the quantum skyrmionic phase in a 2D helical spin lattice, focusing on the topological nature and stability of this phase. We demonstrate that the quantum skyrmion phase remains stable over a broad parameter range before transitioning to a ferromagnetic phase. The introduction of next-nearest-neighbor interactions improves the stability of this phase and shifts its topological boundary. A dynamical quantum phase transition (DQPT) is observed when the system is rapidly quenched from the skyrmion phase to a trivial ferromagnetic phase, indicated by nonanalytic behavior in the rate function. In contrast, no DQPT is observed when the system is quenched to a helical phase. The study of topological entanglement entropy and scalar chirality reveals that scalar chirality remains continuous and fluctuation-free across both phases, while topological entanglement entropy is almost constant in the skyrmion phase but experiences enhanced fluctuations in the helical phase. These results suggest that topological entanglement entropy serves as an effective tool to distinguish between these phases and pinpoint quantum phase transitions.

The second part of the thesis addresses the role of quantum skyrmions in quantum thermodynamics, specifically in the context of quantum heat engines. A primary challenge in quantum thermodynamics is the phenomenon of "quantum friction," which leads to irreversible work due to quantum inter-level transitions. To overcome this challenge, we propose a quantum heat engine based on a plasmonic skyrmion lattice. We demonstrate that, due to the topological protection of the quantum skyrmion phase, the engine operates with zero irreversible work, eliminating the need for adiabatic shortcuts that are typically required for constructing a reversible quantum cycle. Numerical simulations show that during adiabatic evolution, the propagated states differ from the initial states only by geometric and dynamical phases, leading to zero transition matrix elements and no irreversible work. By utilizing plasmonic modes and electric fields, the quantum cycle is driven, with the quantum skyrmions in the plasmonic lattice serving as the working substance. This approach enables precise control over the engine's output power and thermodynamic work by manipulating the number of quantum skyrmions, offering a promising path toward the realization of efficient quantum heat engines.

This work provides a comprehensive understanding of quantum skyrmions, shedding light on their role in quantum phase transitions, entanglement dynamics, and their potential applications in quantum thermodynamics. It opens new possibilities for the design of efficient quantum heat engines and contributes to the broader understanding of topological phenomena in quantum systems.