Abstract

Topology plays an important role in condensed matter physics. Among many topological states, e.g., the quantum Hall states, topological insulators, and Weyl semimetals, magnetic states with topological spin structures have attracted considerable attention due to emergent electromagnetic phenomena arising from the Berry phase associated with the noncollinear and noncoplanar spin configurations. One of the challenging problems in these magnets is flexible generation and control of the spin textures with different topology, leading to their novel functionality useful for next-generation devices. Although such a problem has been discussed for several specific cases, the previous studies lack a generic viewpoint. As most of the topological spin textures are commonly described by superpositions of multiple spin helices, more comprehensive study is desired for deeper understanding and further exploration of their topological physics.

In this thesis, we aim to theoretically investigate a comprehensive way to generate and control the topological spin textures. For this purpose, we propose the "spin moiré" picture for the topological spin textures composed of multiple spin helices, in analogy with the moiré in optics. Specifically, for two-dimensional skyrmion lattices (SkLs) and three-dimensional hedgehog lattices (HLs), we study the effects of several different parameters to control the moiré patterns, such as the amplitudes of superposed helices, the twist angles between the helical directions, and the relative phases of the helical waves. We elucidate not only the modulations of the spin textures but also the evolution of the topological properties and the emergent electromagnetic fields.

First, we investigate the effect of the amplitude modulation by changing the spatial anisotropy in the magnetic interactions. Performing variational calculations for an effective spin model for noncentrosymmetric itinerant magnets, we show that the HLs turn into other magnetic states with dimensional reduction by the anisotropy. We also find topological transitions from the HLs to topologically trivial states, by identifying and tracing the real-space positions of the topological defects, hedgehogs and antihedgehogs, and the flows of the emergent magnetic field. Second, we discuss the effect of the twist angle on the HL. By clarifying the systematic evolution of the topological objects for the twist angle and the net magnetization, we find topological transitions with successive changes in the number of hedgehogs and antihedgehogs by their pair annihilation. We also perform a variational calculation based on the Ginzburg-Landau free energy and demonstrate the evolution of the spin structures and the emergent electromagnetic fields in an external magnetic field. Finally, we investigate the effect of the phase degree of freedom on the spin moiré. We propose the hyperspace representation to treat the phase systematically, and apply it to two types of SkLs. Identifying and tracing the topological objects in the hyperspace, we elucidate the phase diagram including several different topological phases distinguished by the skyrmion number as a function of the phase and the net magnetization.

Our results in this thesis reveal that the modulations of the spin moirés through the moiré parameters can drive systematic generation and control of the topological spin textures and their topological properties. Our theoretical framework established in this thesis would provide a versatile tool to investigate the topological magnetism. The spin moiré picture and the results based on it would pave the way for further exploration of emergent electromagnetic phenomena from the topological spin textures.