Abstract

Chirality, which is also termed handedness, i.e., left- and right-handed, often plays a decisive role in condensed matter physics. Among many chiral materials, chiral magnets have attracted considerable attention due to the topological characteristics arising from their peculiar magnetic textures like a helix, vortex, and flux. In this thesis, we focus on an archetype of such chiral magnetic textures, called a chiral soliton lattice (CSL). The CSL is experimentally found in monoaxial chiral magnetic conductors, such as $CrNb_3S_6$ and $Yb(Ni_{1-x}Cu_x)_3Al_9$. These compounds exhibit a chiral helimagnetic structure (CHM) in the absence of an external magnetic field. Once a magnetic field is applied perpendicular to the chiral axis, the CHM turns into the CSL, whose period increases with the magnetic field, and finally relaxes into a forced ferromagnetic state (FFM) above a critical field. The CSL has been studied theoretically for a long time since the pioneering work by Dzyaloshinskii in 1960s. The previous studies mostly focused on the magnetic properties of the CSL on the basis of effective spin-only models by omitting the itinerant electron degrees of freedom. However, the CSL exhibits intriguing electronic properties as well, such as the nonlinear negative magnetoresistance in $CrNb_3S_6$. In addition, a peculiar lock-in of the CSL was discovered in the $Yb(Ni_{0.94}Cu_{0.06})_3Al_9$; the period is locked at a particular value while changing the magnetic filed. Since these behaviors remain elusive in the previous studies for the spin-only models, it would be important to include the itinerant electrons for better understanding of the CSL.

In this thesis, we aim to theoretically explore the magnetic and electronic properties of the CSL by explicitly taking into account the interplay between the chiral magnetic texture and itinerant electrons. For this purpose, we investigate a minimal model for describing such interplay in the chiral magnets, an extension of the one-dimensional Kondo lattice model with the Dzyaloshinskii–Moriya (DM) interaction. We study the ground state and the finite-temperature (T) properties by using variational calculations and quantum Monte Carlo (QMC) simulation, respectively.

First, we discuss the ground-state properties of the model by performing variational calculations. In the absence of the magnetic field, we show that the model exhibits the CHM whose period depends on the spin–charge interaction, the DM

interaction, and electron filling. In an external magnetic field, the CHM turns into the CSL. We show that the itinerant electrons modify the development of the CSL from that in the spin-only models used in the previous studies. In particular, we find that the period of the CSL can be locked at a set of particular values dictated by the Fermi wave number. The lock-in is explained by the gap opening in the electronic states due to the scattering of itinerant electrons by the chiral solitons. We also find the the same mechanism can lead to a spontaneous formation of the CSL even in the absence of the applied magnetic field. We discuss our findings as a possible mechanism for the lock-in observed in $Yb(Ni_{0.94}Cu_{0.06})_3Al_9$.

We also investigate the finite-T properties of the model by the QMC simulation. Using this unbiased method beyond the variational study, we confirm that the model exhibits the CHM and CSL at low T by calculating the spin structure factor. By computing the optical conductivity and the winding number of the CSL, we find that the coherent part of the optical conductivity increases along with the decrease of the chiral solitons; namely, the system exhibits a peculiar negative magnetoresistance proportional to the soliton density. While raising T, the CSL melts by thermal fluctuations and the coherent conduction is suppressed. These results clearly indicate that the electrical transport in the CSL is governed by the spin scattering of itinerant electrons by the chiral solitons. We also discuss that our results are qualitatively consistent with the experimental data for the monoaxial chiral magnets such as $CrNb_3S_6$.

Our results in this thesis unveil nontrivial properties in the CSL arising from the interplay between itinerant electrons and localized magnetic moments. There, the chiral magnetic texture is not merely a given internal magnetic field to the itinerant electrons: there is nontrivial feedback from the itinerant electrons which affects the magnetism. In other words, the magnetic and electronic states are determined in a self-consistent manner by optimizing the total free energy of the system. Our complementary study by the variational calculation for the ground state and the QMC simulation at finite T reveals that the interplay plays an important role in the peculiar properties that have not been obtained in the spin-only models in the previous studies, such as the lock-in of the period of CSLs, the spontaneous formation of the CSL at zero field, and the field and T dependences of the nonlinear negative magnetoresistance. Our results pave the way for further exploration of the spin–charge interplay in the chiral magnets.