Abstract

Chirality, which is also termed handedness, 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 noncolinear and noncoplanar magnetic textures, such as helices and vortices. An archetypical example of the chiral magnetic texture is a chiral helimagnetic state (CHM) in monoaxial chiral magnets. The CHM turns into a chiral soliton lattice (CSL) and a chiral conical magnetic state (CCM) in the field perpendicular and parallel to the chiral axis, respectively. Such chiral magnetic textures lead to peculiar transport phenomena, such as a nonlinear negative magnetoresistance in the CSL and nonreciprocal transport in the CCM. On the other hand, cubic chiral magnets show three-dimensional chiral magnetic textures, which are called the magnetic hedgehog lattices (HLs). The HLs have also attracted much attentions due to the topological Hall and thermoelectric effects presumably originating from the peculiar emergent magnetic field regarded as a periodic array of magnetic monopoles and antimonopoles.

Theoretically, most of the previous studies for the chiral magnets have been done for spin-only models with an antisymmetric exchange interaction, which is called the Dzyaloshinskii-Moriya (DM) interaction. Although such models successfully explain many interesting magnetic properties, there still remain a lot of open issues, especially on the role of the interplay between the chiral magnetic textures and itinerant electrons in the electronic and magnetic properties. It is highly desired to clarify these issues beyond the previous studies based on the spin-only models.

In this thesis, we theoretically investigate the magnetic, electric, transport, and optical properties of the chiral magnets by taking into account the effects of itinerant electrons. We study an extension of the spin-charge coupled model with the antisymmetric spin-orbit coupling. In particular, we focus on monoaxial and cubic chiral magnets, which exhibit the quasi-one- and three-dimensional chiral magnetic textures, respectively.

First, we discuss the magnetic and electric properties of the CSL which appears in the monoaxial chiral magnets, such as $CrNb_3S_6$ and $Yb(Ni_{1-x}Cu_x)_3Al_9$. By variational calculations for the ground state, we find that the one-dimensional spin-charge coupled model with the DM interaction shows the CHM in the ab-

sence of the magnetic field and turns into the CSL in the magnetic field perpendicular to the chiral axis. 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 due to the gap opening in the electronic state. Also, by performing Monte Carlo simulations, we find that the system exhibits a peculiar negative magnetoresistance whose field dependence is correlated with that of the soliton density.

Next, we discuss nonlinear optical responses and nonreciprocal transport phenomena in the CCM state for the same model under the magnetic field parallel to the chiral axis. By using the nonlinear response theory, we find that the CCM exhibits the electric magnetochiral effect originating from the breaking of spatial inversion and time reversal symmetries. We also clarify the effect of thermal fluctuations on the electric magnetochiral effect by using Monte Carlo simulations. Furthermore, we find that the CCM shows the second harmonic generation and the photovoltaic effect. In particular, we show that the photovoltaic effect in the CCM changes in not only the magnitude but also the sign depending on the external field and the frequency of light. In addition, we explore the nonreciprocal spin transport in the monoaxial chiral magnets by using the spin-dependent Landauer method. We show that a nonreciprocal spin current can be generated in both CHM and CCM, which depends on the chirality, period, conical angle, and polarization of the spin current.

Finally, we discuss the stabilization mechanism and topological properties of the HLs in noncentrosymmetric metals, such as B20-type compounds. We investigate the ground state of an effective spin model with long-range interactions arising from the itinerant nature of electrons, by variational calculations and simulated annealing. We find that two types of HLs are stabilized at zero field by the synergetic effect of the spin-charge and spin-orbit couplings. We also find that the HLs exhibits a variety of multiple phase transitions in applied magnetic field, including topological ones driven by pair annihilation of the monopoles and antimonopoles. We also find that the motion of the monopoles and antimonopoles suggests a repulsive interaction between them, in contrast to the previous study in the continuum approximation.

Through this thesis, we have unveiled nontrivial magnetic, transport, and optical properties of the chiral magnetic textures in noncentrosymmetric metals. The results reproduce the experimental results qualitatively, for example, the magnetoresistance and lock-in in the CSL, the electric magnetochiral effect in the CCM, and the stable HLs even at zero field. Our findings indicate a new direction to design the candidate materials by clarifying the contributions of itinerant electrons to the stability of the chiral magnetic textures. Moreover, our results for the linear and nonlinear transport phenomena in the chiral magnets provide a foundation for next-generation electronic devices.