Abstract

Ferromagnetic Kondo lattice models on geometrically frustrated lattices are studied for exploring unusual magnetic and electronic states. In particular, we mainly investigate spin scalar chiral ordering with a noncoplanar spin configuration, which leads to a topologically nontrivial electronic state, called the Chern insulator. The aim of the present thesis is to clarify (i) whether such noncoplanar spin chiral order can occur in the spin-charge coupled systems on geometrically frustrated lattices, (ii) the parameter range and the stabilization mechanism of the noncoplanar ordering, (iii) how the noncoplanar order is stable against modulations of band structure, (iv) how the chiral ordering is affected by quantum spin fluctuations, and (v) how magnons affect transport properties of the system. For the purposes of (i)-(iii), we investigate the ground-state properties of the model with classical localized spins by using variational calculation, perturbation theory, and simulated annealing. We study the model on a triangular lattice as well as other frustrated lattices, such as triangular-to-kagome, face-centered-cubic, checkerboard, and pyrochlore lattices. With regard to the issues (iv) and (v), we perform the linear spin wave analysis by introducing the Holstein-Primakoff transformation to the localized spins, and calculate the magnon dispersion, the reduction of magnetic moments, and transport properties by the Green function method and the linear response theory. As a result, for the triangular-lattice system, we find that a noncoplanar four-sublattice ordering with a finite spin scalar chirality emerges at and around 1/4 filling, in addition to the 3/4-filled case, which was predicted to be induced by the perfect nesting of the Fermi surface. The 1/4-filling phase is stable in a wider range of parameters than the 3/4-filling one, and includes a large region of gapped Chern insulator, which exhibits the quantized anomalous Hall effect. We extend the analysis by introducing modifications of transfer integrals, such as by including the next nearest-neighbor hopping and by modulating the triangular lattice to a kagome lattice. As a consequence, we find that the newly-found chiral order at 1/4 filling remains robust for such changes, whereas the 3/4-filling phase is rapidly destabilized as the nesting is lost. Bearing the contrastive behavior in mind, we next examine the origin of the noncoplanar ordering by the fourth-order perturbation theory in terms of the Hund's-rule coupling. Among the resultant effective four-spin interactions, we find that a biquadratic interaction is critically enhanced with a positive coupling constant near 1/4 filling, which favors the noncoplanar ordering. The origin of large positive biquadratic interaction is ascribed to the Fermi surface connection by the four-sublattice ordering wave vectors, which we call the generalized Kohn anomaly. We also study other frustrated lattices systematically, such as checkerboard, face-centered-cubic, and pyrochlore lattice. We clarify that similar noncoplanar orders emerge near 1/4 filling and that the positive biqiuadratic interaction plays a common, important role in these frustrated lattices. The

results suggest that the generalized Kohn anomaly is a universal mechanism for stabilizing noncoplanar orders in frustrated spin-charge coupled systems. We also investigate the effect of the competition between the double-exchange ferromagnetic and superexchange antiferromagnetic interactions on a triangular lattice. As a result, we find that nontrivial magnetic and electronic phases are stabilized by the competition. One of them is a noncoplanar three-sublattice order which is stabilized in the lightly-doped region. This has an umbrella-type spin configuration with a net magnetic moment and a staggered spin scalar chirality Another one is a collinear ferrimagnetic state, which is realized for large Hund's-rule coupling at special filling, 5/8 filling. In this state, the system spontaneously differentiates into the up-spin kagome network and the isolated down-spin sites, which we call the kagome network formation. In the kagome network state, the electronic structure shows a massless Dirac node at the Fermi level. The Dirac electrons are almost fully spin-polarized due to the large Hund's-rule coupling. Although localized spins are treated as classical spins thus far, we next examine the effect of quantum fluctuations of localized spins by the linear spin wave analysis. As a result, we find that the four-sublattice chiral order at 3/4 filling is fragile against quantum fluctuations, whereas it remains robust at 1/4 filling. We also find that the reduction of magnetic moment in the chiral phase is considerably small compared to those in typical antiferromagnetic phases in localized spin systems without itinerant electrons. In addition, by extending the analysis, we find that quantum fluctuations give rise to the magnon Hall effect due to the spin scalar chirality. Interestingly, the magnon Hall coefficient changes its sign while varing the Hund's-rule coupling. We also show that magnon current is generated by an electric field in the spin-charge coupled system. These results suggest that the magnon Hall effect can be driven by an external electric field. Our results elucidate that noncoplanar ordering is widely observed in frustrated Kondo lattice models, and that there is a common stabilization mechanism originating from the coupling between charge and spin degrees of freedom. The robustness will be beneficial for the realization of the chiral order in real materials. Moreover, novel transport phenomena that we found will stimulate further experimental and theoretical studies in the spin-charge coupled systems, and open new possibility in developing spintronics.