論 文 の 内 容 の 要 旨

論文題目　Unconventional Magnetic and Transport Phenomena in Frustrated Kondo Lattice Systems

（フラストレート近藤格子系における非従来型の磁性と輸送現象）

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Recently, effects of geometrical frustration of the lattice structure on spin-charge coupled systems have attracted considerable attention, because the coupling between itinerant electrons and a nontrivial magnetic order under the geometrical frustration can lead to novel phenomena. In particular, the discovery of peculiar transport phenomena, such as an unconventional anomalous (or a topological) Hall effect in some pyrochlore oxides, has driven a lot of researchers to study the frustrated spin-charge coupled systems. Theoretically, it was clarified that the topological Hall effect is caused by the coupling to a peculiar noncoplanar spin ordering with a finite spin scalar chirality. In other words, the scalar chirality brings nontrivial topology in the system. The idea was examined on several frustrated lattices, such as kagome, face-centered-cubic, and triangular lattices. Particularly, it was pointed out that, in the triangular lattice system, the perfect nesting of the Fermi surface at 3/4 filling might lead to a noncoplanar four-sublattice ordering and the quantized topological Hall effect. While these previous studies have successfully revealed the nontrivial relation between the Berry phase and the topological Hall effect, fundamental questions have been left unclear so far: when and how does such a noncoplanar spin order emerge, what is the role of coupling between charge and spin degrees of freedom in energetically stabilizing such ordering, and what else does the noncoplanar order bring about electronic and transport properties?

The aim of the present thesis is to clarify (i) whether such noncoplanar spin ordering can occur in the spin-charge coupled systems on geometrically frustrated lattices, (ii) the parameter range and the stabilization mechanism of the noncoplanar ordering, and (iii) how the noncoplanar order is stable against perturbations, such as modulation of band structure and quantum spin fluctuations. In particular, quantum fluctuations play a significant role in frustrated magnets because of severe competition between many possible ordered states. It is also relevant to consider the realization in real materials. Therefore, we also aim at unveiling (iv) how the chiral ordering is affected by quantum spin fluctuations and how magnons affect transport properties of the system.

In order to address these issues, we focus on the ferromagnetic Kondo lattice model which is one of the simplest models describing the interaction between itinerant electrons and localized spins. The model is also known as an effective model for several materials, such as manganese oxides. For the purposes of (i)-(iii), we investigated the model with classical localized spins. We studied the ground-state phase diagram by using the variational calculation and the perturbation theory in terms of the spin-charge coupling for the model on several different frustrated lattices, such as triangular, triangular-to-kagome, face-centered-cubic, checkerboard, and pyrochlore lattices. We examined the stability of noncoplanar spin scalar chiral orders in a wide range of model parameters, i.e., electron density, Hund's-rule coupling, and antiferromagnetic superexchange interaction between localized spins. With regard to the issues (iii) and (iv), we applied the linear spin-wave analysis by introducing the Holstein-Primakoff transformation to the localized spins. We calculated the magnon dispersion, the reduction of magnetic moments, and transport properties by the Green function method and the linear response theory.

For the triangular lattice system with classical localized spins, we find that a noncoplanar four-sublattice ordering with a finite scalar spin chirality emerges at and around 1/4 filling. This is a new phase, while a similar state was predicted by the perfect nesting of the Fermi surface at 3/4 filling. 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 insulating state characterized by a Chern number. The chiral-ordered phases exhibit the quantized topological Hall effect; namely, the Hall conductivity takes a quantized value in the insulating regions. We also extend the analysis to the triangular lattice with band structure deformations, such as by next nearest-neighbor hopping and modulating to a kagome lattice (we call it the triangular-to-kagome lattice), i.e., for a continuous change of the lattice structure from the triangular lattice to the kagome lattice by modulating the transfer integrals in a periodic way. As a consequence, we find that the newly-found chiral order at 1/4 filling remains robust for such change, whereas the 3/4 filling phase is rapidly destabilized as the nesting is lost. The result suggests that the 1/4-filling phase is stable against modification of the band structure, reflecting the fact that it is not stabilized by the nesting of the Fermi surface.

We also examine the origin of the noncoplanar ordering by considering the fourth-order perturbation theory in the Hund's-rule coupling. Among the resultant four-spin interactions, we find that a biquadratic interaction is enhanced with a positive value near 1/4 filling, which is potentially a cause of 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 lattices. We clarify that similar four-sublattice orders emerge near 1/4 filling also in these frustrated lattices. From the perturbation theory, we confirm that the positive biquadratic interaction plays a common, important role in stabilizing the noncoplanar order.

Although localized spins are treated as classical spins thus far, we next examine the effect of quantum spin fluctuations 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 the quantum fluctuation gives rise to the magnon Hall effect due to the spin scalar chirality in the current spin-charge coupled system. The result suggests that the magnon Hall effect can be driven by an external electric field because the system has the interaction between magnons and itinerant electrons.

The results in this thesis elucidate that the 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 in these systems. The 1/4-filling chiral phase, which is discovered in this thesis, is stable against not only modulation of band structure but also quantum spin fluctuations. The robustness will be beneficial for the realization of the chiral order in real materials, and it is expected that the chiral phase is observed in a broad range of real triangular-lattice systems such as delafossites. Moreover, the system might exhibit the novel transport phenomenon, i.e., the magnon Hall effect induced by an electric field. Such a peculiar transport property has the potential for technological applications. For instance, the system can be a converter between magnon current and electron current working in the absence of the spin-orbit interaction. Therefore, our results will stimulate further experimental and theoretical studies in the spin-charge coupled systems, and open new possibility in developing spintronics.