# 論文の内容の要旨

## Theory of surface states and transport phenomena in topological magnon systems

## （トポロジカルマグノン系における表面状態と輸送現象の理論）

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In this thesis, we investigate the surface states appearing due to the nontrivial topology of the magnon wave functions and transport phenomena related to the Berry curvature of magnons. Recently, topological properties of particles in materials have attracted a lot of attention. An important example is a quantum Hall insulator exhibiting a quantized transverse conductivity in magnetic fields. The transverse conductivity is contributed by the chiral edge states of electrons, which arise from the nontrivial topology of in the electron band structure. Another example is a quantum spin Hall insulator with helical edge states protected by time-reversal symmetry. In particular, when the system conserves spin, helical edge states convey a pure spin current. The higher-dimensional extensions of quantum spin Hall insulators are called three-dimensional topological insulators, and possess surface states of electrons with Dirac dispersion. The surface states show interesting properties such as "spin momentum locking," in which the spin direction is fixed to crystal momentum of electrons. The coupling of the electric and magnetic degrees of freedom of electrons in three-dimensional topological insulators also leads to a unique phenomenon known as the topological magnetoelectric effects.

As well as the edge and surface states, the electrons in the bulk of materials are also known to give rise to nontrivial transport phenomena due to their Berry curvature. In particular, the relationship between the Berry curvature and the nonlinear response to external fields has attracted much attention in recent years. One of the representative studies is the nonlinear Hall effect. Unlike the linear Hall effect associated with the integral of Berry curvature, the nonlinear Hall effect is described by the dipole of Berry curvature, and does not require breaking time-reversal symmetry.

While many important concepts concerning these topological properties have been proposed for electronic systems, their counterparts have also been investigated for bosons such as magnons, photons, phonons, and triplons. In particular, magnons, which are quasiparticles of spin waves, are of interest as transport carriers in magnetic materials. Magnons are electrically neutral bosons, and have possible applications in spintronics since

they carry spin without Joule heating. In addition, it has been experimentally confirmed that magnons can propagate in magnetic materials such as yttrium iron garnet over long distances of about 10 mm. Spin currents carried by magnons are used instead of electric currents, for example, to design logic circuits.

The topological properties of magnons are expected to give rise to many non-trivial transport phenomena in magnetic materials, such as transverse thermal and spin currents. The magnonic analogs of quantum Hall insulators and quantum spin Hall insulators in two dimensions have been proposed so far, and possess chiral and helical edge states of magnons, respectively. The chiral (helical) edge states convey energy (spin) current in the direction perpendicular to the temperature gradient. Among topological materials, magnonic systems corresponding to three-dimensional topological insulators are expected to exhibit various novel properties. However, it is not always possible to directly apply the constitutive principles of topological materials proposed for electronic systems to magnonic systems. For electrons, three-dimensional topological insulators require the Kramers degeneracy, which appears in fermionic systems with time-reversal symmetry. On the other hand, since magnons are bosons, the usual time-reversal symmetry does not give rise to the Kramers degeneracy. For this reason, a magnonic analog of three-dimensional topological insulators has not been constructed so far.

Not only the magnon edge and surface states of magnetic materials, but also magnons flowing in the bulk exhibit nontrivial transport phenomena related to the topology of their band structure, or the Berry curvature. The magnon spin Nernst effect is particularly interesting since the pure spin current perpendicular to the temperature gradient can be generated in the antiferromagnets. To realize such a spin current, magnon states with upward and downward magnetic moments should flow in opposite directions. The first theoretical suggestion of the magnon spin Nernst effect was proposed in the honeycomb lattice antiferromagnet with the Dzyaloshinskii-Moriya interaction. Since the Berry curvature with opposite signs arise in magnons with upward and downward magnetic moments from the Dzyaloshinskii-Moriya interaction, the above counter-propagating magnon current is realized. The magnon spin Nernst effect in the previous study was described as a linear response to the temperature gradient, and has been observed experimentally in the antiferromagnet $MnPS_3$. However, the Dzyaloshinskii-Moriya interaction is a specific interaction which is non-negligible only in magnets with strong spin-orbit couplings. Therefore, in magnets which contain only light atoms, it has been difficult to generate a pure spin current by such a mechanism, since the Dzyaloshinskii-Moriya interaction is quite small. In order to expand the possibility of transport phenomena in magnetic materials, it is important to study the topological properties of magnons as a nonlinear response, which has not been explored yet.

In this work, we propose several models of three-dimensional magnetic materials with Dirac surface states of magnons protected by symmetries. In addition, we investigate the nonlinear transport properties of magnons in the bulk of magnets, which arise from their Berry curvature. In Chapter 3, we propose a model of the magnon system corresponding to three-dimensional topological insulators for the first time (see Figure 1). The model is designed to satisfy the pseudo-time-reversal symmetry, which gives rise to Kramers pairs of magnons. We define the topological invariants which characterize the system, and confirm the correspondence with the Dirac surface states of magnons. Due to the non-Hermiticity in Bogoliubov-de Gennes systems, the topological invariants are different from those of electrons. In the proposed model, depending the parameters of interactions, there appear both phases with odd and even Dirac cones. The former is topologically robust, and the latter is not necessarily robust. We summarized these in a phase diagram, by using the simplified formula of the topological invariants for the inversion-symmetric systems. While the surface states of magnons proposed here are unprecedented states in the magnetic materials, the model is constructed under the artificial setup having two spins at each site. Therefore, it seems to be difficult to realize this in real materials. In addition, in order to satisfy the time-reversal symmetry which is responsible for the topologically-protected surface states, it is necessary to fine-tune the interactions between the spins in the model, such as the Heisenberg interaction and the Dzyaloshinskii-Moriya interaction. Therefore, the next direction of the study is to realize the Dirac surface states of magnons in more natural models.

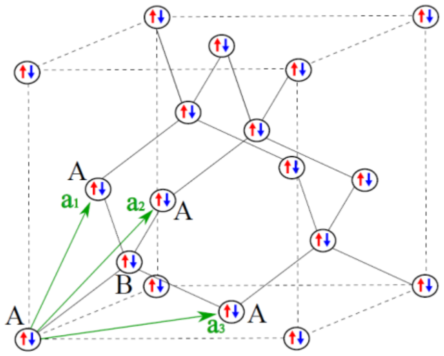

Figure 1: Diamond lattice magnet having two spins at each site, which is proposed as the first model of magnonic analogs of 3D topological insulators.

In Chapter 4, we focus on the fact that the combined symmetry of time-reversal and half translation gives rise to the Kramers degeneracy of magnons. We construct a model with Dirac surface states of magnons protected by this symmetry. The magnon band structure is shown in Figure 2. This is classified as a magnonic analog of topological crystalline insulators, which are materials having the surface states of electrons protected by crystalline symmetries. Fortunately, the above combination symmetry is realized in real magnets. We find that the van der Waals magnet $CrI_3$ is a candidate material for the magnon system proposed here. We calculate the band structure of magnons in $CrI_3$ assuming the parameters estimated by density functional theory calculations, and confirm the existence of the Dirac surface states. We also propose a unique electric field response for these surface states. An applied electric field in magnets are known to change the strength of the Dzyaloshinskii-Moriya interaction via spin-orbit interaction. The resulting effect is understood in terms of the Aharonov-Casher effect, in which magnons obtain vector potentials depending on their magnetic moments. When the Aharonov-Casher effect occurs in the magnon surface states with spin-momentum locking, the numbers of magnons on one and the other surfaces increase and decrease, respectively. We evaluate the energy current flowing in this process by using the linear response theory. Phase diagrams are also constructed for the honeycomb lattice stacking system and the system corresponding to the van der Waals magnet $CrI_3$. In the former system, it is found that there are topological phases with an even and odd number of Dirac cones, as well as the phase corresponding to the Weyl nodal-line semimetals. We also find that in $CrI_3$, Dirac surface states of magnons appear in a sufficiently wide range of parameters around those estimated by the density functional theory calculations.

In Chapter 5, we construct a second-order response theory for the temperature gradient and show that the magnon flow perpendicular to the temperature gradient can be described by a dipole moment of the product of the energy and the Berry curvature. This can appear in magnetic materials when they break the inversion and rotation symmetries, and does not require the complex hopping term in the Hamiltonian. Therefore, in the nonlinear response regime, the transverse current of magnons is expected in the magnets with the negligibly small Dzyaloshinskii-Moriya interaction. In particular, we focus on the Néel antiferromagnets in this study. Due to the PT symmetry of them, the signs of the Berry curvatures are opposite between the magnon states with magnetic moment upward and downward. Thus, the expected result is the spin current conveyed by the counter-propagating transverse current, i.e., magnons with magnetic moment upward and downward flowing in opposite directions. We show that such nonlinear spin Nernst current arises in simple honeycomb, square, and diamond lattice Heisenberg antiferromagnets without the Dzyaloshinskii-Moriya interaction. In particular, the directions of the spin current in the honeycomb and diamond lattice antiferromagnets are changed by the externally applied lattice strain and pressure, respectively. In addition, by comparing with the linear magnon spin Nernst current observed in the antiferromagnet $MnPS_3$, we estimate the order of the nonlinear magnon spin Nernst current in the strained honeycomb lattice antiferromagnets. We confirm that the nonlinear spin Nernst effect is in the observable range.

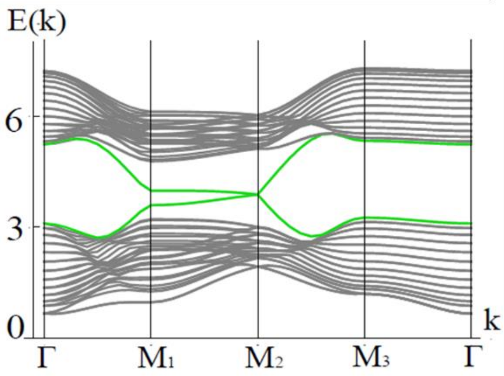

Figure 2: Magnon band dispersion of a magnonic analog of topological crystalline insulators. Dirac surface states are shown by green.

To summarize, this thesis proposes novel states and transport properties related to the band topology and the Berry curvature of magnons. The surface states of magnons proposed in Chapter 3 and 4 are expected to have many interesting properties, as is the case of electronic systems. The nonlinear spin Nernst effect of magnons proposed in the Chapter 5 can be expected in magnetic materials even without the Dzyaloshinskii-Moriya interaction. Therefore, the nonlinear spin Nernst effect of magnons can be one of the few ways to generate spin currents in magnets which does not contain heavy atoms, such as organic magnets. In addition, strain- and pressure-tunable spin currents can be generated in honeycomb and diamond lattice antiferromagnets, respectively. We expect that our results will lead to new ways of the manipulation of magnons and spin currents, which can be first enabled by their topological properties, and will stimulate the field of spintronics.