論文の内容の要旨

Spin waves and solitons in uniaxial chiral magnets

(一軸性カイラル磁性体におけるスピン波とソリトン)

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Chiral magnets are noncentrosymmetric magnets with Dzyaloshinskii–Moriya interaction (DMI). The DMI stabilizes a helical order with a period determined by the competition with the Heisenberg exchange interaction. Magnetic field and anisotropy induce higher harmonics of the mode of helical order and localized structures such as skyrmion and chiral soliton emerge.

In this thesis, we study a spin model of uniaxial chiral magnets representing the material $Cr_{1/3}NbS_2$. In the absence of magnetic field, the ground state shows a helical order propagating in the direction of the helical axis, which is set to the z-axis. The main results of this thesis consist of two parts. One is about non-reciprocal spin waves when the field is applied parallel to the helical axis, and the other is about the classical ground state phase diagram under tilted magnetic field and the surface barrier, which explains the hysteresis experimentally observed in micrometer-sized samples. We mainly study the following Hamiltonian on the tetragonal lattice:

$$\mathcal{H} = -\sum_{\boldsymbol{j}} \left[J_{\parallel} \vec{S}_{\boldsymbol{j}} \cdot \vec{S}_{\boldsymbol{j}+\hat{z}} + D \left(\vec{S}_{\boldsymbol{j}} \times \vec{S}_{\boldsymbol{j}+\hat{z}} \right)^{z} + \vec{H}_{\mathrm{ex}} \cdot \vec{S}_{\boldsymbol{j}} - \frac{K}{2} \left(S^{z}_{\boldsymbol{j}} \right)^{2} + \sum_{\mu=x,y} J_{\perp} \vec{S}_{\boldsymbol{j}} \cdot \vec{S}_{\boldsymbol{j}+\hat{\mu}} \right]. \tag{1}$$

The second term is the Dzyaloshinskii–Moriya interaction (DMI) and the third term is the Zeeman coupling with the external magnetic field $\vec{H}_{\mathrm{ex}} = (H^{x}_{\mathrm{ex}}, 0, H^{z}_{\mathrm{ex}})$.

In Chap. 2, we review several theoretical basics related to this thesis. Chiral magnets show non-trivial and non-uniform spin structures, such as conical and skyrmion states due to the DMI. Their dynamics is described by the Landau–Lifshitz–Gilbert equation, used for the numerical calculations in Chap. 3. We then focus on a chiral soliton lattice emerging in the perpendicular field ($\vec{H}^{x}_{\mathrm{ex}} = (H^{x}_{\mathrm{ex}}, 0, 0)$). It is a periodic structure of discommensurations called chiral solitons and shows a logarithmic divergence of the inter-soliton distance with increasing field. We review analytical solutions of the chiral sine-Gordon model[1] and temperature-field (T–H^{x}_{ex}) phase diagram

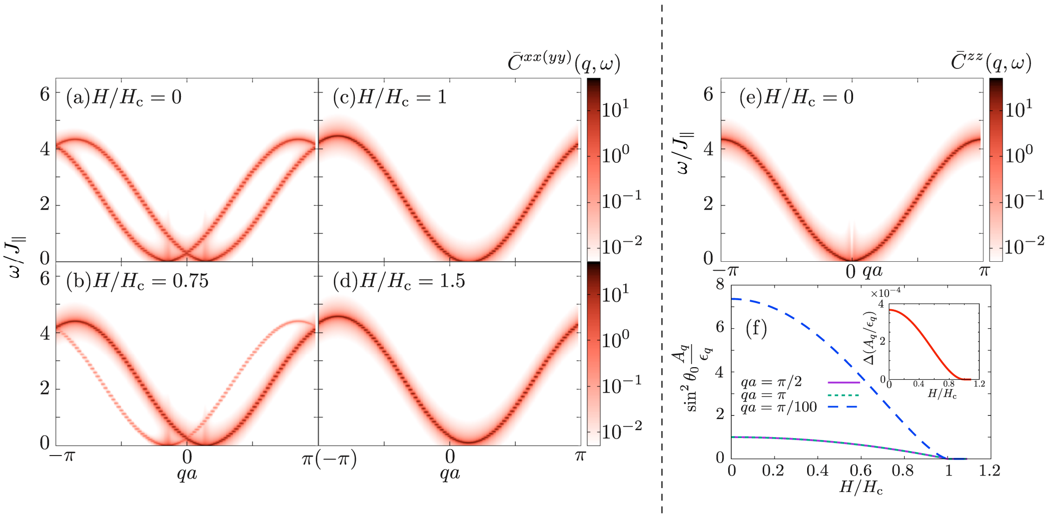

Fig 1: Dynamical spin structure factors, $C^{xx(yy)}(q,\omega)$ (a)–(d) and $C^{zz}(q,\omega)$ (e), and the field dependence of the intensity for several values of q (f). $D = 0.5J_\parallel$ and $K = 0$.

studied by Schaub and Mukamel[2]. The phase diagram has a single phase boundary consisting of two lines of continuous phase transitions and a line of discontinuous phase transition in between, and the discontinuous phase transition was attributed to attractive interaction of solitons. Their analysis will be applied to the tilted-field case in Chap. 4. We summarize the two types of continuous phase transitions classified by de Gennes[3].

In Chap. 3, we discuss the non-reciprocity in spin waves. This non-reciprocity is known in the uniform state in non-centrosymmetric ferromagnets. We calculate the dynamical spin structure factor $C^{\mu\nu}(q,\omega)$ in the conical state in the field below the saturation. We find that there are two branches of peaks in its transverse component, and that the non-reciprocity develops through the asymmetry in their intensity between $+q$ and $-q$ rather than the peak energies in Figs. 1 (a) and (b). At and above the critical field, the weaker peak disappears and is absent, as shown in Figs. 1 (c) and (d). We also investigate the case of the exchange antiferromagnetic coupling, which is related to $Ba_2CuGe_2O_7$ and α-$Cu_2V_2O_7$. We also simulate the Landau–Lifshitz equation starting from the configuration generated by the classical Monte Carlo simulation, and calculate $C^{\mu\nu}(q,\omega)$, which agree well with the results of the spin wave approximation.

In Chap. 4, we study the properties of uniaxial chiral magnets with classical spins in tilted magnetic field $\vec{H}_{\rm ex} = (H^x_{\rm ex}, 0, H^z_{\rm ex})$. In the first part of this chapter, we discuss the phase transitions using the soliton and wave pictures. Laliena *et al.* determined the ground state phase diagram and found two multicritical points and discontinuous phase transition between two continuous phase transitions[3, 4]. By regarding the parallel component $H^z_{\rm ex}$ as temperature T, the structure of the phase diagram is the same as that studied in Ref. [2]. The phase boundary is shown in Fig. 2 (a). According to de Gennes's classification, upper and lower continuous transitions are the instability type and nucleation type, respectively. The nucleation-type continuous phase transition can be explained by a condensation of solitons. Following Ref. [2], we perform a linear analysis of small deviation from the uniform state, and identify three regions separated by the light-blue line. The region labeled "κa: pure imaginary", does not have solitons, but a distorted conical order appears. Because there is no coarse grained field theory describing this order, we derive its Landau energy in a similar way to Ref. [2] but with some technical difference, and determine its phase boundary and the location of the tricritical point. They are consistent with the numerical results, and

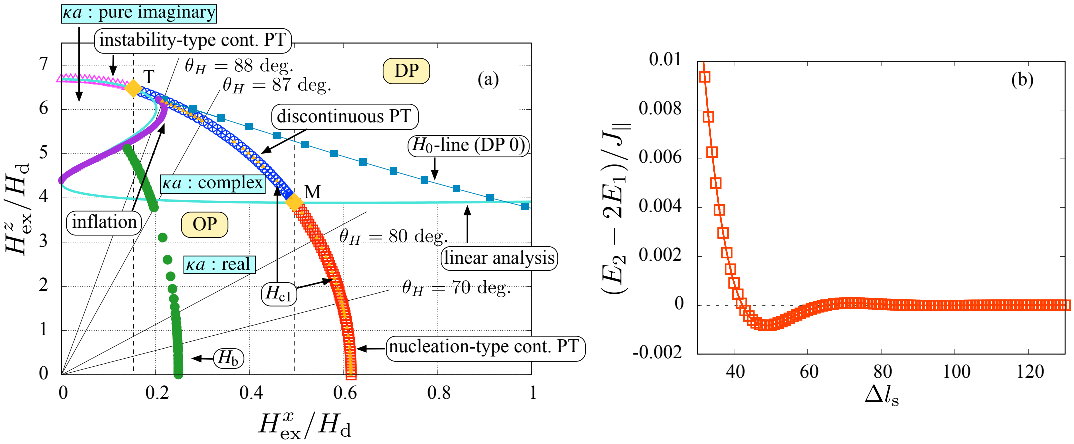

Fig 2: (a) Ground state phase diagram under the tilted magnetic field. “PT”, “DP”, and “OP” represent phase transition and disordered phase, and ordered phase, respectively. Phase diagram consists of two phases: Ordered phase with periodic modulation in the low field side of the phase boundary and disordered phase (uniformly polarized state) in the high field side. (b) Profile of the attractive interaction between two solitons as a function of inter-soliton distance. $D = 0.16J_{\parallel}$ and $K = 5.68H_{\mathrm{d}}$ with $H_{\mathrm{d}} = 2[(J_{\parallel}^2 + D^2)^{1/2} - J_{\parallel}]$.

in this sense our Landau expansion is valid. In the other two regions labeled “κa: real” and “κa: “complex”, tails of solitons decays in space without and with oscillations, respectively. The spin profile determine the sign of soliton interaction. In the tilted-field (H^z_{ex}–H^x_{ex}) case, we find that the origin of the discontinuous phase transition is also the cluster formation due to the attractive interaction and the soliton interaction changes its sign at the multicritical point, which are the same mechanism as in T–H^x_{ex} phase diagram[2]. Figure 2(b) shows an example of the attractive interaction. We actually construct the effective description using solitons on the discontinuous phase transition line, by considering two competing energy: the nearest neighbor attractive interaction of solitons $E_{\mathrm{int}} \equiv \min_{\Delta l_{\mathrm{s}}}(E_2 - 2E_1) < 0$ and the single soliton energy $E_1 > 0$. A line determined by the condition $E_1 + E_{\mathrm{int}} = 0$, describes very well the true discontinuous phase transition line in the wide range and thus we demonstrate that the soliton picture is also effective in the attractive soliton region. We also study the instability of soliton by taking account of the spin structure around its center, and evaluate the instability field line called the H_0 line in this thesis. We find that the instability mechanism is the unwinding of the soliton structure due to the spin motion toward the helical axis to unwind the soliton structure.

In the second part of Chap. 4, we study a surface barrier of solitons in a semi-infinite system, and find that when solitons interact attractively, their interaction with the surface is also attractive. We attribute the origin of a large hysteresis observed in experiments for micrometer-sized $Cr_{1/3}NbS_2$ to the presence of this barrier through the quantitative comparison between calculation results and experimental data. Note that in the phase diagram the hysteresis exists in a wider region than the region where the discontinuous phase transition is theoretically predicted. We calculate two fields related to the hysteresis loop in micrometer-sized $Cr_{1/3}NbS_2$: The barrier field H_{b}, at which the surface barrier of entering solitons vanishes, and the nucleation field H_{c1}, at which the energy of a single soliton vanishes. H_{c1} is equivalent to the thermodynamic critical field H_{c} for the nucleation-type continuous phase transition, while slightly lower than the discontinuous phase transition line. In magneto-resistance experiments, hysteresis closes at the saturation field H_{sat}, which is almost the same as the thermodynamic transition field, in increasing field, and in decreasing field, magneto-resistance shows a clear jump at the jump field H_{jump}, which

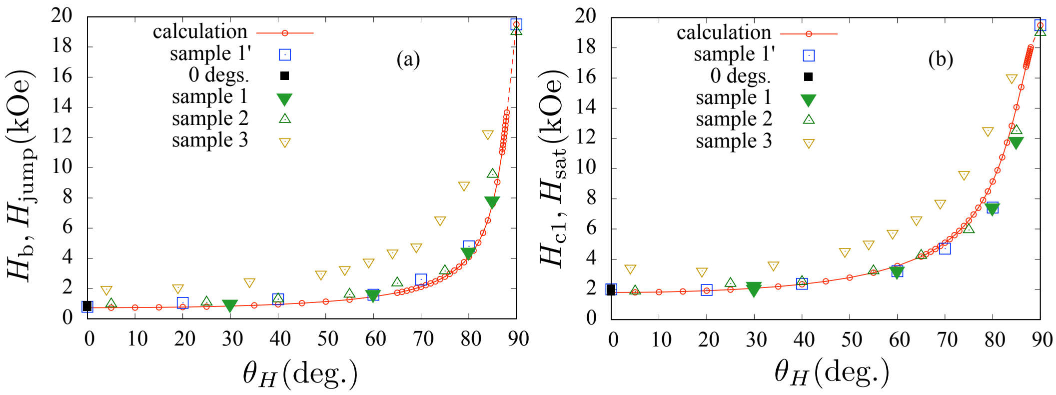

Fig 3: (a) Comparison between the jump field $H_{\rm jump}$ (experiment) and the barrier field $H_{\rm b}$ (calculation). (b) Comparison between the saturation field $H_{\rm sat}$ (experiment) and the nucleation field $H_{\rm c1}$ (calculation). There are large demagnetizing effects in the case of sample 3. Experimental data are obtained by R. Aoki and Y. Togawa. Theoretical results are obtained by the present author (Y. M.).

is highly reproducible. We compare $H_{\rm b}$ and $H_{\rm c1}$ with $H_{\rm jump}$ and $H_{\rm sat}$, respectively, and find good agreement, as shown in Fig. 3 except for the sample 3, with large demagnetizing effects. The theory of the surface barrier is applicable to a skyrmion system, but a sharp jump may not be expected because of its elongation instability.

In summary we have first found the non-reciprocity in the non-uniform state through the spectral intensity. We have also elucidated the roles and properties of chiral solitons in tilted magnetic field, particularly, the region of attractive solitons which cause the discontinuous phase transition and the new mechanism for solitons to destabilize at high fields, and the soliton surface barrier related to the hysteresis in experiments. We have clarified that the interaction between the attractive soliton and the surface is also attractive. This suggests the possibility to observe attractive solitons bound near the surface in experiments.

References

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