Multistep Topological Transitions Among Meron and Skyrmion Crystals in a Centrosymmetric Magnet

Topological spin textures, such as skyrmions and merons, have recently attracted much attention as potential candidates for high-density information carriers. Controlling the transformation between different types of these quasiparticles is an important challenge, while these transitions have mostly been limited to a few non-centrosymmetric systems, where they are driven by the Dzyaloshinskii–Moriya interaction. Here we demonstrate multistep topological transitions among a variety of meron and skyrmion crystal states in a centrosymmetric magnet $GdRu_2Ge_2$. These are governed by the competition between Ruderman–Kittel–Kasuya–Yosida interactions at inequivalent wave vectors. These findings demonstrate that even a simple centrosymmetric magnet can be a promising material platform to realize a richer variety of nanometric quasiparticles with distinctive symmetry and topology.

Topological swirling spin textures, such as skyrmions and merons, have recently attracted much attention as a unique building block for high-density magnetic information devices. Magnetic skyrmions are characterized by the topological charge defined as

$$N_{sk} = \frac{1}{4\pi}\int \boldsymbol{n}\cdot\left(\frac{\partial \boldsymbol{n}}{\partial x}\times\frac{\partial \boldsymbol{n}}{\partial y}\right)dxdy, \quad (1)$$

which represents how many times the spin directions wrap a sphere. **n**(**r**) is the unit vector along the local magnetic moment **m**(**r**). In general, skyrmion, antiskyrmion, meron, and antimeron are characterized by N_{sk} = -1, +1, -1/2, and +1/2, respectively, as shown in Fig. 1.

The controlled transformation among different types of such quasi-particles may lead to the multiple-valued memory function, which is an important challenge. However, it was previously achieved only in a few non-centrosymmetric systems characterized by Dzyaloshinskii-Moriya interaction [1], and a further search for novel materials and mechanisms to realize a wider variety of exotic magnetic quasi-particles is highly anticipated.

In this research, we exhaustively investigated magnetic structures in a centrosymmetric magnet $GdRu_2Ge_2$ by neutron and resonant X-ray scattering experiments [2]. Our target material $GdRu_2Ge_2$ is characterized by $ThCr_2Si_2$-type crystal structure of centrosymmetric tetragonal space group *I*4/mmm. By the detailed neutron and resonant X-ray scattering experiments, we identified two kinds of inequivalent wave vectors at $\mathbf{Q}_A = (q, 0, 0)$ and $\mathbf{Q}_B = (q/2, q/2, 0)$ with $q \sim 0.22$ in three kinds of magnetic phases, Phases II, III, and IV under magnetic field *B* parallel to the [001] direction.

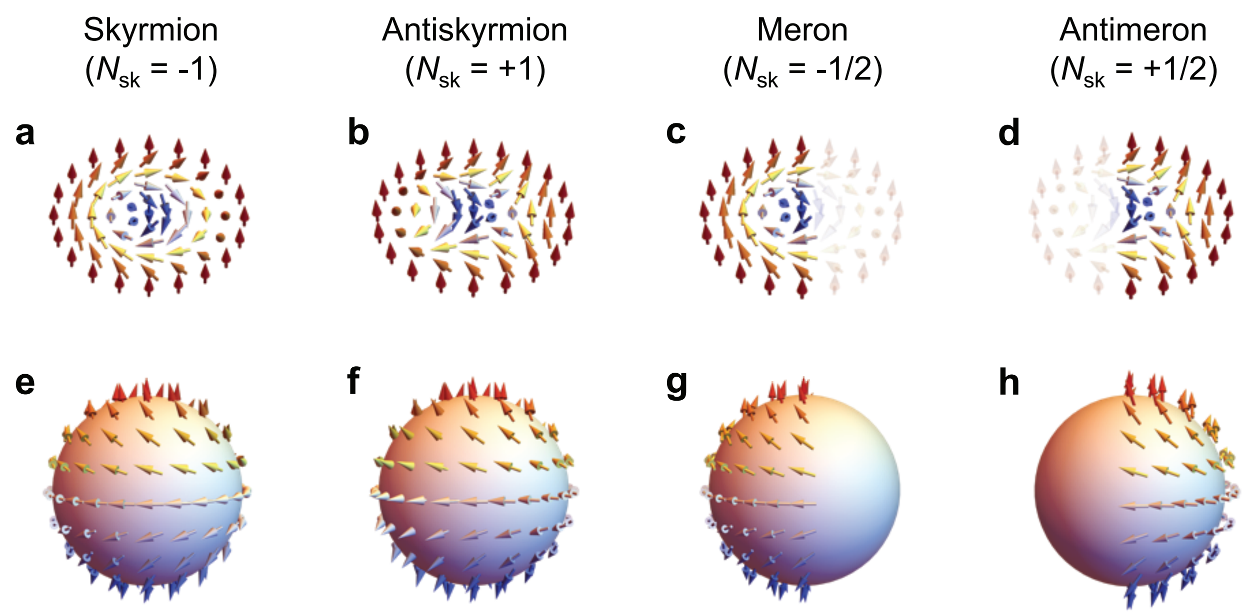

Figure 1: (a-d) Schematic illustration of various topological spin textures such as skyrmion (a), antiskyrmion (b), meron (c), and antimeron (d) spin textures. (e-h) Their projections onto a unit sphere. Skyrmion and antiskyrmion are characterized by integer values of N_{sk} since the spins wrap whole unit spheres, while meron and antimeron are characterized by half-integer values of N_{sk} since the spins wrap half of the unit spheres.

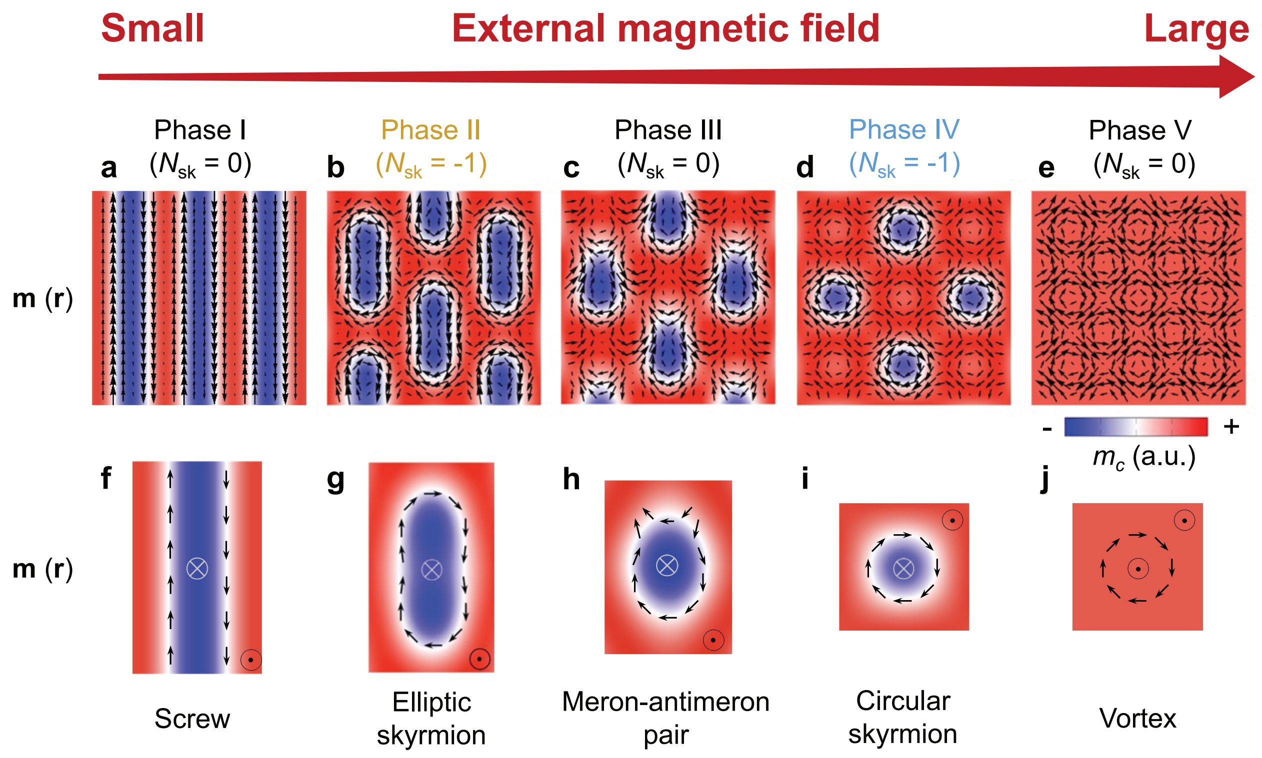

Figure 2: Experimentally deduced magnetic structures for $GdRu_2Ge_2$. (a-e) The magnetic structure **m**(**r**) for Phases I, II, III, IV, and V for magnetic field *B* parallel to the [001] direction, reconstructed based on the resonant X-ray scattering experiment. The black arrows and background color represent the in-plane and out-of-plane components of local magnetic moment **m**(**r**), respectively. (f-j) Schematic illustration of spin textures in (a-e).

We also performed the polarization analysis of the scattered X-ray beam, and we quantitatively identified each magnetic modulation component. Based on the experimental result, we successfully reconstructed the real-space spin texture for Phases I, II, III, IV, and V, as summarized in Fig. 2. In this material, multistep topological transitions among the elliptic skyrmion, meron-antimeron pair, and circular skyrmion phases are induced by applying the external magnetic field.

We also perform the simulated annealing based on the effective magnetic Hamiltonian, where the competition between Ruderman-Kittel-Kasuya-Yosida interactions at inequivalent wave vectors is assumed. The theoretically obtained magnetic structures well reproduce the experimentally deduced ones, which suggests the delicate balance between magnetic interactions mediated by itinerant electrons is the key to the formation of the exotic topological spin textures, including meron-antimeron pair and two distinctive skyrmion crystal phases. These findings demonstrate that even a simple centrosymmetric magnet with competing interactions can be a promising material platform to realize a wider variety of magnetic quasi-particles with distinctive symmetry and topology, whose stability can be tuned by various external stimuli.

REFERENCES

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H. Yoshimochi[1], R. Takagi[1,2], J. Ju[1], N. D. Khanh[3], H. Saito[1], H. Sagayama[4], H. Nakao[4], S. Itoh[4,5], Y. Tokura[1,3], T. Arima[1,3], S. Hayami[6], T. Nakajima[1,3] and S. Seki[1,2] ([1]The Univ. of Tokyo, [2]JST-PRESTO, [3]RIKEN-CEMS, [4]KEK-IMSS, [5]J-PARC MLF, [6]Hokkaido Univ.)