（別紙様式５）

変革を駆動する先端物理・数学プログラム（FoPM）
国外連携機関長期研修　報告書

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I did the International Research Experience in Groningen, Netherlands. Groningen is a student city located in the north of the Netherlands. Almost 25 percent of the population of the city is students. It makes Groningen the city with the highest student population density in the Netherlands and one of the youngest cities in Europe, where the average age is 36 years old. Moreover, Groningen is made up of people from a wide variety of countries; More than 120 nationalities live there. In this young and international city, I spend three weeks and had a great experience.

I did joint research at the University of Groningen. My collaborators are Prof. Maxim Mostovoy and Mr. Josse Muller at Zernike Institute for Advanced Materials. We theoretically studied magnetic topological defects, which is one of the topics in condensed matter physics. Since the magnetic topological defect can store and carry information, they are expected to be used as information carriers in future magnetic memory. The most famous magnetic topological defect is a magnetic skyrmion, which has a vortex-like spin texture of nanoscale. Since the magnetic skyrmion is regarded as a two-dimensional (2D) magnetic particle of nanoscale, the magnetic skyrmion can become a compact information carrier transferring information in two directions. Therefore, in order to realize next-generation memory using the magnetic skyrmions, methods for stabilizing skyrmions and efficient manipulation of the magnetic skyrmions have been intensively studied. In our joint research, we focus on a three-dimensional (3D) magnetic skyrmion rather than the 2D one in order to expand the potential application of the magnetic topological defects. Owing to the 3D particle nature, the 3D magnetic skyrmion can transfer information in all (three) directions in materials. Realizing such a 3D magnetic particle will open up the possibility of designing 3D magnetic devices. Our purpose is to construct a model for the 3D magnetic skyrmion and to identify the situation where the 3D magnetic skyrmion is energetically stable.

The 3D skyrmion is qualitatively different from the 2D skyrmion. Based on the homotopy group, the 2D skyrmion appears in models with the S^2 (two-dimensional sphere) order parameter, while the 3D skyrmion appears in models with the SO(3) order parameter. Therefore, models for 2D and 3D skyrmions are quite different. For example, a ferromagnetic Heisenberg model, which is one of the fundamental models for magnets, has a classical spin as the order parameter. Since the symmetry of the classical spin is equal to the S^2 symmetry, the 2D magnetic skyrmion has a chance to appear there. Meanwhile, the 3D magnetic skyrmion characterized by the SO(3) order parameter never appears. Thus, to construct the model for the 3D magnetic skyrmion, the key question is what is the SO(3) order parameter in magnets. In this joint research, we discussed candidates of the SO(3) order parameter in magnets and candidate materials. However, the order parameter of the model does not necessarily ensure the energetically stable magnetic topological defect. Indeed, to stabilize the 2D magnetic skyrmion in the ferromagnetic Heisenberg model, additional magnetic interactions other than a ferromagnetic interaction are needed: for example, the Dzyaloshinskii–Moriya interaction and antiferromagnetic interaction. Of course, it is not clear whether such interactions play an important role in stabilizing the 3D magnetic skyrmion as well, since the order parameters are different. Thus, another key question is what interaction is important to stabilize the 3D magnetic skyrmion. We constructed a SO(3) model with various interactions and investigated their effect on the ground states by using numerical simulation. As a result, we found the SO(3) order parameter in magnets and understood the tendency of the effect of interactions on the ground states.

Through this collaboration, I have deepened my understanding of magnetic topological defects and acquired new numerical methods. New knowledge of the 3D magnetic skyrmion and homotopy groups has allowed me to review my previous work about the 2D magnetic skyrmion from a new perspective. The newly acquired numerical methods will expand the scope of future research. Outside of research, I enjoyed lunch, drinking, and sports with Ph.D. students. In particular, it was very exciting to talk about physics and customs with people of various nationalities. In addition, the experience of spending a long time abroad was an important experience for my future international career. Therefore, this International Research Experience improved my research skills and global communication skills. I deeply appreciate Prof. Maxim Mostovoy and FoPM for giving me this opportunity.