（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 had the opportunity to visit the University of Zurich in Switzerland, which is not only the largest university in Switzerland but also holds the distinction of being the first state-founded university in Europe. While at the university, I was based at the Irchel campus, where the Physics building is located in the northeast of Zurich. Specifically, I was a part of Professor Titus Neupert's research group. Professor Neupert specializes in condensed matter theory, with a particular focus on phenomena related to geometry and topology.

I did joint research at University of Zurich. My collaborators are Prof. Titus Neupert and Dr. Tomáš Bzdušek. We theoretically studied nonlinear responses on hyperbolic lattices. Hyperbolic lattices are lattices which have a non-Euclidean geometry (negative curved space) and that play a paramount role at the frontier of both theoretical and experimental physics. Negative curved space means a curved hyperbolically like a saddle surface and such space has been studied in cosmology and particle theory. Therefore, hyperbolic lattices have applications in holographic descriptions of strongly coupled systems and models for quantum chaos, quantum gravity, and quantum entanglement. Also in condensed matter theory, hyperbolic lattices have been studied and hyperbolic analogs of topological insulators show that bulk topological invariants and protected edge modes persist in hyperbolic space. Furthermore, hyperbolic lattices are realized experimentally in circuit quantum electrodynamics and topolectrical circuits. Therefore, hyperbolic lattices are good platform to study the physics of negative curved space and have attracted much attentions.

However, hyperbolic lattices do not have periodicity unlike typical crystalline materials, and we cannot use a Bloch’s theorem which is widely used in the condensed matter fields. Since we cannot use Bloch’s theorem, we have to do exact numerical diagonalization of the Hamiltonian to obtain single particle energy. This requires abundant computational resources and preempts any treatment of macroscopically large systems even in the noninteracting limit. However, recent study develops a technique to obtain energy bands efficiently. By using this technique, new topological phase is revealed in hyperbolic lattices. Such phase is related to the second Chern number which is integer reflecting the geometrical features of systems. Since topological phase does not relate to the second Chern number in two-dimensional Euclid lattice, there is no Euclidean analog of such new phase. We focused on this new phase, and we studied responses on the hyperbolic lattices. In particular, we studied nonlinear responses related to the second Chern number.

Thorough this collaboration, I acquired knowledge in the field of hyperbolic lattices, which was previously unfamiliar to me. Furthermore, I learned some techniques of numerical studies to calculate the energy spectral of hyperbolic lattices and second Chern number. This new knowledge and technique will arrow me to expand my research field. I also enjoyed an interaction with group members in Titus’ group. In Titus’s group, we eat lunch and drink coffee every day and sometimes we eat some cakes. And I also did BBQ and went to river to swim with group members. I was surprised that many houses have a place to BBQ and the river in the city center is like a swimming pool where people swim freely. The opportunity to interact with students from various backgrounds is hard to obtain in Japan, and it was a valuable experience.

In addition to my research at the University of Zurich, I had the privilege of visiting other universities and institutes in the Zurich area, recommended by Professor Titus Neupert. I visited Eidgenössische Technische Hochschule Zürich (ETH Zürich) and I met a Dr. Sayantika Bhowal who study multipole. I was interested in her researches and I learned many interesting studies and useful references about multipole. This experience will be of

great help to me in my future research. I also visited a Paul Scherrer Institute (PSI) and I did a informal seminar. PSI is a research institute located about an hour outside the city center of Zurich. I talked about my previous research, and I heard study of Prof. Christopher Mudry. His research is related to some spin systems and I could learn mathematical approach to the topological phases of spin systems.

This international research experience not only allowed me to explore the novel realm of hyperbolic lattices but also facilitated interactions with a diverse array of individuals, extending beyond the University of Zurich to include ETH Zurich and PSI. This experience was immensely valuable, equipping me with knowledge not only in hyperbolic lattices but also in the realm of spin systems, which bears relevance to my research. Beyond the realm of physics, I relished the opportunity to engage with fellow students in Professor Titus Neupert's group, gaining insights into Swiss culture. Moreover, I marveled at the beauty of Zurich, with its historic architecture and the accessibility of the Alps for hiking via train. In addition, I learned other culture from Japan through interactions with group members and that experience is an important for my future international career. I would like to appreciate Prof. Titus Neupert for hosting me and FoPM for their financial support during this visit.