（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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所属部局	理学系　研究科　　物理学　専攻
受入先	Prof. Angel Rubio and Prof. Michael Schüler
日程	西暦 2024 年 2 月 26 日　～　西暦 2024 年 2 月 26 日

Dirac electrons are electrons that obey the laws of relativistic quantum mechanics (the Dirac equation). Though originally being a concept of higher-energy physics, analogies of such electrons can now be found in a variety of solids. The interaction between such three-dimensional Dirac electrons in solids and laser light is the main research topic during my Ph.D. and FoPM course. Especially, the framework of Floquet engineering has proven to be a powerful way of analyzing such interactions while also providing insight to the quantum geometrical and topological nature behind them. As both Floquet engineering and quantum geometry/topology in materials are both fields primarily driven by theorists, it is always a valuable experience as an experimentalist to have discussions with them to deepen my understanding. I prepared two seminar talks on both my experimental and theoretical results on the light-induced anomalous Hall effect of bismuth, and discussed my results with two theorist groups.

1.　Seminar at Rubio Group.

On February 26th, 2024 (10:00 central European time, 18:00 Japan standard time), I held an online seminar at Prof. Angel Rubio’s group at the Max Planck institute for the structure and dynamics of matter. The group has many publications on Floquet engineering of Dirac electrons (which is my topic of interest), and they are especially unique in that they consider realistic effects such as optical absorption and carrier scattering when light interacts with Dirac electrons, which is often times disregarded or kept vague in theoretical studies. Since I worked on both experiments and theories of Floquet engineering of three-dimensional Dirac electrons, I was particularly interested in how they would view our interpretation of the data, and whether they noticed something that I overlooked.

During the seminar, we had a lot of interesting conversations. In the following, I will pick up two particular discussions we had.

(1) On the definition of topological invariants for complicated Hamiltonians.

Floquet engineering (especially in the Sambe representation) requires an infinitely large Hamiltonian (the Floquet Hamiltonian). The main part of my second section involves the characterization of topological properties of a small portion of this Floquet Hamiltonian, and its systematic behavior against the mass term and anisotropy. One of the members pointed out that he felt the definition of topological properties may become questionable during the procedure of extracting said small portion. This was a viewpoint I didn’t have when I was writing my recent paper (Phys. Rev. Research **6**, L012027 (2024)), and was intriguing to me. Since the Floquet engineering framework doesn’t necessarily require the Sambe representation, it motivated me to think of a more rigorous way to define topological properties of Floquet systems.

(2) On the “population imbalance mechanism” of light-induced anomalous Hall effect

The “population imbalance mechanism” is a unique mechanism proposed by Rubio group to microscopically understand the light-induced anomalous Hall effect of graphene. I was not certain of its role for my experimental setup, and I was eager to hear what the members of Rubio group had to comment about it. One member commented that, based on the dynamics of the observed Faraday rotation, he thinks it is unlikely that injection currents play a dominant role. Another member also commented that, since the population imbalance mechanism is an interference effect, the probe polarization dependence may shed light onto the role of the mechanism. For the main experimental results we used polycrystalline and rotational symmetric samples, but this comment may be extended to assist the interpretation of our recent results obtained by measuring single crystal samples.

As I have never held a lengthy official seminar talk before, it was a very good experience for me. Based on the reactions from the attendees, I believe the seminar was beneficial for both of us.

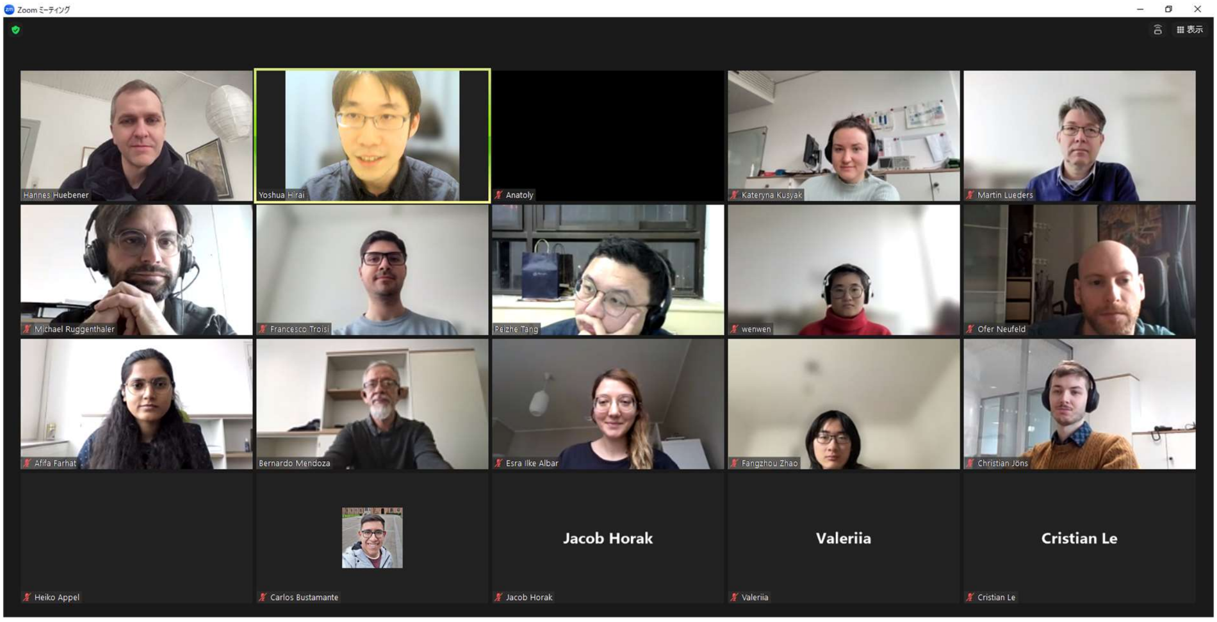

Photo with attendees of the online seminar at Rubio group.

2. Seminar at Schüler Group.

Later that day (14:00 central European time, 22:00 Japan standard time), I also had an online seminar with Prof. Schüler’s group at the University of Fribourg. The group is expert in theoretical frameworks of nonequilibrium states of matter and quantum geometry. Since the light-induced anomalous Hall effect of bismuth involves both the nonequilibrium distribution of Floquet state and the Berry curvature (which is a quantum geometrical quantity), I thought it would be a good experience to present my work to them. Due to the time limitation the depth of discussion was limited compared to the previous seminar, I still had interesting discussions with them.

One such discussion included a very fundamental aspect of light-matter interaction in three-dimensional Dirac electrons. The discussion began as a question on the selection rules and symmetry properties of one-photon resonances in three-dimensional Dirac electrons. My understanding at that time was that the Dirac Hamiltonian inherently embodies certain selection rules, but I have never quite associated them with symmetry properties. The discussion provided me with a new aspect of viewing light-matter interaction.

It was also good that we had very honest and generous discussions on experimental details. I noticed that we had very different common sense on measurement schemes (especially on the required sample size for certain measurements), which I believe was beneficial for both of us.

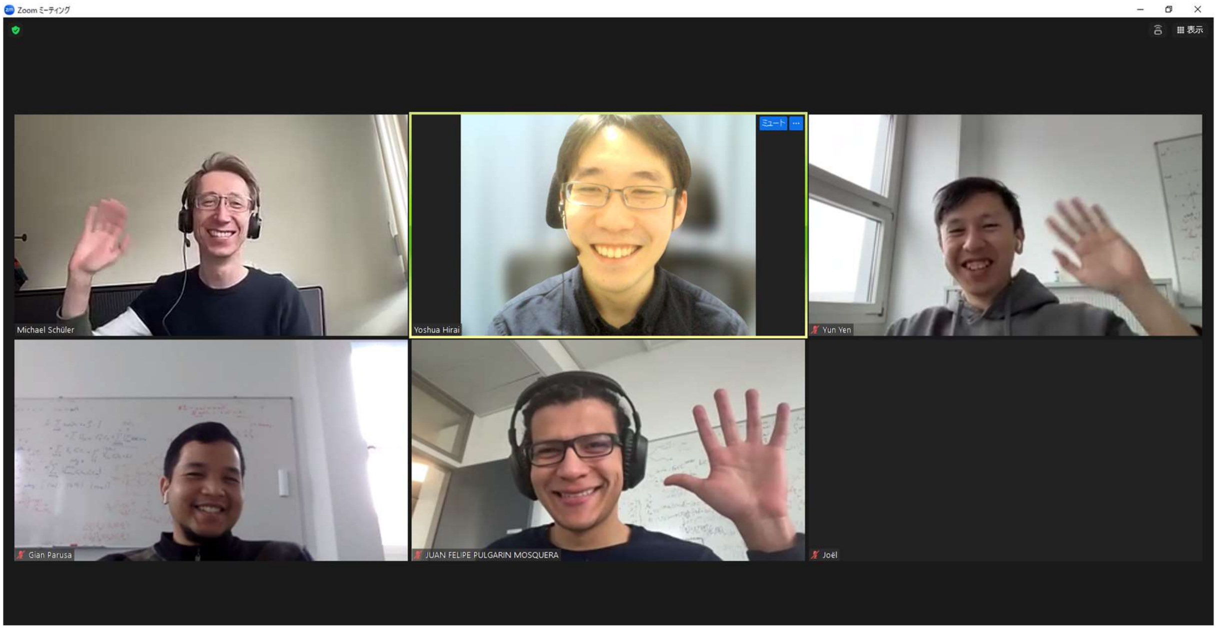

Photo with attendees of the online seminar at Schüler group.