

The Report of a MERIT Long-term Overseas Dispatch

Duration : 24/5/2019-15/10/2019

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Ogata group, 2nd year of Ph.D

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【Summary】

From May 24th, 2019 to Oct. 15th, 2019, I stayed in Köln, NRW, Germany and worked in a collaborate project with Prof. Achim Rosch in University of Köln. In this report, I will describe the project and the daily life in Köln.

【Research project】

Recently, a material named “Twisted Bilayer Graphene (TBG)”, which has two sheets of graphene stacked and twisted by a tiny angle in opposite direction, has been attracting much attention. It is shown that when the twist angle is a particular angle – the angle is called “magic angle” -, TBG has flat bands on the Fermi energy. In this system with the flat bands, many previous studies have been given in many field such as quantum Hall effect, Mott insulator and superconductor.

In our project in this stay, we tried to understand the origin of a charge order that is breaking the rotational symmetry of TBG, which is observed by a experiment (Y. Jiang, *et al.*, Nature (London) **573**, 91 (2019).).

At first, we focused on a coupling between valleys with opposite chirality, which is neglected in previous studies, by using the mean field theory. The coupling was expected to break the rotational symmetry. However, even though the coupling really breaks the rotational symmetry, we proved that a given charge order cannot have a Moiré-size anisotropic order.

As a next step, we introduced an anisotropy in the inter-layer hopping and discussed a given charge order and its stability by calculating an energy gain. As a result, we got a stripe like charge order that resembles with the one given by the experiment. Additionally, we found that the anisotropy in the inter-layer hopping breaks the flat band condition and the flat band becomes gapped. Now some questions are remained. First, we could not finish the discussion on the stability of the gapped state during my stay. We also have to discuss how we can understand and reproduce the d-wave type charge order in AA stacking area.

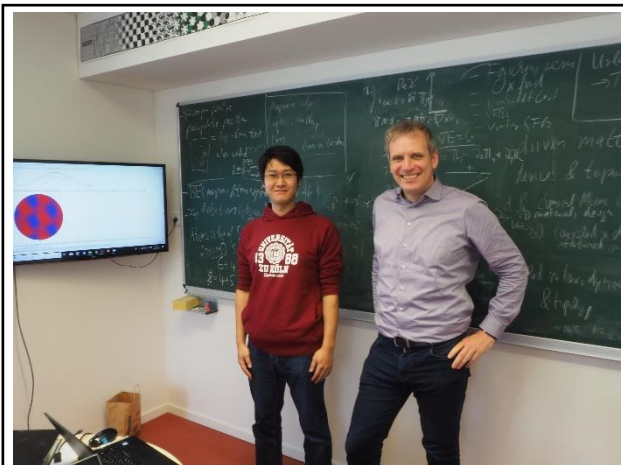


Fig.1. Me(left) and Prof. Achim Rosch (right)

To solve these questions, we are going to keep contact and calculate a higher order flat band condition case and a perturbation amplitude dependence of the energy gain.

【Daily life in Köln】

Köln is a city by Rhein in west end of Germany with the 4th biggest population in Germany. The Köln city was terribly destroyed in WWII, so the most part of the city is relatively modern. However, the Dom (Köln Cathedral, Fig.2 left) was not completely destroyed, and now is a symbol of Köln. Because it was free to enter, I visited the Dom many times. Köln is in 50° N, thus in summer the sunset time is later than 10 p.m. and it's usually not really hot compared to Japan. However, in this year, I experienced the hottest day ever in Germany and it was a terribly day because the German buildings do not have cooling system.

The Rosch group was large group and in a excursion 14 people joined (Fig.2. middle). In the research institute, I found that almost no student worked in late night and on holidays. It's really different from Japan. In Germany, not only in university but also in other fields people believe that having holidays improves the efficiency of their work in weekdays. I also found a difference in terms of carrier scheduling of Ph.D students. I asked students who submitted their Ph.D thesis how they are planning about after getting Ph.D. They said they had still a contract and they would consider after getting Ph.D. I felt this system allows students to focus on their project.

I enjoyed German culture from many aspects. Especially, I enjoyed Kölsch (the local beer in Köln, Fig.2. right). Kölsch has fruity and light taste, but less hoppy bitter taste. In Köln, when the glass is empty, the next glass of beer is served soon unless we show a sign by using a coaster. Kölsch was the BEST beer to drink in a hot day.



Fig.2. (left) Dom (middle) group excursion (right) Kölsch

【Acknowledgement】

I thank Prof. Achim Rosch for his supervising in our project and people in Rosch group and in the institute for their help in many aspects. I also thank Prof. Masao Ogata to arrange a chance to visit Köln. In this stay, I.T. was supported by JSPS Overseas Challenge Program for Young Researchers.