（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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Research activities at DESY

I stayed at Deutsches Elektronen-Synkrotron (DESY) at Hamburg, Germany for a month. DESY is a central research institute for both experimental and theoretical particle physics in Europe, and I especially worked in the Cosmology group led by Professor Thomas Konstandin and Professor Géraldine Servant. Aside from the research project, I joined their activities as well.

A typical week consisted of a seminar on Monday, a journal club on Thursday, plus a few irregular lectures or seminars. I also gave a seminar about my works on metastable cosmic strings and gravitational waves. The journal club was held jointly with other divisions of the theory group working on Higgs physics or formal theories.

I primarily discussed the cosmology of axion-like-particles with Professor Géraldine Servant, she is one of the pioneers of the axion kinetic misalignment mechanism, a compelling production mechanism of the axion dark matter.

As a researcher working also with experimentalists, she focused more on connections with observations. When I told her about a possible novel field dynamics in some setup, she immediately asked me about how it modifies the preferred model parameters, and hence, impacts search strategies. I found this is the sound reaction and realized that I was being too academic.

Discussions with the other members also gave me a lot of new ideas. I talked with Professor Thomas Konstandin, an expert on the cosmological phase transition, about the role of gauge fields in such transitions (which turned out to be irrelevant in most cases). Some of the members were working on the data analysis of a pulsar timing array (PTA), a gravitational wave experiment using pulsars. Recent PTA results have been the motivation of my recent works on cosmic strings, so discussion with them were insightful. For instance, although PTA experiments usually assume isotropic stochastic gravitational waves, it is surprisingly hard to detect anisotropies. According to their results, it cannot be resolved even when there is only one bright source.

Project: axion cosmology

Axions are hypothetical particles originally introduced to solve the strong CP problem in the Quantum Chromodynamics (QCD). They are Nambu-Goldstone bosons associated with the breaking of the Peccei-Quinn (PQ) symmetry broken primarily by the QCD anomaly. It turned out that they are also an attractive dark matter candidate.

Axions are known to have profound impacts on the history of the Universe. For example, when the PQ symmetry is broken after inflation, cosmic strings and domain walls form and they contribute to the dark matter abundance. Also, it can be probed by gravitational wave observations.

Recently, one often speaks of axion-like-particles (ALPs), which is not necessarily tied to the strong CP problem. Some scenarios in string theories are known to predict multiple axions, and thus, ALPs still make a well-motivated dark matter candidate. In this case, however, the potential for the scalar field may be radically different from the one for QCD axions. Our project is to deepen the understanding on such scenarios and elucidate the cosmological and observational consequences. The work is still ongoing.

Life in Hamburg

Despite the cold and snow, Hamburg was a comfortable city to live in. (Actually, the snow was anomalous. People repeatedly told me that I have chosen a wrong month.) I rented an apartment near DESY and was able to cook there. Germans consider potatoes as their staple food. In supermarkets, you can find them sold in a bag of 1-2.5 kilograms.

There are practically no language problems, as people in Germany speak English well. They are even surprised when I replied in German (which I learned as an undergraduate).
The public transport was reliable except when there is a strike---which was the case on the day of my return flight. I ended up walking to the nearest train station, which was about thirty-minute walk, instead of the bus stop immediately next to the apartment.
Hamburg has been thriving as a port and has rich history and culture. The weekends were naturally enjoyable. There are many museums (which do not close even on Sundays), and the Fischbrötchen, Hamburg's traditional fish burger, was also great.
Still, the highlight would be the opera show at Hamburgische Staatsoper---an opera company with centuries of history. Luckily, I was able to enjoy the last show of *La Traviata* there. (By the way, they offer an astonishing discount for students---a seat of €120 was only €15, even including bus tickets. Highly recommended if you are eligible.)

Conclusion

I spent a valuable time in Hamburg, not only because of academic discussions, but also because I could experience how it is to live, interact with people and do research abroad. I would like to close this report by expressing gratitude to the members of the DESY theory group, who warmly welcomed me and provided me various insights.



Figure 1: My office in DESY.



Figure 2: Fischbrötchen. The drink is also produced in Hamburg.