（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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With financial support from Forefront Physics and Mathematics Program to Drive Transformation (FoPM), I stayed in Switzerland from October to December and participated in research activities about ultracold neutrons (UCN) in the UCN Physics group at the Paul Scherrer Institute (PSI). The UCN Physics group is currently commissioning the n2EDM experiment to search for the electric dipole moment (EDM) of neutrons. An EDM of a fundamental particle is an important observable related to CP symmetry breaking and a key physical quantity in the search for the origin of matter in the current universe. As my specialty is to search for electron EDM using francium (Fr) atoms, my research shares some similarities with the n2EDM experiment in terms of searching for EDMs, although the target particles are different. Through this research activity, I have deepened my knowledge of the techniques for precise measurement of EDMs.

The activity I was particularly involved in during my stay was cesium magnetometry (CsM), which measures a background magnetic field by monitoring the interaction between Cs atoms and the magnetic field using a laser. Whether the measurement targets are neutrons or Fr atoms, the precise measurement of the EDM is conducted by applying an electric and magnetic field to the ensemble of the target particles and measuring the energy level shift induced by the interaction between the EDM of the particles and the electric field. At the same time, the interaction between the magnetic dipole moment of the particles and the magnetic field also causes an energy level shift. Therefore, identifying the configuration of the magnetic field exactly is necessary in order to reduce systematic errors and to extract the effect of EDM precisely. For this purpose, in the n2EDM experiment, the magnetic field gradient in the two central precession chambers storing neutrons is derived by installing 112 CsMs around the chambers (Fig. 1) and measuring the magnetic field there. I worked on building a CsM calibration setup.

The result obtained from each CsM may carry on an offset because, for example, the Cs cells of the CsMs can be magnetized. Therefore, it is necessary to calibrate each CsM cell for a precise measurement of the magnetic field. The relative offset between CsMs can be determined by measuring the intentionally generated magnetic field by several CsMs in the magnetic shield (Fig. 2) eliminating the background magnetic field and comparing the results obtained from each CsM. I contributed to setting up the calibration system. Polarization maintaining fibers are used to transmit laser light to the Cs cells in the magnetic shield previously used in the nEDM experiment. In the beginning, their transmissions were very unstable and the intensity of transmitted light fluctuated up to 100% of the amplitude. By repeatedly trying and testing the configuration of fibers and other optical elements, I finally stabilized the light transmission down to about 20% of the amplitude. Also, I exchanged an amplifier for the signal from the photon detector of CsM to reduce the noise. I investigated the magnetic field in the shield using a fluxgate magnetometer. However, I didn't make it to extract the signal from CsM. This is thought to be because the magnetic field in the magnetic shield was disturbed by contamination there and the output of CsM had noise varying with time. In the future, it is necessary to understand the contamination and noise. As mentioned above, I made steady progress on the necessary tasks for CsM calibration.

In addition to CsM calibration, I also worked on several other studies on the measurement of the magnetic field using Cs atoms. I analyzed the data of the previous CsM measurements taken at PTB Berlin and confirmed the stability of the CsM measurements by calculating the Allan deviations. Further, I used a special magnetic field scanner (the gradiometer) and measured the magnetic contamination of parts to be installed in the n2EDM experiment. The gradiometer employs a different kind of CsM that is also based on laser light and Cs cells. This device measures the gradient of magnetic fields due to the contamination of parts. This measurement is essential for the n2EDM experiment as the magnetic field in the chamber has to be controlled very precisely for the precise measurement of the neutron EDM. The acceptable magnetic dipole strength the parts may have ranges from a few nAm^2 to a few tens of nAm^2 depending on where they are installed. By measuring the magnetic moment, it was confirmed whether contamination of each part is acceptable or not.

Through the above activities, I have gained knowledge of measuring magnetic fields precisely using CsM. Eliminating the systematic error caused by the magnetic field is essential in the precise measurement of the electron EDM using Fr atoms as well. Further consideration is important regarding the applicability of the knowledge gained during this stay to the measurement of electron EDM.

Moreover, I was involved in other activities. I attended the Symposium University of Tokyo – ETH Zurich – University of Zurich, which took place from 15th to 17th October, and presented my poster. The symposium was very interdisciplinary, and I enjoyed listening to lectures on fields such as architecture and teaching, which I do not have much exposure to in my daily research life. Also, I participated in the BRIDGE workshop: Bridging Research Innovations in Diverse muon and neutron science by GEneral collaboration between Japan and Switzerland, which took place from 18th to 20th October. There, I communicated with researchers and students in neighboring fields. In addition, I attended a class about low energy particle physics at ETH Zurich. I not only developed my knowledge in fields related to my specialty but also experienced the atmosphere of a European university.

As the statements above indicate, this stay was very valuable for me. I would like to thank the UCN Physics group for giving me the opportunity to do such a study, FoPM for providing financial support, and everyone who has helped me during this stay.

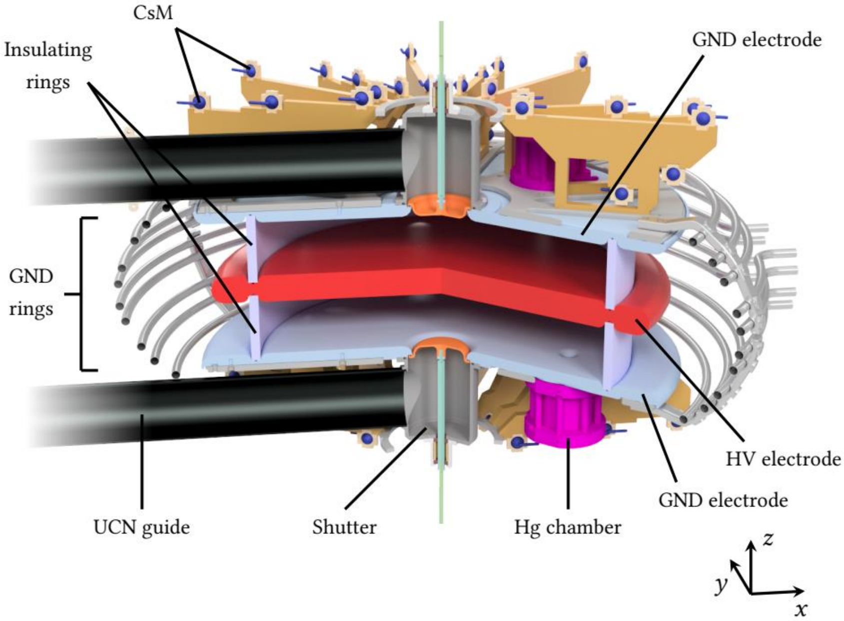

Fig. 1. CsMs installed around the precession chambers. The volumes of both chambers are bounded by the insulating rings and electrodes. This figure is adapted from D. Pais's doctoral thesis (ETH Zurich, 2021).

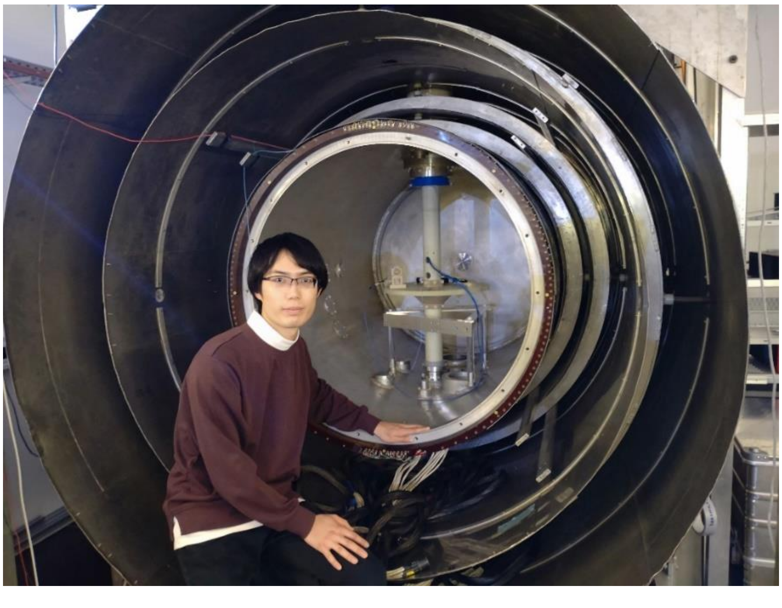

Fig. 2. Me in front of the magnetic shield.