（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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日程	西暦　2022 年　8 月　1 日　～　西暦　2022 年　9 月　11 日

I joined an experiment at PSI in Switzerland in August and September. In the experiment, we measured muonic X-rays of some materials. The muonic X-rays are transition X-rays emitted from a muonic atom, which is an atomic binding state formed by a negative muon and a nucleus. The experiment was a part of a Muon Induced X-ray Emission (MIXE) collaboration, a PSI project aiming to develop and apply the experimental methods of a non-distractive elemental analysis of materials. Since the muonic X-ray is a characteristic X-ray, it can be used for elemental analysis. The property of elemental analysis using muonic X-rays is that muon can investigate a deeper area of the materials than other elemental analysis methods. It is because the energies of muonic X-rays are higher than electric transition X-rays owing to muon's heavy mass. This method is useful, especially in the field of archeological artifacts or operand studies of devices. The MIXE project aims at exploiting high-energy muonic X-rays to provide bulk, depth-sensitive, and non-destructive elemental analysis methods sensitive to basically all the elements.

The measurement was conducted with a Ge detector array shown in the picture below. Ge detectors are the typical photon detectors of muonic X-ray spectroscopy because it shows high energy resolution and enough detection efficiency from a few keV to a few MeV, which covers most of all elements' muonic X-ray energy. The Ge detector array includes two Ge detectors, which we brought from Japan. These two Ge detectors are well studied their performance during my master's course. The experiment preparation was done from 1st to 24th August, and the muonic X-ray measurement using a muon beam was held from 25th August to 5th September. I joined all the preparation and measurement. I mainly treated the data acquisition system of our Ge detectors, taking data, setting the proper parameters for each detector, and synchronizing data acquisition systems used in PSI. I also did an online analysis of the energy calibration of Ge detectors and the performance of Compton suppressors, which I will explain below.

The primary purpose of the experiment for us was to get the standard efficiency calibration references of Ge detectors. The evaluation of the Ge detector's efficiency is important to analyze the composition ratio of materials using the spectrum taken by Ge detectors. The energy of muonic X-rays of high atomic number elements shows over 2 MeV, but standard gamma-ray sources only have energy below about 1.8 MeV. Therefore, to evaluate the efficiency of Ge detectors over 2 MeV photon energy, another way of evaluation should be conducted for each Ge detector. There are some ways to evaluate the performance from a few MeV to about 10 MeV, such as using the gamma-ray emission from the resonant reaction of low-energy proton and Al, making the short live gamma-ray source ^{66}Ga, and measurement of gamma-rays from neutron capture of low elemental isotopes. But these methods need to be conducted at other facilities such as tandem accelerators or nuclear power plants. Therefore, the performance evaluation method which can be performed in muon accelerator facilities is required. In this situation, we measure the relative intensities of muonic X-rays of ^{197}Au and ^{208}Bi as the standard calibration references of Ge detectors in this experiment. The muonic X-rays of ^{197}Au and ^{208}Bi are from a few keV to around 6 MeV. So, these energies and relative intensities can be used as useful reference data for efficiency and energy calibration in the high-energy region at muon facilities. This measurement was performed with the Ge detector, which we brought from Japan because our Ge detector's full energy peak detection efficiency was precisely measured using high-energy gamma-rays from the resonance reaction of a proton and ^{27}Al at the tandem accelerator in RIKEN.

We also performed the test measurement of non-destructive analysis of meteorites with Compton suppressors. Some kinds of meteorites include low carbon components; it is important to know these compositions in earth and planetary science. The muonic X-rays of carbon are about 75 keV, and the Compton component, which is the main background component of the spectrum taken by Ge detectors, is dominant in such a low-energy region. Therefore, when we measure the muonic X-rays from the carbon with other higher atomic number elements, the peak signal is on the large background component, and the statistic error becomes large. We are developing a photon detection system using Compton suppressors to improve the signal-to-noise ratio by reducing the Compton component. In the MIXE experiment, we also measured the low composite carbon in some meteorites and evaluated the performance of the Compton suppressors.

We are writing a thesis about the development of the photon detection system, including the results of this experiment. We are also preparing a proposal for an experiment on a theme of my doctoral course, owing to the experience of discussions with staff and students in PSI during the experiment.