Development of wide range photon detection system for muonic X-ray spectroscopy[†]

R. Mizuno,[*1] M. Niikura,[*1,*2] T. Y. Saito,[*3,*1,*4] T. Matsuzaki,[*2] H. Sakurai,[*1,*2] A. Amato,[*5] S. Asari,[*6] S. Biswas,[*5] I. Chiu,[*7] L. Gerchow,[*5] Z. Guguchia,[*5] G. Janka,[*5] K. Ninomiya,[*8] N. Ritjoho,[*9] A. Sato,[*10] K. von Schoeler,[*11,*5] D. Tomono,[*12] K. Terada,[*13] and C. Wang[*5]

We have developed a photon detection system for muonic X-ray spectroscopy. Since muonic X-rays have characteristic energies for each element, they are used for nondestructive elemental analysis, the so-called "muon induced X-ray emission (MIXE)."[1)] Muonic X-rays are also used as a method to measure the nuclear charge radii and distributions.[2)] The energies of the Lyman series of the muonic transition range from a few tens of keVs to 6 MeV depending on the atomic number. To identify the element from the energy of muonic X-ray and conduct charge radius measurements using muonic X-ray spectroscopy, a highly accurate X-ray measurement system applicable to a wide energy range is required. Therefore, in the present study, we developed a wide-energy-range photon detection system for MIXE and nuclear charge radius measurements. The detector system comprised high-purity germanium (Ge) detectors with bismuth germanium oxide (BGO) Compton suppressors. The signals from the detectors are readout with a digital acquisition system. BGO Compton suppressors were adopted to reduce the background, because detection of the muonic X-rays at low energy regions from light elements is limited by the signal-to-noise (S/N) ratio.

Three types of Ge detectors were used to cover a wide energy range. The detector performance of the proposed system in the entire energy range below 10 MeV was evaluated through offline source measurements and in-beam experiments using the ^{27}Al(p, γ)^{28}Si resonance reaction.[3)] Optimization of the parameters used in the digital waveform processing was essential to achieve the best performance of the system. With a sufficient number of anchor points for energy calibration, an energy accuracy of 0.3 keV was achieved. By selecting the appropriate timing pick-off method, a timing resolution (σ) of 10–20 ns was obtained. The absolute efficiency was also determined with 3% accuracy. The detector performances under high count-rate conditions of up to 10 kHz were investigated. A Monte-Carlo based simulation using GEANT4 was performed, and the obtained results were in agreement with the measurement results, so that configurations of each spectroscopy setup can be optimized using GEANT4.

The performance of the system was demonstrated in the MIXE experiment at Paul Scherrer Institute (PSI). The performance of BGO Compton suppressors was evaluated through measurements of meteorites containing a low composition of carbon and a high composition of higher atomic number elements. The use of Compton suppressors improves the S/N ratio of the muonic X-ray originating from carbon under such conditions, because the energy peaks of K_α X-rays emitted from carbon in the spectrum are on the top of the Compton component of muonic X-rays of heavier elements. Based on the result, the BGO Compton suppressors improved the S/N ratio by a factor of 1.9 and 3.9, depending on the energy region, and the carbon component of the Allende meteorite with 0.3 wt% could be detected.

In the present study, we also proposed a calibration method for the photon detector at the muon facility. As the in-beam measurement for calibrating high energy photons, such as proton or thermal neutron induced resonance reaction, cannot be conducted at the muon beam facility, general references for high-energy photon calibration are required for performing *in situ* calibrations. The muonic X-rays of the high Z elements can be used as the reference, as they have a high energy of approximately 6 MeV. The energy and relative intensity of the muonic X-rays emitted from ^{197}Au and ^{209}Bi are measured at PSI using the Ge detector, with the detection efficiency calibrated under an energy of 11 MeV using ^{27}Al(p, γ)^{28}Si resonance reaction in advance. The energy and intensity references obtained in the present study provide a method for performing general calibrations at the muon facility.

References
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*1 Department of Physics, University of Tokyo
*2 RIKEN Nishina Center
*3 Atomic, Molecular and Optical Physics Laboratory, RIKEN
*4 Center for Nuclear Study, University of Tokyo
*5 NUM Division, Paul Scherrer Institut
*6 Department of Chemistry, Osaka University
*7 Hierarchical Structure Research Group, Japan Atomic Energy Agency
*8 Institute for Radiation Science, Osaka University
*9 School of Physics, Institute of Science, Suranaree University of Technology
*10 Department of Physics, Osaka University
*11 Institute for Particle Physics and Astrophysics, ETH Zurich
*12 Research Center for Nuclear Physics (RCNP), Osaka University
*13 Department of Earth and Space Science, Osaka University

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