Activity of MuSIC Muon Beamline at the RCNP Cyclotron Facility 2019

The MuSIC beamline is in a long shutdown for accelerator upgrade work. Before the shutdown some experiments were completed and data analyses were ongoing. Some significant results were obtained in 2019 and published in a paper. In this report, let us introduce these two selected topics at MuSIC.

Non-destructive elemental analysis using negative muon

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Non-destructive elemental analysis is useful as a fundamental technique in various scientific research fields. In recent years, non-destructive elemental analysis method using negative muon (MIXE: Muon Induced X-ray Emission) has been developed, and applied for various samples [1]. In this paper, we report the first result on analysis of archeological samples in RCNP-MuSIC [2].

The muon irradiation experiment was performed at the M1 beamline in MuSIC. We prepared an old Japanese coin (Tempo-koban, 19th century, Japan) sandwiched by copper plates of 0.1 mm thickness as a sample. A muon beam with momentum of 60 MeV/c from the beamline passed through two plastic scintillation counters and impinged on the sample. The muonic X-rays emitted from the sample were measured by two high-purity germanium detectors (CANBERRA; GC3018 and BE2020). The muon irradiation time was 13 minutes. The intensity of the proton beam from the accelerator during irradiation was 1.1 μA, and the number of muons injected in the sample was about 500 /s. Figure 1 shows the muonic X-ray spectrum obtained from this experiment. Although the sample was covered by the copper plates, the muonic X-rays originated from the gold and silver were clearly observed. Because the muon was captured on the highly-excited atomic muon level in the initial stage of capture process, cascaded muonic X-rays such as KX-rays, LX-rays, and MX-rays have been observed. In this work, we focused on the muonic Ag (4-3) X-rays at 303 keV and 305 keV, and muonic Au (5-4) X-rays at 400 keV and 405 keV for identification of elemental composition. The obtained X-ray intensity ratio was Au(5-4)/Ag(4-3)=1.21±0.23. By using the calibration curve between muonic X-ray intensities and elemental composition for silver-gold alloys [3], the elemental composition of Au in the sample was determined as 52.5± 9.8 %. This value was in good agreement with the result by MIXE at J-PARC (61±6 wt% in about 4 hours measurement) [4], and the result from destructive analysis (57 %) [5].

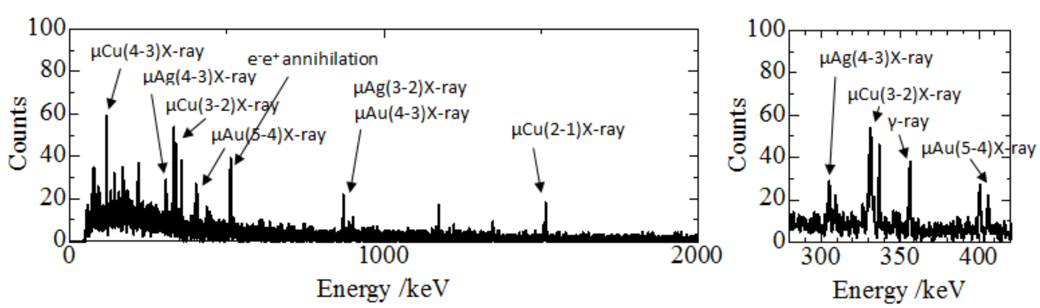

Figure 1: (left) muonic X-ray spectrum obtained by muon irradiation for Tempo-koban. The numbers in parentheses in muonic X-rays mean the change of principal quantum number of atomic muon by muonic X-ray emission. (right) expanded muonic X-ray spectrum of μAu (4-3) and μAg (5-4) X-ray region.

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Muon irradiation test of SRAM device for soft error study at MuSIC facility

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Radiation-induced soft error means a temporary fault in semiconductor devices due to a single event upset (SEU). The SEU is an upset of memory information in a static random access memory (SRAM) and is caused by the transient signal induced by energetic ionizing radiation. The main cause of soft error is well-known to be the cosmic-ray neutron on the ground level because the neutron can deposit sufficient charge to cause a SEU through the nuclear reaction between neutron and constituent nuclei in devices. In recent years, a progressive reduction in radiation tolerance on soft errors has become evident since the critical charge, i.e., the threshold deposition charge to cause a SEU, has decreased by the miniaturization and low voltage operation of circuits. Consequently, the muon-induced SEU is drawing attention and many works were reported from 2010 [1].

More recently, the negative muon irradiation test [2], [3] was firstly performed at J-PARC/MUSE [4]. The negative muon-induced SEU cross sections were derived by dividing the observed number of bit errors by the incident muon fluence and were compared to those of positive muon. The experimental result clearly showed the significant effect of the nuclear negative muon capture reaction on the occurrence of SEUs. At MUSE, it is difficult to detect a single muon individually because of time structure of pulsed muon beam. Thus, there is an uncertainty in the measurement of the muon fluence. In the present work, we have performed an irradiation test of a SRAM device with a direct current (DC) beam at MuSIC (Muon Science Innovation Channel) [5] in RCNP. The incident muon fluence was measured by counting muons one-by-one by taking an advantage of the DC muon beam. The purposes of this work are to make the measured cross sections at MUSE more reliable and to demonstrate the availability of MuSIC for the soft error study.

During the experiment, the 65-nm technology SRAM device, which was used in the previous test at MUSE, was irradiated by the negative muon beam with the momentum range from 34 to 38 MeV/c. A plastic scintillator placed at upstream of the device was used to count the number of incident muons directly. Also, two germanium detectors were placed at downstream of the device to count muonic X-rays from device board. The number of stopping muons in the SRAM chip, which has the significant effects on SEUs due to the nuclear muon capture reaction, was estimated based on the information of the X-rays.

The experimental results are reported in detail in Ref. [6]. Here, we show one of them in Fig. 1. The negative muon-induced SEU cross section of measured at MuSIC and MUSE are plotted as a function of incident muon momentum. Both the experimental SEU cross sections are in good agreement within the error bar representing the statistical uncertainty. As a result, we validated the SEU cross sections measured previously at MUSE and demonstrated that the MuSIC facility is useful for the study of muon-induced soft errors in addition to the facility.

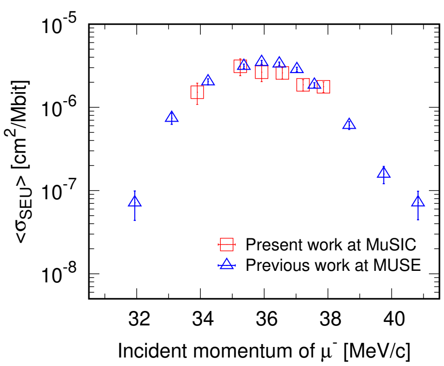

Figure 1: Comparison of the negative muon-induced SEU cross sections measured at MuSIC [6] and MUSE [2]. The SRAM chips were operated at the voltage of 0.9 V

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