Measurement of the energy spectra of hydrogen isotopes from nuclear muon capture in ^{nat}Si

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We have measured the energy spectra of protons and deuterons generated via the nuclear muon capture reaction on Si. The experiment was performed using the M1 beam line of Muon Science Innovative muon beam Channel (MuSIC) at Research Center for Nuclear Physics (RCNP), Osaka University. A 100-μm thick silicon target was irradiated by the negative muon beam and the emitted protons and deuterons from the Si target were successfully measured by using a ΔE-E telescope that consists of a 325-μm thick silicon detector (ΔE) and a 25-mm thick CsI(Tl) detector (E). The measured spectra are preliminarily compared with those calculated by the particle and heavy ion transport code system (PHITS).

1. Introduction

Soft errors induced by cosmic ray have been recognized as a major threat for the electronics used at the ground level. The soft error is caused by an upset of the memory information induced by the energy deposition in devices by energetic ionizing radiation. Recently, cosmic-ray muon-induced soft errors have attracted much attention due to the reduction of soft error immunity on static random access memories. Our previous work [1],[2] reported that the negative muon has much more serious effect on the occurrence of SEUs compared to the positive one because of the emission of ions from nuclear muon capture in Si. Moreover, it was pointed out that helium ions, namely alpha particles have a predominant contribution to SEUs among all particle and ion species.

Figure 1 shows a schematic illustration of the physical process of the nuclear muon capture in ^{28}Si. After losing incident kinetic energy and stopping in ^{28}Si, the negative muon is captured by the atom into high orbital momentum states, forming a muonic atom. The captured muon cascades down to the 1-s orbit while emitting characteristic X-rays. Approximately 35% of the captured negative muons decay into an electron and two neutrinos in the 1-s orbital. The remaining negative muons are finally absorbed by the nucleus, and highly excited nuclei are formed. Then, the nucleus is deexcited by emission of neutrinos, photons, neutrons, and other light ions [3]. Thus, the capture reaction generates a heavy recoiling nucleus with simultaneous emission of secondary light ions (protons, deuterons, α-particles, etc.).

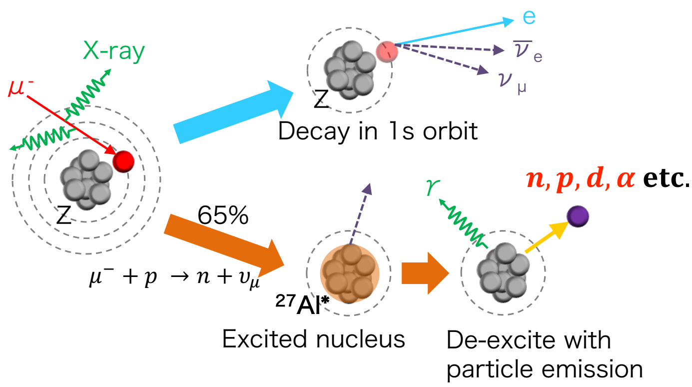

Figure 1: Physical process of the nuclear muon capture reaction on ^{28}Si.

S. Sobottka and E. Wills have conducted the experiment to investigate the energy spectra of these ions [4]. A Si(Li) detector was irradiated by a muon beam and a spectrum of the energy deposition by the light ions and recoiling nucleus in the detector was measured. As a result, they suggested that the charged-particle emission probability per muon capture is 0.15 ± 0.02. The particle identification (PID) of the emitted ion was not performed in the experiment. Hence, the energy spectra of the individual light ions species have not been measured so far. Therefore, there is an uncertainty in the estimation of the muon-induced soft error rate. Under these circumstances, we have performed a new measurement of the energy spectra of light ions emitted from the nuclear muon capture in Si.

2. Experimental method

The experiment was conducted in the M1 muon beam line of RCNP-MuSIC. The facility produced pions through nuclear reaction between a 392-MeV proton beam and a graphite target. The produced pions almost decay into muons in a superconducting solenoid magnet and the decayed muons are transported downstream to the beam exit. During the experiment, the K400 ring cyclotron was operated with the average current of 1.1 μA.

Figure 2 shows the experimental setup placed in the M1 beam line. A vacuum chamber was connected to the beam exit. Two 100-μm thick Si targets were mounted at the center of the chamber at an angle of 45° to the beam direction. The size of the target is 5 cm × 5 cm. The targets were irradiated by the muon beam with the average momentum of 36 MeV/c. Two forward plastic scintillators (PSs) with the size of 5 cm × 7 cm × 0.5 cm^t were set to count the number of incident muons. Another PS for veto counting was placed to detect muons passing through the targets. Two telescopes were mounted parallelly to the targets at both the upstream and downstream of the targets to detect the secondary ions and measure their kinetic energy. The distance between the targets and telescopes was 15 cm. The telescope consists of a 325-μm thick silicon detector (ΔE) and a 25-mm thick CsI(Tl) detector (E).

During the experiment, the coincidence event of the upstream PSs was set to be the trigger of the data acquisition (DAQ) system. The signals from individual detectors were amplified and shaped by shaping amplifiers for the pulse height measurement. The outputs from the amplifiers were fed into an analog-to digital converter (ADC). Thus, the energy deposition in each detector was measured during the experiment.

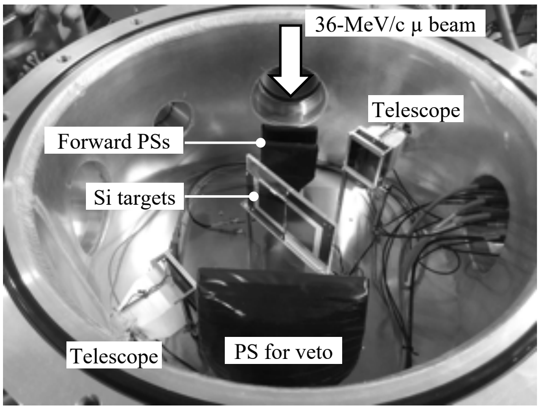

Figure 2: A picture of the experimental setup.

3. Experimental result

The PID was performed event by event by a conventional ΔE-E method using the energy loss (ΔE) in the 325-μm thick Si detector (ΔE) and the total energy (E) that is obtained by the sum of ΔE and the deposition energy in the 25-mm CsI detector. Figure 3 shows a two-dimensional event plot of ΔE versus total energy E. The PID was successfully achieved and each hydrogen isotope is clearly separated. The total event numbers of protons and deuterons were approximately 2400 and 800 during the 26-hour irradiation time, respectively. Figure 4 shows the measured energy spectra of proton and deuteron. The vertical axis in Fig. 4 represents the number of events observed during the experiment. The absolute values of the emission probabilities are now under analysis.

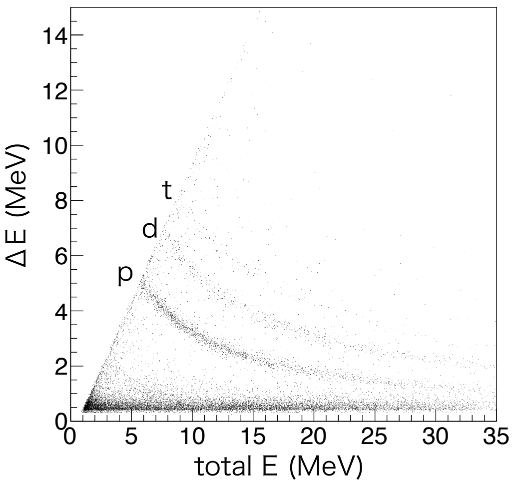

Figure 3: Energy loss in the silicon detector versus total energy obtained from silicon and CsI detectors.

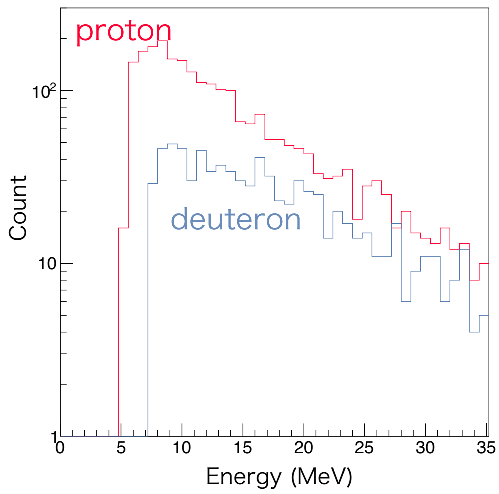

Figure 4: The energy spectra of proton and deuteron emitted from nuclear muon capture in ^{nat}Si.

4. Comparison with the PHITS calculation

The PHITS code can calculate the energy spectra of particles emitted from the nuclear muon capture reaction. In the PHITS calculation [7], a proton in the nucleus is randomly selected and converted to a neutron to simulate the elementary process:

$$p + \mu^- \rightarrow n + \upsilon_\mu.$$

The energy that corresponds to the mass of muon is distributed to the neutron and the muon neutrino. Then, the time evolution of all nucleons inside the nucleus is simulated by JQMD (JAERI quantum molecular dynamics) [5] and a few fast nucleons and/ or light cluster ions (d, t, alpha, etc.) are emitted via this dynamical process. The subsequent evaporation process is calculated by GEM (generalized evaporation model) [6]. The details of the calculation are described in [7].

Figure 5 shows the calculated energy spectra of protons and deuterons from the nuclear capture reaction on ^{nat}Si. Currently, we cannot make a direct comparison between the calculated spectra and the experimental ones shown in Fig. 4, because the absolute value of the emission probability has not yet been determined for the experimental data. Hence, the yield ratios of proton to deuteron in the energy range from 7 to 35 MeV are compared between both the calculation and measurement. The calculated ratio is 29:1, while the experimental one is 3:1. Thus, we found a large inconsistency between the simulation and experiment with respect to the yield ratios of proton to deuteron.

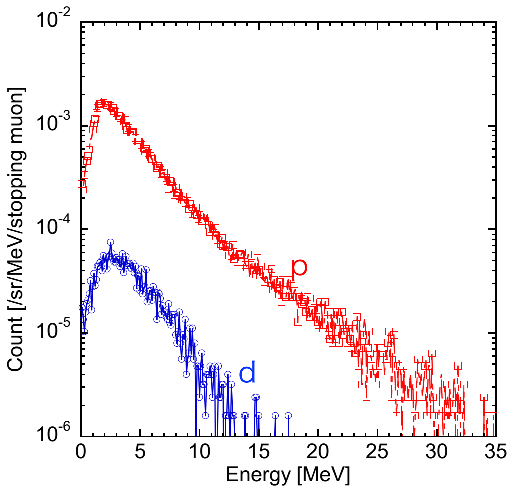

Figure 5: The calculated energy spectra of proton and deuteron by PHITS.

5. Summary and future plan

The energy spectra of protons and deuterons emitted from the nuclear muon capture reaction were successfully measured by using the ΔE (325-μm thick silicon)-E (25-mm thick CsI) telescope. In addition to the measurement, we performed the preliminary comparison with the result calculated by PHITS, and found that there is a large discrepancy between the simulation and experiment. For more quantitative comparison with the simulation and the estimation of muon-induced soft error rates based on this measurement, it will be necessary to determine the absolute value of the measured energy spectra. Moreover, we plan to measure the energy spectrum of alpha-particle that is expected to have the most crucial effect on negative muon induced single-event upsets as suggested in [1].

Acknowledgement

This work was supported by JST-OPERA Program Grant Number JPMJOP172, JAPAN, Grant-in-Aid for

Scientific Research (B) (No.16H03906) and JSPS Fellows (No.19J12649) from the Japan Society for the Promotion of Science (JSPS) and Kyushu University Platform of Inter/Transdisciplinary Energy Research (Q-PIT).

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