Measurement of impurity nuclides in 10.75 MeV/nucleon ^{136}Xe beam in the atmosphere

T. Kambara*[1] and A. Yoshida*[1]

On the basis of a fee-based facility sharing program,[1)] private companies in Japan use 95 MeV/nucleon Ar and 70 MeV/nucleon Kr beams from the RIKEN Ring Cyclotron (RRC) to simulate single event effects (SEE) of semiconductor devices by high-LET components of the cosmic rays.[2)] Recently, the demand for heavier ions with higher LET for the SEE test has significantly increased, which has led us to prepare for fee-based Xe-ion irradiations. Because the samples are irradiated in the atmosphere at RIBF, the beam passes through various materials before the sample and fast secondary nuclides produced by nuclear reactions in the materials may contaminate the beam. We study the beam impurities with radiochemical measurements and previously reported results for the Kr beam.[3)]

During a machine-study beamtime in February 2018, we measured the beam impurities of a 10.75 MeV/nucleon ^{136}Xe beam from RILAC2 and RRC. The setup at the E5A beamline is shown in Fig. 1. The beam spot was spread with a pair of wobbler magnets on the beam line. The beam passed through a Kapton window with a thickness of 25 μm and diameter of 50 mm into the atmosphere, followed by an ionization chamber (IC), AE-1341S, which was produced by Applied Engineering Inc,[4)] to measure the beam intensity.

In the IC, the beam passed four 6 μm thick mylar foils and a 15 μm thick Al-foil electrode. A test sample of a Si wafer (100 mm diameter and 0.5 mm thick) was attached directly to the exit of the IC to simulate semiconductor devices of clients. The total length of the beam path in the atmosphere was approximately 39 mm. No energy-degrader plates were used in these irradiations. From the output-current measurement of the IC, the total number of primary Xe ions was estimated to be approximately 1.17×10^{10} for a 10 minutes irradiation. According to SRIM calculation,[5)] the energy of the primary Xe ions was approximately 2.3 MeV/nucleon at the surface of the sample in which the ions stopped.

We measured the γ rays from the irradiated sample with a Ge detector 12 times from 7 min to 17.2 days after the irradiation. We analyzed the observed γ-ray peaks according to the tabulated transition energies, lifetimes, and branching ratios,[6)] and identified 15 radionuclides from ^{135}Xe to ^{159}Ho. Then, we extrapolated the decay curves of the radioactivity to the end of the irradiation time to obtain the production probabilities of the radionuclides normalized to one incident ^{136}Xe ion.

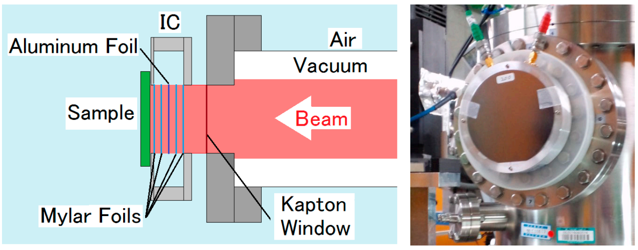

Fig. 1. Schematic diagram (left) and photograph (right) of the setup of irradiation.

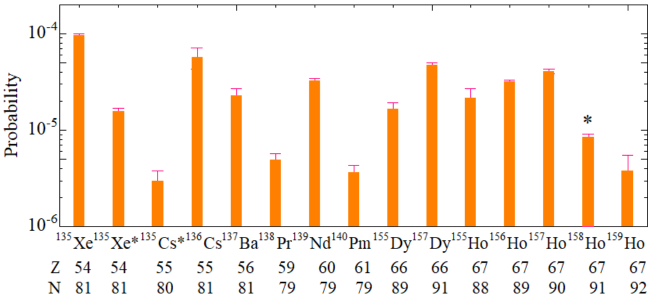

Fig. 2. Measured production probabilities of radionuclides. Because the tabulated γ-emission probabilities of ^{158}Ho are in the relative values, the maximum probability is assumed to be 100% of the parent decay.

Figure 2 shows the obtained nuclide-production probabilities. Because the Xe ions in the sample had much lower energy than the Coulomb barrier, all the observed radionuclides were produced in the upstream materials and implanted in the sample. The ratios of the observed radionuclides in the beam were below 10^{-4} and the total impurity would be below 1%.

Dy ($Z = 66$) and Ho ($Z = 67$) can be produced only in the Al electrode of the ionization chamber. We suppose that the Ho-isotopes were produced through the complete nuclear fusion reactions followed by multiple neutron emissions, and the observed ^{155}Dy and ^{157}Dy were mostly the daughters of ^{155}Ho and ^{157}Ho, respectively.

References

1) `http://ribf.riken.jp/sisetu-kyoyo/` (in Japanese text).
2) T. Kambara, A. Yoshida, RIKEN Accel. Prog. Rep. **48**, 239 (2015).
3) T. Kambara, A. Yoshida, Record of 2018 IEEE Radiation Effects Data Workshop (REDW), p. 94.
4) `http://www.o-yo-giken.co.jp/` .
5) J. F. Ziegler, `http://www.srim.org/` .
6) R. B. Firestone, *Table of Isotopes* (Wiley Interscience, 1998).

---

*[1] RIKEN Nishina Center