Comparison of Code Simulation and Measurements: Radio-activation of ZrO_2 by Proton Beam Irradiation

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1. Introduction

In proton irradiation experiments with more than a few MeV in proton energy, radio-activation of targets is essentially caused by proton-induced nuclear reactions. In this paper, we irradiated 20 MeV proton beam to ZrO_2 target with average current of 400 nA. We measured emitted gamma ray energy to detect residual isotopes in the ZrO_2 target by using HPGe detector, and we also measured gamma dose rate by using radiation survey meter. Then we calculated radio-activation of ZrO_2 target by Monte Carlo code simulation to compare measured and calculated results.

2. Experiments

2.1. Proton beam irradiation

To measure activation of ZrO_2, we irradiated proton beam to ZrO_2 + Y (3mol%) compound (Table 1). The 20 MeV pulsed proton beam line (Fig. 1), which was installed at KAERI (Korea Atomic Energy Research Institute), was used for this experiment with 4 mA current, pulse width of 100 μsec, repetition rate of 1 Hz, and flux of 7.95×10^{11} proton/cm^2·sec. We put ZrO_2 target in front of 0.5 mm aluminum window so the protons lost their energy about 2.8 MeV by penetrating beam window. The actual incident proton beam energy to ZrO_2 target was about 17.2 MeV. We irradiated 1257 pulses, so total proton beam flux was about 1.00×10^{15} proton/cm^2·sec.

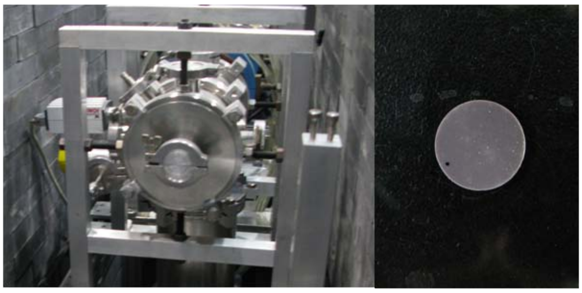

Fig 1: 20 MeV beam line at KAERI (left), and proton beam irradiated ZrO_2 target.

Table 1: Characteristics of ZrO_2 sample

Molecular Formula	Density [g/cm^3]	Sample Geometry
ZrO_2 + Y (3 mol%)	6.05	φ10 mm × 1 mmt

2.2. Code simulation

First, we calculated secondary neutron produced by proton beam with MCNPX v. 2.5 code [1] and production rate of radioisotopes in ZrO_2 target with PHITS v. 2.23 code [2]. With these results of MCNPX and PHITS code simulation, we calculated radio-activity and gamma-ray energy intensity of equipments with various proton beam operation condition by using DCHAIN-SP code [3]. Finally we evaluated gamma dose rate from the previously calculated gamma-ray energy intensity with MCNPX code [4]. The schematic diagram of the model applied to the code simulation is shown in Figure 2.

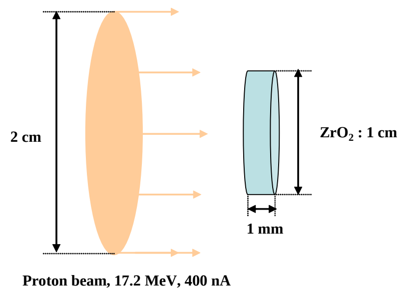

Fig. 2: The schematic diagram for code simulation

2.3. Measurement and Comparison

After proton beam irradiation to the target, dose rate of the ZrO_2 target was measured by radiation survey meter (FH40GL-10, THERMO), and residual radio-isotopes of target were analyzed by a high purity germanium detector (GR1518, Canberra, Inc., relative efficiency: 15%, Full width half maximum @1.33 MeV: 1.8 keV). Before we measured residual radio-isotopes of target, we had measured gamma ray background for a day to subtract environmental gamma ray background [5]. In this method, we can verify only gamma emitted radio-isotopes, but pure beta emitter. Finally, we compared calculated residual radio-isotopes and dose rate with measured data.

3. Results

In this experiment, we could measure residual radio-isotopes and dose rate immediately after proton beam irradiation. Because calculated dose rate of the ZrO_2 target at 0 day in figure 4 was about 30 mSv/h. It was excess dose rate for handling the ZrO_2 target for person, so we waited 20 days to cool down the radioactivity of the ZrO_2 target. Then we measured residual radio-isotopes and dose rate.

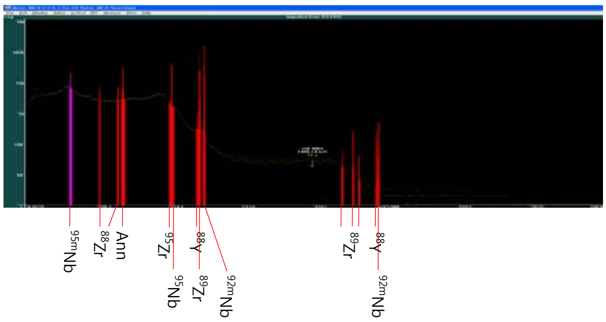

Fig. 3: Measured gamma ray energy spectrum.

Table 2: Major residual radio-isotopes in ZrO_2 target.

Radio-Isotope	$T_{1/2}$ [d]	Energy [keV]	Intensity [%]	Activity [nCi] Measured	Activity [nCi] Calculated
^{95m}Nb	3.61	235.69	24.8	-	0.063
^{87}Y	3.33	388.53 484.80	82.2 89.8	- -	0.61
^{95}Zr	64.0	724.19 756.72	44.27 54.38	45.60 45.43	44.45
^{88}Zr	83.4	392.9	97.30	190.2	186.86
^{95}Nb	34.9	765.8	99.81	1447.0	1399.67
^{88}Y	107	989.04 1836.06	93.7 99.2	34.63 35.03	31.80
^{89}Zr	3.27	909.15 1657.3 1713.0 1744.5	99.04 0.106 0.745 0.123	2086.0 2080.0 2044.0 2043.0	1672.16
^{92m}Nb	10.2	912.93 934.50 1847.5	1.78 99.07 0.85	6412.0 6454.0 6658.0	5743.79

Figure 3 show background subtracted gamma ray energy spectrum of the proton beam irradiated ZrO_2 target. We compared calculated and measured radio-activity of the proton beam irradiated ZrO_2 target (Table 2). The major residual radio-isotopes of the proton irradiated ZrO_2 target are ^{95}Nb, ^{89}Zr, ^{92m}Nb, and ^{88}Zr. The difference was about maximum 10 %. In this result, we excluded radio-isotopes having a long half life, because their production was too small to detect by HPGe detector.

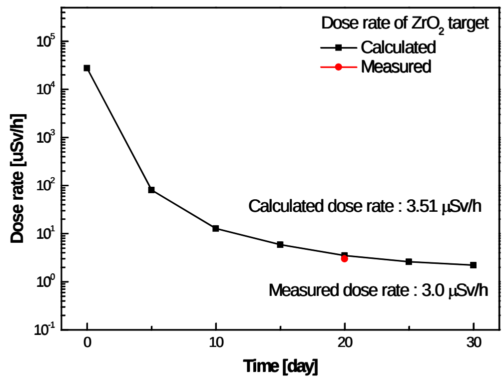

Fig. 4: Measured and Calculated of dose rate for ZrO_2 target.

As the results, we might think that code simulation of the proton beam irradiated ZrO_2 target was well fitted to real results. For radiation safety of person who experiments proton beam irradiation to some targets, we need to simulate radio-activation of targets to estimate level of dose rate before proton beam irradiation.

4. Conclusion

The major residual radio-isotopes of the proton irradiated ZrO_2 target are ^{95}Nb, ^{89}Zr, ^{92m}Nb, and ^{88}Zr. The difference of measured and calculated activity is about maximum 10 %. The dose rate of measured and calculated for the proton irradiated ZrO_2 target was 3.0 μSv/h and 3.51 μSv/h respectively.

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