Simulation of Radiation Dose and Neutron Incidence rate for various neutron shielding materials

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1. Introduction

Proton Induced X-ray Emission(PIXE) analysis method is one of the non-destructive analysis methods that analyze materials by using the characteristic x-ray arising from target substance when irradiating protons on the target [1]. Generally the beam extracted from the accelerator shows the Gaussian distribution on the transverse direction but PIXE analysis requires a beam with a uniform particle distribution [2]. Therefore, a beam line for PIXE analysis is composed of diffuser foil that scatters proton beam, collimator for selecting a uniform portion of the scattered beam or a nozzle system. A beam extracted from the accelerator generates many neutrons and gamma rays due to this collision between the collimator and diffuser foil. Therefore, since generated neutrons and gamma rays can cause radioactivation on surrounding substances, it must be shielded using appropriate shielding materials. This paper has performed an analysis on the radiation dose absorbed by the carbon plate used as the energy degrader in the PIXE analysis beam line using the 13-MeV cyclotron and a shielding study on the neutrons generated in the nozzle system [3]. Using the Particle and Heavy Ion Transport code System (PHITS) program [4], a shielding effect comparison was conducted on the polyethylene, borated polyethylene and paraffin which is representing substances used as shielding materials of neutrons and shielding evaluation was conducted through thickness calculation in order to shield the neutrons being generated.

2. Methods and Results

In this section, a configuration of nozzle system designed for PIXE analysis and a simplified geometry for PHITS analysis of neutron emission is introduced. In addition, the radiation dose being accumulated in the energy degrader that make up the nozzle system is calculated and a study of comparative analysis on neutron shielding effect according to three types of shielding materials used commonly in shielding neutrons was performed.

2.1 Simulation model and beam conditions

The beam nozzle system is composed of energy degrader that attenuates the 13MeV protons into 3MeV energy, a beam nozzle that reduces the beam being scattered due to energy degrader and selects a uniform portion of the beam and exit foil that maintains the vacuum in the beam nozzle.

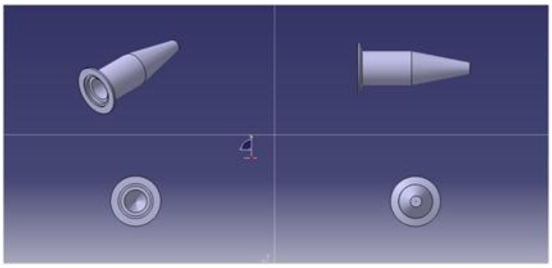

Fig. 1. Beam nozzle.

Fig. 1 is showing beam nozzle. In Fig. 1, the energy degrader is located in the groove in the nozzle and the attenuated beam passes through the exit foil in the exit of the nozzle and incidents on the target. In order to calculate the dose and to simulate the neutron incidence rate, a simulation model was configured by simplifying the nozzle. A simulation model is shown in Fig. 2.

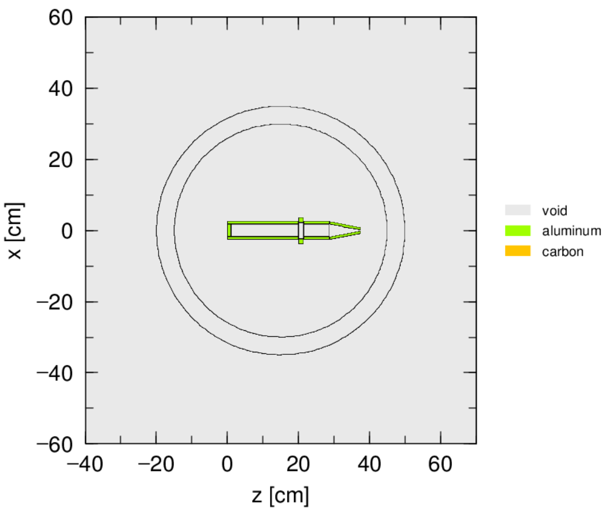

Fig. 2. Simulation model to obtain radiation dose and neutron incidence rate.

Nozzle material was composed of aluminum and the energy degrader was composed of carbon, and in order to perform the shielding calculation, two spherical surfaces were made around the nozzle to compose the cell for shielding the neutrons using these two surfaces. For the neutron shielding region, neutron shielding materials polyethylene, 5% borated polyethylene and paraffin was specified in the thickness of 5, 7, 10, 12, 15cm respectively and the number of neutrons passing through this shielding material was analyzed.

Table I: Beam conditions used in the simulation

Beam type	Energy [MeV]	Radius [cm]	spread angle [degree]
Proton	13	0.4	0.1

Beam conditions used in the simulation were shown in Table I. The beam that used is a proton beam having the energy of 13MeV extracted from cyclotron with the radius of 0.4cm and the spreading angle designated as 0.1 degree and progress in a single direction of Z axis.

2.2 Dose calculation of energy degrader

13MeV proton beam extracted from cyclotron is degraded into the energy of 3MeV as it passes through the energy degrader made of carbon, at this time, the proton beam accumulates the energy in the energy degrader. Energy absorbed by such substances can be represented by a radiation dose of Gray unit.

Fig. 3 is showing the distribution of number of particles according to the deposit energy of the energy degrader. In Fig. 3, it can be seen that many number of particles are distributed in the energy between 9 and 10-MeV. Averaged deposit energy value and converted radiation dose on all incident protons are shown in Table Ⅱ. A unit of deposit energy is MeV/cm^3-proton which is deposit energy of one proton being deposited into 1cm^3.

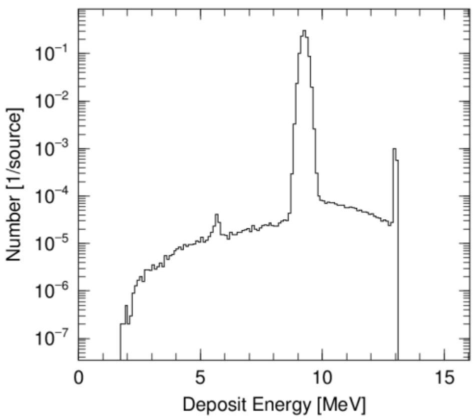

Fig. 3. Distribution of number of particles according to the deposit energy of the energy degrader.

Equation (1) is the process of conversion the deposit energy into radiation dose. The beam current in the calculation of radiation dose have used 1 μ A.

$$9.2588[MeV/cm^3 \cdot proton] \times 1.6 \cdot 10^{-13}[J/MeV] \times \frac{1000}{2.23}[cm^3/kg] \times 6.25 \cdot 10^{12}[protons/s] \quad (1)$$

Table Ⅱ: Deposit energy and radiation dose of energy degrader

Deposit energy [MeV]	Radiation Dose [Gy/s]	Radiation Dose [MGy/h]
9.2588	4151.93	14.95

2.3 Neutron flux

Fig. 4 shows the nuclides generated in the nozzle system and the generation amount of each nuclide. x axis represents the number of neutrons and y axis represents the number of protons, and the generation amount of nuclides which corresponds to the number of protons and neutrons can be found on the right side bar. Nuclides are generated more when the color is red. In Fig. 4, it can be seen that approximately 10^{-4} neutrons are generated per incident proton.

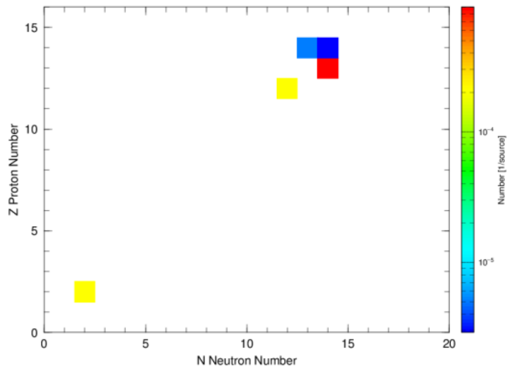

Fig. 4. Nuclides generated from beam nozzle system

When shielding neutrons, it is important to use hydrogen-rich material because hydrogen is effective at absorbing neutrons [5]. Most widely used substances are polyethylene, boron-loaded polyethylene and paraffin. In this paper, in order to investigate the shielding effect according to the thickness of 3 types of aforementioned shielding materials, a neutron flux leaking according to the thickness of 5 to 15cm was simulated. The results are shown in Fig. 5 and Table Ⅲ.

Fig. 5 shows the flux of neutrons that passes through the shielding materials for each thickness of 5, 7, 10, 12, 15cm on the three types of shielding materials (polyethylene, a borated polyethylene and paraffin). Among the three types of shielding materials, the neutron flux according to thickness was shown to abruptly fall in 5% boron loaded polyethylene. In the case of paraffin, it has shown a high neutron absorption rate when the energy of neutron was reduced. Polyethylene compared to paraffin and borated polyethylene did not have a good neutron shielding effect. Accurate figures of neutron flux indicated in Fig. 5 are summarized in Table Ⅲ.

Fig. 6 shows the moving path of neutrons in the xz plane when assigned with shielding thickness of 5, 10, 15cm on the three types of shielding materials.

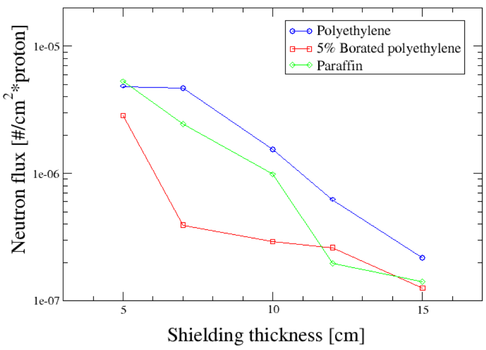

Fig. 5. Flux of neutrons according to thickness of the shielding materials.

Table Ⅲ: Neutron flux per proton according to thickness of shielding materials

Thickness \ Material	Polyethylene	5% borated polyethylene	Paraffin
5	4.8349E-06	2.8452E-06	5.2952E-06
7	4.6983E-06	3.9289E-07	2.4487E-06
10	1.5462E-06	2.9199E-07	9.8457E-07
12	6.2084E-07	2.6080E-07	1.9621E-07
15	2.1811E-07	1.2569E-07	1.4058E-07

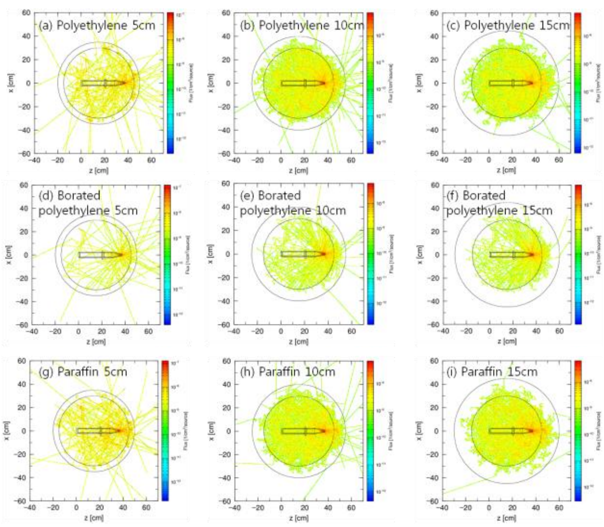

Fig. 6. Neutron track distribution in the xz plane.

At this time, the z axis is the progressive direction of particles in longitudinal direction, and the x axis is transverse direction perpendicular to the longitudinal direction and means the horizontal direction. Fig. 6 shows that even in the track of neutrons, the borated polyethylene is effectively shielding the neutrons.

3. Conclusions

In this paper, in order to obtain the radiation dose absorbed by the energy degrader and to shield the neutrons generated in the PIXE nozzle system composed of energy degrader and proton beam nozzle, a comparative analysis on the three types of most commonly used shielding materials, such as polyethylene, borated polyethylene and paraffin blocks was conducted for its shielding effects. The energy deposited in the energy degrader is 9.2MeV and indicates the radiation dose which corresponds to 14.95MGy/h when investigated with beam current of 1 μ A. In addition, after comparing the shielding effects on the three types of shielding materials, borated polyethylene have shown the most absorption rate of neutrons and seemed to be the most appropriate shielding material. Conclusively, by performing a comparative analysis on the three representing neutron shielding materials, it is determined that it can contribute to the finding of neutron shielding materials suitable in the field of neutron shielding, and in the future, by performing the activity calculation due to gamma ray, the results of this study is hoped to be utilized as the basic data of shielding analysis.

REFERENCES

[1] M.E. Fedi et al., Nucl. Instrum, Methods phys. Res., Sect. B189, 56, 2002.
[2] Michael Nastasi, James W. Mayer, Yongqiang Wang, Ion Beam Analysis : Fundamentals and Applications, pp163, 2014
[3] Sae-Hoon Park, Yu-Seok Kim, J. Korean Phys. Soc. 63, 1291, 2013.
[4] Norihiro Matsuda et al., "PHITS 2.64 : Particle and Heavy Ion Transport code System", RIST
[5] Robert C. Singleterry, Jr., and Sheila A. Thibeault, Materials for Low-Energy Neutron Radiation Shielding, June 2000.