Characterization of the Neutron Flux Energy Spectrum Produced by 35 MeV Proton Beams at KIRAMS MC-50 Cyclotron with a Beryllium Target

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1. Introduction

Neutron source play essential roles in various industrial and scientific fields. In particular, the fast neutron can be used to study of irradiation effect of neutrons on single event upset of semiconductor devices, materials, and bio-sciences. There are several approaches to obtain neutron beams with the desired energy spectrum such as a nuclear research reactor, a neutron-emitting radio isotopes (^{252}Cf and Be-couple ^{241}Am), and a bombarding proton beams on a target. In the bombarding proton beams case, neutron beams are generated mainly through the (p, n) charge exchange reaction. By adjusting the beam energy, the target material and the thickness of the target, the resulting neutron spectrum can be controlled to a certain degree. Beryllium is widely used as the target material because of its high melting point, good thermal conductivity and many other advantaged features.

The purpose of present work is to characterize the neutron flux energy spectrum which produced by a beryllium target with 0.5 cm thickness at 35 MeV energy providing by the MC-50 cyclotron of the KIRAMS (KOREA). Neutron spectrum at the irradiation position of the MC-50 cyclotron was measured by using activation method and been unfolded with the both interactive codes as SAND [1] and STAYSL [2].

2. Methods and Results

The MC-50 cyclotron provides protons of variable energies up to 50 MeV and neutron are produced by bombarding protons on a beryllium target. Fig. 1 is a schematics diagram of the neutron production system, showing the beryllium target, proton beam direction and neutron collimator of length about 3.75 cm. The irradiation position are kept on the horizontal plane which is at a distance of 165 cm from the end of the graphite collimator. The neutron beams are generated when a 0.5 cm thick beryllium target is bombarded by 35 MeV protons at a constant current of 20 μA.

Activation method is a simple and widely used method for measuring neutron energy spectrum [3, 4]. The foil size is small enough to ensure a uniform neutron field at the irradiation position. Difference foil materials can measure neutron in different energies. Activation method depends greatly on the spectrum unfolding technology.

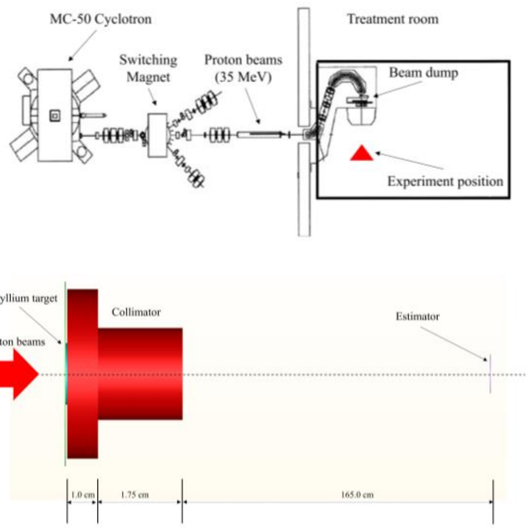

Fig. 1. Schematic diagram of MC-50 cyclotron facility in KIRAMS (top) and the experimental setup (bottom).

The fundamental of activation method for measuring neutron spectrum is described as a group of activation foils with known activation of sections of the nuclides are irradiated at the measuring position. The relationship between single reaction and neutron spectrum is therefore given in the Eq. 1.

$$A_i = \int_0^\infty \phi(E).\sigma_i(E).d(E) \quad (i = 1, 2, \ldots, n) \quad (1)$$

In the Eq. 1, A_i is a single nuclear reaction of foil i, $\phi(E)$ is a neutron energy spectrum, $\sigma_i(E)$ is a nuclear reaction cross section of foil i at the neutron energy E, n is the number of adopted nuclear reaction channel. Stable nuclei are activated by neutron irradiation and A_i is obtained by measuring gamma-rays coming from activated nucleus. $\sigma_i(E)$ can be obtained from an evaluation of the database and therefore $\phi(E)$ can be obtained by solving the Eq. 1.

The initial neutron energy spectrum to be adjusted was obtained based on the MC simulation. Two MC codes were adopted to generate the initial energy spectrum as MCNPX and PHITS.

Table. 1. Characteristic parameters of each foil and measured reaction rates.

Nuclear reaction	Mass (mg)	Abundance (%)	Gamma energy (keV)	Reaction rate (s^{-1})
Ti^{46}(n, p)Sc^{46}	141.9	8	1120.51	4.89445x10^{-17}
Ti^{47}(n, p)Sc^{47}	141.9	7.3	159.4	2.59738 x10^{-20}
Ti^{48}(n, p)Sc^{48}	141.9	73.8	1037.5	1.84629 x10^{-18}
Cu^{63}(n, γ)Cu^{64}	0.284	69.17	511.1	1.53757 x10^{-16}
Co^{59}(n, γ)Co^{60}	61.2	100	1332.5	1.55328 x10^{-16}
Co^{59}(n, p)Fe^{59}	61.2	100	1291.56	3.75284 x10^{-18}
Co^{59}(n, 2n)Co^{58}	61.2	100	810.76	3.58215 x10^{-17}
Fe^{56}(n, p)Mn^{56}	132	91.72	846.76	4.06643 x10^{-18}
Mg^{24}(n, p)Na^{24}	28.3	78.99	1368.6	1.10228 x10^{-17}
Ni^{58}(n, p)Co^{58}	28.3	68.077	810.76	2.83952 x10^{-17}
Ni^{58}(n, 2n)Ni^{57}	28.3	68.077	127.19	1.96465 x10^{-18}
Zn^{64}(n, p)Cu^{64}	231.3	48.6	511	1.2262 x10^{-17}
In^{115}(n, γ)In^{116m}	248.3	95.7	1293.54	6.18555 x10^{-16}
In^{115}(n, n')In^{115m}	248.3	95.7	336.24	1.68522 x10^{-17}
Sc^{45}(n, γ)Sc^{46}	50.7	100	1120.51	7.98723 x10^{-17}
Na^{23}(n, γ)Na^{24}	478.4	100	1368.55	6.99989 x10^{-19}
Dy^{164}(n, γ)Dy^{165}	30.3	28.2	361.67	1.08802 x10^{-14}
Ag^{109}(n, γ)Ag^{110m}	171.9	48.161	65.775	1.1246 x10^{-18}
Au^{197}(n, γ)Au^{198}	223.17	100	411.8	3.11699 x10^{-16}

The MCNPX and PHITS will supplement together in some lacking feature of simulating with proton particles. In the simulation, the experimental configuration consisting of the beryllium target, graphite collimator, sample, and surrounding cyclotron parts was modeled. Track length estimators (cell detectors) of 1.27 cm diameter and 0.127 mm thickness were used for the tally. The Los Alamos LA-150 library [5] up to 150 MeV processed into the ACE type format for MCNP and PHITS were used as transport cross sections. Since no neutron transport cross section data for beryllium was available in the energy range above 20 MeV, cross section data for beryllium up to 100 MeV in the 100XS library [6] was used instead.

Nineteen kinds of activation foils were used in the experiment. The diameter of these foils are of 1.27cm diameter. Table 1 presents the characteristic parameters of activation foils and measurement data of the single nuclear reaction rate. The gamma-rays spectra of the irradiated foils were counted by the HPGe detector with defined efficiency curved in advance. The single reaction rates were calculated by using the Eq. 3.

$$A_i \frac{C.\lambda_i}{\gamma_d.\varepsilon.N_i.(1-e^{-\lambda^i.t_i}).(1-e^{-\lambda^i.t_c}).(1-e^{-\lambda^i.(t_m)})} \quad (3)$$

Where, C is the net peak are of the gamma-ray spectrum, γ_d is the branching-ratio of gamma-rays, ε is the detection efficiency, N_i is the number of nucleus for foil i^{th}, λ_i is decay constant of nucleus i^{th}, t_i is irradiation time, t_c is cooling time, and t_m is measuring time.

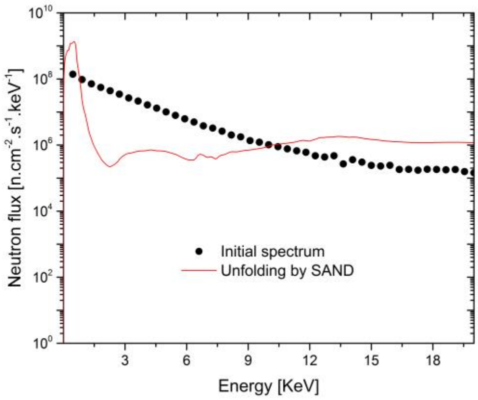

Fig. 2. Unfolding result by SAND code.

The neutron energy range from 10^{-4} to 20 MeV was divided into 640 energy groups. The initial spectrum and the results of spectrum unfolding were shown in Fig. 2.

3. Conclusions

Measurements made with foil-activation technique provided valuable information about the neutron spectrum in the irradiation position of the MC-50 cyclotron in KIRAMS. The group cross sections of a certain thickness of foil were processed before unfolding. The results of spectrum unfolding are generally consistent. If the result is not dependent on the initial spectrum, SAND code will be perfect. From the above analysis, the experiment is successful due to the suitable foils and spectrum unfolding methods.

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