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バージョン：

DDTTNY Measurement of Accelerator-based Neutron via C(d,n) Reaction by 30-MeV Deuteron by means of Multiple-foil Activation Method

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Abstract: *The design of deuteron accelerator neutron source facilities requires reliable yield estimation of neutrons from deuteron-induced reactions. We have so measured systematically double-differential thick target neutron yields for carbon target using GRAVEL unfolding code. ^{nat}C bombarded by deuterons of 30-MeV following the multiple-foil activation method in order to investigate the neutron production yields as high-intensity neutron sources. Neutrons emitted at angles 0, 10, 20, 30, 45, 90 degrees were studied and measured angular distribution is considerable.*

Keywords: Accelerator-based Neutron; Deuteron Induced Reaction; DDTTNY; Activation Method; Unfolding

1. INTRODUCTION

The knowledge of reactions induced by fast neutron beams has grown in interest since the advent of accelerators capable of delivering high-current deuteron beams in a few tens of MeV. Impinging and subsequent absorption of charged-particle beams in thick targets is able to generate intense neutron. Accelerator-based neutron sources are considered as one of promising neutron sources in various neutron application fields such as production of radioisotopes for medical use [1], fusion material irradiation test [2] and so on. Among all accelerator-based neutron, deuteron induced reaction on a neutron converter made of C or Be is promising for radioisotopes production. In the method, a neutron converter which has larger thickness than the incident deuterons are used to generate intense neutron. The converter is called thick target. In the design of deuteron accelerator facilities, it is important to estimate double-differential thick target neutron yields (DDTTNY) from deuteron-induced reactions on the basis of experimental data and theoretical model calculations. Highly reliable DDTTNY are required for safety design, estimation of radioisotope (RI) production yield, and its purity. The neutron energy spectra are commonly measured by using multiple foil activation method, TOF method and such neutron detectors as Bonner spheres and liquid scintillators. In the present work, we adopt the multiple-foil activation method among them to measure wide neutron emission angles at once. Unfolding method is necessary to derive the DDTTNY in the method. Up to now, we have measured systematically DDTTNYs for the neutron converter made of carbon at deuteron energy from 10 to 50 MeV. In the present work, we have analyzed the experimental data for the C(d,n) reaction at deuteron energy of 30MeV. GRAVEL code [3] was used for the unfolding process.

2. EXPERIMENT

2.1 Irradiation Experiment

A multiple-foil activation experiment was conducted by Tandem Accelerator Facility at Japan Atomic Energy Agency. Deuterons were accelerated to 30-MeV and bombard on a neutron converter made of thick carbon target of 2-mm in thickness. The thickness of carbon was determined to deposit all of deuteron kinetic energy inside. The stopping length of 30-MeV deuteron in carbon was calculated by SRIM code [4]. Then, accelerator-based neutrons were generated via the C(d,n) reactions. Multiple foils made of ^{nat}Ni, ^{nat}In, ^{27}Al, ^{59}Co, ^{93}Nb, ^{nat}Zr and ^{nat}Zn having size of 10-mm x 10-mm x 0.1-mm^{t} were irradiated by the neutrons. Amount of natural abundance (%) are listed in Table 1. The foils were located at 0, 10, 20, 30, 45, 90 degrees of neutron emission angles. The foils were irradiated for 2 hours by 200-nA deuteron beam. A schematic illustration of the irradiation setup is shown in Figure 1. Once deuteron particle incident on the carbon target it attempts to produce neutron and after that this neutron fluency are responsible for changing the atomic configuration in multiple-foil.

2.2 Gamma-ray Measurements of Activated Foils

After irradiation, gamma rays emitted from the irradiated samples were measured with a high-purity germanium (HP Ge) detector. The irradiated foils were placed at 5-cm apart from the detector head. The amount of nuclide produced at the end of irradiation (EOI) of the produced nuclide at each angle were noted. To suppress gamma rays of natural background, detector head was surrounded by lead blocks. There is some method to derive volume source detection efficiency using a point standard source. But, we treat the irradiated foils as point source for simplicity, and it is good approximation for the detection geometry (5-cm apart from the detector head).

3. DATA ANALYSIS

By the HP Ge detector measurements, number of atoms of products; Y_k produced via the interested reaction; k was derived. Y_k can be expressed by the following equation:

$$Y_k = \int R_k(E)\, \phi_k(E)\, dE$$

where $R_k(E)$ and $\phi_k(E)$ show the production rate function, and DDTTNY of the reaction k, respectively. In the unfolding process, the equation is approximated by using neutron groups E_i, and it is expressed as:

$$Y_k = \Sigma_i R_{k,Ei}\, \phi_{k,Ei}$$

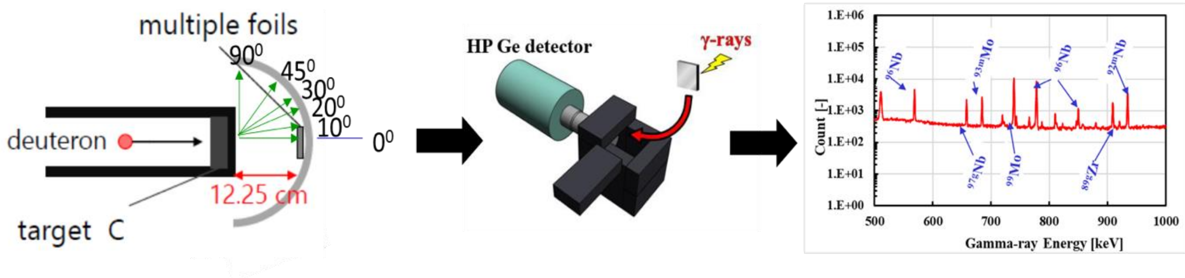

Fig. 1. Schematic diagram of the total experiment process. Multiple foils are placed at different angle for angular distribution of activity and then for production rate. After counting from HP Ge detector, emitted gamma ray energy peaks from irradiated samples has been observed.

Table 1. Isotopic components of samples [1,5]. Amount of the respective sample used for each of the angle position for irradiation in this study.

Foil	Abundance (%)	Sample weight (mg)					
		0^0	10^0	20^0	30^0	45^0	90^0
^{nat}Ni	$^{58}Ni(68.08)$ $^{60}Ni(26.22)$ $^{61}Ni(1.14)$ $^{62}Ni(3.63)$ $^{64}Ni(0.93)$	700	694	697	686	694	698
^{27}Al	100	104	105	104	105	104	105
^{59}Co	100	155	152	152	157	153	159
^{93}Nb	100	171	172	173	173	171	171
^{nat}In	$^{113}In(4.29)$ $^{115}In(95.71)$	250	244	257	246	234	238
^{nat}Zr	$^{90}Zr(51.45)$ $^{91}Zr(11.22)$ $^{92}Zr(17.15)$ $^{94}Zr(17.38)$ $^{96}Zr(2.80)$	153	153	153	153	153	153
^{nat}Zn	$^{64}Zn(49.17)$ $^{66}Zn(27.73)$ $^{67}Zn(4.04)$ $^{68}Zn(18.45)$ $^{70}Zn(0.61)$	233	233	233	233	233	233

where $R_{k,Ei}$ and $\phi_{k,i}$ show the production rate function and DDTTNY of reaction k for neutron group E_i, respectively. In the present study, the production rate function was calculated by following equation [6]:

$$R_{k,Ei} = \sigma_{k,E_i} \frac{N_T}{\lambda_k} \frac{Q}{t} \Omega_T (1 - e^{-\lambda_k t})$$

Since this equation cannot be solved analytically, the unfolding method is required. In the present work, we adopted GRAVEL code which is one of the mostly used conventional unfolding code.

In this relation, σ_{k,E_i} is reaction cross section (cm^2) and used from evaluated nuclear data library EAF-2010 [7]. N_T is total number of atoms in the sample per surface unit, λ_k is decay constant of the product nuclide (per sec), Q is beam particle charge (μC), t is irradiation time (sec), Ω_T is solid angle (sr) covered by the foils, and subscripts k and E_i are number of reaction and energy bin (MeV) respectively. Using the response functions, the unfolding was performed by the GRAVEL code [3] based on the iterative approximation method. Before that we checked initial guess spectrum by PHITS 3.02 [8] which is shown in Figure 2.

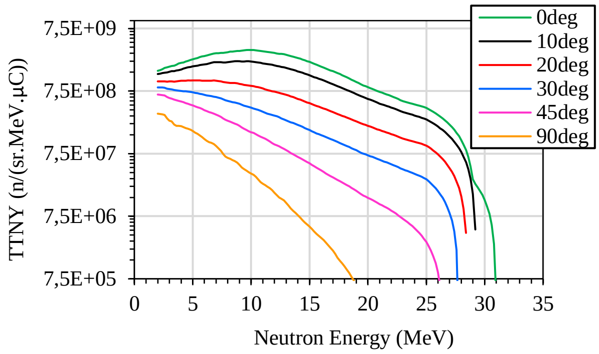

Fig. 2. Default spectrum by PHITS 3.02 simulation. In PHITS calculations using INCL, GEM [9], DWBA [10] and EBITEM models reproduce the spectrum shapes well. The Shen formula [11] was chosen as a calculation option of total reaction cross section instead of the default option with the NASA [12] formula.

4. RESULTS AND DISCUSSION

Double-differential thick target neutron yields (DDTTNYs) from carbon target which is irradiated by 30-MeV deuterons were measured at the Tandem Accelerator Laboratory in Japan Atomic Energy Agency (JAEA). At first, after irradiation, gamma rays emitted from the activated multiple foil were measured with a Ge detector, and the amount of nuclide produced at the end of the irradiation (EOI) of the produced nuclide at each angle (0, 10, 20, 30, 45, 90 degrees) was calculated. DDTTNYs for each angle was derived from the obtained nuclide production amount and analyzed response function by using Unfolding method. The unfolding neutron spectrum were obtained by using GRAVEL code. During the χ^2 minimization it has been considered that ratio of calculated DDTTNYs values to experimental ones should be unity in where spectrum shows more meaningful. However, in this study, we observed almost unity for all reactions used in unfolding but some have slight deviation by maximum 4%. The experimental DDTTNY at maximum laboratory angles from carbon irradiated by 30-MeV deuterons are shown in Figure 3.

The neutron spectra were integrated to obtain the yield of neutrons at all angles from thick target. Integrations were performed on neutron spectra.

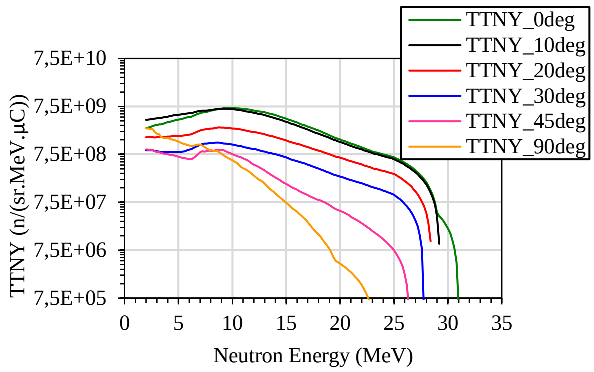

Fig. 3. Measured double-differential thick target neutron yields (DDTTNY) at 0° from carbon target irradiated by 30-MeV deuterons.

In Figure 4, the angular distributions of neutrons from are shown for 0, 10, 20, 30, 45, 90 degrees angels and the corresponding values are shown in Table 2.

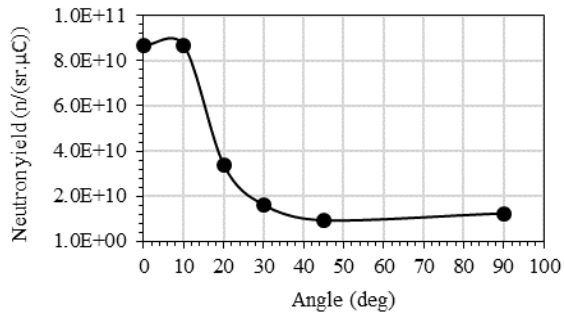

Fig. 4. Angular distribution of neutron production integrated over neutron energy when 30-MeV deuterons incident on thick carbon target.

The agreement of the activation data is fair, see Fig. 4. Angular distribution of neutron yields clearly exhibit a decrease with increasing angle. It has slight change in 10 degrees where value of neutron production yield became 0.12% higher than 0 degree. Further investigation may consider for this happening.

Table 2. Energy integrated neutron yield with angles.

Angle (deg)	Neutron Production Yield (n/(sr.μC))
0	8.691×10^{10}
10	8.701×10^{10}
20	3.388×10^{10}
30	1.606×10^{10}
45	9.192×10^{9}
90	1.231×10^{10}

5. SUMMARY AND CONCLUSIONS

The double-differential thick target neutron yields (DDTTNYs) of ^{nat}C bombarded with 30-MeV deuterons has been measured by multiple-foil activation method. Deuteron particle were accelerated by an accelerator at the Tandem Accelerator Laboratory in Japan Atomic Energy Agency (JAEA). Multiple foils (^{nat}Ni, ^{nat}In, ^{27}Al, ^{59}Co, ^{93}Nb, ^{nat}Zr, ^{nat}Zn) were placed 12.25-cm downstream of the generated neutrons so that the center of the foil was oriented at 0, 10, 20, 30, 45, 90 degrees are irradiated for 2-h with beam particle current 200-nA. The neutron spectra for each degree of multiple-foils position are estimated (Fig. 3) with good justification by their χ^2-valued and ratio of calculated values to experimental ones. The integrated values of neutron production have real tendency to change with angles, as it decrees with angular variation which defines the status of the measurement.

In conclusion, measurement of DDTTNYs using accelerator-based neutrons from the C(d,n) reaction with 30-MeV incident deuteron energy is auspicious in terms of quality. This study is a part of our entire experiment so some of our preliminary results are included in this analysis. We hope to estimate the medical radioisotopes production amount for diagnostic imaging studies and therapeutic applications by using obtained DDTTNYs.

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