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Measurement of Neutron Yields from Thick Al and SUS304 Targets Bombarded by 5-MeV and 9-MeV Deuterons

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Double differential thick target neutron yields from 5 and 9 MeV deuteron incidence on aluminum and SUS304 stainless steel were measured at the Kyushu University Tandem Accelerator Laboratory. An aluminum, and a SUS 304 foil which were thick enough for a deuteron to stop in the foils were placed at the center of a vacuum chamber. An NE213 liquid organic scintillator was employed to detect neutrons emitted from targets. To consider the contribution of scattered neutrons from the floor, we also measured neutron yields with an iron shadow bar located in front of the scintillator. Because incident deuteron beam was not pulsed and the Time-of-Flight method was not applied, the energy spectrum was derived from unfolding the light output spectrum using the FORIST code. The response function of the detector was calculated with the SCINFUL-QMD code. The experimental results were compared with the calculation data of the TALYS and PHITS code, and it turned out that the calculation data does not reproduce the experimental ones satisfactorily.

KEYWORDS: deuteron, TTNY, NE213, Unfolding, PHITS, TALYS

I. Introduction

The IFMIF-EVEDA (International Fusion Material Irradiation Facility-Engineering Validation and Engineering Design Activity)[1] activities in the framework of EU-Japan Bilateral Agreement for the Broader Approach for Fusion, an accelerator has been developed for demonstration of 9 MeV - 125 mA deuteron beam[2]. Reliable evaluation of radiation dose by the deuteron induced nuclear reactions and analysis of shielding data by deuteron beam are essential for safety license to the accelerator facility. However, experimental data of deuteron induced neutron production yields are scarce below 10 MeV.

For niobium, copper, titanium and carbon, 5 MeV and 9 MeV deuteron induced TTNYs (Thick Target Neutron Yields) were measured in our recent work[3]. In this paper, deuteron incident TTNYs for aluminum and SUS304 stainless steel target is derived, and compared with the PHITS[4] and the TALYS[5] calculations.

Aluminum is usually used to construct a vacuum duct of the accelerator. SUS304 is also usually used as vacuum chamber of the accelerator. It is important to analyze radiation dose from these target materials bombarded by deuteron beam.

II. EXPERIMENT

1. Experimental Setup

The experiment was performed at the 1st target room in the Kyushu University Tandem Accelerator Laboratory. The experimental setup is illustrated in **Figure 1**.

The deuteron beam from the tandem accelerator was delivered to a compact vacuum target chamber in the target room. The chamber was insulated from other experimental apparatus and the ground of the experimental room in order to acquire the deuteron beam current.
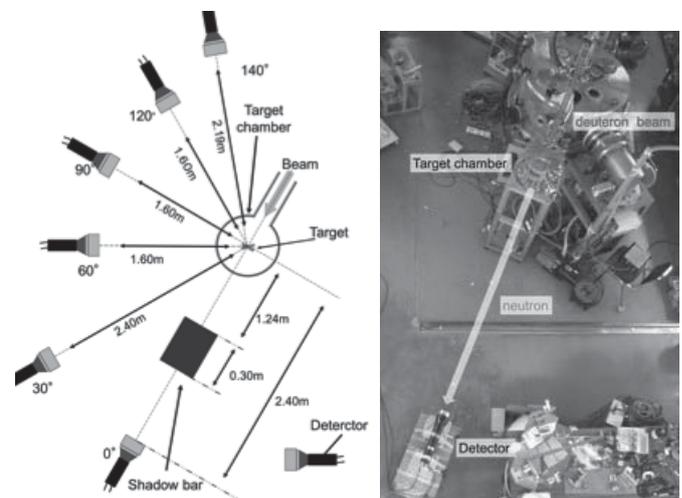
Fig.1 Experimental set up.

The incident energy of deuteron was 5 MeV for the aluminum and 9 MeV for the SUS304 targets, respectively.

A 0.5 mm thick aluminum and a 0.2 mm thickSUS304foils were chosen as targets and placed at the target frame of the vacuum chamber. These target thicknesses were obtained enough to completely stop the incident deuteron by the SRIM code[6].

An NE213 liquid organic scintillator, 50.4 mm thick and 50.4 mm in diameter, optically coupled with a Hamamatsu H1942 or a H6410 photomultiplier was adopted as a neutron detector. The electronic pulse signal as the light output of the scintillator was carried to NIM and CAMAC electronics and recorded as integrated charge information into 2 ADCs with different length of gates to separate neutron and γ ray events.

The measurement angles were 0, 30, 60, 90, 120 and 140 degrees for the aluminum measurement, and 0 and 90 degrees for the SUS304. The neutron detector was placed at each direction. The distances from the target to the neutron detector were varied from1.6 to 2.4 m depending on available area of the experimental room.

In order to evaluate contribution of neutrons from floor and wall in the experimental room, the measurement which an iron shadow bar, 150 mm × 150 mm and 300 mm thick, was set between the target and the neutron detector for each direction, was also done as background measurement.

Examples of light output spectra for foreground and shadow bar (background) measurements normalized by the number of incident deuterons for an aluminum target are shown in **Figure 2**.

2. Data Analysis

First, γ ray events were separated in the light output spectra using the two gate integration method because the NE213 scintillator is sensitive to γ rays in addition to neutrons. **Figure 3** shows the two dimensional plot of events separated from γ ray ones in low light output region.

Second, the charge spectra of neutron events were converted to the amount in units of electron equivalent, MeVee, using γ rays from ^{133}Ba (Eγ = 0.36 MeV), ^{137}Cs (Eγ = 0.66 MeV),^{60}Co (Eγ = 1.17 and1.33 MeV) and ^{241}Am-Be (Eγ = 4.44 MeV) standard γ ray sources. The calibration curve was given by fitting the Compton edge events of these γ rays. The relationship between the charge recorded into an ADC and the light output is shown in **Figure 4**.

The time-of-flight method was not applied because the deuteron beam was delivered to the target vacuum chamber continuously and it was difficult to produce pulse beam at the accelerator facility. The neutron energy spectra were derived from unfolding the integrated charge spectra as the scintillation light output ones using the response functions of the NE213 scintillator. The response functions were calculated by the SCINFUL-QMDcode[7]. **Figure 5** indicates the calculated response functions.

Fig. 2 Examples of raw spectra normalized by the number of incident deuterons for an aluminum target. Upper and lower lines stand for foreground and background measurements,respectively.
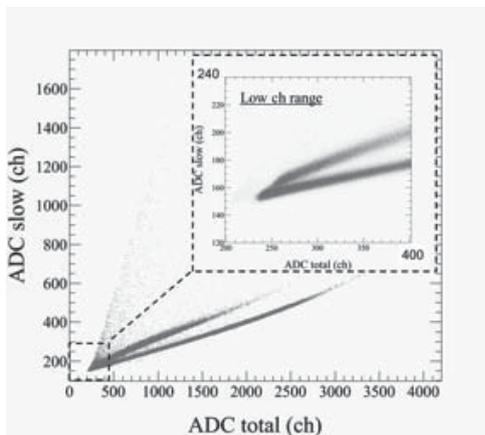
Fig. 3 The two dimensional plot of neutron and γ ray discrimination using the two gate integration method.
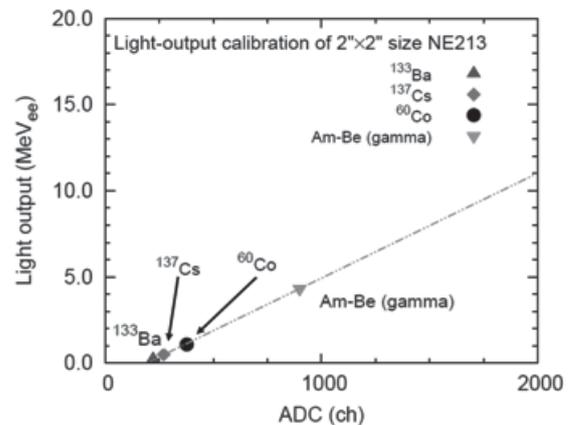
Fig. 4 The relationship between charge recorded into an ADC ch and electron equivalent light output.
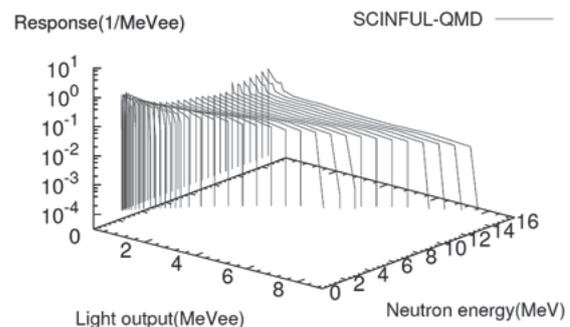
Fig. 5 Example of response function of NE213 using the SCINFUL-QMD code.

The unfolding of the light output spectra were performed by the FORIST code[8].

III. RESULTS AND DISCUSSION
1. Validation of Analysis
For validation of the unfolding method, the measurement of neutrons from an ^{241}Am-Be and a ^{252}Cfas well known neutron energy spectra was performed.
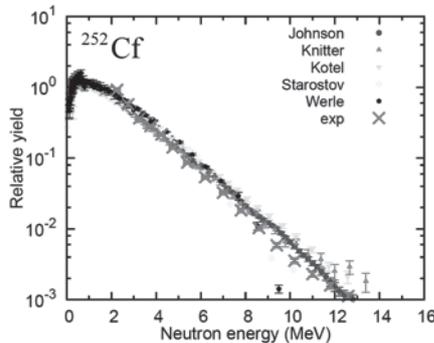
Fig. 6 Measured neutron energy spectraof^{252}Cf compared with previous experimental data[8-12].

Our measured data ^{252}Cf neutron spectrumshows the same tendency as previous data[8-12] above 2 MeV in **Figure 6**. The minimum neutron energy was about 1-2 MeV for both neutron sources.

The experimental energy spectrum of ^{241}Am-Be neutrons reproduces overall shape of neutron energy spectra by Marxh et al.[13] in **Figure 7**. However,our data doesnot reproduce the structure in the region between 7 and 10 MeV. This is because theneutron thick target yield [n/MeV/sr/μC] and the light output bins were roughly divided in this dataanalysis.

2. TALYS and PHITS calculations
PHITS and TALYS calculations are performed for the thick target neutron production yield.

In TALYS calculation, the An-Cai potential[14]for deuteron incidence was applied. The output of TALYS code is neutron-produced double differential cross-section.

To compare TALYS calculation with our experimental data, equation (1) is used and the energy loss of deuteron in the thick target was considered in this calculation.

$$\frac{d^2Y}{dE_n d\Omega_n} = N \int_0^{E_0} \left[\frac{d^2\sigma}{dE_n d\Omega_n} \right]_{(E_d,\theta_n)} \left[\frac{dE_d}{dx} \right]^{-1}$$
$$\times exp\left(-\int_{E_d}^{E_0} \sum_{non} (E')dE' \right) dE_d, \qquad (1)$$

where$d^2Y/dE_n d\Omega_n$ is the double differential thick target neutron yields, N the atomic number density of target, E_0 the incident deuteron energy, $d^2\sigma/dE_n d\Omega_n$ the neutron-produced double differential cross-section, E_d the deuteron energy in the target,$[dE_d/dx]$ the stopping power of the target, $\sum_{non}(E')$ the macroscopic total reaction
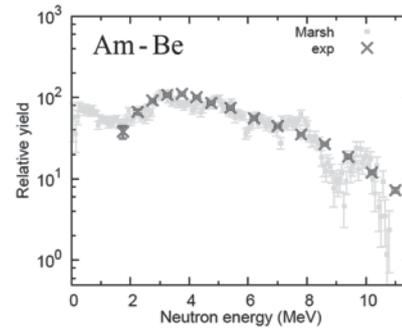
Fig. 7 Measured neutron energy spectra of ^{241}Am-Be compared with data acquired by Marxh *et al.*[13].
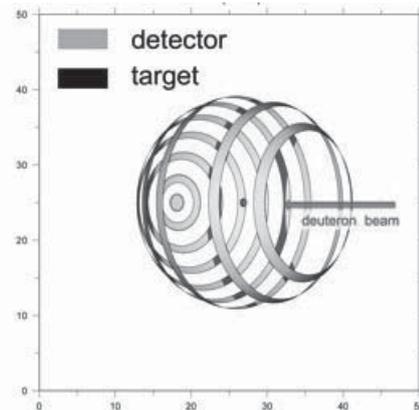
Fig. 8 Calculation geometry in the PHITS calculation.

cross-section.

For PHITS calculation, QMD (Quantum Molecular Dynamics)[15]and GEM (Generalized Evaporation Model)[16]were adopted. The PHITS calculation geometry is simplified one illustrated in **Figure 8**. The switching time from QMD to GEM is 150 fm/c.

The NASA's formula[17] was applied to total cross-section for nucleus-nucleus collision in the PHITS calculation.

3. Comparison with the calculated results
The experimental results of the double differential TTNYs for 5 MeV deuteron incidence on aluminum and9 MeV incidence on SUS304 are shown in **Figure 9** and **10**, respectively.

In the case of aluminum target, PHITS calculation agrees with the experimental data except for neutron energies below 7 MeV at 0˚. On the other hand, TALYS does not reproduce experimental dataabove7 MeV. Both codes underestimate the experimental values below 7 MeV at 0˚. This trend was confirmed for carbon target in our recent work[18]. This is probably because there is a problem in the calculation of the direct and pre-equilibrium processes for the light nuclei in TALYS.

For SUS304 target, PHITS reproduces energy spectrum approximately. The calculation result by TALYS agrees with the experimental data below 8 MeV. However, the code underestimates the experimental data above that energy. With respect to both targets, PHITS and TALYS show different tendency. It is because that both codes do not treat the nature of deuteron stripping reaction accurately.

4. Error evaluation
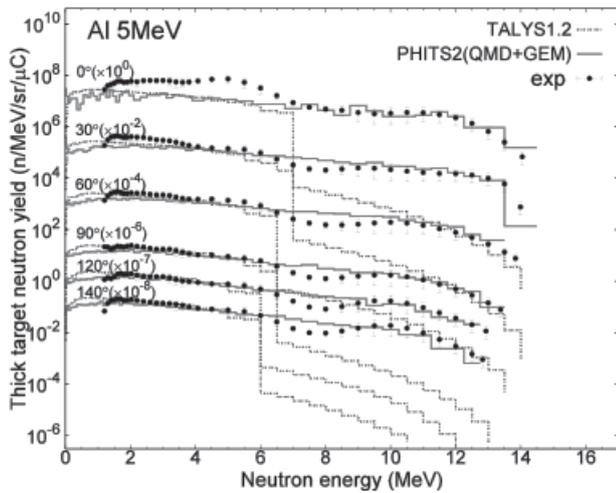
Fig. 9 Double differential neutron thick target yield for 5 MeV deuteron induced on aluminum.

Fig. 10 Double differential neutron thick target yield for 9 MeV deuteron induced onSUS304.

SUS304 targets.

The error bars shown in **Figure 9** and **10** include the statistical error and the uncertainty from unfolding by FORIST. The systematic errors were mainly caused by uncertainty of solid-angle, gamma-ray rejection, the accuracy of response function of SCINFUL-QMD, and neutrons scattered by materials and air, the error thus

Table 1 Error of Thick Target Neutron Yields.

Error origin	Error [%]
Solid angle	2.1-3.2
Total count of incident deuteron	<1.0
Dead time	<1.0
Gamma-ray rejection	5.0
Response function of NE213	<17
Effect of neutron scattered	<4.0
Total systematic error	**18.3-18.5**

estimated to be2.1-3.2%,5%, 17% and 4%, respectively. The values are summarized in **Table 1**.To estimate the effect of neutrons scattered in the air, calculation by PHITS code with the evaluated nuclear data files JENDL-4.0[19] was performed.

IV. SUMMARY

The double differential TTNYs from 5 MeV deuteron incidence on aluminum and 9 MeV deuteron incidence on SUS304 targets were measured for radiation dose estimation with reasonable validity at the high power deuteron accelerator facility. The light output spectra were unfolded by the FORIST code in order to derive the neutron energy spectra because it was unable to generate pulsed deuteron beam.

PHITS reproduces the experimental data approximately except for energy region below 7 MeV at 0˚ for an aluminum target. On the other hand, TALYS underestimates the measured values above 8 MeV for both aluminum and

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