

Measurements of Neutron Emission Spectra and ^7Be Production in Li(d,n) and Be(d,n) Reactions for 25 and 40 MeV deuterons

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The neutron spectra in Li(d,n) and Be(d,n) reactions for $E_d = 25, 40$ MeV were measured from ~ 1 MeV to highest energy of secondary neutrons at ten laboratory angles between 0- and 110-deg with the time-of-flight (TOF) method. In addition, the number of ^7Be accumulated in the targets was also measured by counting the γ -rays from ^7Be using a pure Ge detector to obtain ^7Be production cross-section and yields.

1. Introduction

The Li(d,n) , Be(d,n) reactions are expected as high-intensity neutron production reactions, in particular the $^{\text{nat}}\text{Li(d,n)}$ reaction using a liquid lithium target will be adopted in IFMIF (International Fusion Materials Irradiation Facility) [1]. For the design and operation of the neutron source, detailed knowledge is required on the energy-angular neutron emission spectra of the $^{\text{nat}}\text{Li(d,n)}$ and $^9\text{Be(d,n)}$ reactions, and the radioactivity (^7Be , ^3H etc.) accumulated in the targets. The neutron flux and spectral data are indispensable for precise estimation of the neutron irradiation effects and radiation shielding, and the radioactivity accumulation is of great concern for the management of the targets. However the data status is not good enough as shown by marked differences among experimental data [2]. We have started experiments on the neutron emission spectrum of the $^{\text{nat}}\text{Li(d,n)}$ and $^9\text{Be(d,n)}$ reaction and the radioactivity induced in the target using the AVF cyclotron ($K=110$) at CYRIC, Tohoku University [3].

This paper presents the experiments on the 1) neutron emission spectra and the 2) production of radioactive nuclide, ^7Be , for the $^{\text{nat}}\text{Li(d,n)}$ and $^9\text{Be(d,n)}$ reaction with thick target for 25,40 MeV deuterons. The neutron spectra were measured for almost entire range of secondary neutrons at ten laboratory angles between 0- and 110-deg with the time-of-flight (TOF) method using a beam swinger system. The number of ^7Be accumulated in the targets was measured by counting the γ -rays from ^7Be using a pure Ge detector. Besides, to improve the data accuracy of the thick target yields of neutrons and the radioactivity accumulated in the target, we have also measured the data for a thin lithium target at 40 MeV and the excitation function of the $^{\text{nat}}\text{Li(d,x)}^7\text{Be}$ reaction below 40 MeV by applying a stacked target method. Experimental results are compared with other experimental data and calculations. A part of results for 25 MeV were reported in ref. 3.

2. Experimental apparatus

The experimental setup is presented in Fig.1. A deuteron beam accelerated by the AVF cyclotron was transported to the target room No.5 equipped with a beam-swinging system and a neutron TOF channel [4]. The beam swinger system changes the incident angle of the beam onto the target from 0- deg to 110-deg and enables to measure angular distributions with fixed detector setup.

The targets (Li,Be) were metallic plate of natural elements. The lithium target was prepared by mechanical pressing of a lithium ingot under argon atmosphere to avoid oxygen contaminant and the lithium ingot was cleaned up thoroughly prior to the pressing to avoid carbon contamination. The lithium and beryllium targets were ~ 8 mm and ~ 3 mm thick for 25 MeV, respectively to stop the incident beam within the targets. For 40 MeV, We prepared a thin lithium target (~ 0.85 mm) and a stacked targets that consists of eight lithium plates with different thickness ($\sim 1.3, \sim 6.7, \sim 1, \sim 4.7, \sim 0.9, \sim 2.7, \sim 0.7, \sim 3.4$ mm, total thickness ~ 21.4 mm) to measure not only thick target neutron spectra but also excitation function of the $^{\text{nat}}\text{Li(d,x)}^7\text{Be}$ reaction. They were set on a remotely-controllable target changer together with a beam viewer of aluminum oxide. The support frame of the target was isolated from the ground to read beam current on the target and was surrounded with a copper mesh biased about -600 V to suppress secondary electron emission.

The target chamber was shielded with a 2.5 m thick concrete wall having a beam channel for collimators. Iron collimators, 10-cm-diam, were inserted into the beam channel to collimate neutrons from the target. Emitted neutrons were detected by NE213 scintillation detectors, 14 cm-diam \times 10 cm-thick or 5 cm-diam \times 5 cm-thick equipped with pulse-shape-discrimination (PSD). The larger and smaller detectors were placed around ~ 11 m

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and ~3.5 m from the target (fig.1), respectively. The shorter flight path was adopted to measure the low energy part (~1-5 MeV) of the neutron spectrum by low pulse-height bias (~600 keV). The TOF, PSD and pulse-height data were collected event by event as three parameter list data for off-line analysis [5].

3. Experimental procedure

The pulse width was generally less than 1 ns in FWHM, and the beam current on the target was around 5 nA. The beam current was digitized and recorded by a multi-channel scaler for normalization of the neutron TOF spectrum and the ^7Be production measurement. The TOF data for 25 MeV were obtained at ten laboratory angles (0, 5, 10, 15, 20, 25, 30, 40, 60 and 90 deg), for 40 MeV at nine laboratory angles (0, 10, 15, 20, 30, 40, 60, 90 and 110 deg), respectively.

The activities of ^7Be accumulated in the lithium and beryllium target were measured by detecting 477 keV γ -rays due to the decay of ^7Be in the targets bombarded by a deuteron beam during the neutron spectrum measurement with a pure Ge detector (EURICIS MESURESE GPC50-195-R) and a multi-channel analyzer.

4. Data analysis

4.1. Neutron spectrum

Neutron TOF spectra gated by a PSD signal and lower pulse-height bias were converted into energy spectra. The efficiency vs energy curves of the detectors were calculated by a revised version of the Monte Carlo code SCINFUL [6] that was verified to be accurate with in $\pm 5\%$ up to 80MeV [7]. The spectra were normalized by the integrated beam current and the corrected for the effect of the attenuation in the sample and air using the data of W. P. Abfalterer et al. [17] and LA150 [18].

4.2. ^7Be activity

The induced ^7Be activity was determined from the γ -ray counts by the pure Ge detector, and corrected for the decay, the peak efficiency of the Ge detector, the self-absorption effect in the samples and the beam current fluctuation during irradiation. The efficiency of the Ge detector was determined by the calculation using the Monte Carlo code EGS 4 [8]. The calculated results were confirmed at several energy points with standard γ -ray sources. In the case of the stacked samples, we took into account the energy degradation and the attenuation of projectiles through the targets. In each stacked sample, the energy of projectile deuteron was calculated by the TRIM code [15] and the number of projectile deuterons were corrected for the attenuation using the total cross-section calculated by Shen's formula [16].

5. Results and discussion

5.1. (d+Li, d+Be) neutron spectra

For 25 MeV, the present results for the $^{\text{nat}}\text{Li}(d,n)$ and $^9\text{Be}(d,n)$ neutron spectrum at ten laboratory angles are shown in Fig.2 and Fig.3, respectively. The low limit is as low as around 1 MeV. The error bars of the spectra represent the statistical errors mainly. In Fig.4, the present data at 0, 20, 60, 90 deg are compared with the experimental data by Lone et al at 23 MeV [2] and the calculation by the M^cDelicious code [14]. The data of Lone et al are reported only for 0-deg.

The experimental spectra are divided into two parts; a high-energy tail region (only for $^{\text{nat}}\text{Li}(d,n)$) due to direct stripping reactions and a main peak region centered around 10 MeV which is a main neutron source in IFMIF. The data by Lone et al. are in good agreement with the present one in the 10-23 MeV region while they are much larger in the low energy region. Such a high yields of low energy neutrons as seen in the other data is unlikely for the reaction of light element like Li which has a very strong recoil effect. For the high energy tail region, the data by Sugimoto [9] at 32 MeV are closer to the present one rather than those by Lone et al. and calculation. It is necessary to clarify the spectrum in this energy region because high-energy neutrons cause much more damage due to large helium production cross-sections and larger energy of primary-knock-on atoms.

The intensity of high-energy tail is highest around 15-deg while total neutron yields are highest at 0-deg. The former conclusion is in agreement with Sugimoto [9] and can be interpreted by the angular momentum effect in the $^7\text{L}(d,n_0,1)^8\text{Be}$ reaction. Therefore, to reduce the influence of high-energy neutrons and obtain higher intensity irradiation field, neutrons to angles close to 0-deg will be preferable. The present data can be used to assess the applicability of calculation codes and models for the neutron emission spectrum of the reaction [10].

For 40 MeV, the present results with the thick and thin target of ${}^{\text{nat}}\text{Li}(d,n)$ neutron spectrum at nine or seven laboratory angles are shown in Fig.5 and Fig.6, respectively. In Fig.7, the present data at 0, 20, 60, 90 110 deg are compared with the other data collected by Simakov et al [14]. Similarly as the spectra at 25 MeV, the experimental spectra are in good agreement with the other data around 6-25 MeV region, but different at both low energy region (<5 MeV) and high energy region (>30 MeV).

5.2. ${}^7\text{Be}$ activity

The measured ${}^7\text{Be}$ activity was compared with other experimental data and the calculation by the code IRAC [11] used for activity assessment of accelerator components. Figures 8 and 9 show the comparison of the present results, the IRAC code and other experimental data [12,13] for Li and Be, respectively. For the lithium data, the present results at 25 MeV look to be consistent with the data around 22 MeV [11] and at 40 MeV [12], but are substantially higher than the IRAC calculation. The production of ${}^7\text{Be}$ via the (d,n) reaction on elemental lithium will be due to the ${}^7\text{Li}(d,2n)$ and the ${}^6\text{Li}(d,n)$ reactions mainly. Figure 10 shows the comparison of the experimental data and the IRAC calculation for the ${}^{\text{nat}}\text{Li}(d,2n)$ reaction cross-section. The present data is in good agreement with other ones at low energy region (6.8, 9.3 MeV). The IRAC code underestimates the ${}^7\text{Li}(d,2n)$ cross-sections and this may be a principal reason of the underestimation of the IRAC code for the ${}^7\text{Be}$ production rate. For the beryllium data, similar underestimation is observed and reported even for the new code [10].

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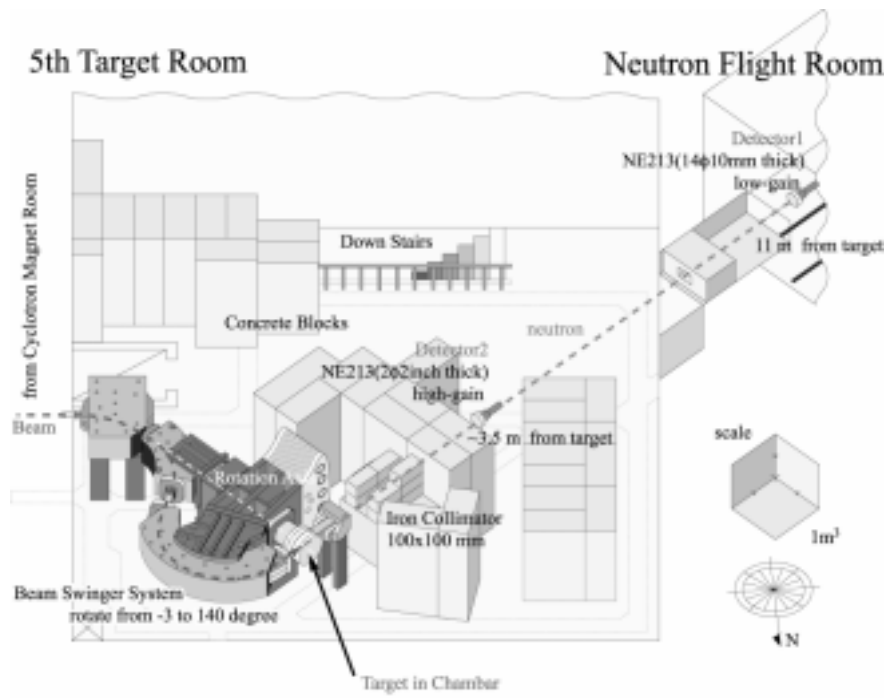


Fig.1: The layout of TR 5 at CYRIC, Tohoku University

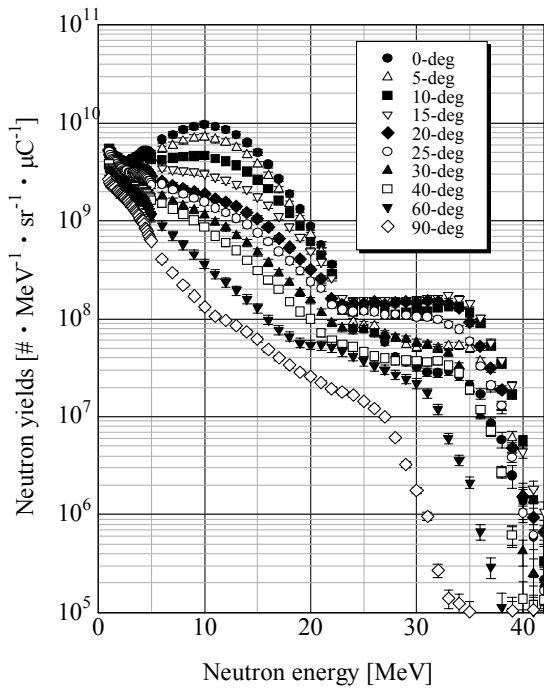


Fig.2: The neutron spectra of thick lithium for incident deuteron energy of 25 MeV

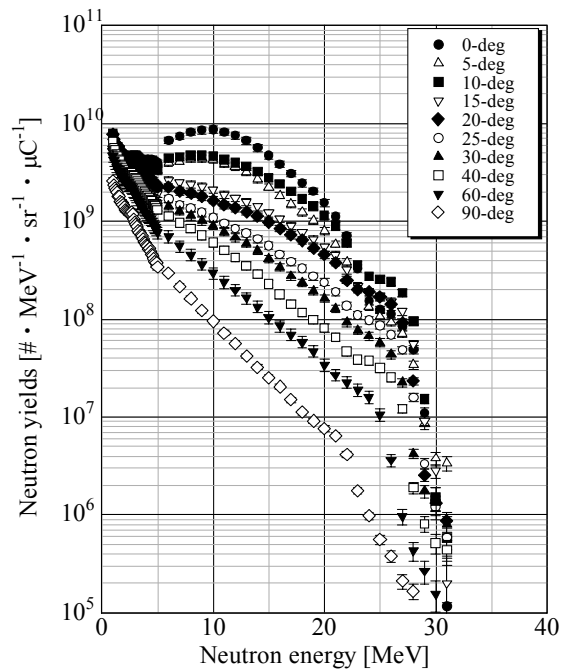


Fig.3: The neutron spectra of thick beryllium for incident deuteron energy of 25 MeV

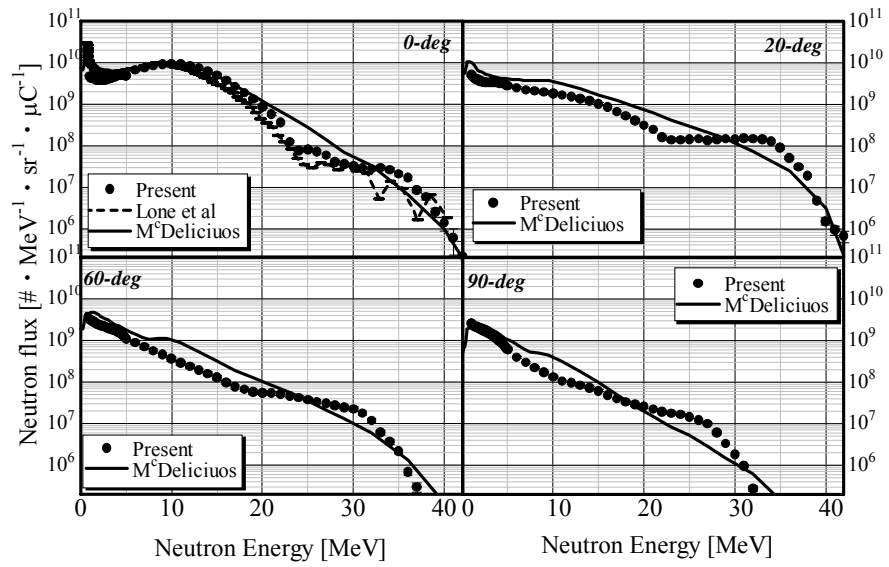


Fig.4: Comparison of the present Li(d,n) neutron spectrum with the data by Lone et al [2] and M^cDelicious calculation [14].

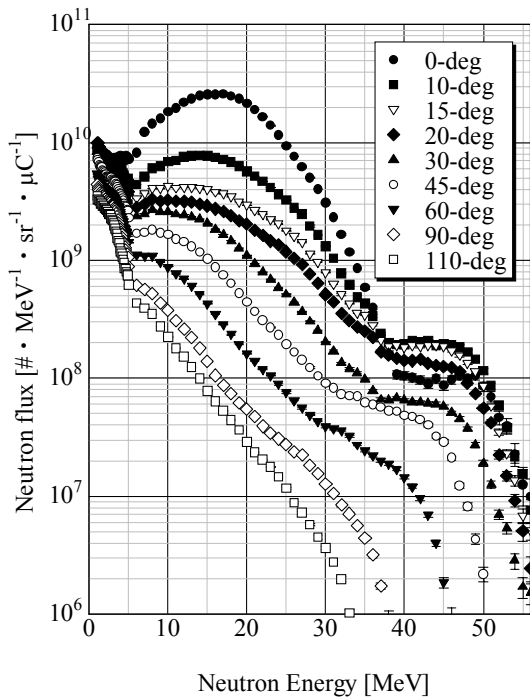


Fig.5: The neutron spectra of the thick lithium for incident deuteron energy of 40 MeV

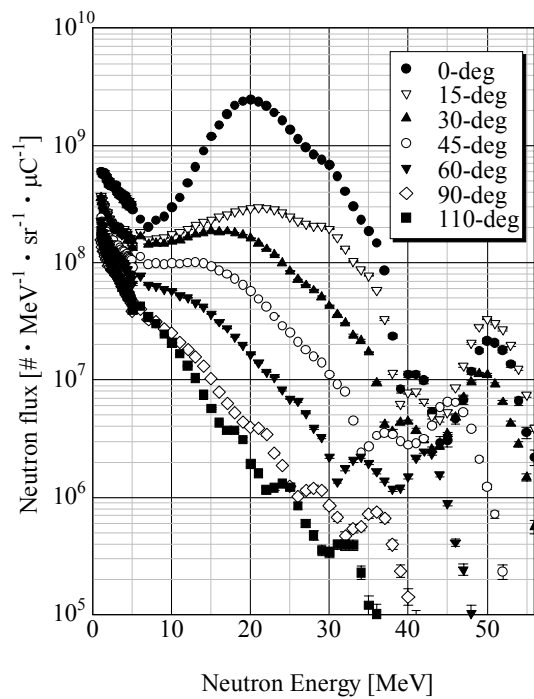


Fig.6: The neutron spectra of the thin lithium for incident deuteron energy of 40 MeV

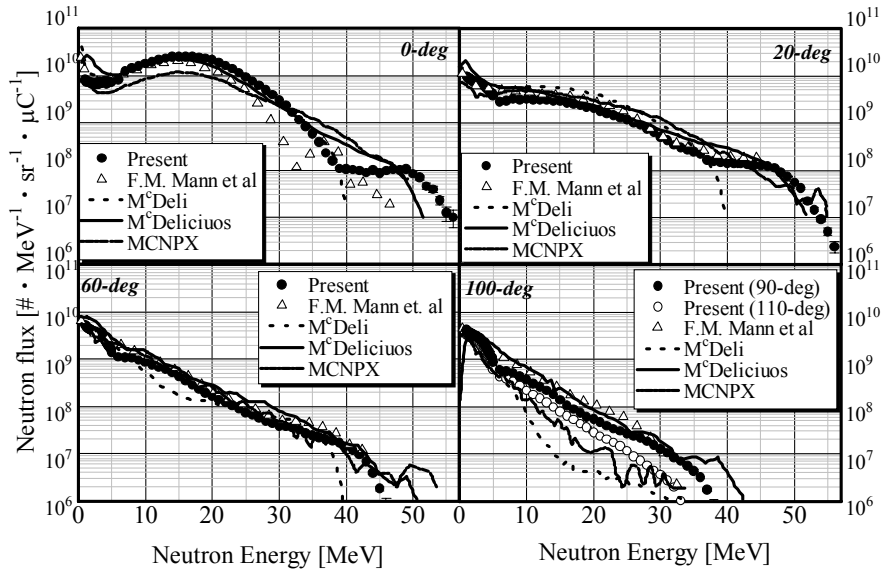


Fig.7: Comparison of the present $^{nat}\text{Li}(d,n)$ neutron spectrum with the other experimental data and calculation collected by Simakov et al [14].

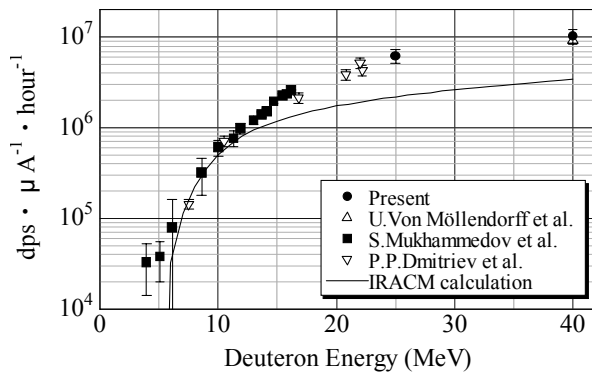


Fig.8: ^7Be production rate *via* the $^{nat}\text{Li}(d,x)$ reaction

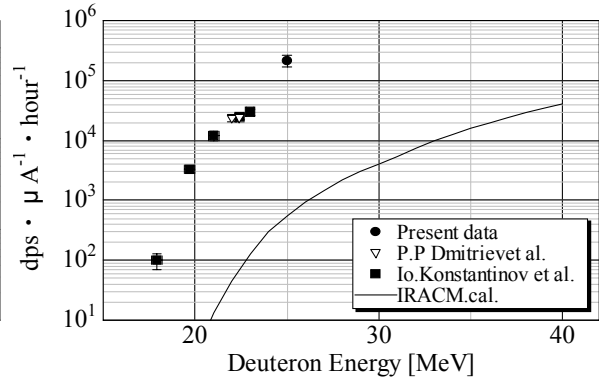


Fig.9: ^7Be production rate *via* the $^9\text{Be}(d,x)$ reaction

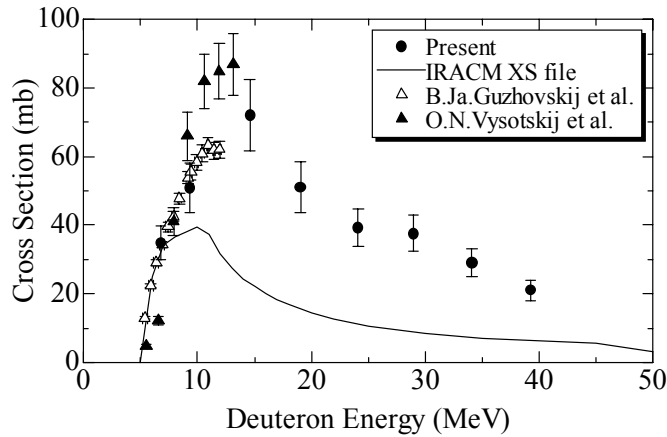


Fig.10: $^{nat}\text{Li}(d,2n)^7\text{Be}$ reaction cross-section