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**ARTICLE**

# Light ion production in 175 MeV quasi mono-energetic neutron induced reactions on carbon, oxygen, and silicon

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Double-differential cross sections of light ions (p, d, t, $^3$He, and α) from carbon, oxygen, and silicon induced by 175 MeV quasi mono-energetic neutrons were measured using the Medley setup at the The Svedberg Laboratory (TSL) in order to benchmark evaluated nuclear data and nuclear reaction models. The Medley is a conventional spectrometer system which consists of eight counter telescopes. Each telescope is composed of two silicon surface barrier detectors as the ΔE detectors and a CsI(Tl) scintillator as the E detector for particle identification. The telescopes are placed at angles from 20° to 160° in steps of 20°. The measured double-differential production cross sections of light ions for oxygen and silicon are compared with PHITS calculations using the following nuclear reaction options: the high-energy nuclear data library (JENDL/HE-2007), the quantum molecular dynamics (QMD) model, the modified quantum molecular dynamics (MQMD) model, and the intra-nuclear cascade (INC) model based on the Bertini Model.

***Keywords: 175 MeV; quasi mono-energetic neutrons; light ion production; double-differential cross sections; carbon; oxygen; silicon; PHITS; benchmark***

## 1. Introduction

Recently, there have been increasing nuclear data needs for neutron-induced light-ion production at intermediate energies from 20 MeV to 200 MeV for various applications related to neutron transport and dosimetry for radiation safety, dose estimation in advanced particle therapy, soft error prediction in microelectronic devices, etc. For these applications, double-differential cross sections (DDXs) of light-ion production are required to validate nuclear reaction models. However, the experimental data are currently scarce over 100 MeV. In the present work, therefore, we have measured DDXs of light ions (p, d, t, $^3$He, and α) from carbon, oxygen, and silicon induced by 175 MeV quasi mono-energetic neutrons using the Medley spectrometer at the The Svedberg Laboratory (TSL) in Uppsala in order to satisfy these needs. Previously, measured double-differential light-ion yield data were reported in Refs.[1,2]. In this work, we derive the DDXs averaged over the quasi mono-energetic neutron spectrum accepted with the time-of-flight (TOF) method. Finally, the measured DDXs are compared with the high-energy nuclear data library, JENDL/HE-2007 [3], and some built-in reaction models in PHITS [4].

## 2. Experimental method

Details of the experimental method have been reported in Refs.[1,2,5]. Only brief summaries are described here.

Four disc-shaped targets (C, $CH_2$, Si, and $SiO_2$) placed in the Medley chamber were irradiated by quasi mono-energetic neutrons generated by the $^7$Li(p,n)$^7$Be reaction. Each target size is summarized in **Table 1**. The $SiO_2$ target was used as the oxygen target by the subtraction of silicon contribution. Energy and angular distributions of light ions produced from the target were measured with the Medley spectrometer which is composed of eight telescopes placed at angles from 20° to 160° in steps of 20°. Each telescope consisted of two silicon surface barrier detectors (50~60 μm and 1000 μm) as the ΔE detectors and a CsI(Tl) detector as the E detector. Moreover, the incident neutron spectrum was measured using the same spectrometer with both $CH_2$ target and carbon target by means of a conventional proton recoil method. The $^7$Li(p,n)$^7$Be reaction produces both peak and low-energy tail neutrons. Therefore, a time-of-flight (TOF) method was used in order to reduce

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the contribution of low-energy tail neutrons in the accepted incident neutron spectrum. The off-line data analysis will be explained in the following section.

Table 1. The size of targets used in the measurement.

| Target | Thickness (mm) | Diameter (mm) |
|---|---|---|
| C | 1.0 | 22 |
| $CH_2$ | 5.0 | 25 |
| Si | 0.96 | 25 |
| $SiO_2$ | 1.0 | 25 |

## 3. Data reduction procedure

Data analysis procedure based on ΔE-E particle identification technique is the same as in Refs.[1,2,5]. Energy calibration of all detectors was made using the relation between measured pulse height and calculated energy deposition in each detector as follows. Events in the ΔE-E bands were fitted with respect to the energy deposition in the ΔE detectors, which was determined from the thickness and the energy loss calculated with SRIM code [6]. A linear response is expected for silicon detectors in the measured range of energy. The ΔE detectors were calibrated using the point where each charged particle starts to punch through the ΔE detectors. For the energy calibration of the E detectors, the following approximate expression was applied to each light ion, which reflects a non-linear relationship between the light output, $L$, and the energy deposition, $E$, in the CsI(Tl) scintillator:

$$E = a + bL + c(bL)^2 \quad \text{for hydrogen isotopes} \qquad (1)$$

$$E = a + bL + c\ln(1 + dL) \quad \text{for helium isotopes} \qquad (2)$$

where $a$, $b$, $c$ and $d$ are the fitting parameters. The parameter $c$ depends on the kind of charged particles. The efficiency correction due to the reaction losses in the CsI(Tl) scintillator was made using the same method as reported in Ref.[1].

The incident neutron spectrum accepted by the TOF gate was obtained from the net recoil proton spectrum from *np* scattering in the measurement of $CH_2$ target. Details of deriving the neutron spectrum have been reported in Ref.[5]. The obtained neutron spectrum is shown in **Figure 1**. After the TOF gate cut, about half of the accepted neutrons are included in the peak component around 175 MeV and the rest is composed of the low energy tail. The tail component below 70 MeV is negligibly small as shown in Figure 1.

The measured double-differential light-ion production cross sections for the target $k$ were determined using the following expression:

$$\frac{d^2\sigma_k(\theta,E)}{dEd\Omega} = \frac{Y_k(\theta,E)}{Y_{\rm H}} \frac{N_{\rm H}}{N_k} \frac{\Phi_{\rm CH_2}}{\Phi_k} \frac{\Omega_{\rm CH_2}}{\Omega_k} \frac{f_{\rm CH_2}(E)}{f_k(E)} \frac{1}{\Delta E} \left(\frac{d\sigma_{\rm H}}{d\Omega}\right) \qquad (3)$$

where $Y(\theta,E)$ is the net counts in a certain energy bin ΔE at laboratory scattering angle $\theta$ for each ion, $Y_{\rm H}$ is the net counts in the recoil proton peak and the number of the net counts due to *np* scattering is obtained using measurement at 20° for both $CH_2$ and carbon targets. The *np* scattering spectrum is deduced by subtracting the contribution of C(n,xp) reaction from the $CH_2$ measurement. The effective efficiency which includes the reaction loss effect in the CsI(Tl) scintillator is $f$(E), $\Phi$ is the relative neutron flux, and $N$ is the number of the target nuclei. The differential *np* scattering cross section ($d\sigma_{\rm H}/d\Omega$) is taken from NN-online [7]. In Eq. (3), the solid angle $\Delta\Omega$ is given under an assumption that the target is treated as a point source.

Finite target thickness causes non-negligible effects on both energy-loss and particle-loss of generated light ions. Thus, the measured spectrum is distorted in the low-energy region. To correct these effects, we used the TCORR code [8] which was developed previously in the data analysis of light-ion production measurements at 96 MeV with the Medley spectrometer.

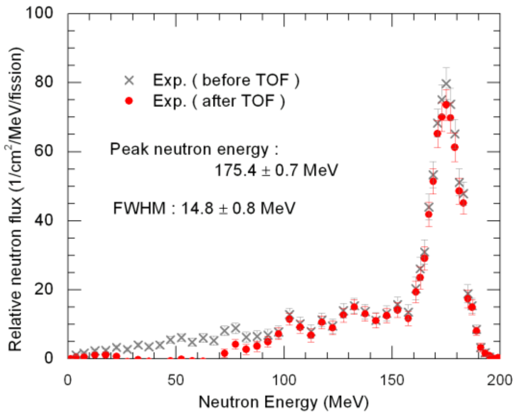


Figure 1. Accepted quasi mono-energetic neutron spectrum. Cross and solid circles are the measured data before and after the TOF gate cut, respectively.

## 4. Experimental results and their comparisons with PHITS calculations

The measured DDXs of light ions are compared with the calculations by PHITS code [4] using the following nuclear reaction options: the high-energy nuclear data library (JENDL/HE-2007[3]), the quantum molecular dynamics (QMD) model, the modified QMD with coalescence model (MQMD)[9], and the intra-nuclear cascade (INC) model based on the Bertini model. The generalized evaporation model (GEM) is employed for the statistical decay process following the dynamical process described by QMD, MQMD, and INC. The accepted quasi mono-energetic neutron spectrum after TOF gate cut shown in Figure 1 is used as the input neutron spectrum in the PHITS calculation. Some results of oxygen and silicon are presented below. It should be noted that there is no comparison with the INC model calculation for deuterons and α particles, because the present INC model cannot predict the production of such light clusters because the reaction mechanism is not considered.

### *4.1. Oxygen*

**Figure 2** shows the result of proton production DDXs at four angles, 20°, 60°, 100°, and 140°. The calculation with JENDL/HE-2007 gives a fairly good description of the measured energy spectra except at 140°. The PHITS calculations with three different reaction models (INC, QMD, and MQMD) underestimate the measurement in the high emission energy range at backward angles and in the intermediate energy range at 20°.

The result of deuteron production DDXs is shown in **Figure 3**. All three calculations with JENDL/HE-2007, QMD and MQMD fail to reproduce the experimental data satisfactorily. However, the MQMD calculation tends to enhance deuteron production over the wide emission energy range, compared with the original QMD calculation which underestimates largely the experimental data.

**Figure 4** shows the result of α production DDXs. Both the PHITS calculations with JENDL/HE-2007 and MQMD are in better agreement with the measurement than that with QMD.

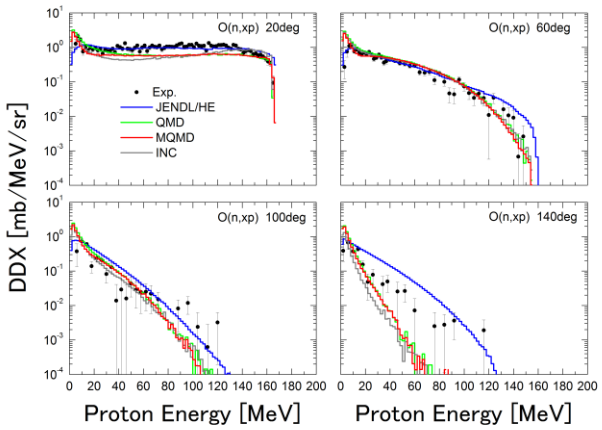


Figure 2. Comparison of the measured DDXs and the PHITS calculations for the O(n,xp) reaction.

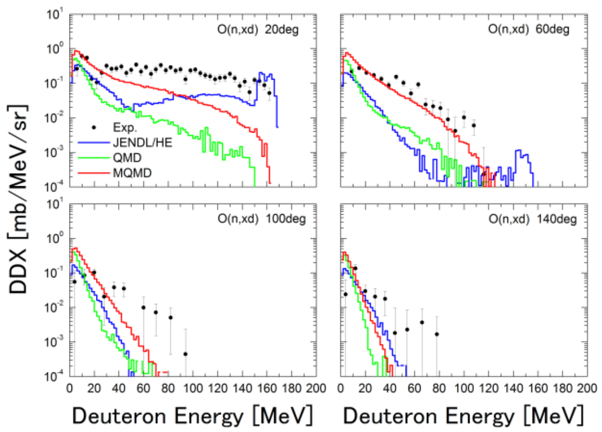


Figure 3. Comparison of the measured DDXs and the PHITS calculations for the O(n,xd) reaction.

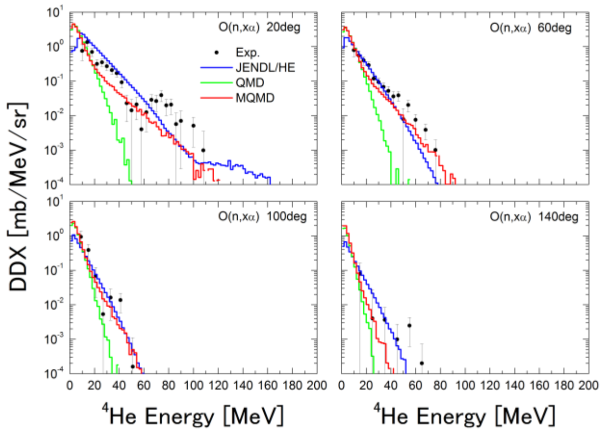


Figure 4. Comparison of the measured DDXs and the PHITS calculations for the O(n,xα) reaction.

### *4.2. Silicon*

The result of proton production DDXs for silicon is shown in **Figure 5** at four angles, 20°, 60°, 100°, and 140°. The calculation with JENDL/HE-2007 gives a better description of the measured DDXs over the whole angles than the other calculations, except in the high energy region at 60°. Both QMD and MQMD calculations reproduce the measured DDXs to the similar extent, whereas the INC calculation underestimates largely the measured DDXs over the whole emission energy range at backward angles.

**Figure 6** presents the result of deuteron production DDXs. There are obvious differences among three calculations with JENDL/HE-2007, QMD, and MQMD. The calculation with JENDL/HE-2007 shows a better agreement with the measured DDXs than those with QMD and MQMD over whole angles, except for overestimation seen in the high energy region at 60°. It is found that the MQMD calculation improves remarkable underestimation shown in the QMD calculation over the wide emission energy range. However, it still underestimates the measurement above 40 MeV, particularly at 20°.

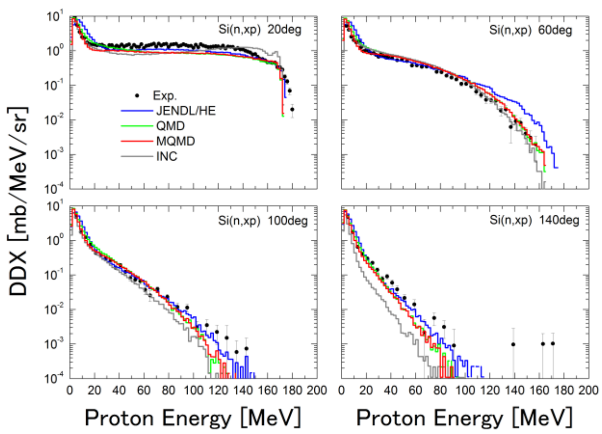


Figure 5. Comparison of the measured DDXs and the PHITS calculations for the Si(n,xp) reaction.

**Figure 7** shows the result of α production DDXs. The PHITS calculation with MQMD leads to enhancement of α production at high emission energies, and shows a better agreement with the measurement than those with QMD and JENDL/HE-2007 over the whole angular range.

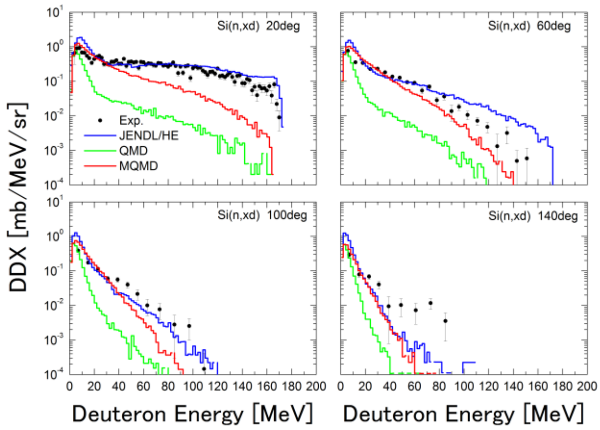


Figure 6. Comparison of the measured DDXs and the PHITS calculations for the Si(n,xd) reaction.

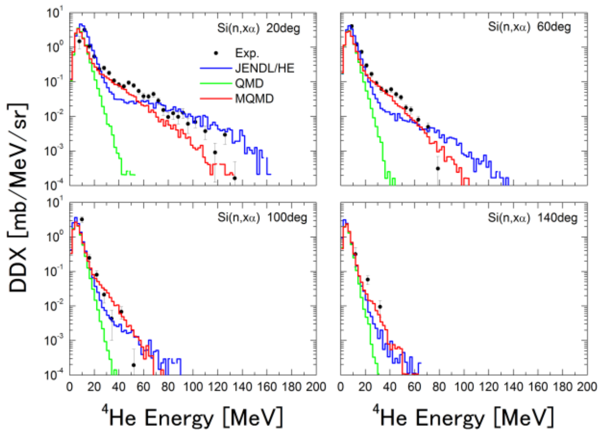


Figure 7. Comparison of the measured DDXs and the PHITS calculations for the Si(n,xα) reaction.

## 5. Summary and conclusion

The double-differential cross sections (DDXs) of light-ion production for carbon, oxygen and silicon were measured with 175 MeV quasi mono-energetic neutrons using the Medley spectrometer at the The Svedberg Laboratory (TSL) using the time-of-flight method. The measured DDXs for oxygen and silicon were compared with the PHITS calculations in order to perform the benchmark test of the high energy evaluated file, JENDL/HE-2007, and the reaction models used in PHITS.

The calculation with JENDL/HE-2007 shows overall reasonable agreement with the present measurement. Discrepancies among the reaction models appear in the emission of complex particles (d, t, $^{3}$He, and α). It was found that the modified QMD with a coalescence model (MQMD) can improve large underestimation seen in the high energy part of the original QMD calculation.

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