Progress in NUCLEAR SCIENCE and TECHNOLOGY, Vol. 1, p.69-72 (2011)

ARTICLE

# Production of protons, deuterons, and tritons from carbon bombarded by 175 MeV quasi mono-energetic neutrons

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We have measured double-differential yields of protons, deuterons, and tritons produced from carbon induced by 175 MeV quasi mono-energetic neutrons using the MEDLEY setup at the TSL neutron beam facility. The measured data are used for benchmarking of a high-energy nuclear data file, JENDL/HE-2007, and both intra-nuclear cascade (INC) model and quantum molecular dynamics (QMD) calculations.

***KEYWORDS: 175 MeV, quasi mono-energetic neutrons, double-differential yield, hydrogen isotopes, PHITS***

## I. Introduction

In recent year, there have been increasing nuclear data needs for neutron induced light-ion production at intermediate energies (20 to 200 MeV) for various applications related to neutron transport and dosimetry for radiation safety and efficiency calculations of neutron detectors. To benchmark evaluated nuclear data and nuclear reaction models, we have measured double-differential production yields of light ions ($p$, $d$, $t$, $^3$He, and $\alpha$) from carbon induced by 175 MeV quasi mono-energetic neutrons at the The Svedberg Laboratory[1)] (TSL) in Uppsala. Up to now, we have reported some preliminary results of proton production cross sections.[2)] In the present work, we have extended our data analysis so as to include double-differential production yields of deuterons and tritons. The experimental data are compared with the calculations using the PHITS code[3)] with evaluated high-energy nuclear data and nuclear reaction models.

## II. Experimental method

Details of the experimental setup have been reported in Refs.[1,2)]. Quasi-monoenergetic neutrons generated by using the $^7$Li($p,n$)$^7$Be reaction irradiated a 1mm-thick carbon target 22 mm in diameter. Energy and angular distributions of neutron-induced light-ion production yields from carbon were measured with the MEDLEY setup shown in **Fig.1**. The MEDLEY setup is composed of eight telescopes placed at angles from 20° to 160° in steps of 20°. Each telescope consists of two silicon surface barrier detectors as the ΔE detector and a CsI(Tl) detector as the E detector. Light ions produced from the carbon target placed at the center of the MEDLEY were detected by the eight telescopes. Moreover, the incident neutron spectrum was measured using the same setup with a $CH_2$ target 1mm thick and 25 mm in diameter by means of a conventional proton recoil method.

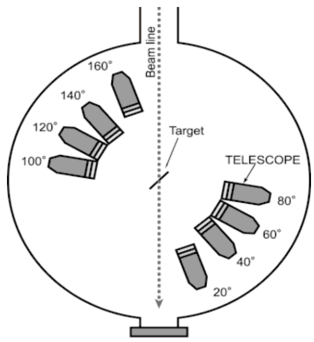


**Fig.1** Arrangement inside the MEDLEY chamber

## III. Data analysis

Data analysis procedure based on the ΔE-E particle identification technique is basically same as in the previous measurements at 96 MeV[4-7)]. **Figure 2** shows an example of two-dimensional scatter plots of pulse height signals from two ΔE detectors ($\Delta E_1$ and $\Delta E_2$) located at 20 degrees. Each light ion is found to be clearly separated

Energy calibration of all detectors was made using the data themselves. 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 the SRIM code[8)]. For the energy calibration of the E detectors, the following approximate expression was applied to protons, deuterons, and tritons, which reflects a non-linear relationship between the light output and the energy deposition in the CsI(Tl) scintillator[4)]:

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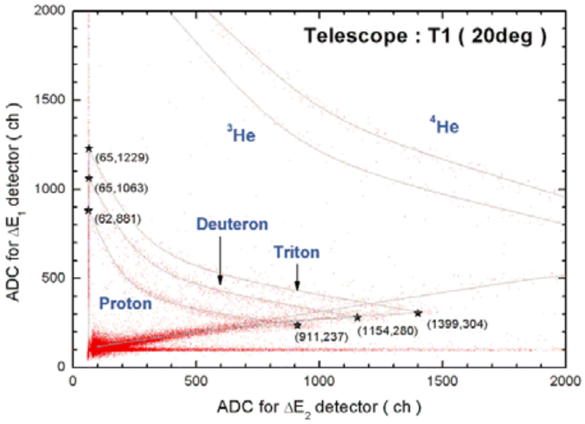


**Fig.2** Two-dimensional scatter plots of particle identification for $\Delta E_1$-$\Delta E_2$. The solid lines are guided lines.

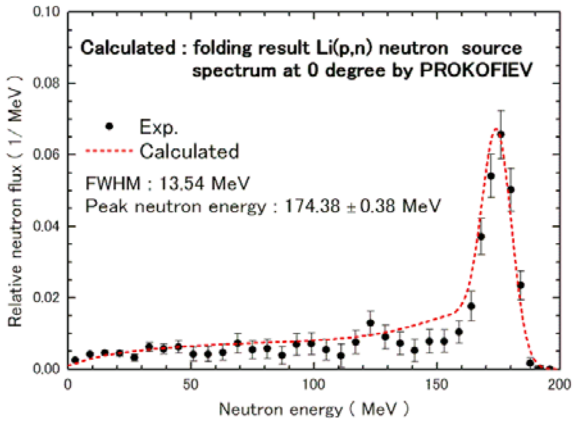


**Fig. 3** Measured and calculated incident neutron spectra

$$E = a + bL + c(bL)^2, \qquad (1)$$

where $L$ is the light output, and $a$, $b$ and $c$ 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 for proton has been reported elsewhere[9]. It was estimated from the calculation using the PHITS code for proton energies up to 200 MeV, and the result was validated by our past experiment using 160 MeV protons[9]. The efficiency corrections for deuteron and triton were made by an alternative method[10], because the treatment of deuteron- and triton-induced reactions in the PHITS code is less reliable than that of nucleon-induced reactions. The reaction loss is caused by a non-elastic nuclear interaction in the CsI(Tl) scintillator in the case where there is no escape of an incident ion from the CsI(Tl) scintillator. Therefore, the efficiency correction can be made using the probability that an incident ion will undergo a nonelastic nuclear interaction in the slowing down process, which is calculated using the data of the stopping power and the nonelastic cross section. It is equivalent to the reaction cross section because the compound elastic component can be neglected in the incident energy range of interest. The deuteron and triton reaction cross sections were calculated using optical potentials[11,12]. It was confirmed that the proton efficiency correction made by this method coincides with the PHITS result. Finally, the corrections at 150 MeV are 19, 20 and 12 % for proton, deuteron and triton, respectively.

The incident neutron spectrum was obtained from the data analysis of recoil protons from np scattering in the measurement of $CH_2$ at 20°. By subtracting the contribution from C(*n,xp*) reactions using the measured data of C, we can derive the net recoil proton spectrum. Finally, it was converted into the source neutron spectrum by using the efficiency correction and the np scattering cross section taken from NN-online[13]. **Figure 3** shows the result along with the source neutron spectrum calculated using an empirical formula[14]. Both the spectra are normalized by the number of peak neutrons, and the calculated spectrum is smeared using a Gaussian function with the same experimental energy resolution. The measured neutron spectrum shows good agreement with the calculated one within the errors.

The measured double-differential production yields of protons, deuterons and tritons per incident neutron on the target were determined with using the following expression:

$$\left(\frac{d^2Y}{dEd\Omega}\right)_j = \frac{N_j(E,\theta) \times \dfrac{1}{f(E)}}{S_n \times \Delta E \times \Delta\Omega}, \qquad (2)$$

where $j$ denotes the kind of particles ($p$, $d$, and $t$), $N_j(E,\theta)$ is the net counts in a certain energy bin $\Delta E$, $f(E)$ is the effective efficiency which includes the energy loss effect in the CsI(Tl) scintillator, and $S_n$ is the total number of incident neutrons on the target. In **Eq. (2)**, the solid angle $\Delta\Omega$ was given under an assumption that the target is treated as a point source. It was confirmed that this assumption is valid by a comparison of PHITS simulation between a point source and a plane source, in which the difference is only 1 %.

**Figure 4** shows the measured (*n,xp*) spectra from 20° to 140° in steps of 40°. **Figures 5 and 6** shows the measured (*n,xd*) and (*n,xt*) spectra from 20° to 80° in steps of 20°. For protons and deuterons, the measured double-differential yields show a strong angular dependence at high emission energies above 20 MeV, whereas the angular distribution seen in the measured triton double-differential yields is less steep than those of protons and deuterons, particularly at small angles.

## IV. Benchmark using PHITS code

The measured double-differential yields are compared with the PHITS calculations using three nuclear reaction options, the evaluated nuclear data library (JENDL/HE2007[15]), the quantum molecular dynamics[16] (QMD), and the intra-nuclear cascade model[17] (INC). Note that INC is used for only proton, because INC cannot predict dynamical process of complex particle production. The source neutron spectrum calculated using the empirical formula is used as an input of the PHITS calculation. It

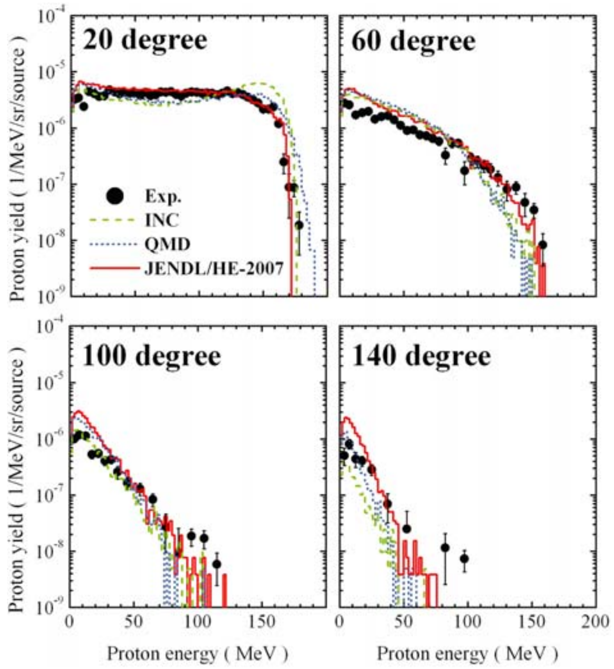


**Fig. 4** Comparison between measured (*n,xp*) spectra from 20° to 140° in step of 40° and calculation results of JENDL/HE2007, QMD and INC models

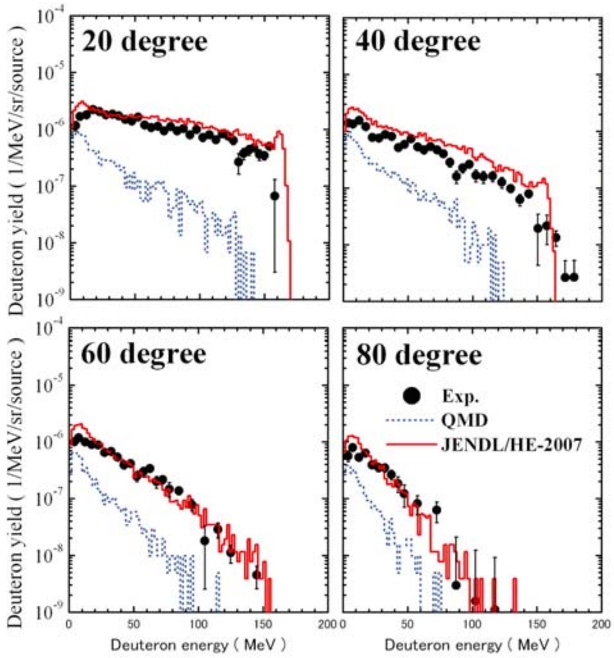


**Fig. 5** Comparison between measured (*n,xd*) spectra from 20° to 80° in steps of 20° and calculation results of JENDL/HE2007 and QMD model

should be noted that the energy loss of charged particles generated by nuclear reactions in the carbon target is taken into account in the PHITS calculation.

**Figure 4** shows an example of the results of proton production yields. There are some appreciable differences among three calculations at 20° and 140°. The calculation with JENDL/HE2007 shows excellent agreement with the measurement over the wide emission energy at 20°. The QMD calculation gives a reasonably good description of the spectra below 20 MeV and the calculation with INC underestimates the measured yields at 140°.

The results of deuteron production are shown at angles from 20° to 80° in **Fig. 5.** The calculation with JENDL/HE2007 shows reasonably good agreement with the measured deuteron data at small and large angles. However, the QMD calculation underestimates the measurement remarkably over the wide emission energy.

For triton production, **Fig. 6** shows the results at angles from 20° to 80°. The calculation with JENDL/HE2007 shows relatively better agreement with the experimental data than the QMD calculation, although it overestimates the measured yields at 20° and 40°. The QMD calculation shows the tendency similar to deuteron production and underestimates the experimental data remarkably over the whole angles.

Total production yields for protons, deuterons, and tritons for both measurements and calculations are obtained by integrating over the whole outgoing energy range and the angular range from 20° to 80°. Comparisons between them

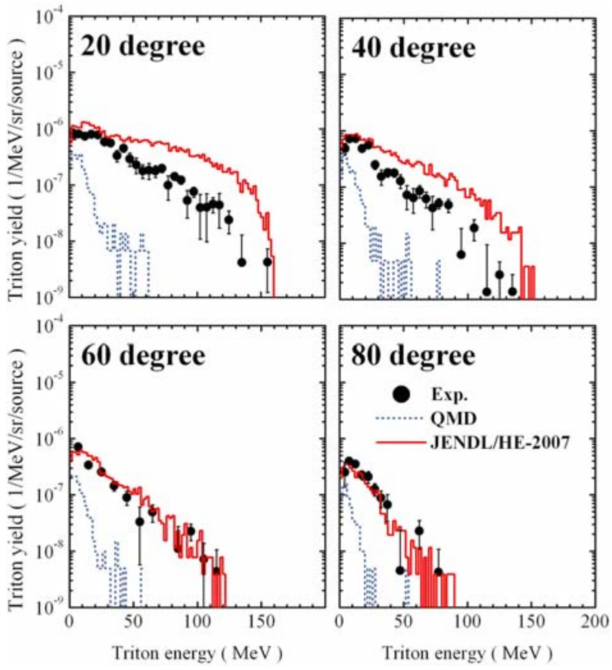


**Fig. 6** The same as in Fig.4, but for triton production

are showed in **Fig. 7**. The relative ratio of the measured production yields is given by approximately 10:3:1 for proton, deuteron, and triton, respectively. For proton, all the calculations are in reasonably good agreement with the experimental data, whereas the calculations with

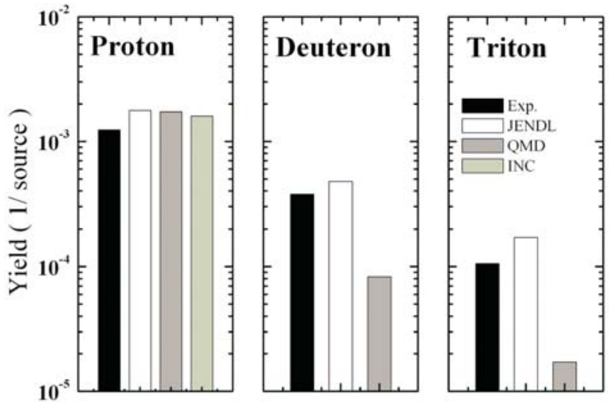


**Fig. 7** Comparison between measured total production yields and calculated ones with JENDL/HE2007, QMD and INC for proton, deuteron and triton.

JENDL/HE-2007 for deuteron and triton overestimate the experimental data and the QMD calculations underestimate them remarkably.

## V. Summary and conclusions

We have measured the double-differential production yields of protons, deuterons, and tritons from carbon bombarded by 175 MeV quasi-monoenergetic neutrons at the The Svedberg Laboratory (TSL). The measured yields were compared with the PHITS calculations to benchmark evaluated nuclear data and nuclear reaction models. As a result, the PHITS calculations with JENDL/HE-2007 reproduce the measured yields better than the QMD calculations particularly for deuterons and tritons. For protons, a large difference in the calculated spectra at 20° appears obviously among the nuclear reaction model options. The calculation with JENDL/HE2007 data is in the best agreement with the measurement over the wide emission energy at 20°. However, the PHITS calculations with JENDL/HE-2007 overestimate remarkably the measured triton yields at 20° and 40°. Further improvement in JENDL/HE-2007 will be necessary.

We plan to carry out a similar measurement and benchmark for silicon in the future.

## VI. Acknowledgements

The authors would like to thank the staff of the The Svedberg Laboratory for their assistance during the experiments. This work was supported by Grant-in-Aid for human resource development from Kyushu Industrial Technology Center and Sasakawa Scientific Research Grant from the Japan Science Society.

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