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Measurement of light-ion production at the new Uppsala neutron beam facility

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Abstract. A collaborative research project has been launched on neutron-induced light-ion production measurements using the new Uppsala neutron beam facility. The available energy range of quasi mono-energetic neutron beams is extended up to 175 MeV. Double-differential cross sections (DDXs) of light-ion production (p, d, t, ^{3}He, and α) are measured using 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. Response of the scintillators to 160 MeV protons is measured to test the performance. The measured response is reproduced well by a PHITS transport calculation. The DDXs of light-ion production are measured for Ca at 94 MeV and C at 175 MeV at angles between 20° to 160° in steps of 20°. The preliminary experimental (n,xp) data are shown in comparison with a model calculation using the TALYS code and the evaluated cross sections in the JENDL high-energy file.

1 Introduction

Recently, there have been increasing nuclear data needs for neutron-induced light-ion production at intermediate energies, especially 20 to 200 MeV, for a wide variety of applications, such as radiation treatment of cancer therapy, neutron dosimetry at high altitude and space, single event effects in microelectronics, and accelerator-driven transmutation of nuclear waste. To satisfy these needs, a series of experiments have successfully been performed for several targets (C, O, Si, Fe, Pb, and U) at 96 MeV using the quasi mono-energetic neutron facility at the The Svedberg Laboratory (TSL) [1–3]. Similar light-ion production measurements have been carried in the incident energy range below 100 MeV at other facilities as well [4,5]. However, there has been no systematic measurement at energies between 100 and 200 MeV until now.

The Uppsala neutron beam facility has recently been upgraded [6], so that quasi mono-energetic neutron beams are available with higher intensity than the previous one for energies up to 175 MeV. Using the new facility, systematic measurements have been planned of double-differential cross sections (DDXs) for light-ion production induced by 175 MeV neutrons. The MEDLEY spectrometer setup used in the previous experiments at 96 MeV [1,3] is partly modified by installing such a thick CsI scintillator as the E-detector that light ions generated from reactions by 175 MeV neutrons are fully stopped in the scintillator. In the present work, some preliminary measurements are performed as the feasibility demonstration. One of them is to measure the response of CsI scintillators to 160 MeV protons as the performance evaluation test, i.e., estimation of the reaction tail. The DDXs of (n,xp) reactions on Ca at 94 MeV (hereafter, measurement-I) and on C at 175 MeV (measurement-II) are measured using the MEDLEY setup. The experimental DDXs for Ca are compared with a model calculation using the TALYS code [7]. Also, a preliminary result is presented for comparison between the measured C(n,xp) spectrum at 20° and the evaluated cross sections in the JENDL high-energy file [8].

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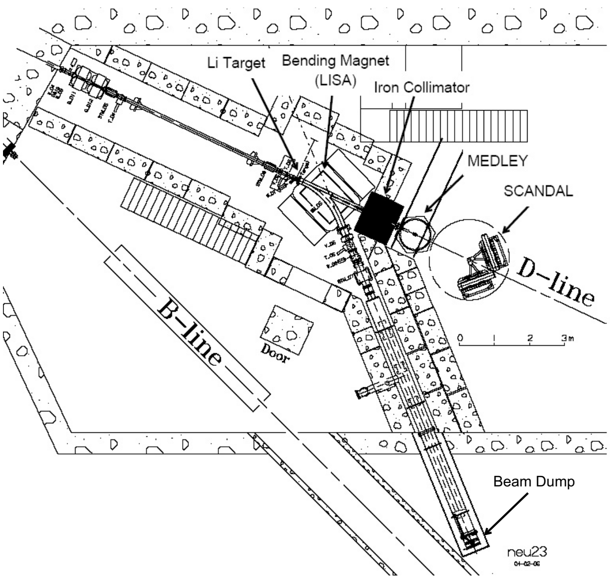

Fig. 1. New neutron beam facility at TSL and experimental setup.

2 Experimental methods

Figure 1 shows the new Uppsala neutron beam facility [6] at the TSL and the experimental setup of MEDLEY experiments [9]. Protons from the cyclotron impinge on an enriched ^{7}Li target, and neutrons are produced by the ^{7}Li(p,n)^{7}Be reaction. In measurement-I, the 98.5 MeV protons produces neutrons with a peak energy of 94 MeV using a lithium target 8 mm thick, while the 180 MeV protons produces neutrons with a peak energy of 175 MeV using a 23.5 mm thick target in measurement-II. The neutrons are transported to the MEDLEY chamber passing through a 100-cm long and conical iron collimator whose diameter is 54 mm at the end of collimator. The neutron flux was about 3.1×10^5 n/(cm^{2}s) with a proton beam intensity of 3.4 μA in measurement-I, while it was about 4.3×10^4 n/(cm^2 s) with a proton beam intensity of 0.3 μA in measurement-II. The proton beam passing through the Li target is deflected by a bending magnet into the beam dump and integrated in a Faraday cap in order to monitor the beam current. In addition, a pre-collimator made out of lead blocks was installed temporarily inside the bending magnet to reduce a background component and improve the signal to background ratio. The distance from the Li target to the center of MEDLEY chamber was 3.74 m. The relative neutron beam intensity is monitored by the integrated proton beam current at the beam dump and by both a thin film breakdown counter and an ionization chamber mounted downstream of the MEDLEY setup.

The MEDLEY setup and construction details of each telescope are illustrated in figure 2. MEDLEY consists of eight three-element telescopes mounted inside a vacuum chamber with a diameter of 90 cm. Each telescope consists of two fully depleted silicon surface barrier detectors serving as ΔE detector and a CsI(Tl) scintillator serving as E detector. The thickness of the ΔE detectors is in the range of 50–60 μm for the first one, and 400–500 μm for the second one. The CsI(Tl) scintillators were upgraded from the previous ones [1–3], and have a total length of 100 mm which is enough to stop high-energy protons produced in the 175 MeV measurement. They have a cylindrical shape with 50 mm diameter, where the last 30 mm are tapered to 18 mm diameter to match the size of a Hamamatsu S3204-08 photodiode for the light readout. The signals from each telescope are processed using the same data acquisition system as in the previous 96-MeV measurements [1–3].

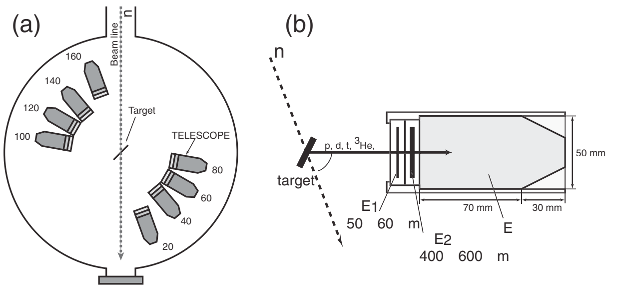

Fig. 2. MEDLEY setup: (a) arrangement of eight telescopes inside the MEDLEY chamber, and (b) construction details of each telescope.

Calcium and carbon targets are placed at the center of the MEDLEY chamber. The carbon target was 22 mm in diameter and 1.0 mm thick, and the calcium target was 29 mm in diameter and 230 μm thick. For absolute cross section normalization, a polyethylene (CH_2) target with 25 mm diameter and 1.0 mm thickness was used. Instrumental backgrounds are also measured by removing the target from the neutron beam.

Since the ^{7}Li(p,n) reaction produces peak neutrons and low-energy tail neutrons, time-of-flight (TOF) measurements are used to reject the tail neutrons. The TOF data are measured as a time difference between master trigger signal and RF timing signal from the cyclotron.

3 Data reduction procedure

The data reduction procedure based on the ΔE-E technique is the same as in the previous 96-MeV measurement and explained in detail in refs. [1, 3, 16]. Here the procedure for the measurement-II is briefly described.

Energy calibration of all detectors is obtained using the data themselves. Events in the ΔE-E bands are fitted with respect to the energy deposited in the two ΔE silicon detectors, which is determined from the thicknesses and the energy losses calculated with the SRIM code [10]. One example is shown in figure 3(a) for the present 175-MeV measurement.

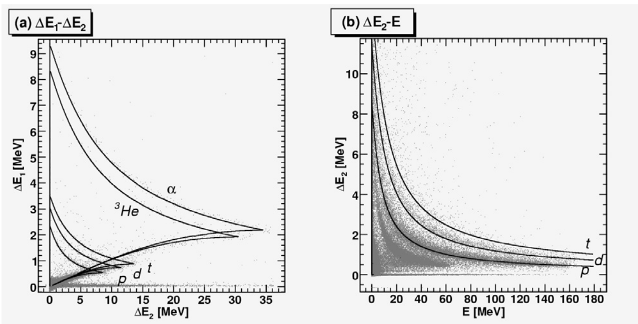

Fig. 3. Calibrated ΔE_1-ΔE_2 plot for telescope 1 at 20 degree in the left panel (a). The solid lines correspond to calculation results of energy-loss values for proton, deuteron, triton, ^{3}He and α particles. Calibrated ΔE_2-E plot for telescope 1 at 20 degree in the right panel (b). The solid line corresponds to calculated energy-loss values for protons.

For the energy calibration of the CsI(Tl) scintillator, the following approximate expression is applied to hydrogen isotopes [9]:

$$E = a + bL + c\,(bL)^2\,, \tag{1}$$

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. For the small CsI(Tl) scintillators, the c parameter was found by Tippawan [12] to be 0.0032 for protons. For the new CsI(Tl) scintillators, the derived c parameter was found to be ~0.001 for protons. Figure 3(b) shows a result of the energy calibration for ΔE_2 and E detectors for the 175-MeV measurement.

The measured TOF data are used for selection of light-ion events induced by neutrons in the main peak of the source neutron spectrum.

Some corrections are necessary to obtain final DDX data. Background events measured in target-out runs are subtracted from the target-in runs after normalization to the same neutron fluence. Corrections due to the finite target thickness are made in the method described in ref. [1]. However, it should be noted that this correction has not yet been applied in the present analysis of the 175-MeV measurement. The finite efficiency of the CsI(Tl) scintillator is corrected using the Monte Carlo simulation method discussed below.

The number of the net counts due to np scattering is obtained using measurements of the (n,p) spectrum at 20° for both the targets, CH_2 and C. The result is shown in figure 4. Finally, the absolute values of the measured cross sections are determined using the reference np cross sections in the same method as in refs. [1,3]. The np scattering cross sections are taken from NN-online [13].

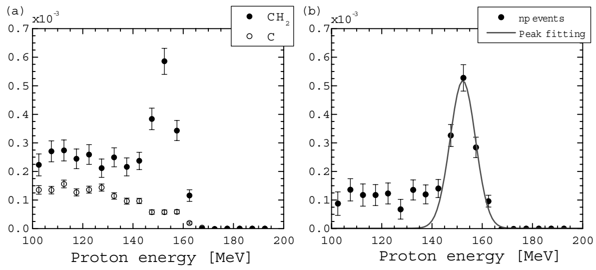

Fig. 4. Measured np scattering peak: (a) the contribution from C in the CH_2 data and (b) the net np peak with a Gaussian fitting.

4 Results and discussion

4.1 Response of CsI(Tl) scintillator to protons

The performance of the newly-installed CsI(Tl) scintillators was investigated using a 160-MeV proton beam with very low intensity, i.e., about 100 protons per second, prior to the 175 MeV neutron measurement. The proton beam was formed by installing a collimator system into the B-line shown in figure 1, which consists of a combination of a tantalum scatterer with a thickness of 4 mm and a graphite collimator with a diameter of 4 mm. The counter telescope depicted in figure 2(b) was placed near the exit of the B-line to measure the response of the Cs(Tl) scintillator to 160-MeV protons.

In figure 5(a), the measured proton spectrum normalized to the observed peak corresponding to 160 MeV is presented together with a Monte Carlo simulation using the PHITS code [14]. Note that the energy resolution of the oberved peak was 1.7 MeV in FWHM, although it is not shown in the figure. Due to nuclear interactions a certain fraction of incident protons does not fully deposit their energies into the CsI(Tl) scintillator. This leads to the so-called reaction tail which is seen in the low-energy region. The PHITS simulation reproduces the measurement well. The fraction of the reaction tail for simulated and experimental data is plotted as a function of proton energy in figure 5(b). The PHITS simulation is in excellent agreement with both the previous work [15] given by the solid line and the present measurement denoted by the full circle with the error. The efficiency of the CsI(Tl) is finally corrected using the PHITS calculation in the data analysis of the C(n,xp) reaction at 175 MeV.

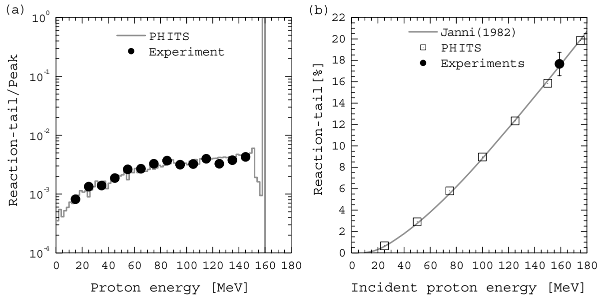

Fig. 5. Measured response of CsI(Tl) scintillator to 160 MeV protons: (a) the ratio of reaction tail to peak with the PHITS calculation, and (b) the fraction of the reaction tail as a function of incident proton energy. The explanation of the symbols and lines is given in the text.

4.2 Ca(n,xp) at 94 MeV

In figure 6, experimental double-differential cross sections of the 94 MeV (n,xp) reaction on Ca are presented for four angles and compared with a model calculation using the TALYS-0.64 code [7]. The detail of the data analysis and the model calculation is reported elsewhere [16]. The TALYS calculation overestimates the low energy region where the evaporation process is dominant, while underestimating the intermediate continuum region at forward angles where the preequilibrium emission is expected to have a large contribution.

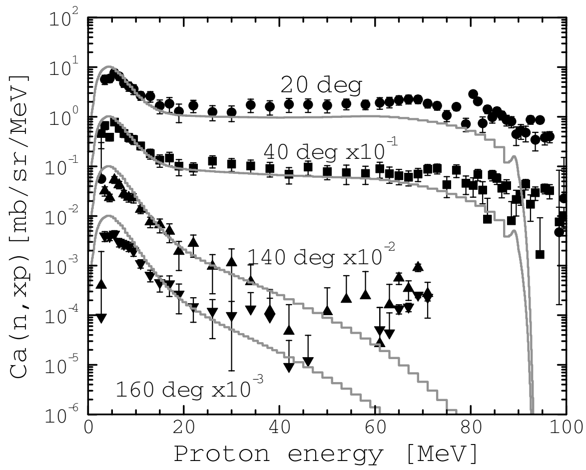

Fig. 6. Comparison of experimental double-differential cross sections for the Ca(n,xp) reaction at 94 MeV (filled symbols with error bar) with the TALYS-0.64 calculation (solid histograms).

4.3 C(n,xp) at 175 MeV

The incident neutron spectrum accepted by the TOF gate was estimated from data analysis of the recoil protons from np scattering in the measurement of the CH_2 target. Figure 7 shows the result together with the source neutron spectrum calculated using an empirical formula [17]. Both the spectra are normalized so that each peak corresponding to 175 MeV is unity. The calculated spectrum is folded using a Gaussian function with the same width as the experimental energy resolution. The measured neutron spectrum is in good agreement with the calculated one. The hatched region above 95 MeV corresponds to the accepted neutron spectrum in the present measurement.

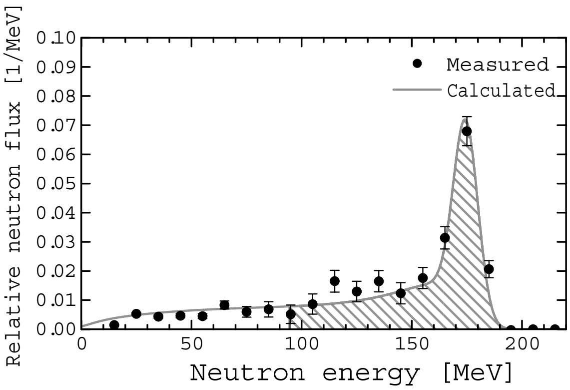

Fig. 7. Comparison between the measured neutron spectrum and calculated one. The hatched region corresponds to the accepted neutron spectrum.

The C(n,xp) spectrum measured at 20° is shown in figure 8. The measured spectrum is compared with a folding spectrum $\sigma^{cal}\left(E_p,\theta_p\right)$ obtained by the following equation:

$$\sigma^{cal}\left(E_p,\theta_p\right)=\int_{95MeV}^{175MeV}\sigma^{eval}\left(E_n,E_p,\theta_p\right)f\left(E_n\right)dE_n, \quad (2)$$

where $f(E_n)$ is the accepted source neutron spectrum shown in figure 7 and the calculated one [17] is used. The JENDL/HE evaluated cross sections [8] are used as $\sigma^{eval}(E_n,E_p,\theta_p)$ in equation (2). As can be seen in figure 8, the calculated (n,xp) spectrum shows good agreement with the measured one in the intermediate proton energy range.

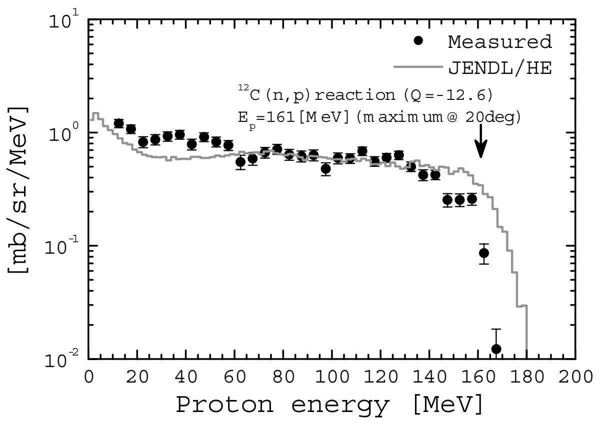

Fig. 8. Comparison of the experimental C(n,xp) spectrum at 20 ° with the folding spectrum calculated from the JENDL/HE evaluated cross sections and the accepcted neutron spectrum.

5 Summary

We have measured the double-differential cross sections of (n,xp) reactions on Ca at 94 MeV and on C at 175 MeV using the new Uppsala neutron beam facility for the first time. The measured Ca data were in reasonable agreement with the TALYS calculation, although the calculation overestimated the evaporation region at all angles and underestimated the preequilibrium region at 20°. Since the background contribution from source neutrons having continuous energies between 95 MeV and 175 MeV could not be subtracted from the measured proton spectra for C, the present measurement was compared with the proton spectrum obtained by folding the JENDL high-energy data and the expected source neutron spectrum. The proton spectrum measured at 20° showed overall good agreement with the JENDL high-energy data. Further analysis including other angles will be required for detailed comparison. In addition, it was confirmed that the measured response of the new CsI(Tl) scintillators to 160 MeV proton was reproduced well by the PHITS transport calculation.

A series of light-ion production measurements is planned for other targets, O, Si, Fe, Pb, and U, at 175 MeV in order to meet nuclear data needs for fast neutron applications.

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