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Neutron induced light-ion production from Iron and Bismuth at 175 MeV

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Abstract. We have measured light-ion (p, d, t, ^{3}He and α) production in the interaction of 175 MeV neutrons with iron and bismuth, using the MEDLEY setup. A large set of measurements at 96 MeV has been recently completed and published, and now higher energy region is under investigation. MEDLEY is a conventional spectrometer system that allows low-energy thresholds and offers measurements over a wide angular range. The system consists of eight telescopes, each of them composed of two silicon surface barrier detectors, to perform particle identification, and a CsI(Tl) scintillator to fully measure the kinetic energy of the produced light-ions. The telescopes are placed at angles from 20° to 160°, in steps of 20°. Measurements have been performed at The Svedberg Laboratory, Uppsala (Sweden), where a quasi mono-energetic neutron beam is available and well characterized. Time of flight techniques are used to select light-ion events induced by neutrons in the main peak of the source neutron spectrum. We report preliminary double differential cross sections for production of protons, deuterons and tritons in comparison with model calculations using TALYS-1.0 code.

1 Introduction

Transmutation techniques in Accelerator-Driven Systems (ADS) involve high-energy neutrons, created in the proton-induced spallation of a heavy target nucleus. The existing nuclear data libraries developed for reactors of today go up to about 20 MeV, which covers all available energies for that application; but with a spallator coupled to a core, neutrons with energies up to 1-2 GeV will be present. Although a large majority of the neutrons will be below 20 MeV, the relatively small fraction at higher energies still has to be characterized. Above 200 MeV direct reactions models work reasonably well [1] [2], while at lower energies nuclear distortion plays a non-trivial role. This makes the 20-200 MeV region most important for new experimental cross section data.

At the The Svedberg Laboratory (TSL) in Uppsala, - Sweden, quasi-monoenergetic neutrons up to 175 MeV are available.The MEDLEY experimental setup is semi-permanently installed at the neutron beam line at TSL and it is designed for measurements of neutron-induced light-ion production cross sections. Previous experiments has been conducted with the MEDLEY spectrometer setup at 96 MeV measuring neutron induced light-ion production cross sections from Fe, Pb, U [4], Si [5], O [6], C [7] and at 175 MeV from C [8], where thicker CsI scintillators have been installed to fully stop the light ions generated in the 175 MeV neutron induced reactions. In the present work the neutron beam line has been updated with the installation of an extra iron shielding in order to reduce the background neutrons. In addition, ΔE detectors 500 μm thick were replaced by those 1000 μm thick to improve particle identification in the high emission energy range. Measurements have been performed in February 2009 at TSL and include production of protons, deuterons, tritons, ^{3}He and α particles at emitting angles between 20° to 160°, in steps of 20°, from the interaction of 175 MeV neutrons with iron and bismuth. In this paper we present preliminary experimental double differential cross section for proton, deuteron and triton production and we compare them with a model calculation using TALYS-1.0 [9].

2 Experimental methods

At the TSL neutron beam facility, a cyclotron is producing a monoenergetic proton beam that impinge on an enriched ^{7}Li target, where neutrons are produced by the ^{7}Li(p,n)^{7}Be reaction [3]. In the present experiment the proton energy was 179.3 (±0.8) MeV and the used ^{7}Li target was 23.5 mm thick, thus producing a quasi-monoenergetic neutron

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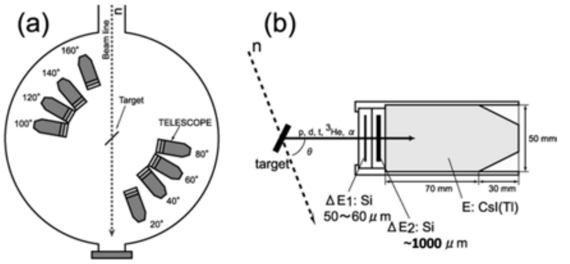

Fig. 1. MEDLEY setup: (a) the MEDLEY chamber and the arrangement of the eight telescopes and of the target, and (b) construction details of each telescope.

beam with average energy of the high-energy peak of 175.0 (±2.5) MeV The proton beam intensity varied between 150 nA to 400 nA, due to operational needs of the cyclotron. The neutrons are transported inside the MEDLEY chamber passing through a cylindrical iron collimator and then through a conical iron collimator. The iron collimator is passing through two iron shielding walls, respectively 100 cm and 50 cm thick. The second iron wall has been installed in October 2007 to further reduce neutron background. The present neutron flight path, from the production ^{7}Li target to the centre of the MEDLEY chamber, is 4618 mm. The quasi-monoenergetic neutron beam at the MEDLEY target position has a diameter of 42.08 mm. A bending magnet situated downstream the ^{7}Li target deflects the proton beam into a beam dump where it is integrated in a Faraday cup in order to monitor the beam current. The relative neutron beam intensity is also monitored by both a thin film breakdown counter (TFBC) [10] and an ionization chamber (ICM) downstream of the MEDLEY setup. In addition the bending magnet works as clearing magnet for other charged particles created in the interaction with the ^{7}Li, and with the beam pipes windows.

MEDLEY consists of eight three-element telescopes mounted inside a vacuum chamber with a diameter of 90 cm. The MEDLEY setup and construction details of each telescope are illustrated in figure 1. The eight telescopes are mounted on rails along radii of the chamber in steps of 20°. The chamber can be rotated by 360°. In the standard configuration, the eight telescopes are at positions 20° to 160° degrees, in steps of 20°, respect to the neutron beam line. 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 first silicon detector of each telescope (Si1) is 50 μm to 60 μm thick, while the second silicon detector (Si2) is 1000 μm thick. The CsI(Tl) scintillators have a total length of 100 mm which is enough to fully stop high-energy protons produced in the 175 MeV reactions. 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 read out. The signals from each telescope are processed using the same data acquisition system as in the previous measurements [5] [6] [7] [8].

At the centre of the MEDLEY chamber are placed the iron and bismuth targets, along with a polyethylene (CH_2) target. The targets are mounted on frames and they can be switched without need to open the chamber and break the vacuum. The iron and bismuth targets have square shape, each of them with side of 25mm. The iron target has mass of 1959.6(±0.1) mg and it is 375 μm thick. The bismuth target has mass of 3130.1(±0.2) mg and it is 0.5 mm thick. The CH_2 target is 25 mm in diameter, 1.0 mm thick, its mass is 461.55(±0.01) mg and it is used for absolute cross section normalization. A fourth configuration without any target on the neutron beam line is used to measure the instrumental background. Since the ^{7}Li(p,n)^{7}Be reaction produces peak neutrons and low-energy tail neutrons, time-of-flight (TOF) measurements are used to select peak neutrons and reject 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 basically the same as in the previous measurements of light-ions production performed with the MEDLEY setup at TSL, and it is explained in detail in [7]. Here we give a brief description of the procedure. The energy calibration of the ΔE silicon detectors and of the E CsI scintillator of each telescope is obtained using the data themselves. Events in the ΔE-E bands are fitted with respect to the energy deposition in the Si1 and in the Si2, which is determined from the thickness of each detector and the respective energy losses. Calculation with the SRIM code (version 2008.04) [11] provided the energy losses of protons, deuterons, tritons, ^{3}He and α particles in each silicon detector. Since linear response is expected in silicon detectors in the present range of energies, punch through energy of each particle in Si1 and in Si2 is linearly fitted with the corresponding detector's channel. In the energy calibration of E detectors we should consider that CsI(Tl) scintillators show a non-linear relationship between light output and energy deposition [12], thus the following approximate expression is applied:

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

where L is the light output, and a, b and c are the fitting parameter. The parameter c depends on the mass of the detected particle [12]. Figure 2 shows a result of the energy calibration for ΔE1 and ΔE2 and for ΔE2 and E detectors at 175 MeV. The solid lines present the calculated energy loss curves for individual light ions, which reproduces well experimental ΔE1-ΔE2 and ΔE2-E bands.

TOF of each charged particle from the MEDLEY target to the detector is calculated according to the energy calibration and it is subtracted from the total TOF. The resulting neutron TOF is used for the selection of light-ion events induced by neutrons in the main peak of the incident neutron spectrum, as described in details [7]. In the present preliminary analysis, the incident neutron spectrum accepted by the TOF cut includes tail neutrons with energies down to 80 MeV. The neutron spectrum includes

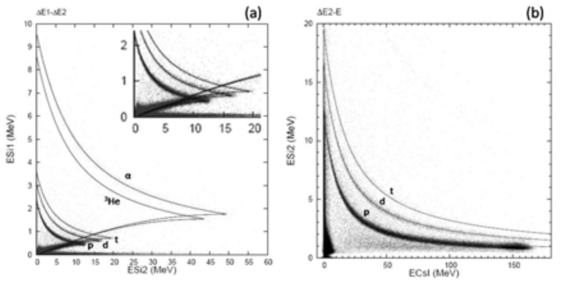

Fig. 2. Calibrated ΔE1-ΔE2 plot for telescope 1 at 20° in the left panel (a). The solid lines correspond to calculation results of energy-loss values for protons, deuterons, tritons, ^{3}He and α particles. The insert in (a) shows detail of hydrogen isotopes calibration. Calibrated ΔE2-E plot for telescope 1 at 20° in the right panel (b). The solid lines correspond to calculation results of energy-loss values for protons, deuterons and tritons.

also a fraction of low energy neutrons, with peaks around 5 MeV and 15 MeV due to wrap around effect. To obtain final double differential cross sections data it is necessary to perform some corrections. Background events measured removing the target inside the MEDLEY chamber are subtracted after normalization to the same neutron fluence. Efficiency correction due to the reaction losses in the CsI(Tl) scintillator has been implemented. The method uses reaction cross sections calculated using optical potentials and it is described in [13]. The number of counts due to (n,p) elastic scattering is obtained measuring the proton spectrum at 20° for the CH_2 target. The absolute values of the measured cross sections are determined using the reference (n,p) cross sections with the same method described in [7]. The (n,p) scattering cross sections are taken from NN-online [14].

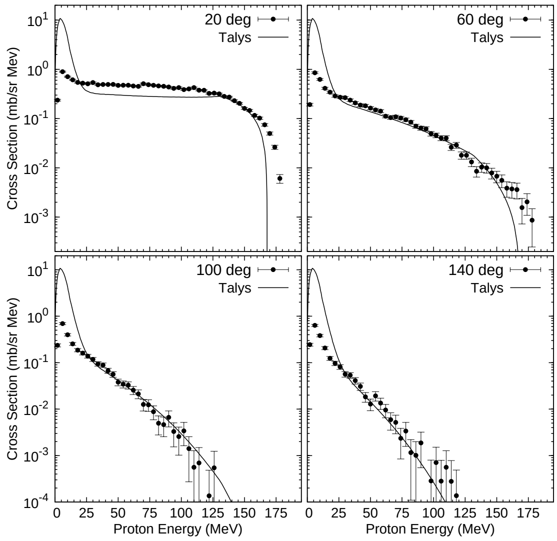

Fig. 3. Comparison between preliminary experimental double-differential cross sections for the Fe(n,xp) reaction at 175 MeV for 20°, 60°, 100°, 140° (filled symbols with error bars) and calculation results of TALYS-1.0 (solid lines). Thick target correction is not yet implemented in this preliminary results, which will lead to an increase of the experimental cross sections in the low energy region.

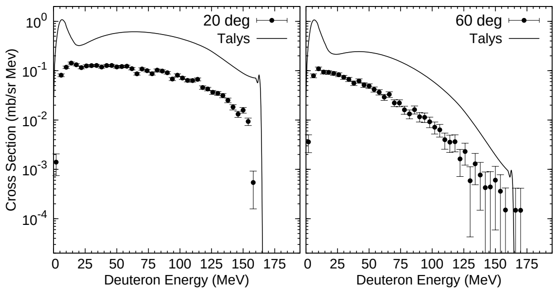

Fig. 4. Same as Fig.3, but for the Fe(n,xd) reaction at 20°, 60°.

4 Preliminary experimental results

The thickness of the iron and of the bismuth targets used in the present experiment causes a non-negligible energy loss and even absorption of the produced light-ions. This leads to a distortion of the measured spectra which has to be corrected for. However in the present preliminary analysis we did not perform yet any correction for the thick-target effect. Therefore we want to emphasize that the reported results underestimate the values of the cross sections in the low energy region.

4.1 Fe(n,xp), Fe(n,xd) and Fe(n,xt) at 175 MeV

In figure 3 we present preliminary experimental double-differential cross sections of the 175 MeV (n,xp) reaction on Fe for four angles and we compare them with a model calculation using the TALYS-1.0 code. The TALYS calculation overestimates the continuum region at 20°, while is in excellent agreement with the experimental results at 60°. At backward angles, the TALYS calculation is also in excellent agreement with the measured cross section over the wide emission energy. The absence of thick-target correction does not allow to compare the low energy region where the compound emission is expected to have larger contribution. In figure 4 we show the preliminary results for deuteron production from iron at 20°, 60°. We observe that the TALYS calculations well describe the behave of the measured cross sections even though overestimate their absolute value. The triton production cross sections from iron at 20°, 40° are presented in figure 5. Also in this case we observe that there is an overestimation of the cross sections by TALYS.

4.2 Bi(n,xp), Bi(n,xd) and Bi(n,xt) at 175 meV

In figure 6 we observe proton production for Bi target: at 20° it is decreasing with energy in the continuum region, leading to an overestimation of the direct reaction contribution by TALYS. At 60° and at backward angles TALYS slightly overestimates the experimental cross sections. The deuteron production from Bi is presented in figure 7. Here

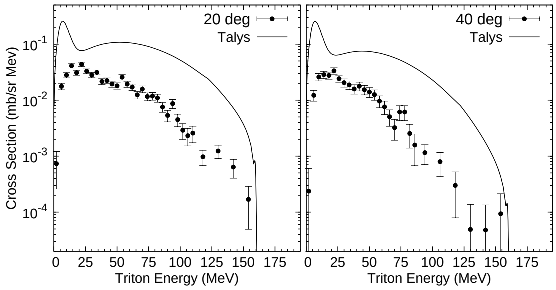

Fig. 5. Same as Fig.3, but for the Fe(n,xt) reaction at 20°, 40°.

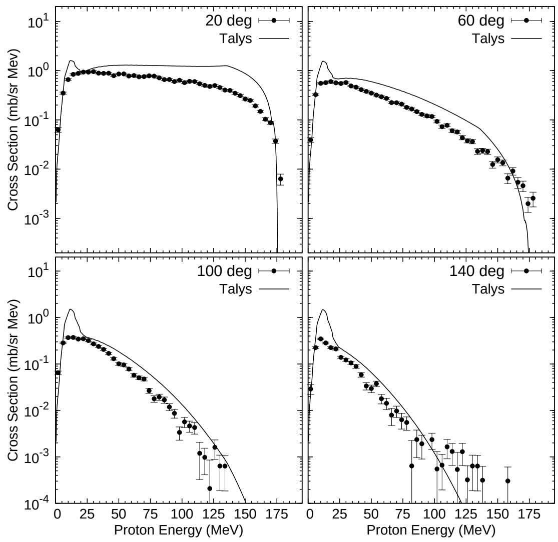

Fig. 6. Same as Fig.3, but for the Bi(n,xp) reaction.

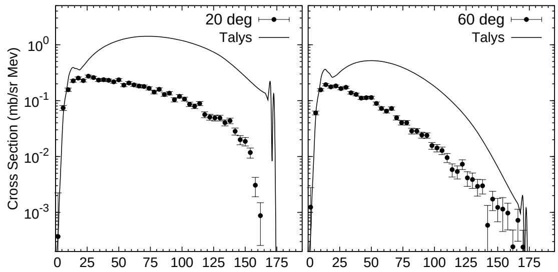

Fig. 7. Same as Fig.3, but for the Bi(n,xd) reaction at 20°, 60°.

the TALYS calculations describe a concave behave in the preequilibrium region of the cross sections that has no correspondence in the experimental results. There is an overall overestimation of the cross sections, that can be observed also in the (n,xt) cross sections reported in figure 8.

5 Conclusion

We have measured light-ions (p, d, t, ^{3}He and α) production in the interaction of 175 MeV neutrons with iron and bismuth at TSL. We presented first preliminary cross sections for protons, deuterons and tritons and we compared them with model calculations by TALYS-1.0 code. These show a better agreement with experimental results for proton production, while we observe a general overestimation

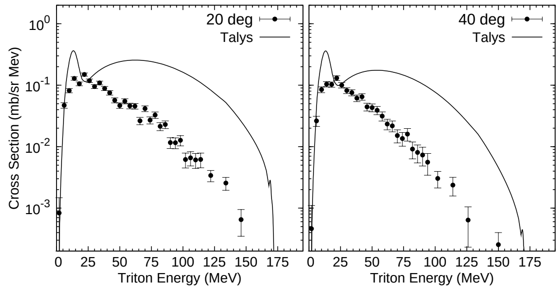

Fig. 8. Same as Fig.3, but for the Bi(n,xt) reaction at 20°, 40°.

for (n,xd) and (n,xt) reactions. However the reported preliminary cross sections are derived from half of the available data set, which is currently under analysis. There is also need to implement thick-target corrections, and to perform better TOF cut.

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