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Studies of neutron-induced light-ion production with the MEDLEY facility

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Abstract. The growing interest in applications involving high-energy neutrons (E > 20 MeV) demands high-quality experimental data on neutron-induced reactions. Such data have been measured with the MEDLEY setup at the The Svedberg Laboratory (TSL), Uppsala, Sweden. It has been used to measure differential cross sections for elastic nd scattering and double-differential cross sections for light-ion production ($A \leq 4$) with targets ranging from C to U and at incident neutron energies around 96 MeV. We summarize the experimental results obtained so far and compared with theoretical reaction model calculations. A new method for correcting charged-particle spectra for thick target effects has been used for data obtained with the MEDLEY facility. The new quasi-monoenergetic neutron beam facility of TSL offers the possibility to extend these measurements up to neutron energies of 175 MeV. In January 2007, the neutron beam facility at TSL has been equipped with improved shielding and pre-collimator to reduce the background observed with MEDLEY during the first experimental campaigns at 175 MeV to an acceptable level. We present the current status of the MEDLEY facility after the shielding upgrade. We summarize also our ongoing projects including both measurements of light-ion production at 175 MeV from C to U targets and fission studies of U-238 in the energy region of 11 to 175 MeV.

1 Introduction

Over the past years development has been made in a wide variety of different applications involving interactions of fast neutrons (20–200 MeV) with nuclei. Examples are dosimetry at commercial aircraft altitudes and in space [1,2] and radiation treatment of cancer within the field of medicine [3], soft-error effects in computer memory within electronics [4], and energy production and transmutation of nuclear waste [5] within energy applications. For all these applications, an improved understanding of neutron interactions is needed for calculations of neutron transport and radiation effects. It should be emphasized that for these applications, it is beyond reasonable efforts to provide complete data sets. Instead, the nuclear data needed for a better understanding must come to a very large extent from nuclear scattering and reaction model calculations, which all depend heavily on nuclear models, which in turn are benchmarked by experimental nuclear reaction cross section data.

The MEDLEY facility [6], located at the The Svedberg Laboratory (TSL) in Uppsala, Sweden, has over the past years performed measurements of double-differential cross sections for the production of light ions by 96 MeV neutrons [6–9]. Recently, we have started a program on measuring angular distributions of fission fragments [10]. The facility has also proven to be a valuable tool in the search for three-body force effects [11]. All these measurements have been performed at the "old" neutron beam at TSL [12]. At this beam, the neutron fluence above 100 MeV, where the cyclotron has to operate in FM mode, becomes too low to collect good statistics within reasonable time and it was therefore decided to construct a new neutron beamline with shorter distance from the neutron production point to the experimental area, thus delivering higher neutron fluxes. This new beamline is in operation since 2004 [13] and opens up the possibility to extend the experimental program and measure neutron-induced reactions at energies up to 175 MeV.

2 Light-ion production studies with MEDLEY

2.1 Experiments and typical results

During the last few years, we have performed a "complete" set of experiments in order to measure double-differential cross sections of the (n,px), (n,dx), (n,tx), (n,^{3}Hex), and (n,αx) reactions from light to heavy nuclide such as carbon, oxygen, silicon, calcium, iron, silver, holmium, lead and uranium around incident neutron energies of 96 MeV. As an illustration, some results for carbon, oxygen, silicon, iron, lead and uranium are presented in figures 1–3. More details can be found in the refs. [6–9]. Note that carbon data are preliminary and calcium, silver and holmium data are under analysis.

Examples of the double differential (n,px) spectra for carbon, oxygen, silicon, iron, lead and uranium are shown at some angles (20°, 60° and 100°) in figures 1–3. The main difference among the data is found at low energy (below

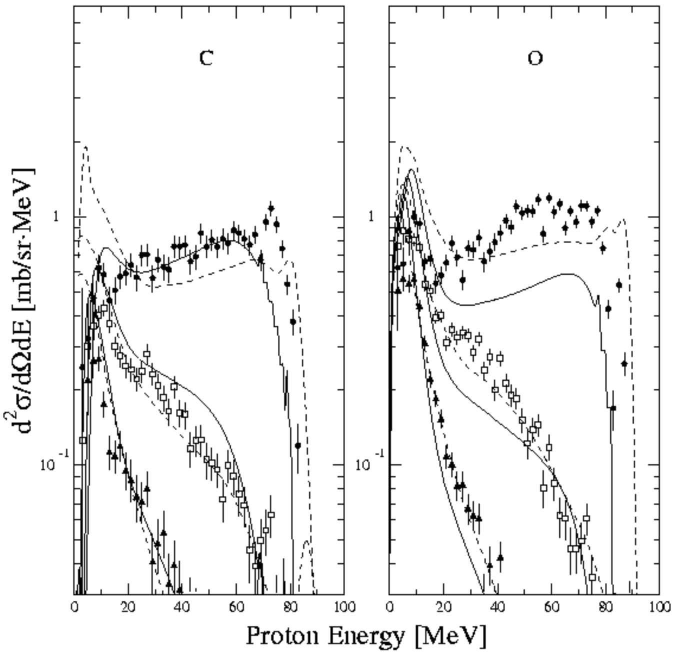

Fig. 1. Experimental double-differential cross sections of the C(n,px) and O(n,px) reactions (left and right, respectively) at 96 MeV at 20°(filled circles), 60° (open squares), and 100° (filled triangles). Solid and dashed curves represent calculations with the TALYS and GNASH codes, respectively.

20 MeV) where a compound component is dominant for medium-weight nuclides, i.e., silicon and iron. These low-energy particles are emitted mainly following the evaporation process of excited nuclei; for carbon and oxygen, the process is less prominent because of low level density while for lead and uranium, this emission is strongly inhibited by the Coulomb barrier. The emission of high-energy protons is strongly forward-peaked and hardly visible in the backward hemisphere. It is a sign of the preequilibrium process. The general trend of the preequilibrium emission becomes dominant with increasing mass number.

2.2 Comparison with theoretical predictions

In figures 1–3, the experimental results are presented together with model calculations. The solid lines show calculations with the TALYS code [14] whereas the dashed lines were obtained by the GNASH code [15]. Overall, both predictions give a fair description of the shape of the spectra for all nuclides. At the forward angles (20°), the GNASH predictions give a better description in the mid-energy region for the light to medium-weight nuclide. Note that there is no calculation by GNASH for uranium. The TALYS results account better for the absolute magnitude of the experimental cross sections at large angles for all nuclide while the GNASH calculations overestimate the high-energy parts of the spectra for the medium-weight and heavy nuclides.

For a detailed comparison with theoretical models, angular distributions are needed. In figures 4–5, experimental angular

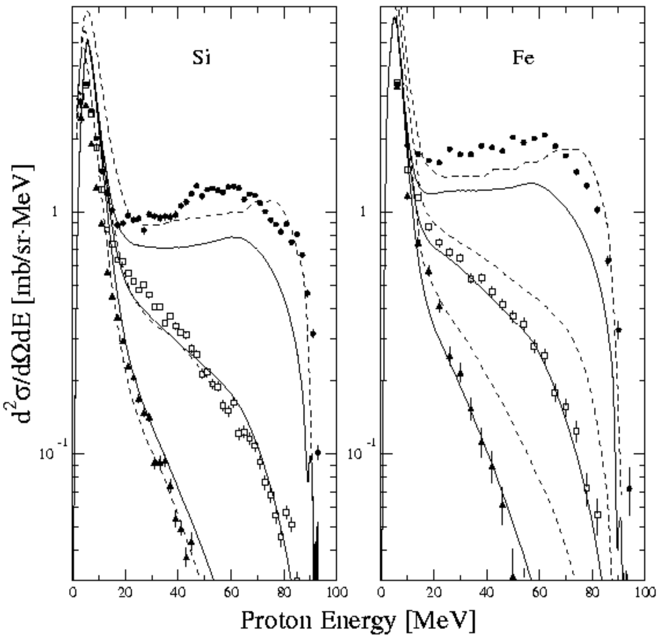

Fig. 2. Same as figure 1, but for Si(n,px) and Fe(n,px).

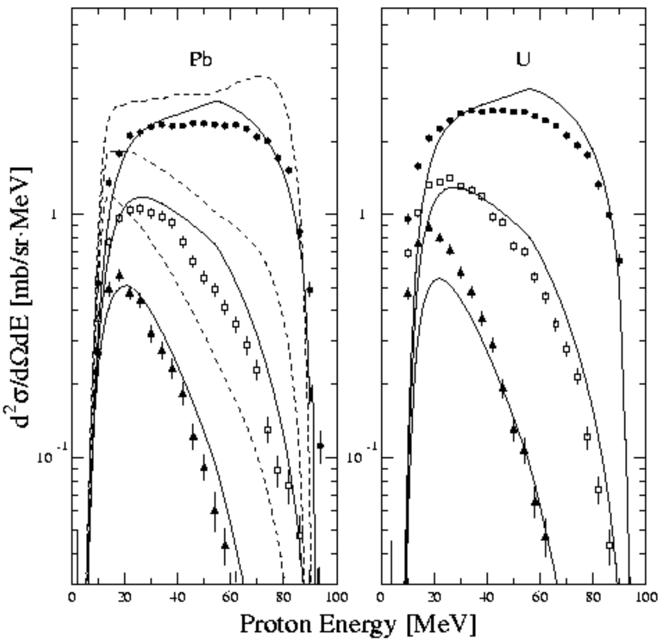

Fig. 3. Same as figure 1, but for Pb(n,px) and U(n,px).

distributions at low, medium, and high proton energies for carbon and oxygen, respectively, are shown together with angular distributions calculated on the basis of the TALYS and GNASH models (see ref. [9] for iron, lead and uranium cases). In general, both models give a good description of the data. In the ref. [8], we have compared the experimental data with a preliminary of TALYS code. They show large discrepancies, especially at low energy regions. Using TALY code, version 0.64, we get a reasonable agreement.

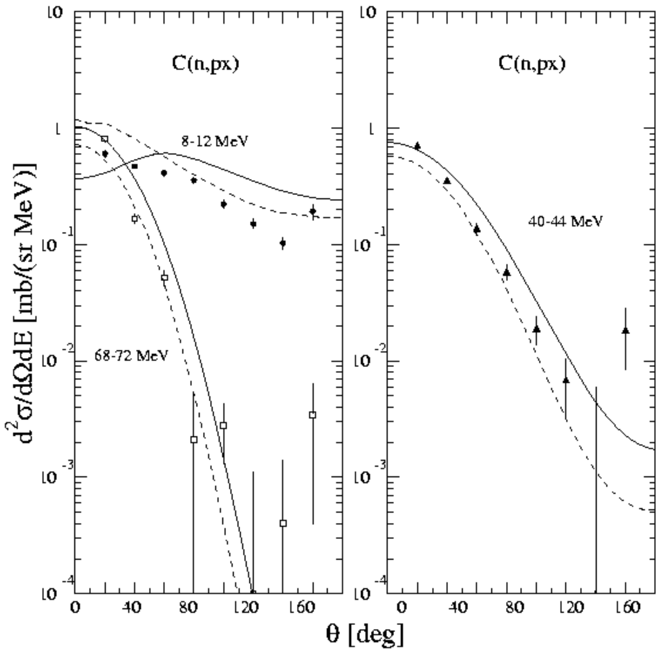

Fig. 4. Angular distributions of C(n,px) cross section at ejectile energies of 8–12 MeV (filled circles), 40–44 (filled triangles), and 68–72 (open squares). Solid and dashed curves represent calculations based on the TALYS and GNASH models, respectively.

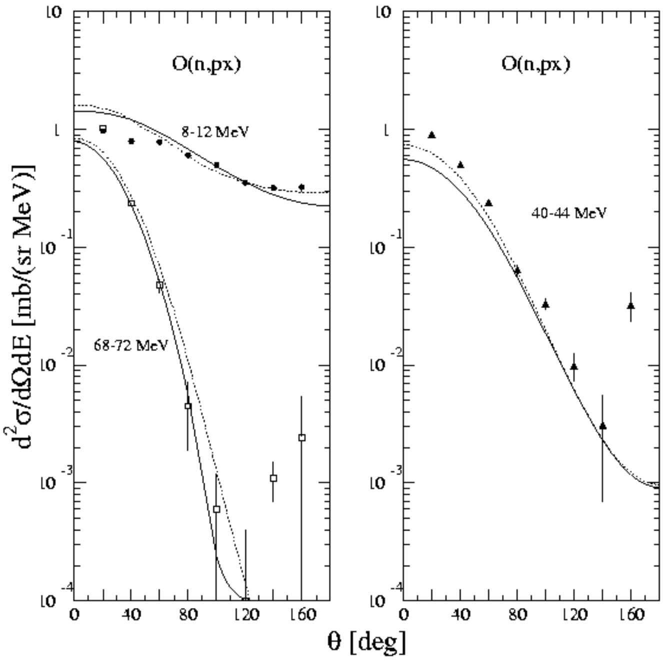

Fig. 5. Same as figure 4, but for O(n,px) cross section.

3 nd elastic scattering

Neutron-deuteron (nd) elastic scattering in the 60–200 MeV range is one of the most promising ways of investigating three-nucleon ($3N$) forces. Recent calculations, (see ref. [11] and reference therein), have indicated that the presence of $3N$ forces should appear as a measurable effect in the angular range of the differential cross section minimum.

The nd elastic scattering differential cross section has been performed at 95 MeV incident neutron energy. Models based on inclusion of $3N$ forces describe nd data in the angular region of the cross-section minimum very well, while models without $3N$ forces cannot account for the data [11] (see fig. 6).

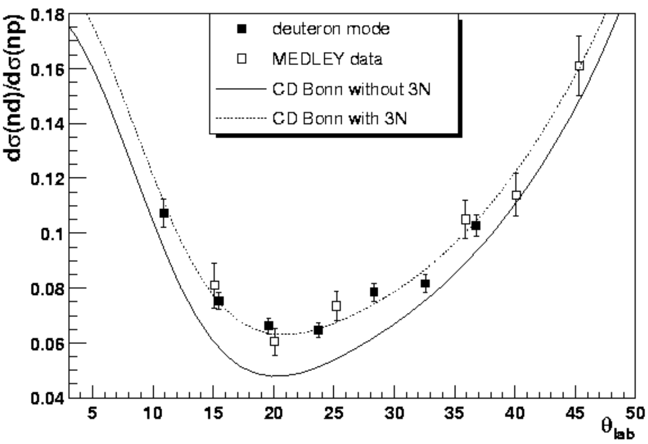

Fig. 6. Ratio of the nd and the np cross sections at 95 MeV as a function of the laboratory angle of the recoiling proton or deuteron [11]. The solid (dotted) line is a cross section calculation, based on the CD-Bonn nucleon-nucleon potential, without (with) three-nucleon effects included.

4 The MEDLEY facility

The charged particles are detected by the MEDLEY setup [6]. It consists of eight three-element telescopes mounted inside a 90 cm diameter evacuated reaction chamber. Each telescope has two fully depleted ΔE silicon surface barrier detectors and one E CsI(Tl) detector. MEDLEY has been equipped with larger CsI detectors to be able to stop protons up to 180 MeV. These new detectors have now been used during several runs and perform according to expectations. The CsI crystals have a total length of 100 mm. The first 70 mm is made cylindrical with a diameter of 50 mm and the remaining 30 mm is tapered to 18 mm diameter to match the size of the readout system. The readout is performed by Hamamatsu S3204-08 photodiodes (PD). The crystals, toghether with the PDs, are mounted inside an aluminum tube and have been manufactured by Saint-Gobain, France. The CsI response function has been tested with 170 MeV proton beam and compared with Monte Carlo simulations, which is decribed elsewhere at this conference [16].

A new method for correcting charged-particle spectra, distorted by energy and particle loss in a thick target [17], has been used for data obtained with the MEDLEY facility [7,8]. It uses an iterative procedure to obtain improved guesses on the inverse response functions for each measured particle energy. The procedure is easy to use, includes a correct treatment of cutoff energies, and has been validated by some test cases.

4.1 Background

During the first runs we have found a rather large background probably due to neutrons from the production target penetrating the concrete shielding. Exchanging the concrete wall to an iron wall has achieved improved background conditions. Available iron blocks from the old CELSIUS ring have actually been used when this reconstruction was undertaken in January 2007. The first data with the new shielding had been taken during February and March 2007. In addition, a pre-collimator, built by holed lead blocks, has been installed temporally inside the clearing magnet. It showed significant improvement of the signal-to-background ratio.

4.2 Data-taking and analysis

As mentioned above, we have collected data on ^{12}C(n,lcp) induced by 175 MeV neutrons early this year. Preliminary double-differential cross sections for carbon are presented in another contribution to this conference by M. Hayashi et al. [16].

5 Outlook

Using the MEDLEY facility at the new Uppsala neutron beam, we plan to measure double-differential cross sections for light-ion production on oxygen, silicon, iron, lead, bismuth and uranium at 175 MeV. Furthermore we will measure the ^{238}U(n,f) cross section, together with angular distributions of the fission fragments, over the energy region of 20 to 175 MeV. The proposed target nuclei are of highest interest within the applications listed above, and, in addition, of key interest for model development.

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