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ARTICLE

Light-ion production in 175 MeV quasi-monoenergetic neutron-induced reactions on iron and bismuth and comparison with INCL4 calculations

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Nuclear data for neutron-induced reactions in the intermediate energy range of 20 to 200 MeV are of importance for several different applications, notably accelerator-driven incineration of nuclear waste. The Medley setup located at The Svedberg Laboratory in Uppsala, Sweden was used for a series of measurements of p, d, t, ^{3}He and alpha particle production from 175 MeV neutrons on various target nuclei. Medley uses an arrangement of 8 detector telescopes placed at angles from 20 to 160 degrees relative to the neutron beam to register event and discriminate among the particle types. Using the ΔE-ΔE-E technique we were able to measure double-differential cross sections over a wide dynamic range. This paper describes the experimental set-up, summarizes the data analysis and reports on recent changes in the previously reported preliminary data set on bismuth. Experimental data are compared with several different model calculations. In this paper we specifically compare the experimental results with INCL4 intra-nuclear cascade calculations combined with the ABLA de-excitation code. Considering the fact that the experimental data are obtained at an energy normally considered too low for intra-nuclear cascade calculations, we do find some systematic difference but generally reasonable agreement.

Keywords: intermediate energy nuclear data; measurement; 175-MeV neutron; light ion production; Fe; Bi; model calculation

1. Introduction

Development of nuclear facilities for accelerator-driven incineration of nuclear waste, particle therapy for cancer treatment, long-range manned space missions, increasing sensitivity of microelectronics to cosmic radiation, and the related dosimetry and radiation safety issues, urge the nuclear data community to provide new and more reliable information on nuclear data for neutron-induced nuclear reaction in the intermediate energy region from 20 to 200 MeV. Especially important for the mentioned applications are double-differential cross sections (DDXs) of light-ion production in neutron-induced reactions. To satisfy these needs a series of measurements around 96 MeV has earlier been performed at The Svedberg Laboratory (TSL), Uppsala [1]. Above 100 MeV, however, experimental data are extremely scarce. In the present work, DDXs for light ions (p, d, t, ^{3}He, and α) from Fe, Bi, and U induced by 175 MeV quasi mono-energetic neutrons were measured using the Medley setup as part of the ANDES project [2] with the special aim to study the amount of tritium production. Here we report on the results for Fe and Bi. The analysis of the U data is still in progress.

In this paper we summarize the experimental efforts, give an overview on the analysis procedure and compare the measured results with model calculations. Preliminary data and comparisons with model calculations have been reported earlier [3,4] but have since been found to be erroneous in the bismuth case. Here we present the Fe and the revised Bi data. Both are still preliminary.

While it has been pointed out that INC models work at energies even below 100 MeV [5] they are still normally considered only in the high-energy domain, i.e. above 200 MeV. In this paper we perform a comparison of the experimental data with INCL4 intra-nuclear cascade calculations combined with the ABLA de-excitation code [6,7].

It is noteworthy that also nuclear model codes coming from the low energy side like the TALYS code,

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originally intended for the energy region up to 200 MeV, are now being extended to 600 MeV with quite some success [8]. This progress is encouraging and will profit from such experimental data as described here.

2. Experimental

We used the quasi-monoenergetic neutron beam available at The Svedberg Laboratory (TSL), Uppsala, Sweden. The neutrons were produced from the ^{7}Li(p,n). The pulsed proton beam with 45 ns repetition time had an energy of 179 MeV, and the Li target thickness was 23.5 mm. This yielded a neutron beam with peak energy of (175± 3) MeV and comprising 40% of the produced neutrons. The remaining 60% form the neutron tail which can, partly, be suppressed by time-of-flight methods (see below) [3]. The neutron energy spectrum was obtained from measurement of elastic *np* scattering from a CH_2 target of similar size than the other targets in the measurement campaign. The relative neutron fluence for the various targets was derived from several standard beam monitors available at TSL; the beam dump monitor, a thin-film breakdown counter and the ionization chamber monitor [3].

The Medley setup consists of a scattering chamber in which an arrangement of eight ΔE-ΔE-E detector telescopes is mounted on a rotating table. The telescopes are placed at different angles (in steps of 20°), and the use of a thin (50-60 μm) silicon surface barrier detector (SSBD), a thick (400-1000 μm) SSBD, and finally a CsI(Tl) detector of sufficient length to stop particles even at the highest energy, allows for particle identification and measurement of double-differential cross sections (ddx) over a wide dynamic range. The lowest detectable particle energy is only limited by the SSBD detector noise. Depending on the particle identification needs, protons with energy down to about 0.5 MeV and alpha particles with energy down to about 4 MeV can be handled. In the present measurement the cutoff is at about 3 MeV for the hydrogen isotopes and about 9 MeV for the helium isotopes. The setup is very flexible since the used SSBD detector thicknesses in each telescope can be adapted for the conditions in each campaign, and, in addition, distance and angle of the telescopes can be changed easily. Within an experimental campaign, each telescope is used at two different scattering angles allowing for cross-checks and ensuring redundancy.

The chamber is evacuated during an experimental run and up to three different targets can be put into or removed from the beam without breaking the vacuum. Targets are placed at an angle of 45° relative to the incident beam, minimizing the energy loss of the produced charged particles. Target thicknesses were 375 μm for ^{nat}Fe (0.295 g/cm^{2}), and 500 μm for ^{209}Bi (0.487 g/cm^{2}). The weights were 1959.6±0.1 mg for the ^{nat}Fe and 3130.1±0.2 mg for the ^{209}Bi target. The energy loss is corrected for in the analysis procedure by means of an iterative procedure [9].

The background is measured by removing the target from the beam. It mainly consists of protons produced from the beam and the beam halo elsewhere in the chamber. Part of the background can be identified as coming from the beam entrance section of the chamber. Such particles have the wrong energy-loss relations but cannot be removed completely by the particle identification. The remaining part affects mostly the backward angles since these telescopes are close to the background source and have low statistics.

Besides energy calibration, particle identification, background subtraction and the mentioned thick-target correction, other important steps of the data analysis comprise correction for the CsI efficiency and time-of-flight (TOF) analysis including subtraction of neutrons from previous proton beam pulses (so-called wrap around). The TOF is obtained only relative using the RF signal from the cyclotron [3]. Due to the short flight path of about 4.5 m, the length of the proton pulse and the achieved time resolution, the accepted neutron spectrum shows a peak at 175 MeV but still comprises a tail extending down to about 90 MeV and still containing approximately 50% of all the events. Therefore, while the data are dominated by monoenergetic neutrons with energy (175 ± 3) MeV, the average neutron energy of all the events contained in the reported data set is about 150 MeV. The model calculations are therefore made at several neutron energies and then folded with the accepted neutron spectrum to be comparable with the experimental data. More details on the experimental procedure are given in Ref. [3].

3. Results and discussion

Preliminary experimental results for Fe and Bi have previously been reported in, e.g., Refs. [3,4]. There they are compared with model calculations obtained with TALYS, a modified version of JQMD [10], and MCNP6. We found that models generally manage to reproduce observed trends and in some cases describe the data rather well. Examples for the latter are the JQMD results for Fe(n,px) (for the 40° angle and higher) and Fe(n,αx). Nevertheless, none of the models is able to give a completely satisfactory description of all the experimental data, with composite particles being especially problematic.

We have recently found a mistake in the thick-target correction for the Bi data and show here comparisons of the new Bi data with model calculations from the INCL4 intra-nuclear cascade code (version 4.5) combined with the ABLA de-excitation code. In **Figure 1** we show results for Bi(n,px) at four different angles. **Figure 2** shows Bi(n,tx), and **Figures 3** and **4** show Bi(n,αx) and Fe(n, αx), respectively, all the same four angles. Model calculations for both a true monoenergetic neutron beam with energy 175 MeV and for the accepted neutron energy spectrum are also shown. The differences of the resulting “washing out” are clearly seen at the high energy end of the 20° data in Figure 1.

While it might seem desirable to correct the experimental data for the still contained low-energy neutron tail and produce true 175 MeV data, we think it is necessary to publish the experimental data as bias-free and model-independent as possible.

Comparing the model calculations in the (n,tx) and (n,αx) cases with the experimental data we find, overall, good agreement, especially at the low energy end. This agreement in especially the (n,αx) case increases our confidence that the thick target correction has been made in a correct way. A systematic difference is, however, observed at the high-energy end, especially at 20°. There, triton and alpha production are overpredicted by the INCL4 calculations. The seemingly large discrepancy at 160° is due to the fact that the experimental data here are exposed to large background which is reflected in the very large uncertainties.

In the (n,αx) cases, shown in Figures 3 and 4, we observe similar trends. Unfortunately, due to identification cutoff and the thick-target correction, the experimental data in the Bi case do, so far, not extend far down enough to verify the steep decrease in cross section below the evaporation top, which is compared to the Fe data, due to coulomb effects, markedly shifted to higher energies.

For the (n,px) data, shown in Figure 1, we find good agreement with the model calculation at both the low and high energy end at 20°. In the intermediate range (50-120 MeV), however, the INCL4 calculations underpredict the experimental data. At 40° we find better agreement in shape but model calculations underestimate the experimental results. At 80° the model calculations overpredict the experimental data at both ends of the energy spectrum.

A publication of the complete and final Fe and Bi data including comparisons with all the mentioned model calculations is in manuscript [11].

4. Summary and conclusion

In this paper we presented our efforts to provide Fe and Bi data for neutron-induced reactions in the 100-175 MeV range, an energy range that has been identified as crucial for several applications. The Fe data have been shown earlier while the Bi data had to be revised due to an earlier mistake in the thick-target correction. Still, both data sets are to be considered preliminary. The experimental results are compared with model calculations obtained from the INCL4.5-ABLA code.

For Bi(n,px) the main difference was an underprediction of the experimental data in the 50-120 MeV range for the most forward angle. Difficult cases like (n,tx) and (n,αx) are described rather well by INCL4.5-ABLA even though the code systematically overpredicts the experimental results in the Fe(n,αx) case. Despite such differences we find that, in general, good agreement between trends and reasonable agreement for the absolute DDX values observed in the experimental data and the model calculations, can be concluded.

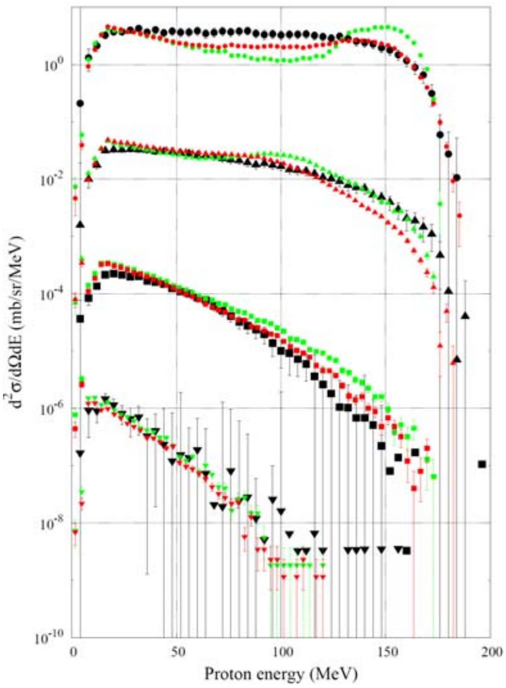

Figure 1. Double-differential cross section data for Bi(n,px). Experimental results (black symbols) are compared with INCL4.5-ABLA calculations for both monoenergetic 175 MeV neutrons (green symbols) and the true experimentally accepted neutron spectrum (red symbols). Data for four different angles are shown: 20° (circles), 40° (upward triangles, scaled by 10^{-2}), 80° (squares, scaled by 10^{-4}), and 160° (downward triangles, scaled by 10^{-6}).

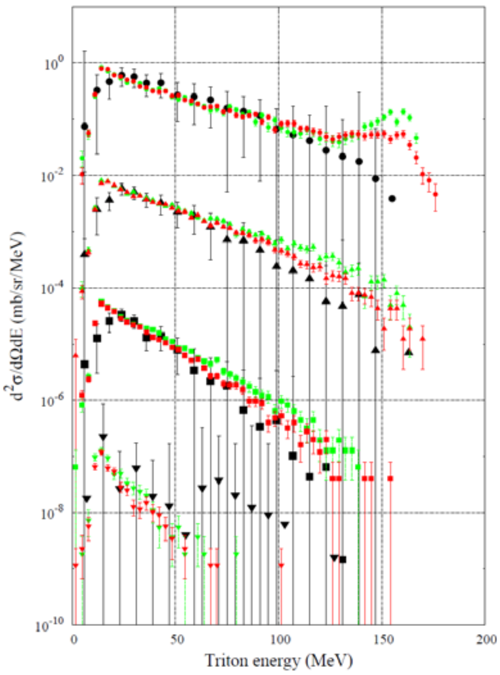

Figure 2. Same as Figure 1 but for Bi(n,tx).

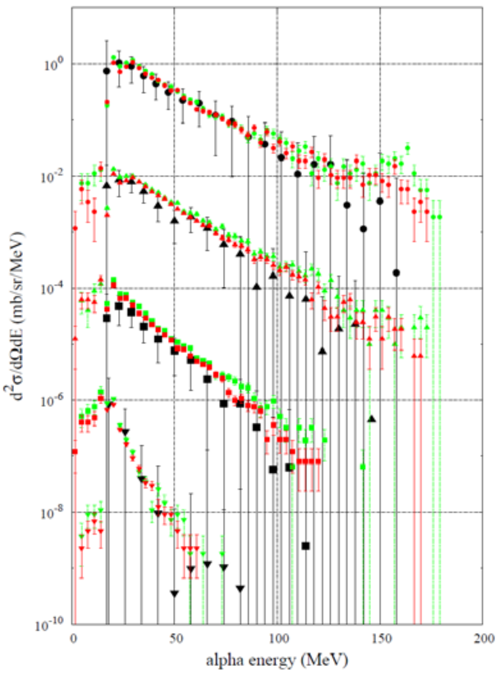

Figure 3. Same as Figure 1 but for Bi(n,αx).

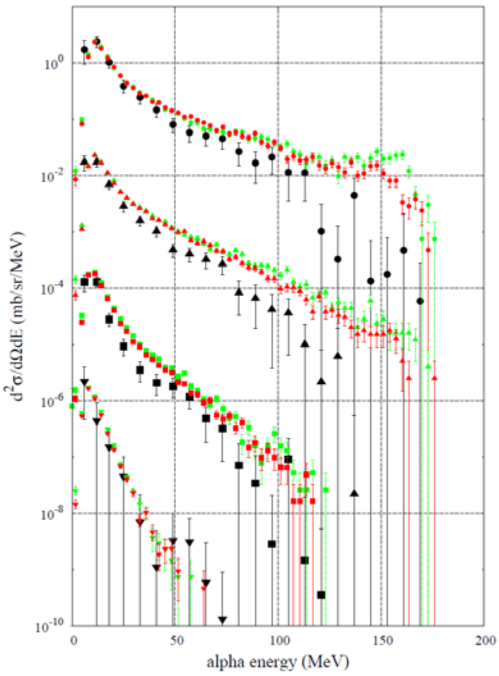

Figure 4. Same as Figure 1 but for Fe(n,αx).

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