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Neutron production in Pb/U assembly irradiated by protons and deuterons at 0.7–2.52 GeV

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Abstract. Relativistic protons or deuterons hit the thick, lead target. Emitted neutrons were multiplied by fission inside the uranium blanket. The high energy neutron field produced in the setup was measured by the means of threshold reactions in activation foils. The comparison with MCNPX 2.6.C simulations was done.

1 Introduction

"Energy plus Transmutation" (E + T) [1] is an international project for the study of spallation reactions, neutron production and transport, and transmutation of fission products and higher actinides by spallation neutrons. E + T setup, which consists of a thick, lead target surrounded by a subcritical natural uranium blanket, was irradiated by protons with energies of 0.7, 1.0, 1.5, and 2.0 GeV, and deuterons with (total) energies of 1.6 GeV and 2.52 GeV.

Relativistic protons and deuterons interacting with the target induced spallation reactions and intense neutron fluxes were created. Emitted neutrons were multiplied by fission inside the blanket. The high energy neutron field produced in the setup was measured by the means of threshold reactions in activation foils. Gamma-rays of produced β-radioactive nuclei were measured with HPGe spectrometers. Yields of selected isotopes were determined with the respect to all necessary spectroscopic corrections.

Experimental results were compared with MCNPX simulations with the aim to test its applicability to describe physical processes proceeding in such a setup and to check the differences between various MCNPX configurations.

2 Experimental apparatus

E + T setup consists of three essential parts: Pb-target, U-blanket, and $(CH_2)_n$ shielding with Cd-layer, see figure 1. The cylindrical target has a diameter of 84 mm and the blanket has hexagonal cross section with a side length of 130 mm. The target/blanket part has a length of 480 mm but it is divided into four sections of 114 mm in length separated by 8 mm gaps, see figure 2. It is placed in a polyethylene shielding of approximately cubic size (≈1 m^3). The inner walls of this container are coated with a cadmium layer with a thickness of 1 mm. The front and the back ends of the setup are without shielding. For the detailed description of the E + T setup, see [1].

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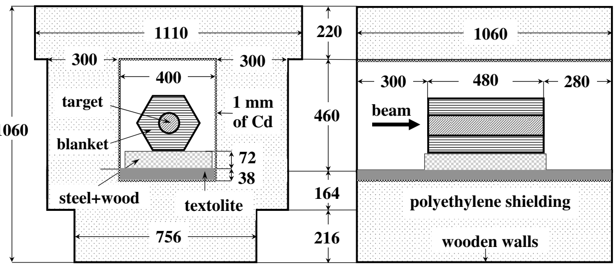

Fig. 1. Front view (left) and cross sectional side view (right) of the "Energy plus Transmutation" setup. Dimensions are in millimeters.

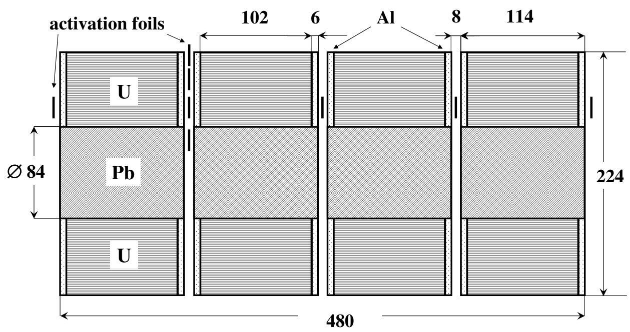

Fig. 2. Typical placement of activation foils (side view). Dimensions are in millimeters.

The produced neutron field was measured by non-threshold (n,γ)-reaction and threshold (n,α), (n,xn)-reactions in Al, Au, Bi, Co, In, Ta, and Y foils of an approximate size of 20 × 20 mm^2 with a thickness of ~0.1 mm. Two sets of activation foils were placed in the gaps between target/blanket sections, first to measure longitudinal distribution and second to measure radial distribution of the produced neutron field, see figure 2.

3 Experimental results

The products of threshold reactions with E_{thresh} from 5 to 60 MeV were observed. The example of typical yields of

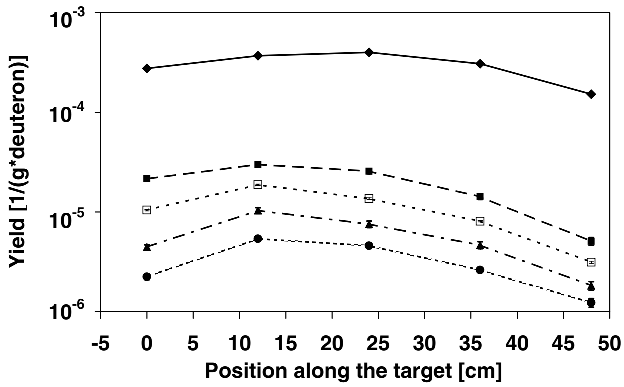

Fig. 3. Longitudinal distributions of the yields of nuclei produced in Al- and Au-foils during the 2.52 GeV deuteron experiment. The lines linking experimental points are delineated to guide readers' eyes. For legend, see the plot below.

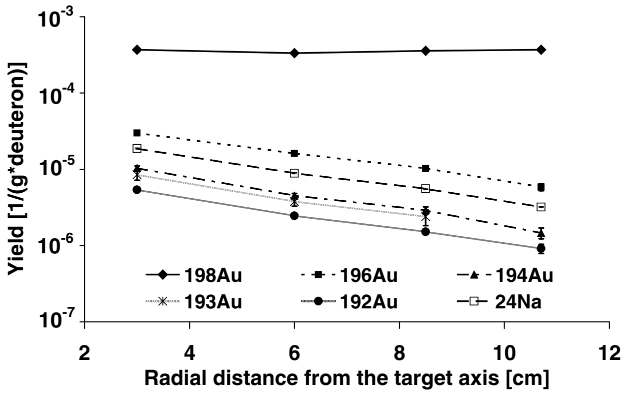

Fig. 4. Radial distributions of the yields of nuclei produced in Al- and Au-foils during the 2.52 GeV deuteron experiment. The lines linking experimental points are delineated to guide readers' eyes.

observed isotopes is shown in the semi-logarithmic scale in figures 3 and 4. The delineated errors (hardly visible at this scale) are only of statistical origin (given by the error of the Gaussian fit of γ-peaks). Systematic errors, mainly the inaccuracy in determination of the beam and activation foils displacement, can contribute up to 30% [2].

The spatial distributions of yields of threshold reactions have similar shapes for all beam energies. The longitudinal distributions of yields change for one order of magnitude and have clear maximum observed in the first gap between target/blanket sections. The radial distributions of yields decrease nearly exponentially with increasing perpendicular distance from the target (beam) axis.

In the contrary, the yields of neutron capture (^{197}Au (n,γ)^{198}Au) only slightly change. This is caused by neutron moderation and scattering in the polyethylene shielding that created an intensive, homogenous field of neutrons with E<1 keV, see figure 5. These low-energy neutrons give major contribution to (n,γ)-reaction in all foils in the setup. Therefore, the longitudinal and radial distributions of yields of ^{198}Au are flat. For more detailed discussion about shapes of longitudinal and radial distributions, see [3].

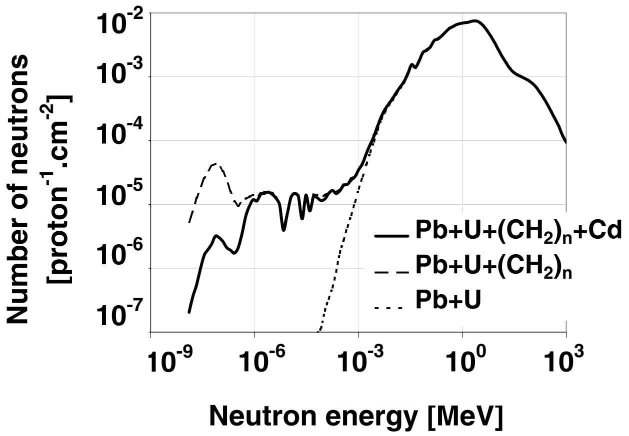

Fig. 5. Influence of the polyethylene shielding and the Cd-layer on neutron spectra (MCNPX simulation of 1 GeV proton irradiation of three different setups). Oscillations in the region between 5×10^{-6} and 5×10^{-4} MeV are caused by resonances in the cross section of neutron capture in ^{238}U (inside the blanket).

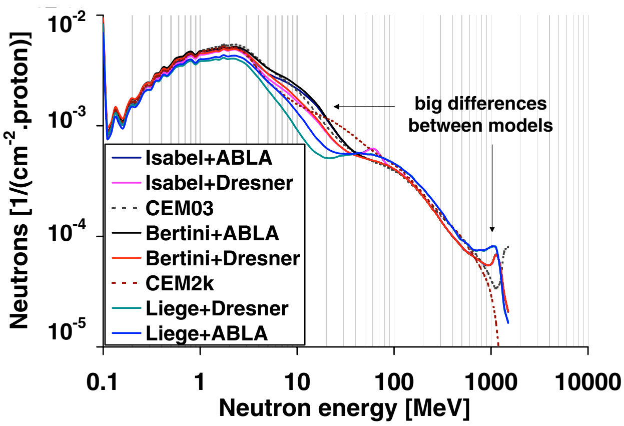

Fig. 6. Neutron spectra in log-log scale. MCNPX simulations of 1.5 GeV proton experiment. All available physics models in 2.6.C version plus the CEM2k model (from 2.5.0 version) were used.

4 Monte Carlo simulations

The Monte Carlo simulations of spallation reactions, neutron production and transport, and activation reactions in the foils were performed with the MCNPX code, version 2.6.C [4]. The influence of possible inaccuracies in the description of E + T setup geometry on high energy neutron component (E > 10 MeV) is negligible [2].

4.1 Neutron spectra simulations

Firstly, we simulated neutron spectra using all combinations of intra-nuclear cascade (INC) models and evaporation models available in MCNPX 2.6.C: Bertini, Isabel, Liège (INCL4) INC models; Dresner and ABLA evaporation models; CEM03 and CEM2k models, which work alone (since 2.6 versions, CEM03 replaced the former CEM2k, thus, the simulations using CEM2k were performed with MCNPX 2.5.0 [5]).

Example of simulation of neutron spectra, produced in the 1.5 GeV experiment, is shown in figure 6. The differences

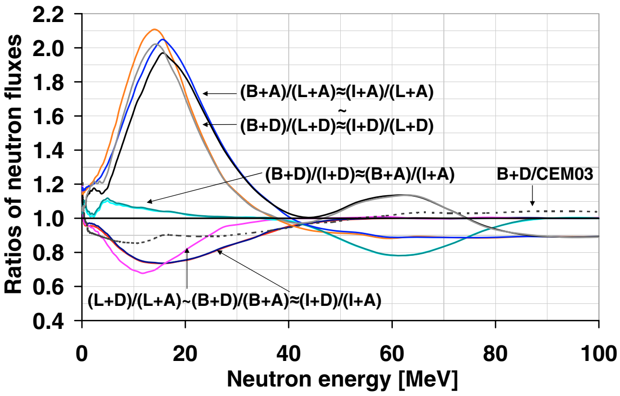

Fig. 7. Ratios of neutron spectra from figure 6 (linear scale). Similar behaviours of different physics models are emphasized.

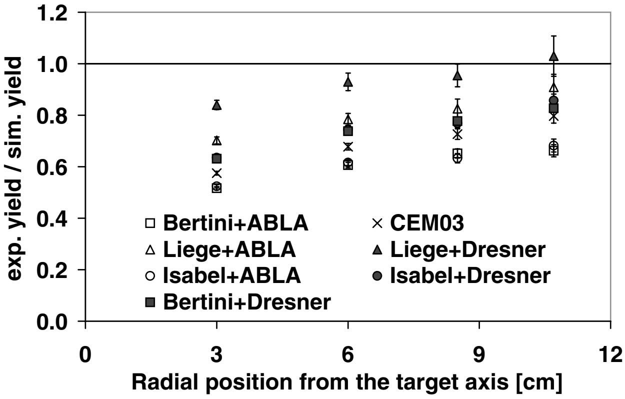

Fig. 8. Absolute comparison of experimental and simulated yields of ^{196}Au in radial direction (1 GeV proton experiment).

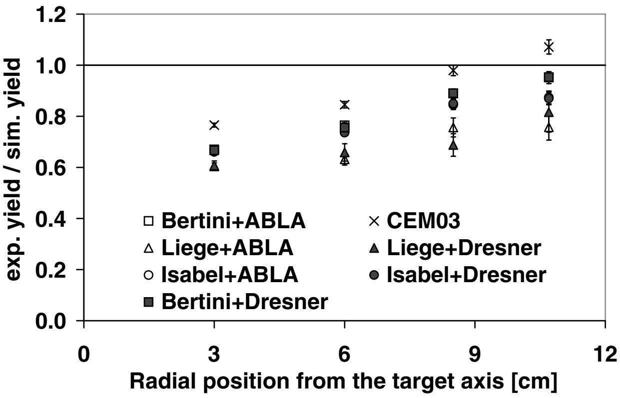

Fig. 9. Absolute comparison of experimental and simulated yields of ^{194}Au in radial direction (1 GeV proton experiment).

between models exceed 20% between 1 and 70 MeV (and even 100% between 10 and 20 MeV) and above 700 MeV.

The region of tens of MeV is of our interest, because the observed threshold reactions have threshold energies there. We focused on this region and plotted ratios of neutron spectra in figure 7. Two separated regions were observed: in first region the simulations differ significantly when different evaporation models are used, in second region when different INC models are used. Rather, the following combinations of INC + evaporation models give the same results (i.e., differences <5%):

- Bertini + Dresner compared with Isabel + Dresner and Bertini + ABLA compared with Isabel + ABLA both in 13–42 MeV and above 76 MeV;
- Isabel + Dresner compared with Isabel + ABLA, Bertini + Dresner compared with Bertini + ABLA, and Bertini + Dresner compared with CEM03 above 38 MeV (the last one until 270 MeV);
- Liège + Dresner compared with Liège + ABLA above 27 MeV.

We interpret this as an evidence of the border between intranuclear cascade and evaporation phase of spallation reaction as they are described in the used models. This point appears to be around 40 MeV.

4.2 Simulations of yields of threshold reactions

To estimate the influence of different INC + evaporation models on simulated yields of threshold reactions in activation foils, we simulated these yields using all models, see examples in figures 8 and 9. Following relations can be seen:

- in the case of ^{196}Au ($E_{\text{thresh}} \approx 8$ MeV) – simulation using Bertini + Dresner gives the same results as Isabel + Dresner (within the error bars); the same holds for Bertini + ABLA compared to Isabel + ABLA;
- in the case of ^{194}Au ($E_{\text{thresh}} \approx 23$ MeV) – simulation using Bertini + Dresner gives the same results as Bertini + ABLA (within the error bars); the same holds for Isabel + Dresner compared to Isabel + ABLA.

Taking into account the threshold energies (above mentioned) and the fact that cross sections of these threshold reactions reach their maxima about 10 MeV after E_{thresh} and have important influence even 20 MeV after E_{thresh}, we conclude that evaporation models (Dresner and ABLA) have dominant influence for neutron energies up to ≃35 MeV. The INC models (Bertini and Isabel) are dominant for higher energies. The Liège INC model has influence on the evaporation part of neutron spectra. This observation agree with the conclusion we have done in the previous section.

From figures 8 and 9 it can be also seen that all of used INC+evaporation models show approximately the same trends. The relative variances between various model combinations are up to 50%.

Therefore, we decided to compare relative values (experimental and simulated shapes in longitudinal and radial distributions) rather than absolute values. The ratios between experimental and simulated yields were normalized to the second foil in each set (which is common in both sets). The shapes in longitudinal direction agree well for all proton beam energies, see figure 10.

In the contrary, the shapes in radial direction differ in dependence on the beam energy. For 0.7 GeV, the ratios between experimental and simulated yields slightly decrease with increasing radial distance from the target axis. For higher proton beam energies, these ratios grow with increasing radial

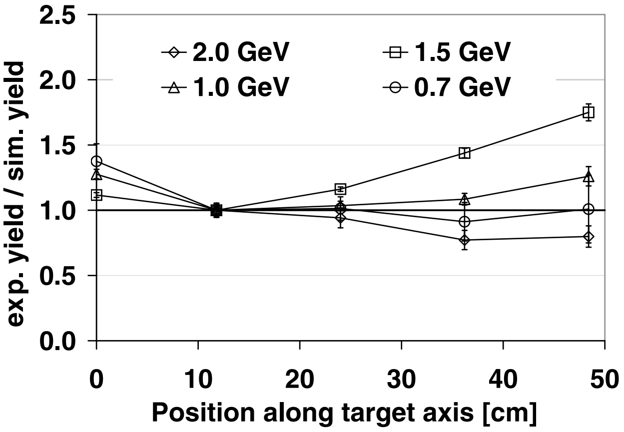

Fig. 10. Relative comparison of experimental and simulated (Bertini + Dresner) yields of ^{194}Au in longitudinal direction for all proton experiments (normalized to the second foil).

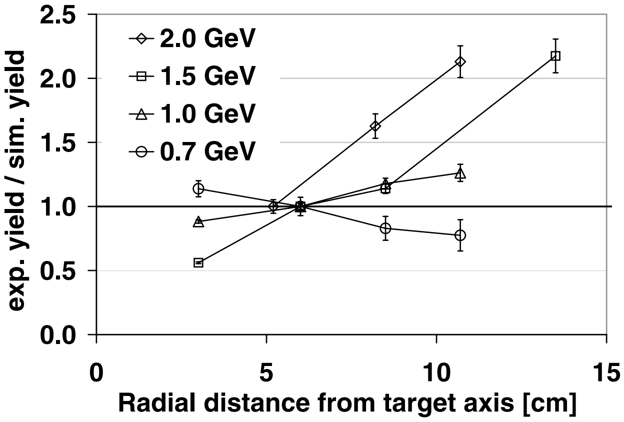

Fig. 11. Relative comparison of experimental and simulated (Bertini + Dresner) yields of ^{194}Au in radial direction for all proton experiments (normalized to the second foil).

distance from the target axis. This difference increases with increasing proton energy, see figure 11.

Neither Bertini nor Isabel (only in its present implementation) nor CEM03 can provide reasonable simulations of deuteron beams with higher energies, see figure 12. Currently, we are in the process of performing simulations of our deuteron experiments using the Liège INC model (included into MCNPX since 2.5 version), but it is much slower than other models.

The detailed analysis of the experiments performed with proton and deuteron beams could reveal the exact identification of the sources of differences observed between experimental data and simulations.

5 Conclusion

We have studied high energy neutron production in the spallation reactions of protons and deuterons in a GeV range with the thick, lead target surrounded by the uranium blanket. The comparison of the experimental results with Monte Carlo simulations was performed using MCNPX 2.6.C.

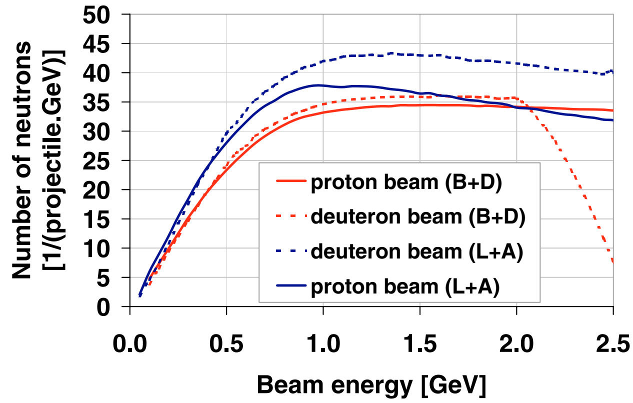

Fig. 12. The number of neutrons produced in the whole E + T setup in dependence on the beam energy (normalized per one incident particle and per unit of energy). MCNPX simulations with the Bertini INC model (the same holds for Isabel and CEM03) show disability to simulate deuteron beam above 2 GeV.

The simulations of the produced neutron spectra significantly differ when different combinations of intra-nuclear cascade and evaporation models are being used. The biggest differences are in the region of tens of MeV and several hunderds of MeV before the beam energy. The border for neutron production in different phases of spallation reaction was found out to be around 40 MeV (neutrons are being produced mainly in evaporation under this point, in intra-nuclear cascade above it).

MCNPX describes well the shape of the longitudinal distributions of the yields of threshold reactions. This is valid for experiments with proton beam energies 0.7–2.0 GeV and all combinations of intra-nuclear cascade models with evaporation models included in the 2.6.C version.

The shape of the radial distributions of experimental yields differs from the simulated one in dependence on the proton beam energy. While in the case of 0.7 GeV the simulations predict slightly steeper increase of the yields with growing radial distance than it was measured, for higher proton beam energies the simulations predict much steeper decrease. The difference between experiment and simulation is the bigger, the bigger the proton beam energy is.

The Liège INC model is the only one in MCNPX that is able to simulate deuteron beams energies bigger than 2 GeV, but it is much more time consuming.

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