EXPERIMENTAL STUDIES OF SPATIAL DISTRIBUTIONS OF NEUTRONS INSIDE AND AROUND THE SET-UP CONSISTED FROM A THICK LEAD TARGET AND A LARGE URANIUM BLANKET IRRADIATED BY RELATIVISTIC PROTONS

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Abstract
We studied the spatial and energetic distribution of neutrons produced by spallation reactions at different places around and inside a simple thick lead target or in more complex installation Energy plus transmutation (consisted of lead target and uranium blanket) irradiated by relativistic protons of different energies from energies 0.5 GeV up to 2.5 GeV using JINR Dubna Synchrophasotron and Nuclotron. The activation detectors were used for neutron field determination. The comparison between experimental and simulated production rates of many threshold reactions makes it possible to test the accuracy of the description of neutron production in the wide neutron energy interval. Experimental results were analyzed and were compared with Monte Carlo simulations provided by LAHET+MCNP and MCNPX code. Simulations were also used for study of possible background and systematic errors produced by biological shielding around our set-ups.

1 Introduction
Spallation reactions induced by intense high energy proton beam in heavy target are ideal source of neutrons for the transmutation of radioactive waste. Accelerator Driven Transmutation Systems (ADTS), where an accelerator is coupled with a reactor, will use such source of neutrons [1]. Detailed studies of neutron production and transport inside a thick target and also more complicated set-ups, consisting of target and blanket, are important for verification and improvement of currently available simulation codes suitable for design of ADTS.

2 Experiments of collaboration Energy plus transmutation
The needed studies of neutron production and transmutation of different radioactive waste materials using simple and also complex set-ups are performed by collaboration "Energy
plus transmutation” using JINR Dubna accelerators (Synchrotron, Nuclotron, and Pha-

sotron). These accelerators provide proton beam in suitable energy range (0.5 - 5 GeV). Collaboration carry out experiments using three types of set-up.

The first is a simple thick lead target. The target is sectioned and has standard diameter 9.8 cm and length 50 cm. Second is the ”Energy plus transmutation” set-up which consists of a cylindrical lead target and an uranium blanket. The lead target has length of 48 cm and a diameter of 8.4 cm. It is surrounded by four sections of a natural uranium blanket. Each section contains 51.6 kg natural uranium and the total uranium content in four sections is 206.4 kg.

Both set-ups were placed into a big external shielding (during some of the simple lead target experiments and during all of ”Energy plus transmutation” experiments). The shielding consists of a container filled with granulated polyethylene. Inner walls are plated with 1 mm sheets of cadmium. Outside dimensions of this container are 100x106x111 cm and total weight is 950 kg. Detailed description and technical drawings of details have been published in [2, 3].

Third set-up is named GAMMA-2. This set-up has target consisting of 20 lead discs, each 1 cm in thickness and 8 cm in diameter and it is surrounded by a 6 cm paraffin moderator [4].

The neutron field in different places inside and around these set-ups were measured using activation detectors. In activation detectors produced neutrons induced (n,xn\gamma), (n,\alpha\gamma) and (n,\gamma) reactions, and \gamma-decaying radioisotopes were produced. Different thresholds of these reactions allow us to probe energy spectra of neutrons. Activation detectors (Au, Al, Bi, Cu, Co, and La) were placed at different positions of the used setup (also inside the lead target or uranium blanket) [3]. This aproach allowed us the determination of production rates of radioactive nuclides, which were compared directly with the results of simulations or were used for deconvolution of neutron energy spectra.

3 Simulations using MCNPX

We made series of simulations to understand influence of different parts of set-ups on accuracy of data, to estimate systematic errors and also to compare obtained experimental data and model assumptions. Simulations were performed by MCNPX 2.3.0 code[5]. Calculations were done in two steps. First, neutron and proton energy spectra were obtained using MCNPX code. Second, the yields of nuclei produced in activation foils were calculated by convolution of these spectra with the corresponding cross-sections. The cross-sections were taken from ENDF/B-IV library [6], for higher energies were taken from EXFOR/CSISRS or calculated by LAHET code.

4 Influence of shielding container

The main task of the shielding container is biological shielding. The high energy neutrons in the MeV region are moderated to the low energies (thermal, epithermal and resonance). The Cd layer significantly absorbs thermal neutrons going back to the space inside the container, but influence of epithermal and resonance neutrons from container is still important.
Figure 1: Example of simulated (MCNPX) neutron spectra inside shielding container with set-up Energy plus transmutation (spectrum on the top of U blanket 11 cm from the front). Simulations with container and Cd layer, with container and without Cd layer, without container are compared.

Figure 2: Contribution of different part of neutron energy spectra to the reaction $^{139}$La$(n,\gamma)^{140}$La in the case of set-up ”Energy plus transmutation” with container

We studied influence of container on neutron spectra inside and around our set-up using MCNPX code to find out which parts of spectra are significantly changed and which are not influenced. The comparison of three types of simulation for neutron energy spectra on the top of U blanket is on Fig. 1. The spectra for these three simulations are the same for energy higher than 0.5 MeV. The spectrum for energy lower than 0.1 MeV starts to drop very quickly in the case of the set-up without container. Spectrum is constant and the same in the energy range from 1 eV up to 0.1 MeV for two simulated cases with container. Peak of thermal neutrons is not visible in the case with container with Cd layer (thermal neutrons are absorbed by Cd).

The main contribution of radioactive nuclei produced by no threshold neutron capture reactions in our experiment (set-up with container and Cd layer) is due to by resonance neutrons. This is true not only for La production (see Fig. 2.) but also for very often used $^{197}$Au$(n,\gamma)^{198}$Au reaction.
5 Comparison of experiments and simulations

The results of three experiments with different set-up each are presented as example. There are shown some results from experiment with ”Energy plus transmutation” set-up [3], GAMMA-2 set-up [6] and simple lead target [7]. Presented results are compared with MCNPX code simulations.

Spatial distribution of low energy neutrons were measured using production rates of the reaction $^{139}$La(n,$\gamma$)$^{140}$La during the experiment with ”Energy and transmutation” set-up and proton energy 1.5 GeV from Nuclotron. Lanthanum samples were placed on the top of uranium blanket. In this case shielding container was used [3]. The experiment with GAMMA-2 set-up with the same proton energy was made without container. The $^{139}$La samples were placed on the top of the paraffin moderator [6]. Comparison of experimental data and MCNPX simulations for these cases is on the Fig. 3. There is nice qualitative agreement between the experiments and the simulations.
Neutrons with MeV energies were measured by different threshold reactions. We compared experimental and simulated data for mentioned experiment with "Energy plus transmutation" set-up [3]. The production of $^{194}$Au isotope by (n,4n) reaction with energy threshold 23.2 MeV is shown as an example on Fig.4. We see good agreement for longitudinal distribution. However simulated radial distribution is much steeper than experimental one.

Spatial distribution of produced neutrons along the simple lead target (diameter 9.8 cm, length 50 cm) irradiated by protons with energy 0.885 GeV was measured during experiment on the JINR Synchrophasotron [7]. The comparison of obtained experimental data and MCNPX simulations is shown on the Fig.5. Nice agreement is possible to see. Difference starts to be visible for last ten centimeters of the target. It looks like the simulations underestimate the development of relativistic particles inside the target.

6 Conclusions and Outlooks

The collaboration "Energy plus transmutation" performed series of experiments with production and transport of neutrons with thick lead target or more complicated set-up irradiated by relativistic protons for benchmark tests of simulation codes. JINR Dubna accelerators are nice tool for such studies and relevant needed data were obtained.

The used shielding container has no influence on the part of the neutron spectra of energy higher than 0.5 MeV. Threshold reactions at activation detectors are produced only by neutrons coming directly from the target. Contribution of MeV neutrons from the container is negligible. Different situation is for radioactive nuclei produced by (n,γ) reactions, which have maximal cross-sections in the thermal, epithermal and resonance range. These nuclei are mainly produced by neutrons which come from the container. Moderation and scattering of neutrons by the container polyethylene produced homoge-
neous field of epithermal, and resonance neutrons (thermal neutrons are absorbed by Cd layer). Container is useful for the experiment, where MeV neutrons are measured. These neutrons are moderated in the container polyethylene and MeV neutrons cannot return back to the interior of the container. But number of neutrons with energy lower than 0.1 MeV is significantly influenced by the shielding container. Production of neutrons with energy lower than 0.1 MeV from set-up is necessary to measure only without the shielding container only.

Overall we observed good qualitative agreement between experimental and simulated data. It is possible to see some underestimation of relativistic particle shower inside the lead target by simulation. Simulated falling of radial distribution of neutrons inside the uranium blanket of ”Energy plus transmutation” set-up is steeper than experimental, too. Running analysis of performed experiments and preparing further experiments will help to understand these discrepancies.

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