Neutron Production in Spallation Reactions of 0.9- and 1.5-GeV Protons on a Thick Lead Target – Comparison of Experimental Data and MCNPX Simulations

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for the collaboration Energy plus transmutation [1]

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Abstract. This study is part of a complex research of Accelerator Driven Transmutation Technologies (ADTT) carried out by a collaboration of the NPI ASCR in Rež with the JINR in Dubna. The aim of the experiment was to check the validity of the model descriptions and the cross-section libraries used in the corresponding Monte-Carlo simulations of spallation reactions, and the propagation of the produced high-energy neutrons passed through a thick target. The experiments were carried out at the synchrophasotron and the Nuclotron accelerators of the Laboratory for High Energies at the JINR. Relativistic protons interacting with a massive cylindrical lead target produced the spallation neutrons. The spatial and energetic distributions of the produced neutron field were measured by the activation of Al, Au, Bi, Co and Cu foils placed on the surface of and next to the target. The HPGe detectors then measured the activity of the foils. The resulting γ-spectra of the activated foils were analysed, the yields of the corresponding radioactive nuclei were determined, and compared with Monte-Carlo based simulations performed both with the LAHET+MCNP code and the MCNPX code.

INTRODUCTION

Spallation reactions can be used to produce high neutron fluxes by bombarding a thick, heavy target with a high-intensity relativistic proton beam. Recently, possible applications, such as accelerator-driven transmutation of nuclear waste [2], have increased the interest in spallation reactions and in the transport of the produced neutrons. The idea of this work consists of the experimental study of the spatial and the energetic distributions of the neutron field (we concentrated our attention mainly on high-energy neutrons) produced in the spallation reactions of high-energy protons on a thick lead target. The main aim is a so-called benchmark test – comparison between experimental data and values obtained from the corresponding simulation codes, which must be able to describe the course of the spallation, interactions of secondary particles, and neutron transport through the target material. There are several such simulation codes and combinations of these codes. They are based on the Monte Carlo method, and they use various physical models of spallation reactions and cross-section libraries of neutron-induced reactions with nuclei. We used MCNPX [3] code and a combination of LAHET [4] and MCNP [5] codes.

I. PERFORMED EXPERIMENTS

This paper reports on two experiments performed at the JINR accelerators. We carried out systematic measurements of the neutron field (and optionally of iodine [6] transmutation) in different set-ups and at different beam energies.
1. Synchrophasotron

The beam of 885-MeV protons from the synchrophasotron hit a multi-section cylindrical lead target (diameter $d = 9.6$ cm and total length $l = 50$ cm) surrounded by a box of expanded polystyrene ($17.6 \times 17.1 \times 52.6$ cm$^3$) that worked as a thermal isolation to allow the measurement of the heat production. A box of granulated polyethylene ($106 \times 106 \times 111$ cm$^3$) surrounded this all and moderated the high-energy neutrons outgoing from the setup; see Fig. 1.

The primary protons with an energy of 885 MeV were stopped after passing about 30 cm in the target. A further part of the target was influenced only by the shower of secondary particles, which consists mainly of neutrons. The irradiation continued for about 2 hours. The number of beam protons was $(3.6 \pm 0.3) \times 10^{13}$ and the electrical current was approximately 0.8 nA.


The second presented experiment was performed at the superconducting synchrotron named Nuclotron with a proton energy of 1.5 GeV on the installation. “Energy plus transmutation” using a Pb/U assembly consisted of a lead target ($d = 8.4$ cm, $l = 48$ cm) plus 206.4 kg natural uranium blanket; see Fig. 2. The whole setup was surrounded by biological shielding consisting of a container filled with granulated polyethylene, which had walls plated with sheets of cadmium. The irradiation continued for about 12 hours. The number of beam protons was $(1.14 \pm 0.05) \times 10^{13}$ and the electrical current was approximately 40 pA.

3. Activation Analysis Method

The spatial distribution of the produced neutron field was measured by the activation of Al, Au, Bi, Co, and Cu foils placed on the surface of and next to the target. We have studied neutron-induced reactions both with a threshold in neutron energy and without it; see Table 1.

The advantage of the activation-analysis method is that detectors can be simple and can have arbitrary format (we used foils $2 \times 2$ cm$^2$ with $50 \ \mu$m thickness), and it is possible to place them at any position of the set-up. The disadvantage is that we measure the amount of neutrons.
TABLE 1. Thresholds of reactions studied by AAM.

<table>
<thead>
<tr>
<th>Activation Reaction</th>
<th>( E_{\text{thresh}} ) [MeV]</th>
<th>Activation Reaction</th>
<th>( E_{\text{thresh}} ) [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^{27}\text{Al}(n,\alpha)^{24}\text{Na})</td>
<td>5.5</td>
<td>(^{199}\text{Au}(n,7n)^{195}\text{Au})</td>
<td>45.7</td>
</tr>
<tr>
<td>(^{59}\text{Co}(n,\gamma)^{60}\text{Co})</td>
<td>-</td>
<td>(^{199}\text{Au}(n,9n)^{195}\text{Au})</td>
<td>62.6</td>
</tr>
<tr>
<td>(^{59}\text{Co}(n,2n)^{58}\text{Co})</td>
<td>10.6</td>
<td>(^{209}\text{Bi}(n,4n)^{205}\text{Bi})</td>
<td>22.6</td>
</tr>
<tr>
<td>(^{59}\text{Co}(n,3n)^{57}\text{Co})</td>
<td>19.4</td>
<td>(^{209}\text{Bi}(n,5n)^{205}\text{Bi})</td>
<td>29.6</td>
</tr>
<tr>
<td>(^{59}\text{Co}(n,4n)^{56}\text{Co})</td>
<td>30.9</td>
<td>(^{209}\text{Bi}(n,6n)^{205}\text{Bi})</td>
<td>38.1</td>
</tr>
<tr>
<td>(^{59}\text{Co}(n,5n)^{55}\text{Co})</td>
<td>41.2</td>
<td>(^{209}\text{Bi}(n,7n)^{205}\text{Bi})</td>
<td>45.2</td>
</tr>
<tr>
<td>(^{197}\text{Au}(n,n)^{197}\text{Au})</td>
<td>-</td>
<td>(^{209}\text{Bi}(n,8n)^{205}\text{Bi})</td>
<td>54.0</td>
</tr>
<tr>
<td>(^{197}\text{Au}(n,2n)^{196}\text{Au})</td>
<td>8.1</td>
<td>(^{209}\text{Bi}(n,9n)^{205}\text{Bi})</td>
<td>61.4</td>
</tr>
<tr>
<td>(^{197}\text{Au}(n,4n)^{194}\text{Au})</td>
<td>23.5</td>
<td>(^{208}\text{Bi}(n,10n)^{204}\text{Bi})</td>
<td>70.8</td>
</tr>
<tr>
<td>(^{197}\text{Au}(n,5n)^{193}\text{Au})</td>
<td>30.2</td>
<td>(^{208}\text{Bi}(n,11n)^{204}\text{Bi})</td>
<td>78.4</td>
</tr>
<tr>
<td>(^{197}\text{Au}(n,6n)^{192}\text{Au})</td>
<td>38.9</td>
<td>(^{208}\text{Bi}(n,12n)^{204}\text{Bi})</td>
<td>87.9</td>
</tr>
</tbody>
</table>

of produced radioactive nuclei, from which it is not always straightforward to determine the incident neutron field. The foil locations are shown in Figs. 1 and 2.

The foils were then measured by the High-Purity Germanium (HPGe) \( \gamma \)-spectrometers. These measurements were accumulated in histograms with 8192 channels, which were processed by the DEIMOS32 [7] code that provides a Gaussian fit of \( \gamma \)-peaks. The acquired areas were corrected for coincidences and other standard decay effects.

II. EXPERIMENTAL RESULTS

1. 885-MeV Experiment at the Synchrophasotron

The yields (number of activated nuclei per gram of activated material and per incident proton) of threshold reactions in gold and aluminum foils are presented as a function of the position along the target in Fig. 3. The maximum intensity of the fast neutron field is located in the region between 7–11 cm from the target forehead.

2. 1.5 GeV Experiment at the Nuclotron

The yields again in units of \( [\text{g}^{-1} \text{ proton}^{-1}] \) of radioactive isotopes produced in Au-sensor foils are shown in Fig. 4. (longitudinal distributions) and Fig. 5. (radial distributions).

III. SIMULATIONS

The processing of the experimental data was accompanied by simulations of the neutron production in spallation reactions. Simulations were performed by MCNPX 2.3.0. code and by combination of LAHET.
2.7. (Bertini INC model with preequilibrium phase) and MCNP4B codes. We made calculations in two steps:
- calculation of neutron (proton) energy spectra (Fig. 6);
- calculation of the yields of produced nuclei by convolution of these spectra with the corresponding cross sections.

We can see from the Fig. 6 that the energetic spectrum is harder at the end of the target than at the beginning.

**FIGURE 6.** MCNPX simulations of neutron spectra at distances 0 cm, 12.5 cm, and 50 cm from the target beginning (Nuclotron setup).

### IV. COMPARISON BETWEEN SIMULATION AND EXPERIMENT

The simulations describe the shape of the spatial distribution quite well up to a distance of 40 cm from the beginning of the target (Fig. 7). The maximum difference in absolute values is about 25%. Beyond 40 cm, the simulation underestimates the experiment, and the ratio of experimental values to the simulated ones reaches two. The simulation underestimates the experiment also in the radial distance (Fig. 8).

**FIGURE 7.** Comparison between the experimental yields of $^{194}$Au, $^{196}$Au, and $^{24}$Na, and the yields from the LAHET+MCNP simulations (Synchrophasotron setup).

**FIGURE 8.** Comparison between the experimental yields of $^{194}$Au and the yields from the MCNPX simulation (Nuclotron setup).

The range of 885 MeV protons in lead is about 30 cm, hence the primary proton beam should cease out behind that point. The same holds for secondary protons produced from primary spallation reactions, as their energy is not greater than the energy of corresponding primary proton. Therefore, we concluded that the simulations underestimate the development of the shower produced by high-energy secondary neutrons and their interactions within the target.

### V. CONCLUSIONS

We have studied the shape and the intensity of neutron field produced in the reactions of relativistic protons in a thick lead target surrounded by moderator by the activation analysis method. We found out that the energetic spectrum becomes harder at the end of the target. We reached good qualitative agreement between experimental data and simulations for high-energy neutron production. The simulations underestimate production of isotopes in foils placed beyond the blanket and at the end of the target. It can indicate a difference between the development of the secondary-particle shower and the fission in uranium blanket in the real experiment and in the model used in the simulations. A further detailed analysis of the sources of the differences between experiment and simulation are in progress, we also plan to carry out a comparison with experiments with different proton energies and setups.

### ACKNOWLEDGMENTS

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REFERENCES