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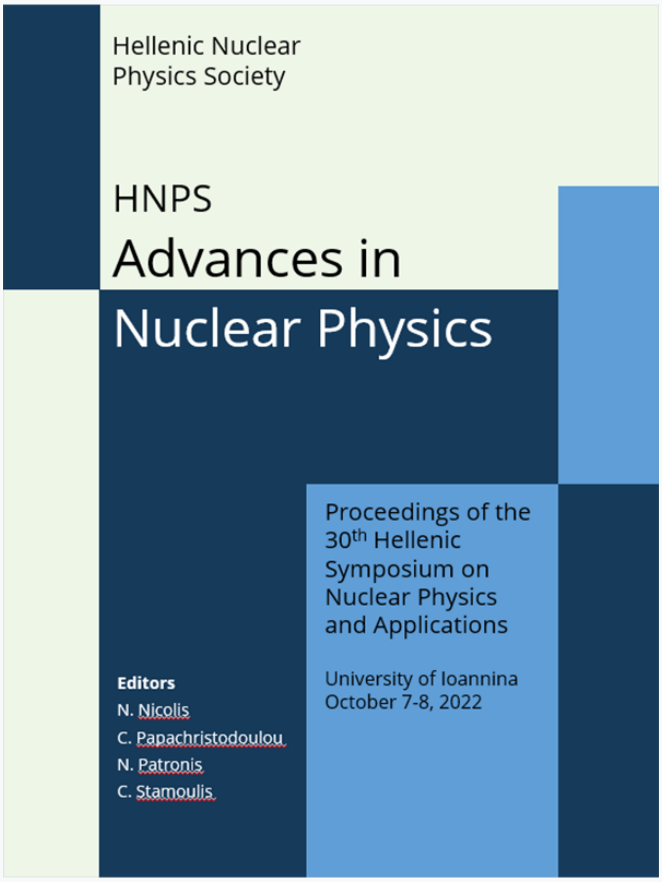


# MCNP simulations for the n_TOF NEAR station

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# MCNP simulations for the n_TOF NEAR station

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**Abstract** The NEAR station is the newest experimental area of the n_TOF facility at CERN, utilizing the spallation process to generate extremely high neutron flux within a broad energy spectrum. As part of the campaign for the determination of the neutron beam spectral features, numerous foils have been irradiated last year and the induced activities were measured implementing a HPGe detector. Experimental data analysis of the irradiated foil's gamma-ray spectra, yielded the saturated activities for each material that can be used to unfold the characteristics of the neutron flux through data deconvolution via the SAND-II code. Since this process is mostly mathematical and does not account for geometry, shielding and scattering effects, correction factors need to be defined and applied to the measured activities in order to produce a more robust and accurate result. For this purpose, Monte Carlo simulations using the MCNP code were performed to investigate the self-shielding of the foils and its effect on both the neutron flux and the gamma rays emitted. Also, a detailed simulation including the full geometry of the experimental setup was developed and used in order to investigate possible influence of the peripheral materials (cement, other foils, mylar, as well as the aluminum sample holder and rails) to the total flux that reaches each individual foil through scattering of neutrons.

**Keywords** MCNP, multiple-foil activation, neutron scattering, self-shielding

## INTRODUCTION

The operation of the n_TOF facility is based on a Proton Synchrotron, through which large numbers of protons are accelerated to high energies (up to 20GeV/c) in bunches and are directed towards a Pb target. The spallation process that takes place generates huge numbers of neutrons with energies in a very broad spectrum from thermal to a few GeV. The neutron beam is directed to the two experimental areas, EAR1 and EAR2, located in a distance of 185 and 20 m, respectively [1, 2]. After the upgrade of the spallation target in 2020 [3, 4], a new experimental area, the NEAR station, was suggested and constructed in a distance of only 3 m from the spallation target [5, 6]. Its aim is to take advantage of the extremely high neutron fluence that is expected in that proximity to the target (~100 times more neutrons than in EAR2). This new beam line is of great scientific significance as it will allow for activation measurements on extremely small samples, as well as radioactive isotopes with very short half lives that were not previously possible [7].

Due to the aforementioned significance, an extensive campaign has been undertaken to determine the spectral features of the neutron beam using a thermalization detector and through the multiple foil activation technique. As part of the latter, numerous foils have been irradiated (Au, In, Sc, W, Bi, Cd Co, Al, Ni) for three weeks in a configuration of two holders, one upstream and one downstream (Fig. 1), and their induced activities were measured using a HPGe detector. The ultimate goal was to utilize those results along with the SAND-II code [8] and unfold the characteristics of the neutron flux through data deconvolution. In order for the results to be used and the unfolding to be more accurate, corrections for the various phenomena that influenced the induced activities (and are not taken into account by the SAND-II code) must be made. The aim of this study is to calculate the correction factors using the MCNP code [9] and to investigate the self-shielding effect, as well as the influence of the neutron scattering on the peripheral materials to the total neutron flux that impinges on each different target foil.

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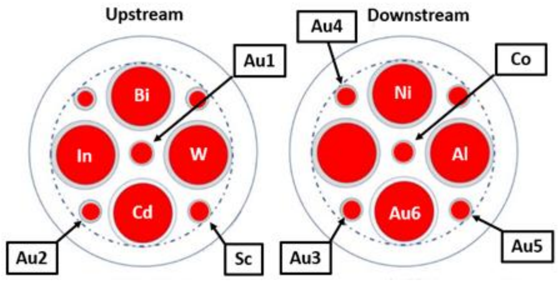


**Figure 1.** *Target configuration on the corresponding holders*

## SELF-SHIELDING

When a neutron beam traverses a material medium, it diminishes exponentially in respect to thickness and with a rate directly dependent on the reaction cross section. For high neutron fluences, this effect is substantial for materials with high resonance peaks. In such cases, the majority of reactions with neutrons of energies near the resonance peak take place in the outer layers of the medium, leading to intense geometrical shielding of the inner ones from the aforementioned neutrons. This phenomenon is called spatial self-shielding.

Due to the fact that most of the material foils used have relatively low cross sections, the investigation of the self-shielding effect was focused on the Au foils (resonance peak at 4.9 eV with up to 27 kb cross section). For this purpose, the MCNP code was used in order to simulate a simple geometry of source and target.

The source was round shaped with diameter that matched that of the target's and produced a pencil beam of neutrons directed towards a 0.05 cm Au target divided in 5 slices of 0.01 cm thickness each, in order to investigate the diminishing effect of the energy-dependent neutron flux in respect to target thickness. The neutron flux emanated from the source is based on the one calculated from the FLUKA team at CERN (Fig. 2).

Results of the mean neutron flux inside each slice of Au in respect to the initial impinging flux on the target, are presented in Fig. 4. As derived, more than 74% of the total reactions with neutrons of 4.75-5 eV energy take place in the first 2 Au slices and only 26% in the remaining thickness, indicating the high geometrical shielding ultimately leading to lower mean absorption per target nucleus.

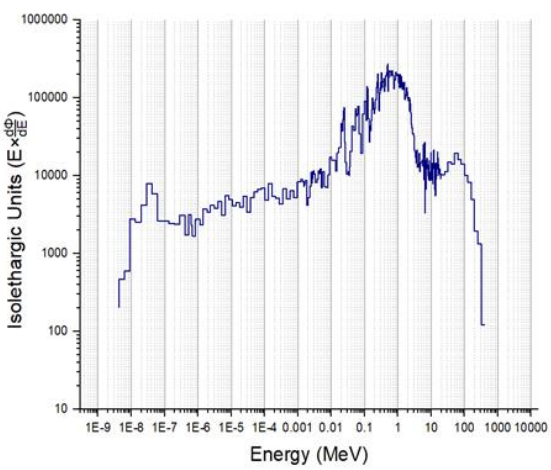


**Figure 2**. *Neutron flux used in the simulations*

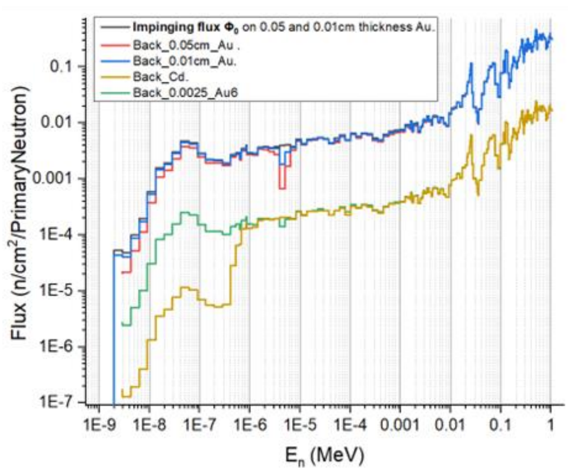


**Figure 3.** *Shielding effect due to upstream Au and Cd foils*

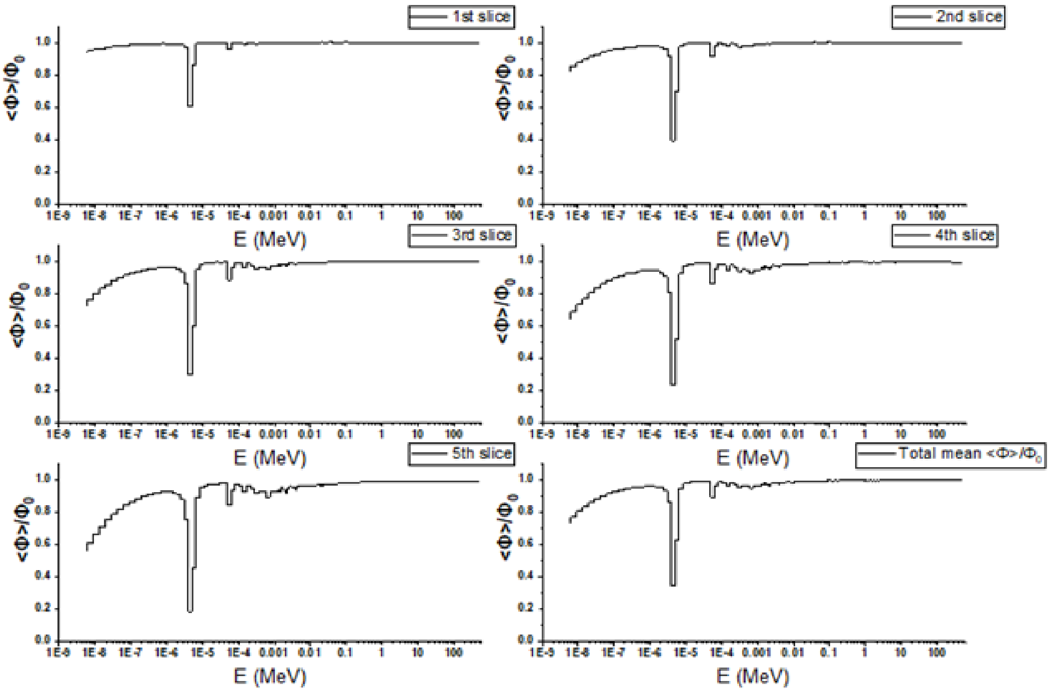


**Figure 4.** *Simulation results for each Au slice and for the total mean flux in the whole Au target of 0.05 cm thickness*

Furthermore, the shielding of the downstream foils from the upstream ones was also studied using similar simulations. In Fig. 3 the impinging and the outgoing flux that reaches the downstream foils are compared for the cases of two Au thicknesses and for the Cd foil. In the case of Au, most of the difference between the two fluxes is focused on the resonance energy region, where only 16.7% and 45.6% transmission of neutrons is expected for 0.05 cm and 0.01 cm thickness, respectively. As far as the Cd foil is concerned, total cuttoff of thermal energy neutrons is expected due to high absorption cross section and thickness (0.1 cm). However, a small flux of neutrons in this energy region is transmitted and reaches the downsrem foil due to the slightly lower diameter (1.27 cm vs 1.3 cm) of the Cd foil.

## NEUTRON SCATTERING DUE TO EXPERIMENTAL AREA GEOMETRY

Neutron scattering on the peripheral materials of the experimental area is expected to have an enhancing effect on the total impinging flux on each material foil and subsequently on the resulting activities. To calculate the magnitude of the scattering effect, a detailed simulation geometry was build (see Fig. 5) including the foils, the two holders along with their mylar covers, the assembly support, the peripheral marble walls and also the back cement wall located at a distance of 4 m from the collimator window.

Figure 6 presents the ratio of the mean neutron, inside the foil, flux for each energy bin, as calculated in the full geometry simulation, to the respective flux derived from a simple geometry simulation (source, upstream and downstream foil), for the case of the Bi upstream target. A small increase of up to 8% magnitude in the mean flux, $<\Phi>$ , is observed across the whole energy range and is attributed to scattering of neutrons in the peripheral materials. In the particular energy region between 0.01 and 1 MeV, a significantly higher increase in the form of acute peaks can be discerned.

The FLUKA simulated flux used for the simulations, predicts a series of minima in certain energy bins in the mentioned region due to absorption of neutrons at the resonances of aluminum materials between the spallation target and the collimator window. These minima, however, are covered by scattered neutrons contributing in the neutron flux inside the foil.

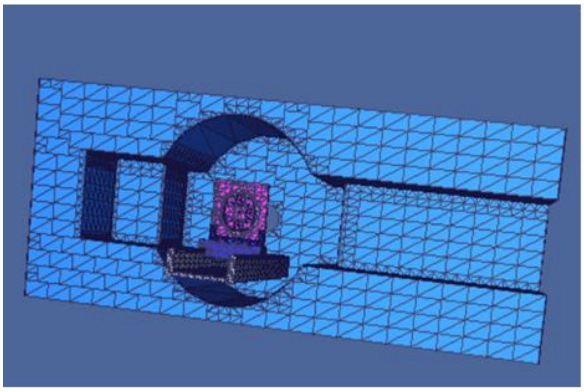

**Figure 5.** *Schematic representation of the full geometry simulation*

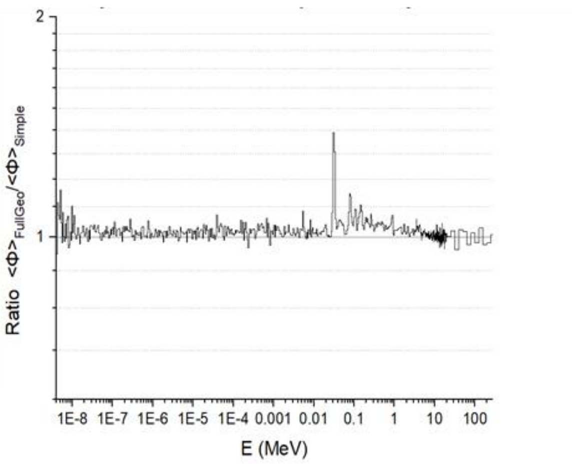


**Figure 6.** *Ratio of <Φ> yield for simulated full geometry to <Φ> yield for simulated simple geometry for the Bi foil*

As a result, the reference flux is significantly lower leading to relatively higher ratio reaching 1.30-1.40 for the 0.03-0.032 and 0.032-0.034 MeV energy bins. For the energy region above 1MeV, the effect is significantly diminished and cannot be distinguished from the statistical variations of the results. Similar behavior is also observed for the other targets.

## CORRECTED ACTIVITIES AND FUTURE PRESPECTIVES

The results of the full geometry simulation that was previously described were used to calculate a single correction factor accounting for all three effects (self-shielding, shielding and neutron scattering). Also, the standard procedure of correcting the yield of the characteristic transitions of each reaction for self-absorption and counting geometry of the emitted γ-rays in the irradiated sample was carried out. The final results of the saturated activities are presented in Table 1.

**Table 1.** *Presentation of corrected experimental saturated activities*

| | | Saturated Activity [Bq/TN] | |
|---|---|---|---|
| Target | Reaction | Before Corrections | After Corrections |
| Au1 | (n,g) | 2.86E-16 | 1.32E-15 |
| | (n,2n) | 3.59E-18 | 4.44E-18 |
| Au2 | (n,g) | 2.62E-16 | 1.16E-15 |
| | (n,2n) | 3.46E-18 | 4.27E-18 |
| Au3 | (n,g) | 2.67E-16 | 1.79E-15 |
| | (n,2n) | 3.84E-18 | 4.07E-18 |
| Au4 | (n,g) | 4.84E-16 | 1.29E-15 |
| | (n,2n) | 3.76E-18 | 3.94E-18 |
| Au5 | (n,g) | 4.49E-16 | 1.24E-15 |
| | (n,2n) | 3.83E-18 | 4.02E-18 |

| | | Saturated Activity [Bq/TN] | |
|---|---|---|---|
| Target | Reaction | Before Corrections | After Corrections |
| Au6 | (n,g) | 7.07E-16 | 8.40E-16 |
| | (n,2n) | 3.90E-18 | 4.00E-18 |
| Cd-114 | (n,g) | 1.32E-17 | 1.36E-17 |
| Sc-45 | (n,g) | 4.40E-17 | 4.29E-17 |
| W-186 | (n,g) | 1.68E-16 | 2.84E-16 |
| Ni-58 | (n,p) | 3.88E-18 | 4.02E-18 |
| | (n,2n) | 2.86E-19 | 2.97E-19 |
| Co-59 | (n,g) | 7.05E-17 | 1.10E-16 |
| | (n,p) | 2.64E-19 | 2.71E-19 |
| Al-27 | (n,a) | 2.95E-19 | 3.00E-19 |

The most significant corrections are for the capture reactions of the Au targets. Most of the total correction is attributed to the self-shielding effect and is diminished as thickness decreases (Au1-0.05 cm vs Au6-0.0025 cm). For the remainder of the reactions the total correction is notably much lower. The next step of this endeavor is to utilize the discussed results along with the SAND-II code in order to unfold the characteristics of the n_TOF neutron flux through data deconvolution [10].

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