OPTIMIZATION OF THE PHOTONEUTRON FLUX EMITTED BY AN ELECTRON ACCELERATOR FOR NEUTRON INTERROGATION APPLICATIONS USING MCNPX AND TRIPOLI-4 MONTE CARLO CODES

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Abstract

Various applications require neutron interrogation to detect special nuclear material (SNM). Carrying out neutron interrogation measurements using the photoneutron flux emitted by an electron accelerator enables to reach average emission intensity on the order of two decades beyond the one produced by deuterium-tritium neutron generators traditionally used for such applications and enables to enhance neutron interrogation performance. In this paper, we characterize the photoneutron flux emitted by an electron accelerator in the energy range of 10 MeV to 20 MeV, and then, optimize the interrogative beam. In order to ensure accuracy and reliability of results, two Monte Carlo codes are used for this study: MCNPX and TRIPOLI-4.

INTRODUCTION

Neutron interrogation is a nuclear measurement technique enabling to detect actinides (^{235}U, ^{239}Pu, etc.) Neutrons are usually produced with a deuterium-tritium generator and thermalized in a dedicated cell in order to increase interaction probability between neutrons and fissile nuclear material. The measurement is based on the detection of prompt and delayed particles emitted further to the fission reactions on actinides. This technique is widely used for homeland security applications [1] and in nuclear waste package characterization studies [2]. We demonstrated previously the experimental feasibility of this technique using a linear electron accelerator [3].

When electrons irradiate the target of an accelerator, Bremsstrahlung photons are generated. The latter can interact by photonuclear reactions before escaping the target. These reactions lead to the production of neutrons commonly referred to as photoneutrons. In the electron energy range of this study (10 MeV to 20 MeV) photoneutrons are mainly created through the giant dipolar resonance. Most photoneutrons are emitted in an isotropic manner following an evaporation process. This approach enables to reach average emission intensity on the order of two decades beyond the one produced by deuterium-tritium neutron generators and enables to expand mass detection limits in neutron interrogation. Higher average emission intensities of the photoneutron flux would enable to expand boundaries of neutron interrogation even further.

This new study aims at gaining accurate knowledge about the photoneutron beam emitted by an electron accelerator and optimizing the latter. Photoneutron flux was characterized according to the three following parameters: angular distribution, energy spectrum, and average emission intensity. Optimization of the photoneutron flux consisted in maximizing photoneutron production and minimizing emission of photons of energy above 6 MeV. Such photons can lead to spurious photofission reactions during measurements. In order to ensure accuracy and reliability of results, two Monte Carlo codes were used for this study: MCNPX version 2.7b [4] developed by the Los Alamos National Laboratory and TRIPOLI-4 version 9 [5] developed by CEA. We carried out this study considering parameters of the electron accelerator of the SAPHIR facility [6]. Electron peak current and pulse duration are respectively of 100 mA and 2.5 µs with 50 Hz repetition frequency. Unless otherwise specified, the target is 1 cm thick with 5 cm diameter. Simulations were conducted with ENDF/B-VII photonuclear cross-sections. For all results, error bars on statistical uncertainties at one sigma are smaller than symbols.

CHARACTERIZATION OF THE PHOTONEUTRON FLUX

In order to determine the photoneutron angular distribution, we simulated a sphere surrounding the target and counted the number of neutrons crossing the sphere in 4° polar angle bins. Fig. 1 presents results obtained with MCNPX for a target made of tungsten or tantalum irradiated by 15 MeV electrons. Although photoneutrons emitted along the diameter of the target are likely to escape from the target with another direction, photoneutrons are overall emitted in an isotropic manner.

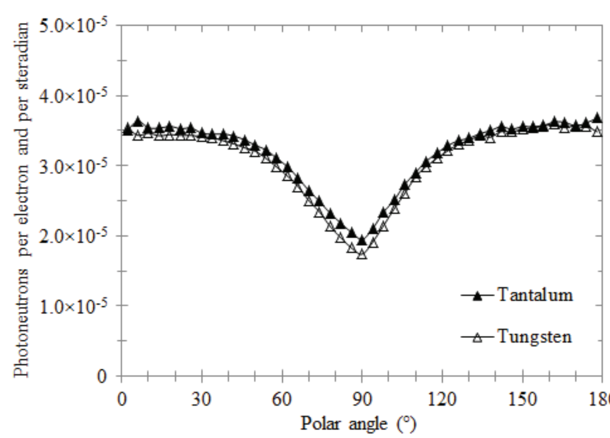

Figure 1: Angular distribution of the photoneutron flux emitted by a tungsten or tantalum target irradiated by 15 MeV electrons.

Photoneutron energy spectrum was determined by counting the number of neutrons crossing the sphere in 200 keV energy bins. Fig. 2 compares results obtained with MCNPX and TRIPOLI-4 for a tungsten target irradiated by 15 MeV electrons. Focus on the low energy region of the MCNPX spectrum is also shown on this figure (calculation conducted for 20 keV energy bins). The energy spectrum is a Maxwell-Boltzmann curve which maximum is reached around 0.5 MeV. The mean energy is close to 1 MeV whatever the electron energy considered between 10 MeV and 20 MeV. We emphasized that shape of the spectrum simulated for a tantalum target is not typical from a Maxwell-Boltzmann curve at low energy (under 0.5 MeV) as illustrated in Fig. 3 and should be investigated.

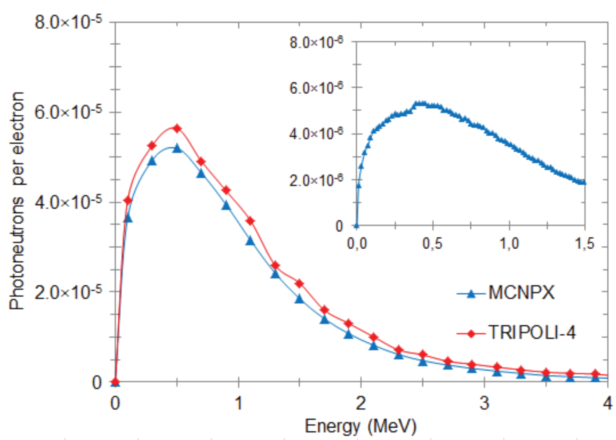

Figure 2: Energy spectrum of the photoneutron flux emitted by a tungsten target irradiated by 15 MeV electrons.

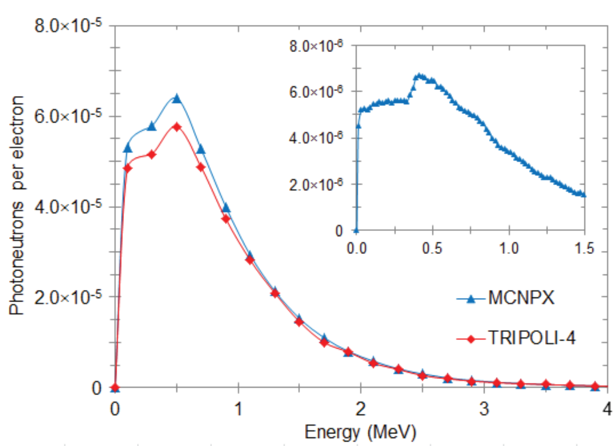

Figure 3: Energy spectrum of the photoneutron flux emitted by a tantalum target irradiated by 15 MeV electrons.

Photoneutron average emission intensity was calculated by multiplying the number of neutrons produced per incident electron on the target, by the number of electrons delivered by the accelerator per second (6.25×10^{17}), by the pulse duration (2.5 µs), and by the frequency (50 Hz). As recommended in a previous study [3], the number of neutrons emitted per electron by a tungsten target was determined with MCNPX from a (γ, xn) production rate calculated by hand from (γ, n) and (γ, 2n) reaction rates using CNDC cross-sections in order to avoid cross-section threshold errors. Simulations carried out for the tungsten target with TRIPOLI-4 and for the tantalum target with both codes were directly determined from a (γ, xn) production rate as no cross-section threshold error is faced during these calculations. Table 1 and 2 present respectively average emission intensities obtained for the tantalum and the tungsten target (statistical uncertainties on production rates are under 0.2%). Gap between results obtained with the two codes is around 10% and emission of 10^{11} neutrons per second is reached at 20 MeV.

Table 1: Average emission intensity of the photoneutron flux emitted by a 1cm thick tantalum target

Electron energy (MeV)	**TRIPOLI-4 ($n.s^{-1}$)**	**MCNPX ($n.s^{-1}$)**	**TRIPOLI-4 / MCNPX**
10	7.14×10^{8}	8.10×10^{8}	0.88
11	2.10×10^{9}	2.32×10^{9}	0.90
12	4.89×10^{9}	5.38×10^{9}	0.91
13	9.94×10^{9}	1.08×10^{9}	0.92
14	1.75×10^{10}	1.89×10^{10}	0.93
15	2.73×10^{10}	2.97×10^{10}	0.92
16	3.98×10^{10}	4.35×10^{10}	0.92
17	5.47×10^{10}	5.98×10^{10}	0.92
18	7.15×10^{10}	7.80×10^{10}	0.92
19	9.00×10^{10}	9.80×10^{10}	0.92
20	1.09×10^{11}	1.19×10^{11}	0.92

Table 2: Average emission intensity of the photoneutron flux emitted by a 1cm thick tungsten target

Electron energy (MeV)	**TRIPOLI-4 ($n.s^{-1}$)**	**MCNPX ($n.s^{-1}$)**	**TRIPOLI-4 / MCNPX**
10	1.11×10^{9}	1.35×10^{9}	0.82
11	2.76×10^{9}	3.26×10^{9}	0.85
12	5.91×10^{9}	6.81×10^{9}	0.87
13	1.14×10^{9}	1.29×10^{9}	0.88
14	2.00×10^{10}	2.23×10^{10}	0.90
15	3.17×10^{10}	3.54×10^{10}	0.90
16	4.69×10^{10}	5.23×10^{10}	0.90
17	6.48×10^{10}	7.23×10^{10}	0.90
18	8.52×10^{10}	9.48×10^{10}	0.90
19	1.07×10^{11}	1.19×10^{11}	0.90
20	1.30×10^{11}	1.45×10^{11}	0.90

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OPTIMIZATION OF THE PHOTONEUTRON FLUX

Increasing thickness of the target enables to boost average emission intensity of the photoneutron beam. We carried out the photoneutron flux optimization study considering electron energy of 17 MeV (energy of reference for experiments). Fig. 4 shows photoneutron average emission intensities calculated using MCNPX and TRIPOLI-4 for 5 mm to 5 cm thick tantalum and tungsten targets. Photoneutron production increases with target thickness until a threshold is reached around 3 cm.

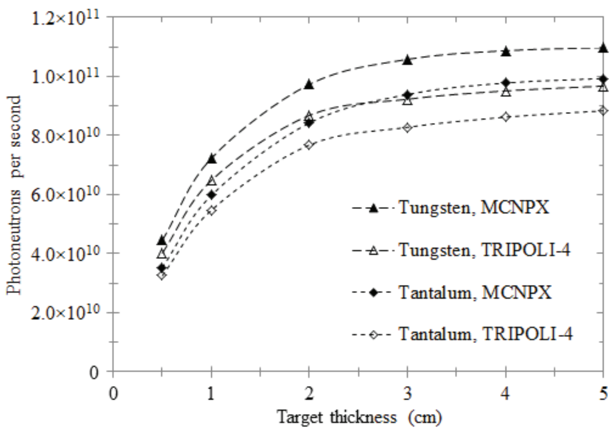

Figure 4: Average emission intensity of the photoneutron flux emitted by a tantalum or tungsten target irradiated by 17 MeV electrons.

Increasing thickness of the target also enables to reduce the number of spurious photons contained in the photoneutron beam and therefore impact of photofission reactions during neutron interrogation measurements. We counted the number of high-energy photons (photons of at least 6 MeV) crossing a sphere surrounding the target. We present results obtained with MCNPX and TRIPOLI-4 in Fig. 5. Spurious photon production decreases with target thickness. Threshold is reached around 3 cm.

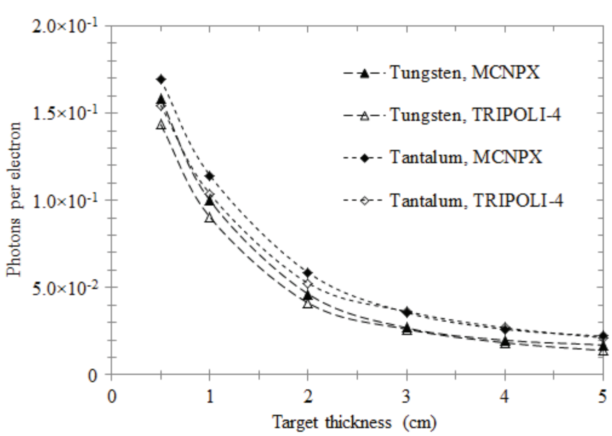

Figure 5: Spurious photon production emitted by a tantalum or tungsten target irradiated by 17 MeV electrons.

We identified that the thickness of the target has an impact on the angular distribution of the photoneutron beam. We simulated the photoneutron angular distribution of 5 mm to 5 cm thick tantalum targets irradiated by 17 MeV electrons. Results obtained with MCNPX are shown in Fig. 6. It can be seen that less photoneutrons emitted in the forward direction escape from the target when thickness increases. It was clarified that this effect is due to the fact that most photonuclear reactions occur close to the surface of the target irradiated by the electron beam (around 1.2 mm deep in the target).

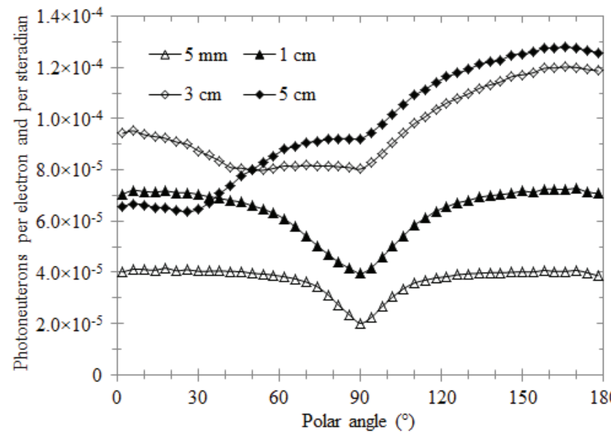

Figure 6: Angular distribution of the photoneutron flux emitted by a tantalum target irradiated by 17 MeV electrons.

CONCLUSIONS AND OUTLOOK

Electron accelerators are powerful photoneutron sources that could offer higher performance in neutron interrogation than traditional neutron generators. Unlike the latter that emit 14 MeV neutrons, usually from deuterium-tritium fusion reactions, the mean energy of the photoneutrons beam is around 1 MeV. Photoneutrons are emitted in an isotropic manner although target geometry effects have to be taken into account. Average emission intensities reached are on the order of 10^{11} neutrons per second with limited spurious photon contamination. Overall, the gap between results obtained with MCNPX and TRIPOLI-4 is around 10%. This slight disagreement is still under investigation.

Work currently in progress aims at evaluating neutron interrogation performance enhancement obtained with an optimized photoneutron beam. We are carrying out measurements with an electron accelerator-based neutron interrogation cell on 220 liter nuclear waste mock-up drum containing samples of uranium and plutonium.

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