Photonuclear reactions in Monte-Carlo simulation (PHOTONUC)

One-year post-doctoral appointment at CEA Paris-Saclay center, 2021 - 2022

Contacts & applications:
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Abstract

*Monte-Carlo codes represent the reference tools for the simulation of particle transport in the field of nuclear instrumentation, for applications concerning the calibration and design of detectors in power reactors, waste monitoring, or nuclear safeguards. In this context, detailed modeling of the physical processes involved requires taking into account the photonuclear reactions induced by high-energy photons (of the order of a few MeV to a few tens of MeV): these reactions release neutrons and other secondary photons, which can therefore contribute to the measurement in the detectors. The distribution of high-energy photons, in turn, depends on the mechanisms of the electromagnetic cascade, which relates the transport of photons to that of electrons and positrons via photo-atomic reactions and the interactions of electrons and positrons by collisions and Bremsstrahlung. To date, a very limited number of benchmarks can be used to characterize the accuracy of Monte-Carlo codes in simulating photonuclear reactions, and the available measurements are often quite old, with very high experimental errors. Preliminary work has revealed differences, sometimes significant (~15%), between the Monte-Carlo codes TRIPOLI-4®, DIANE and MCNP6 on a few simple configurations. The goal of the **PHOTONUC project** is to compare, discuss and if necessary harmonize the simulation strategies of the electromagnetic cascade and the photonuclear reactions implemented in the TRIPOLI-4®, DIANE and MCNP6 codes. A sensitivity study to the modeling parameters will be carried out with the URANIE platform, developed at CEA.*

Introduction

Monte-Carlo simulation is the reference tool for the simulation of particle transport in the field of nuclear instrumentation, for applications concerning the calibration and design of detectors in power reactors, waste monitoring, or nuclear safeguards. In this context, the CEA is developing the TRIPOLI-4® code and the DIANE code, which simulate the transport of electrons, positrons, photons and neutrons [1-4]. To date, very few benchmarks exist to qualify codes in the energy field of interest for **photonuclear reactions**.

Preliminary work to compare TRIPOLI-4®, DIANE and MCNP started in 2019 at CEA, involving the Paris-Saclay center and the CEA/DAM, in the framework of the **PHOTONUC project**. This work consisted in using a few simple configurations resulting from the experiments of Barber and Georges [5], which are one of the rare experiments allowing the validation of photonuclear reactions. These experiments, carried out in the 1950s, consist in irradiating a target of a given material (for example: aluminum, uranium, tantalum, etc.) with a beam of mono-kinetic electrons, by varying the energy of the beam between a few MeV and 40 MeV, then measuring the total number of neutrons emitted by this target, mainly resulting from photonuclear reactions. The benchmark associated with these experiments has been defined so that only the target and the incident electron beam are considered, thus making geometric modeling simple. These experiments are still in use today to validate photonuclear data: see for example [6-8]. Unfortunately, they are marred by an uncertainty of about 15% for each measurement.

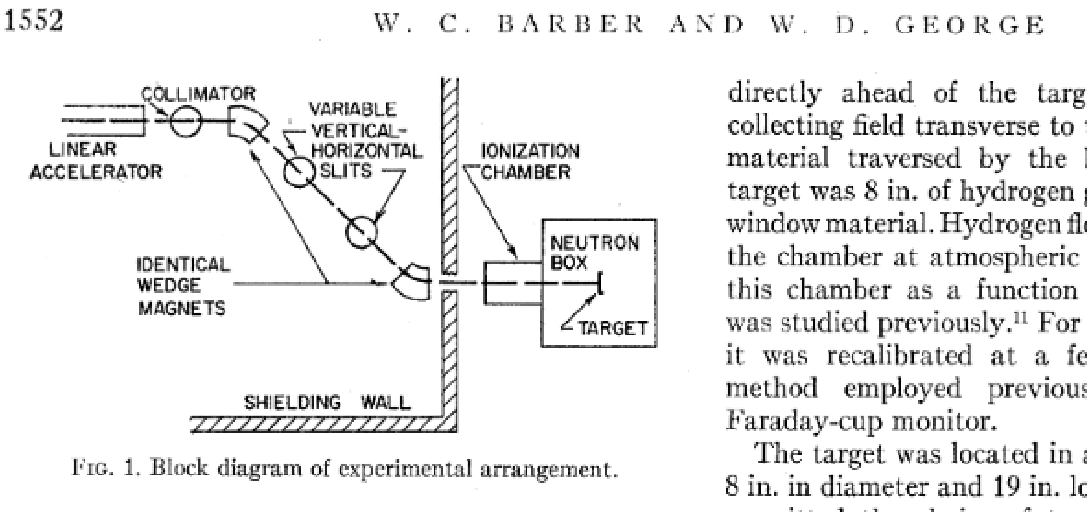

Figure 1 : The experimental setup for the Barber & George benchmark.

This first comparison between TRIPOLI-4®, DIANE and the MCNP6 code (developed at Los Alamos National Laboratory, USA), whose full neutron production results are presented in Figure 2 below, has revealed some large deviations, especially for heavy nuclei. Indeed, for a uranium target for example, a difference of about 15% is observed between the TRIPOLI-4® and DIANE codes on the number of neutrons emitted by the target.

Cible	Energie de faisceau (MeV)	Expérience	MCNP6	DIANE	T4	Exp / MCNP (%)	Exp / DIANE (%)	Exp / T4(%)
Al	22,2	46 ± 7	34 ± 2	33 ± 0	37 ± 2	25	28	19,6
Ta	18,7	520 ± 78	563 ± 8	582 ± 0	513 ± 0	-8,3	-11,9	1,4
Pb	18,7	730 ± 110	606 ± 8	633 ± 0	552 ± 0	17	13,2	24,4
U	16,4	1070 ± 161	1013 ± 14	1072 ± 0	925 ± 0	5,3	0,2	13,5

Figure 2 : Neutron production from various targets, for 10^6 incident particles.

In order to single out these effects and identify the origin of these deviations, we also plotted the particle fluxes as a function of the detection energy and we carried out calculations with a source of photons (by simulating only the photons and neutrons) and with an electron source (by simulating only electrons, positrons and photons, ie without photonuclear reactions). These preliminary comparisons showed that the differences in the integrated values came mainly from the modeling of the electromagnetic shower, as illustrated in figure 3.

Cible	Energie de faisceau (MeV)	MCNP6	DIANE	T4	MCNP/DIANE (%)	MCNP/T4 (%)
Al	22,2	4,76 x 10^5	4,87 x 10^5	5,05 x 10^5	2,31	6,1
Ta	18,7	1,53 x 10^6	1,64 x 10^6	1,46 x 10^6	6,83	5,4
Pb	18,7	1,58 x 10^6	1,70 x 10^6	1,51 x 10^6	7,23	5,6
U	16,4	1,37 x 10^6	1,51 x 10^6	1,29 x 10^6	9,20	5,9

Figure 3 : Number of detected photons for a source of 10^6 electrons (no neutrons simulated).

In the case of an electron-free configuration, a small difference in the number of neutrons detected was observed, but a significant difference in the photon spectrum was clearly demonstrated, as shown in Figure 4.

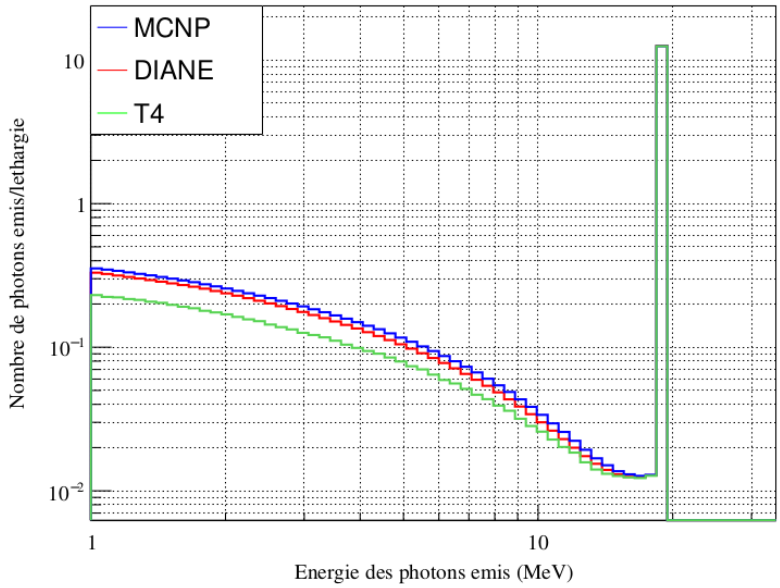

Figure 4 : Number of detected photons for a source including only photons (no electrons simulated).

Scientific goals and work plan

Thus, in order to refine the comparisons and understand the origin of the observed differences, as part of the **PHOTONUC project** we plan to examine the particle production according to each physical phenomenon, in order to estimate the effect of the models chosen by each of the codes. Special focus will be on the **photonuclear reactions**, in view of their central role in relating neutron and photon physics. The **modeling choices** (for example, grouped collisions for electrons, etc.) will be carefully examined and probed.

For this purpose, CEA will hire a **post-doc for a period of 12 months, starting from Fall 2021 (and no later than January 2022)**. The post-doc will be based in the **CEA Paris-Saclay center**, and will be co-supervised between the CEA/Saclay team and the CEA/DAM team.

In order to carry out the project, the proposed **work program** is as follows:

1 / Investigate the state of the art on the simulation of the electromagnetic shower. Getting started with MCNP6 and TRIPOLI-4® codes and their simulation choices with regard to the electromagnetic shower and photonuclear reactions. Modeling of the set of Barber and Georges experiments.

2 / Identification of nuclei and energy ranges for which significant differences exist between the codes. Identification of the models and algorithms responsible for these deviations. Models stemming from codes having state-of-the-art highly sophisticated physical models (for example GEANT4 [9] or PENELOPE [11]) will also be examined in order to confirm the observations. A sensitivity analysis on the parameters of these models will be carried out in order to study the effect on the result of the various parameters, using the URANIE platform [10].

3 / If needed, choice and implementation of improved models. Based on these results, it is desirable, as far as possible, to harmonize the implementation and modeling choices adopted in the codes.

Contacts and applications

The PHOTONUC post-doctoral offer covers **12 months**, starting from Fall 2021 or early 2022 at the latest. **Applications are now open**. To apply, please contact Drs. Sébastien Lemaire (sebastien.lemaire@cea.fr), Alexis Jinaphanh (alexis.jinaphanh@cea.fr), and Andrea Zoia (andrea.zoia@cea.fr) at CEA, by sending a curriculum vitae and a motivation letter. Applications will close on December 2021.

References

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