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Geant4 modifications for accurate fission simulations

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Abstract

Monte Carlo is one of the methods to simulate the generation and transport of radiation through matter. The most widely used radiation simulation codes are MCNP and Geant4. The simulation of fission production and transport by MCNP has been thoroughly benchmarked. There is an increasing number of users that prefer using Geant4 due to the flexibility of adding features. However, it has been found that Geant4 does not have the proper fission-production cross sections and does not produce the correct fission products. To achieve accurate results for studies in fissionable material applications, Geant4 was modified to correct these inaccuracies and to add new capabilities. The fission model developed by the Lawrence Livermore National Laboratory was integrated into the neutron-fission modeling package. The photofission simulation capability was enabled using the same neutron-fission library under the assumption that nuclei fission in the same way, independent of the excitation source. The modified fission code provides the correct multiplicity of prompt neutrons and gamma rays, and produces delayed gamma rays and neutrons with time and energy dependencies that are consistent with ENDF/B-VII. The delayed neutrons are now directly produced by a custom package that bypasses the fragment cascade model. The modifications were made for U-235, U-238 and Pu-239 isotopes; however, the new framework allows adding new isotopes easily. The SLAC nuclear data library is used for simulation of isotopes with an atomic number above 92 because it is not available in Geant4. Results of the modified Geant4.10.1 package of neutron-fission and photofission for prompt and delayed radiation are compared with ENDFB-VII and with results produced with the original package.

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Keywords: Neutron-induced fission; Photofission; Prompt and delayed radiation; Multiplicity; Fission fragment; Time and energy dependencies; Delayed neutrons; cross section; fission rate.

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1. Introduction

Radiation transport simulations are commonly used to aid in the design of systems and experiments. There are several simulations codes used for low-energy physics including MCNP (LANL), VIM (Argonne), and Geant4 (CERN, SLAC). The Geant4 Monte Carlo package was designed and developed by an international collaboration initially mainly for high-energy applications and has an increasing user base attracted by the easy adaptation for different sets of applications. Since then, new extensions have been added for low-energy simulation, including fission. However, some processes such as delayed neutron production have not been implemented.

In addition to the missing delayed neutrons, we also found that the prompt neutron and gamma-ray multiplicity following fission, the cross section and the decay time of the delayed gamma rays are incorrect. This means that Geant4 should not be used for fission simulations because the results would be inaccurate and incomplete. In this work, we modified the Geant4 code to correct the data and the models and to add the missing capability. The results were verified for the main fissionable isotopes with the ENDF\B-VII libraries.

2. Fission simulation with default models in Geant4

We performed Geant4 10.1 simulations with a small sphere of pure nuclear materials hit by a pencil beam of thermal neutrons or 12MeV photons to determine the characteristics of the fission products. Geant4 was run with the NeutronHP model (high precision neutron model for neutron-fission), Cascade model (photofission) and Radioactive Decay Physics to compare the results.

2.1. Multiplicity

Zucker and Holden (1986) measured the prompt neutron multiplicity following neutron-induced fission of several fissionable isotopes as a function of the energy of the incident neutrons. Their data shows an average multiplicity of 2.41 neutrons/per fission for U-235 induced by thermal neutrons. Lengyel et al. (2016) claimed an empirical calculation of average prompt neutrons for photofission, which shows average 3-3.4 neutrons/per fission of U-235 induced by 12MeV photons. Valentine (2001) used an approximation adopted by spontaneous and neutron induced fission modules. The prompt gamma-ray multiplicity ranges from 0-20 gamma rays/per fission with an average that varies with isotope and average prompt neutrons. We used Valentine's model to estimate the average multiplicity values of U-235 induced by thermal neutrons and 12 MeV photons to be ~6.7 and ~7.6, respectively.

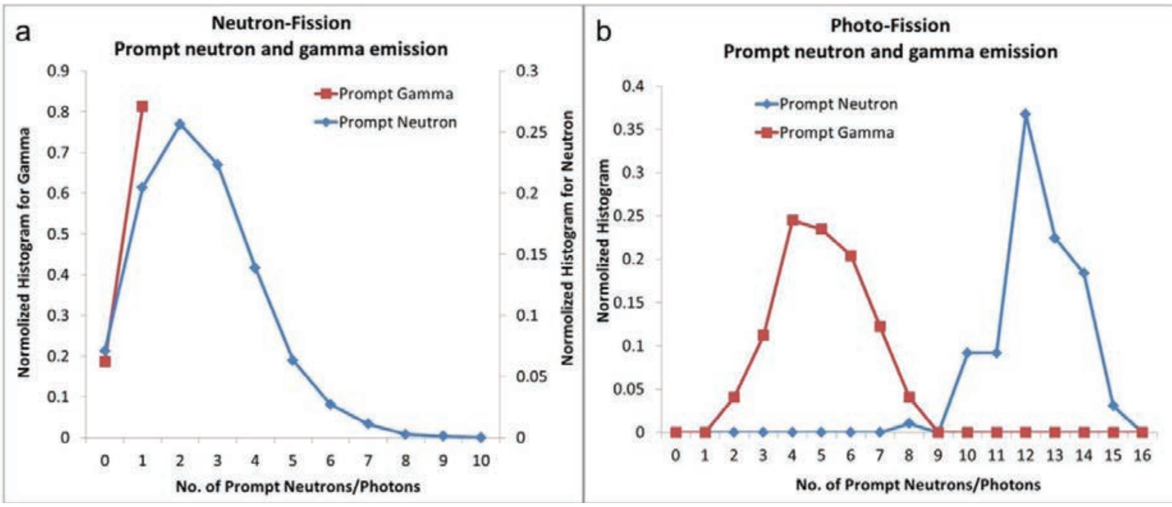

Fig. 1. Prompt multiplicity distributions for neutron induced fission (a) and photofission (b) simulated with Geant4 10.1.