ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR – ABEN
2019 International Nuclear Atlantic Conference - INAC 2019
Santos, SP, Brazil, October 21-25, 2019

Agência Brasileira do ISBN
ISBN 978-85-99141-08-3

DETECTOR SIMULATION IN GEANT4 TO REACH 140BA IN THE URANIUM FISSION FRAGMENT

Eduardo P. Longhini[1], Frederico A. Genezini[1] and Mauricio Moralles[1]

[1] Instituto de Pesquisas Energéticas e Nucleares (IPEN / CNEN - SP)
Av. Professor Lineu Prestes 2242
05508-000 São Paulo, SP
pedroso.longhini@gmail.com.br

ABSTRACT

Exotic nuclei cross sections data became crucial for the nuclei formation study existing in nature and for the reactors engineering. These data are currently determined in experiment realized in post-accelerator or high intensity neutron sources. So, in IPEN is being studied an experiment to calculate the neutron-rich nuclei cross section using the IEA-R1 reactor. The first step is to development software in GEANT4 to determine 140Ba quantities when a Uranium sample is irradiated. 140Ba is an interest element in nuclear astrophysics with half-live sufficient to be detected in Uranium fission chain within nuclear reactors. The GEANT4 Detector Construction class is the class where the Uranium sample and neutron source are localized and the Physics and Process class determine the neutron source beam characteristics. Two tests were performed with different neutron quantities in the irradiated beam which is directed to a Uranium sample, with 20% of U235 and 80% of U238, in box shape. For the first test were produced 121 nuclei. And, for the second test was produced 3568 nuclei, being a value reasonable to detect in the experiment.

1. INTRODUCTION

Post-accelerators and high-intensity neutron sources are allowed to explore nuclei with nuclear structure inside the regions far from the stability line, Fig. 1.

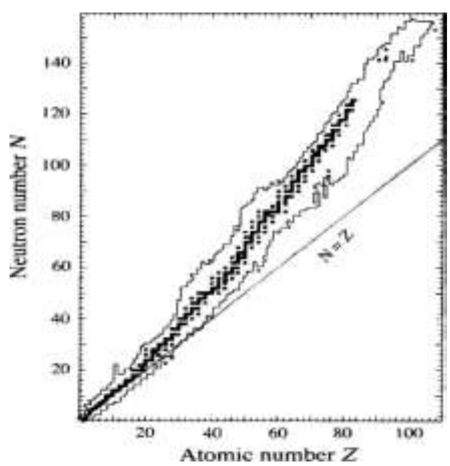

Fig. 1 - Black squares are the stable, long-lived nuclei that occur in nature. Other known cores are within irregular lines and are unstable [1].

There nuclei, knowns as exotic nuclei, have as property to be rich or poor in neutrons quantities, resulting in an asymmetric between proton (Z) and neutrons (N) number. For example, the Lithium-11 asymmetric has as result 2.7, so this element has more neutrons than protons. The half-live values are other useful characteristic for exotic nuclei, it corresponds by an order of magnitude of milliseconds and tens of minutes [2], being sufficient to manipulate their radioactive beams and to analyze the nuclear material interaction, in a neutron-proton asymmetry degree well differentiated from that observed in nuclear stability line nuclei.

To obtain nuclei riches in neutrons data, as cross section, it is necessary a high intensity neutrons sources, as nuclear reactors. In this case, the target nucleus used for the neutron capture process has to be a radioactive nucleus, generating a product nucleus with characteristics far from the stability line [1].

The way to find a target radioactive nucleus is using the fission products. However, any theses products don´t have long half-live to allow a chemical separation after the fissile material irradiation. To get the adequate target radioactive should be, initially, to measure the cross section from a chemical solution with fissile material. So, the irradiation process is going to generate product nuclei rich in neutrons and these products, and the solution too, may capture others neutrons from the neutron beam. By the neutron capture, product nucleus with characteristics far from the stability line may to be produced, with this, they are going to decay. And, with the decay measure is possible to obtain the exotic nucleus interest cross section data [2].

With this experiment type opens the opportunity to understand the nuclei formation process in nature and their relatives abundances, being utilized in researched about nuclear astrophysics and reactor engineering [3, 4, 5].

1.1. Nuclear astrophysics: Nucleosynthesis.

The elements synthesis with mass above iron and nickel are generate by neutron capture process, in temperature, pressure and density physics conditions for the reactions occur in neutron star and supernovas [2]. The Fig. 2 shows the neutron capture process by a nucleus seed, with atomic number Z, in a stellar ambient. The nucleus seed, after capture process, becomes in a neutron rich nucleus. So, with the increase and the excess neutron, the isotopes remain unstable until to decay by beta minus. The decay occurs when it is quicker than the neutron capture, so, the captures stop and begin the nucleus production with atomic number Z+1 [2]. The neutron capture process may be separated in two: s-process and r-process. Their different is the neutron density, respectively, ≈ 108 cm^{-3} and ≥ 1020 cm^{-3} [3].

Fig. 2 - A seed nucleus captures neutrons generating a neutron-rich elemento [6].

The s-process generate nucleus below the bismuth and lead mass region, due the neutrons density slows in the stellar ambient [6] and, also, there nuclei decay by alpha, so, it doesn't permit higher atomic number be created by slow capture [7].

The r-process is responsible to create the chemical elements marjority above the bismuth and transuranic elements mass in nature. Due the neutron intensity flux and temperatures conditions in ambiente stellar [8-15]. It permits the nuclei formation richer in neutrons in time smaller intervals [6]. And, the heavy elements fission process, in the formation chain, serves as seeds for new chains that are formed by neutron captures.

2. OBJECTIVE

To measure the interest nuclei exotic cross section and to compare the value with nuclear data libraries is being studied the better arraignment experiment using as neutron source the IEA-R1 nuclear reactor localized in the Instituto de Pesquisas Energéticas e Nucleares (IPEN). This reactor is the research type with 5MW power and it permits irradiations inside your core with neutron flux until $1{\cdot}10^{14}$ n.cm^{-2}s^{-1}. But, to calculate neutron capture cross section data from fission products should be overcome some difficult technical, like the fissile material quantity may to be used in the irradiation, crew dose, methodology for neutron energy selection and others. So, the study is divided in two parts: simulation in GEANT4 and experiment in IEA-R1.

The simulation is going to measure the radioactive nuclei quantities formed for Uranium sample irradiation in arrangement experiment different and to analyses the dose and detection limit for the nuclear reactor and crew operation safety during the experiment.

So, in this scope, this work has as objective the simulation in GEANT4 to find the 140Ba quantities produced from the Uranium sample irradiation.

3. SIMULATION IN GEANT4

The simulation was realized in the GEANT4 (GEometry ANd Tracking) software in your 10.5 version. It is a GEANT4 series simulation platform, development by CERN, and uses the Monte Carlo methods to calculate particle passage in the matter [16]. The simulation must contain the detector geometry and materials, the particles and physics process for to simulate the experiment.

3.1 Geometry.

In GEANT4 ambient, the detector construction is derived concrete class from G4VUserDetectorConstruction abstract base class. This class able to implement the method Construct (), it modular each detector component or sub-detector, as their shapes/solids, to construct and to place detector geometry volumes, to define sensitive detectors and identify detector volumes which to associate them and others. To define detector geometry is need three conceptual layers: G4VSolid, G4LogicalVolume and G4VPhysicalVolume. G4VSolid requires the shape and size; G4LogicalVolume requires daughter physical volumes, material, sensitivity, user limits, etc; G4VPhysicalVolume requires position and rotation [16].

For simulation, the detector geometry is made with two volumes: World and Uranium sample. The principal is the largest volume called "World". Your shape is a cube with dimensions of 200 x 200 x 200 cm, it was a sufficient local where the neutron source and uranium material was positioned.

The Uranium sample is called daughter volume of the world, in other words, it is within the World. The Uranium sample has a box shape, with 5 x 5 x 5 mm. It contains as material: 80% of U-238 and 20% of U-235, with 19.1 g/cm^3 density. So, the mass this cube is 2,4 kg.

3.2 Particles and Physics process.

For describe particles, the GEANT4 supplies three class levels: G4ParticleDefinition, G4DynamicParticle and G4Track. G4ParticleDefinition requires the particle static properties, as name, mass, spin, PDG, number, etc. G4DynamicParticle requires energy, momentum, polarization, etc. G4Track requires information for tracking in a detector simulation, as position, step, current volume, track ID, parent ID, etc [16].

The particles defined were thermal neutrons (0.025 eV) and they are positioned together in a neutron source. The neutron source launches the neutron beam in the uranium material direction; these neutrons launched are going to fission the uranium nucleus and to form new elements.

For describe physics process, it needs to decide when and where an interaction occurs and to generate the final interaction state. So, for this, GEANT4 supplies an abstract class called G4VProcess. In this class is defined three kinds of actions: AtRest actions (as decay, e^+ annihilation, etc), AlongStep actions to describe continuous actions, occurring along the path of the particle and PostStep actions for describing point-like actions [16].

The physics processes selected are the Radioactive Decay, Transportation processes and NeutronHP. These three processes show the interaction between neutron and uranium material (if it creates new elements and if the new elements decay to others elements). The Radioactive Decay is based in G4RadioactiveDecay class, it is responsible for initializing and loading values from the data libraries, initializing the decay types and the variance reduction and decay chain handling. The G4NeutronHP is a package in GEANT4 allows using evaluated nuclear data libraries in the G4NDL (in a class with data files for the high precision neutron models based in different databases as Brond-2.1, ENDF/B-VII and others) in format, this package is recommended to use it, because the limitations of using evaluated nuclear data libraries [16]. And, to obtain the fragments from Uranium fission in GEANT4 is necessary to active a code: G4NEUTRONHP_PRODUCE_FISSION_FRAGMENTS.

With the particles and physics process defined the next step is to specify all physics process in the simulation in a class called Physics list. So, the majority class to use in GEANT4 is called G4VUserPhysiscsList. This class supplies three methods: ConstructParticle(), ConstructProcess() and SetCuts(). ConstructParticle() requires to define the particles necessary for the simulation. ConstructProcess(), for each particle, requires to assign all the physics processes relevant to the simulation. SetCuts() requires to set the range cuts for secondary production for processes with infrared divergence [16].

4. TESTS TO GENERATE 140Ba NUCLEI

Two tests were generated with different neutron quantities launched in the uranium material direction, Table 1.

	140Ba nuclei
First Test	121
Second Test	3568

In the first test the neutron beam contains 1 thousand of neutrons. And, the 140Ba quantities were 121 nuclei. It shows the simulation permitted to find the 140Ba using the Detector Construction, Particles and Physics Process classes created for the simulation. So, the second test was realized to estimate 140Ba quantities in a 1 million of neutron beam. This situation was realized, because this beam is closer to a nuclear reactor environment, like IEA-R1. For this case, 3568 nuclei of 140Ba were created.

4. CONCLUSIONS

The program is a Uranium sample irradiation example useful which shows how to find fission fragments products and how to calculate the quantities these products. For the interest element, 140Ba, two tests were realized: the first shows the production the 140Ba with 121 nuclei quantities; the second test was realized to calculate the production the 140Ba nuclei in a nuclear reactor environment, where the neutron beam is approximately 1 thousand of neutrons, the quantities calculate was the 3568 nuclei, being a value reasonable to detection in experiment.

Both tests help to understand the classes which permit to construct the physics list class with Radioactive Decay and Hadronic Process. And how to construct the first steps to the experiments with uranium sample and neutron thermal source in the DetectorConstruction class. But, some changes should be realized as the Uranium sample size.

This program is the primary step to obtain the better arrangement experimental to calculate the section cross the astrophysics interest elements. And the next steps for simulation are to add a detector and better irradiation ambient. So, to calculate the dose generate in the irradiation and, so, to determine on the correct shields for radiological protection. Others possible works are to realize a couple between GEANT4 and SERPENTE, the second software may to help better the reactor ambient, approaching the IEA-R1 characteristic and the possible neutron beam launched in the real experiment.

ACKNOWLEDGMENTS

Acknowledge the help of IPEN and source of funding CNEN.

REFERENCES

1. JURANDO, B.; BARREAU, G.; BACRI, C. O. Radioactive target needs for nuclear reactor physics and nuclear astrophysics, **Nuclear Instruments and Methods in Physics Research A** 613, 343-346 (2010).
2. MARTIN, B. R. **Nuclear and Particle Physics:** an introduction. 2^{nd} ed. New York: John Wiley & Sons, 2006. 411 p.
3. Departamento de Física Nuclear. **Laboratório do Acelerador Linear.** São Paulo: USP. [acesso em 05 junho 2018]. Disponível em: http://portal.if.usp.br/fnc/pt-br/laboratorio-do-acelerador-linear-linac.
4. BERTOLLI, M. G.; HERWIG, F.; PIGNATARI, M.; KAWANO, T. Systematic and correlated nuclear uncertainties in the i-process at the neutron shell closure N=82, **Solar and Stellar Astrophysics**, 1-15 (2018)
5. DUDERSTADT, J. J. **Nuclear Reactor Analysis**. 1 ed. New York: John Wiley & Sons, 1976.
6. VILLARI, A.C.C. **Núcleos Exóticos.** São Paulo: USP, [acesso em 19 junho 2018]. Disponível em: http://www.iaea.org/inis/collection/NCLCollectionStore/_Public/22/070/22070690.pdf
7. TERUYA, N. Núcleos exóticos e síntese dos elementos químicos. **Química Nova**, v. 35, no. 2, 360-366 (2012).
8. KRATZ, K., L et al. R-process isotopes in the ^{132}Sn region. **European Physics Journal** 25, s01, 633-638 (2005).
9. BAO, Z. Y. et al, **Neutron cross sections for nucleosynthesis studies**, Atom. Data Nucl. Data Tables 76, 1 (2000).
10. MEYER, B. S. et al, R-process nucleosynthesis in the high-entropy supernova bubble, **The Astrophysical Journal** 399, 656-664 (1992).
11. TOVESSON, F.; LAPTEV, A. B.; HILL, T. S. Fast neutron-induced fission cross sections of 233,234,236,238U up to 200 MeV, **Nuclear Science Engineering** 178, 1 (2014).
12. GORIELY, S.; BAUSWEIN, A.; JANKA, H. R-process nucleosynthesis in dynamically ejected matter of neutron star mergers. **The Astrophysical Journal Letters** 738, L32 (2011).
13. OBRIEN, S. et al. Neutron capture cross section of 139La. **Physics Review**. C 68, 035801 (2003).

14. CHADWICK et al, ENDF/B-VII. 1 nuclear data for science and technology: cross sections, covariances, fission product yields and decay data, **Nuclear Data Sheets** 112, 2887-2996 (2011).
15. CARLSON, A. D. et al, International evaluation of neutron cross section standards. **Nuclear Data Sheets** 110, 3215-3324 (2009).
16. Geant4 Collaboration. **Introduction of Geant4**, Version: Geant4 10.3 (2016).