2021 International Nuclear Atlantic Conference – INAC 2021
Virtual meeting, Brazil, November 29 – December 2, 2021

ISBN: 978-65-594-1256-3

Preliminary results of Monte Carlo study of an experiment to calculate thermal neutron cross section using neutron beam from the IEA-R1 reactor.

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

[1]*pedroso.longhini@gmail.com, IPEN - Av. Prof. Lineu Prestes, 2242 - Butantã, São Paulo - SP, 05508-000*

1. Introduction

Many nuclear reactions play an important role in different knowledge fields. Neutron capture reactions, for example, are fundamental to understand the mechanisms to produce heavy chemical elements in star, called s- and r-process [1-2]. In nuclear reactor physics, this reaction is studied to verify chemical elements that absorbed the neutrons generated in the fission, these elements are called neutron poison and hamper the nuclear reactors operation and safety [3]. In both cases, the calculate of neutron capture probability by nuclei, called neutron capture cross section, is very useful for the progress of this studies.

Neutron capture cross section are, generally, calculated by statistical methods and available in cross section libraries as ENDF and JEFF [1]. But all calculations must be validated by comparison with experimental results. One way to calculate the measurement of neutron capture cross section is to induce neutron reactions in target nucleus using neutron beam from nuclear research reactors and detecting the products from the reactions, like in neutron activation analysis method [4-5].

Neutron activation analysis consists in the conversion of a nuclei to other, mostly radioactive nuclei via nuclear reaction and reaction product measurement. So, a target nucleus is bombarded with neutrons and a compound nucleus is formed. The compound nuclei quantities are measurements by prompt-gamma ray or delayed gamma ray detection, Fig. 1 [5].

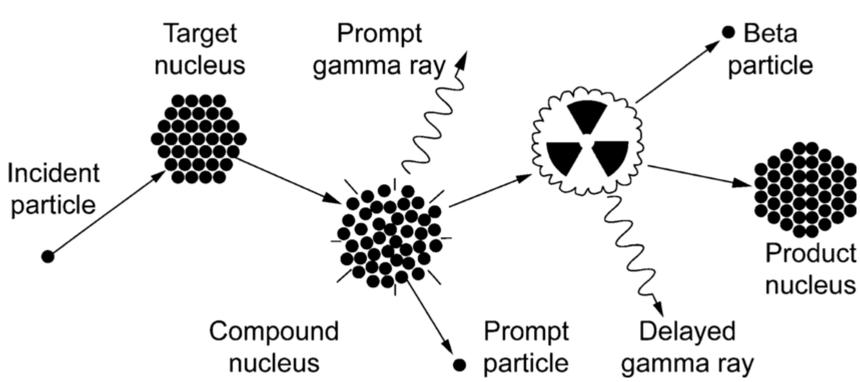

Figure 1: NAA scheme [6].

To develop this experiment type in Brazil, research reactor IEA-R1 is a powerful neutron source. It is localized at the Instituto de Pesquisas Energéticas e Nucleares (IPEN) and the highest power research Brazilian reactor, with 5MW power. The neutron flux in the core can reach is 10^{14} $n.cm^{-2}.s^{-1}$ and irradiations in channels located outside the swimming pool, 10^{8} $n.cm^{-2}.s^{-1}$ [7].

In this work, an experiment was simulated to calculate thermal neutron capture cross section using NAA and neutron beam from IEA-R1. The simulation was developed in Geant4, a Monte Carlo simulation toolkit, and the chemical element used was ^{59}Co.

2. Methodology

The simulation development was divided in three steps: determination of thermal neutron fluence, experiment simulation and determination of peak efficiency.

To determine thermal neutron fluence was simulated the cadmium-difference method with activation of ^{197}Au foil in Geant4. The results from simulation were used in the equation [8]:

$$\Phi_{th} = A\frac{\left(1-\frac{F_{cd}}{R_{cd}}\right)}{N_0 \cdot \sigma_{th} \cdot F_p} \tag{1}$$

where A is reaction rate in Gold foil $^{197}A(n,\gamma)^{198}A$; F_{cd} is Cadmium factor, considered 1.098; R_{cd} is Cadmium ratio; N_0 is Gold nuclei quantities in the sample; F_p is flux perturbation factor, considered 0.98; σ_{th} is Gold thermal neutron cross section, considered $9.834 \cdot 10^{-23}$ cm^2.

To build the neutron beam in Geant4, using GPS methods, is required the beam shape and neutron energy spectrum. The beam shape was determined square because sample has transversal area in format square. The neutron energy spectrum was adapted to Geant4 from calculate performed by IEA-R1 core simulation in MCNP. To run the simulation was considered an fluence value of 10^6 $n.cm^{-2}$.

To calculate the reaction rate $^{197}Au(n,\gamma)^{198}Au$ in the cadmium-difference method, the simulation was development following steps: ^{197}Au foil irradiation without cadmium and with cadmium. In Table I is the input data for ^{197}Au and Cd samples.

Table I: Characteristics for ^{197}Au e Cd samples.

	Au	Cd
Atomic Number	79	48
Isotope	197	106 (1.2%), 108 (0.9%), 110 (12.4%), 111 (12.8%), 112 (24.0%), 113 (12.3%), 114 (28.8%) and 116 (7.6%)
Density	19.30 g/cm^3	8.65 g/cm^3
Dimensions	1x1x0.02 cm	1x1x0.05 cm

The ^{198}Au nuclei quantities, without Cd and with Cd, calculated were, respectively, 98902 nuclei and 1524 nuclei. With these quantities, the cadmium ratio was calculated in 65.03. The value of thermal neutron fluence is:

$$\Phi_{th} = 507278 \text{ n.cm}^{-2}$$

The experiment development in Geant4 was simplest with the components building: ^{59}Co sample, Table II, and HPGe detector.

Table II: Characteristics of ^{59}Co sample.

Characteristics	Values
Atomic Number	27
Atomic Mass	59
Density	8.30 g/cm^3
Dimensions	1x1x0.01 cm

The ^{59}Co sample was positioned in the "World" center and the detector, in vertical on top of sample. The detector position was determined from the delayed gammas angular distribution in the ^{60}Co decay. To analyze the quantities of gammas detected, five different distances between the sample and detector were simulated, from 10 cm to 30 cm, with range of 5 cm. For each distance, the simulation is run 5 times to obtain a statistical approach. The thermal neutron cross section for ^{59}Co was calculated by:

$$\sigma_{th} = \frac{C}{N_0 \cdot I_\gamma \cdot \varepsilon_\gamma \cdot \Phi_{th}} \tag{2}$$

where C is gamma rays quantities counts in the detector, I_γ is emission probability, Φ_{th} is thermal neutron fluence, ϵ_γ is energy peak intensity and N_0 is ^{59}Co nuclei quantities in the sample.

The gamma ray from ^{60}Co decay used to calculate the thermal neutron cross section has energy of 1.173 MeV. This energy has emission probability 99.98% and the energy peak intensity is modified in each different distance between the detector and sample.

To calculate the correct peak intensity in each distance, gamma detection simulations from ^{60}Co decay sample was run. The detector positions were the same to ^{59}Co irradiation simulation. Then, one million of events were generated and from gamma rays counts in the detector, the energy peak intensity was calculated by the ratio between gammas detected quantities and gammas emitted quantities, Table III.

Table III: Energy peak intensity in each distance.

Distance	Values
10 cm	0.004973
15 cm	0.001377
20 cm	0.000626
25 cm	0.000338
30 cm	0.000221

3. Results and Discussion

The thermal neutron cross section results for ^{59}Co in different distances between sample and detector are showed in the Table IV.

Table IV: Thermal Cross Section to ^{59}Co.

Distance (cm)	Thermal Cross Section (barn)
10	38.49 ± 1.52
15	64.31 ± 14.38
20	35.37 ± 6.20
25	39.81 ± 12.35
30	45.18 ± 19.14

The thermal neutron cross section results in the distances 10, 20 and 25 were more accurate when compares with value calculated in the JENDL-4.0 library, 37.21 b. But the distances 20 and 25 cm showed highest uncertainty value while the 10 cm distance showed the lower uncertainty. This difference is causing by gamma ray count in the detector. For the distances 20 and 25 cm, the counts were, respectively, 10 ± 3, 6 ± 2. And for distance 10 cm, the count was 88 ± 9 counts. So, the setup that provided a more accurate result was with 10 cm of distance between sample and detector.

The distances 15 cm and 30 cm, thermal cross section values were lower accurate. For 30 cm, a little quantity of gamma ray arrived in the detector, only 5 ± 2 count. In the 15 cm, the gamma ray count was 41 ± 6, but the thermal cross section inaccurate showed an inappropriate setup.

4. Conclusions

The detection of delayed gamma from ^{60}Co decay was better in setup with 10 cm the distance between detector and sample. Hence, the thermal cross section for ^{59}Co calculated in this setup showed the smallest uncertainty among all distances. The experiment's setup simulated in Geant4 showed to be feasible and to validate it, the experiment must be run in the IEA-R1 irradiation channel. However, other stages of the experiment must be simulated, such as the radiological protection and the structure for fixing the experiment components.

Acknowledgements

Acknowledgements for the technical support from CRPq-IPEN team and funding source CNEN.

References

[1] B. Pritychenko et al. "Calculations of Maxwellian-averaged Cross Section and Astrophysical Reaction Rates Using the ENDF/B-VII.0, JEFF-3.1, JENDL-3.3 and ENDF/B-VI.8 Evaluated Nuclear Reaction Data Libraries," *Atomic Data and Nuclear Data Tables*, vol. 1, pp. 1-148 (2009).

[2] J. Carlson et al. "White paper on nuclear astrophysics and low-energy nuclear physics, Part 2: Low-energy nuclear physics," *Progress in Particle and Nuclear Physics*, vol. 94, pp. 68-124 (2017).

[3] B. Satheesh. "Analysis of the thermal neutron capture cross sections and resonance integrals of the ^{80}Se(n,γ)^{81m,g}Se reactions", *Proceedings of the DAE Symp. on Nucl. Phys*, vol. 59, pp. 578-579 (2014).

[4] R. Reifarth et al. "Reactor neutrons in nuclear astrophysics," *EPJ Web Of Conferences*, vol. 146, pp. 1-3 (2017).

[5] R. Greenberg et al. "Neutron activation analysis: A primary method of measurement", *Spectrochimica Acta Part B*, vol. 66, pp. 193-241 (2011).

[6] M. Glascock et H. Neff "Neutron Activation Analysis and Provenance Research in Archaeology". *Measurement Science and Technology*, vol. 14, pp.1516-1526 (2003).

[7] J.R. Maiorino, "The utilization and operational experience of IEA-R1 Brazilian research reactor", *International Symposium on Research Reactor utilization safety and management*, pp. 1-10 (1999).

[8] C.B. Zamboni, "Fundamentos da Física de Nêutrons". Ed. Livraria da Física (2007).