2011 International Nuclear Atlantic Conference - INAC 2011
Belo Horizonte,MG, Brazil, October 24-28, 2011
ASSOCIAÇÃO BRASILEIRA DE ENERGIA NUCLEAR - ABEN
ISBN: **978-85-99141-04-5**

IMPACT ON GEOMETRIC EFFICIENCY OF HPGE DETECTORS DUE TO UTILIZATION OF COLLIMATORS ON MEASURES OF RADIAL DISTRIBUTION OF NUCLEAR REACTION RATES AT IPEN/MB-01 REACTOR PELLETS.

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ABSTRACT

Since 2007, IPEN/MB-01 reactor team has been working to determine fission and radioactive capture reaction rates along the radial direction in it's fuel pellets accurately. For this purpose, disks with the same fuel enrichment of the fuel pellets (4.3%) are irradiated at 100 watts at central position of reactor core and are later subjected to gamma spectrometry, where the nuclear reaction rates in the radial regions of the disk are discriminated with the use of collimators during the disk spectrometry.

Studying the results it was found that these collimators provoked changes in the geometric efficiency of HPGe detection system, creating discrepancies between the reaction rates obtained experimentally and those obtained via calculation (MCNP Code). To correct these effects, geometric efficiency correction factors were determined through modeling of the detection system and the transport of gamma photons in MCNP. This methodology and results are presented in this work and showed that this type of correction is indispensable in this measurements. Nuclear reaction rates along the radial direction of the fuel with geometric efficiency corrections are also presented and showed good agreement compared with calculated data.

1. INTRODUCTION

Measurements of reaction rate and spectral indices have been conducted in the reactor IPEN/MB-01 for at least 15 years [1,2]. Since 2007, the researchers of the reactor team have been working to determine fission and radioactive capture reaction rates along the radial direction in it's fuel pellets accurately [3,4]. For this purpose, disks with the same fuel enrichment of the fuel pellets (4.3%) are irradiated at central position of reactor core at 100 watts power level for 1 hour. These disks are later subjected to gamma spectrometry, where the nuclear reaction rates in the radial regions of the disk are discriminated with the use of lead collimators. Ten collimators with different diameters have been used, consequently, the nuclear reactions of radioactive capture that occurs in atoms of ^{238}U and the fissions that occurs on both ^{235}U and ^{238}U are measured in function of ten different regions (diameter of collimator) of the UO_2 fuel pellet disk.

The main drawback to this type of experimental technique is that the introduction of these collimators causes, in some cases, major reductions in the geometric efficiency [5,6] of the HPGe detection system (HDS) which can lead to large errors in measurements of nuclear reaction rates. So the count values obtained during the counting process should be corrected. For that, the system was modeled using the code MCNP. A source of photons was included in this modeling to compare the efficiencies between measurements with and without the collimators. The ratio between these calculated efficiency make it possible to obtain correction factors for each of collimators.

This work aims to show the impact of the introduction of these collimators on measures of radial distribution of nuclear reaction rates and the calculated correction factors using photon transport of MCNP using ENDF/B-VII nuclear data library.

2. METHODOLOGY

The collimators have cylindrical symmetry, identical to the irradiated fuel disks. This geometry allows the discrimination of photons from different regions of the disks fuels (concentric rings). The central cavities of the collimators were manufactured by the wire Electro-Erosion process whose precision for cutting lead is the order of a thousandth of a millimeter. Associated with the collimators, filters are also used to attenuate the primary radiation and secondary X-ray from the scattered photons. The first filter is a layer of lead that serves as primary filter and the second and third layers are filters of copper and aluminum that diminish almost completely the scattered photons from the collimator and from the primary filter. The collimator can be seen in figure 1 along with the associated filters in the HPGe detection system.

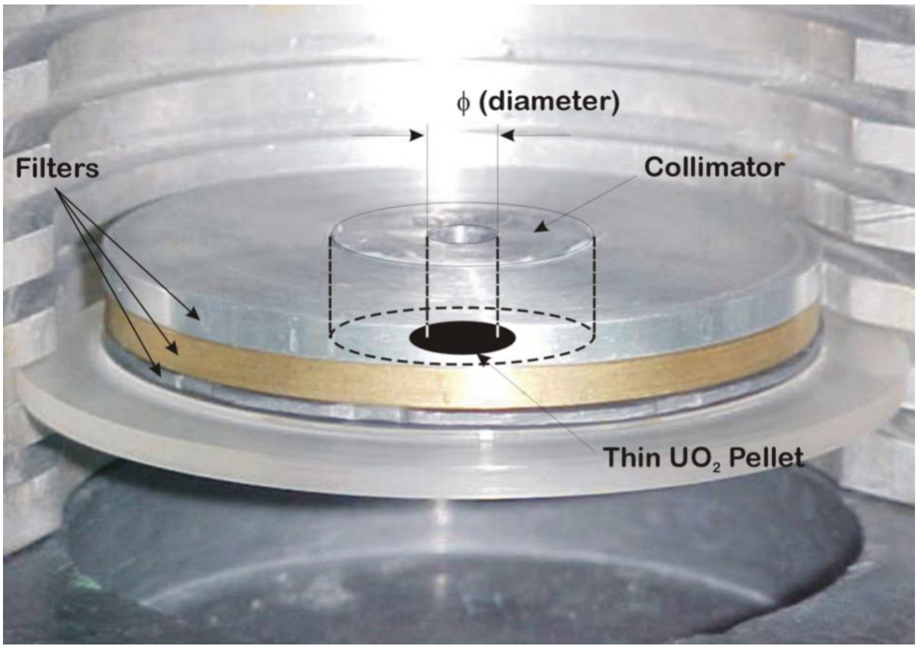

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Figure 1. Collimators and associated filters used to measure nuclear reaction rates in function of radial direction of the fuel pellets.

2.1. Geometric Efficiency Correction

The introduction of collimators in the gamma detection system causes major changes in its geometrical efficiency [5,6]. This effect depends only on the geometry of the analyzed system. This effect is due to reduction of the solid angle between the source and the active region of the germanium crystal which varies with height and diameter of the collimator's cavity. An example can be seen in Figure 2.

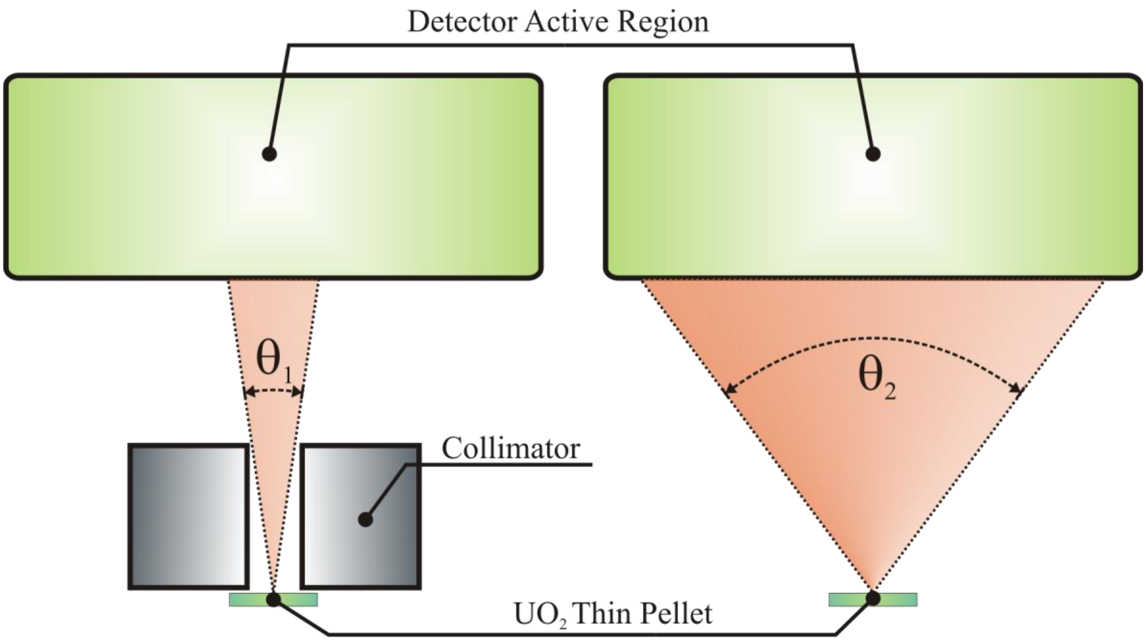

Figure 2. Variation of the solid angle due to insertion of the collimator in the HPGe detector system.

For the measurements obtained in this work two effects are taken into account. First, it is necessary to determine the reduction in efficiency for each of the collimators, since the objective is to compare the measurements for each collimator, and thus obtain values of relative nuclear reaction rates in each of the concentric regions of the irradiated UO_2 disk.

The second effect is due to the unwanted contribution measures of photons from the region covered by the collimator, which deposit their energy in the germanium crystal and end up disturbing the measures for each collimator. This effect is due to the variation the mean free path as the photon emission angle. As greater proximity of the photon emission to the collimator's cavity, the greater will be the effect. Figure 3 pictures the variation of the length of lead that photons have to cross according to the angle of emission.

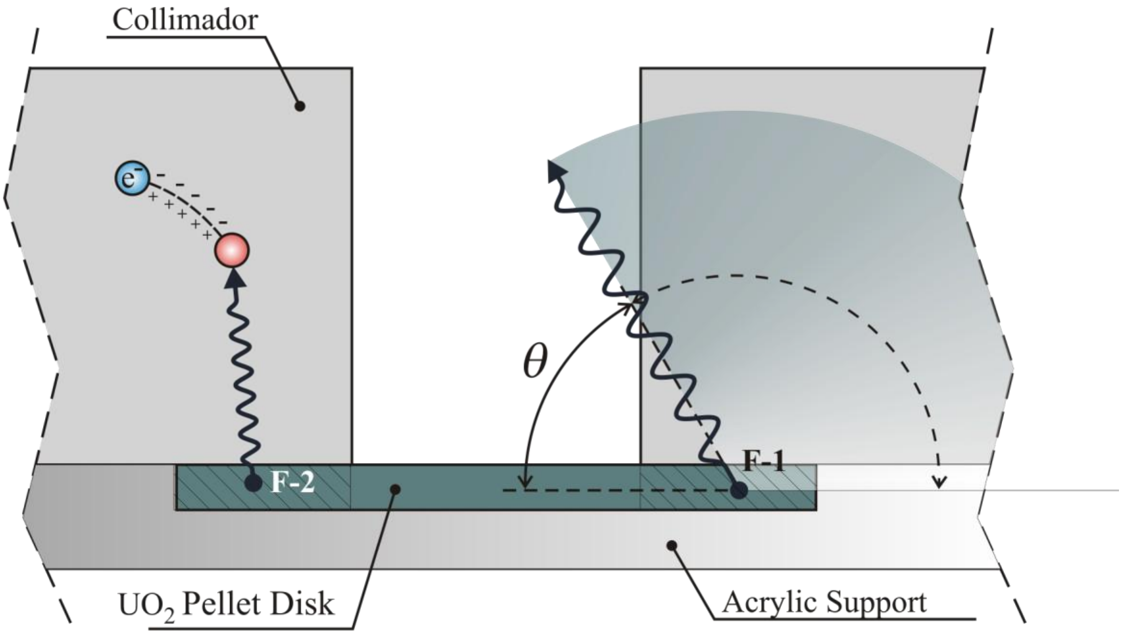

Figure 3. Variation of the mean free path according to the emission angle of the photon.

In Figure 3 are represented two photons, both from the region covered by the collimator. The photon F-1 leaves with an angle θ, passes through a thin layer of lead and is not attenuated and deposit its energy in the detector, and have to be discounted with a correction factor. The photon F-2 leaves with an angle about 90 degrees and suffers the photoelectric effect, being attenuated by the collimator.

For both effects of disturbance correction factors were determined using the photon transport of MCNP code [7] and the standard data library for photon transport. The simulation of the HPGe detection system, the determination of correction factors *FGC* (collimator geometric factor) and *FGA* (geometric factor of the rings) are treated below.

2.1.1. Simulation of the HPGe detection system (HDS) for determining efficiency

To simulate the HDS and determine by calculation its efficiency we used the computer code MCNP. Through this, it is possible to simulate in detail the geometry and determine the characteristics of existing materials in it. The source of europium used in the experimental determination of efficiency was modeled with some of the energies emitted by the same. In the region of germanium crystal was created a "*tally*" f8 ("Pulse Height Tally") [7]. The tally f8 provides the distribution of pulses created in a detector, that is, directly determines the detector's efficiency. The cross-sectional geometry of the HDS software generated with the "Visual Editor X22S" (Vised) can be seen in the figure below.

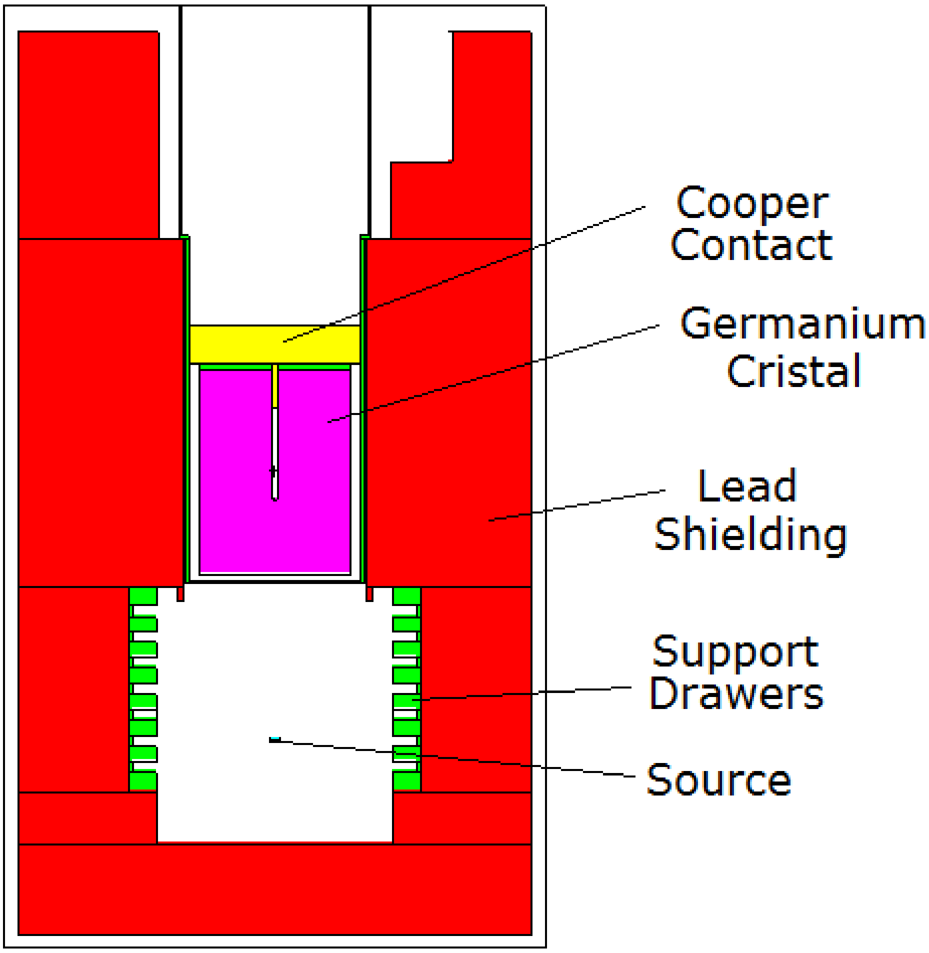

Figure 4. Cross-sectional geometry of the HPGe detection system (HDS) modeled with MCNP.

First, to test whether the input file created in MCNP is consistent with physical reality a source was modeled with the same dimensions as the europium source used to determine the global efficiency of the detector (experimentally) using the standard library of photons from MCNP. This source was placed in sixth drawer of the lead shielding which corresponds to a distance of 6.39 cm of the germanium crystal (the same drawer used in measures of irradiated disks). Photons with energies equal to 244 keV, 344 keV, 778 keV, 964 keV, 1112 keV and 1408 keV was generated and which are some of the energies emitted by ^{152}Eu. For this simulation 2000000 stories were generated, or approximately 160,000 with each photon energy, reducing the uncertainty associated with efficiency to less than 0.5%. The photons were generated uniformly distributed throughout the source with isotropic emission probability. The results were then compared to those obtained experimentally and can be viewed in Figure 5. Based on these results, it appears that the simulation is in accordance with the physical reality and that the geometry is correct.

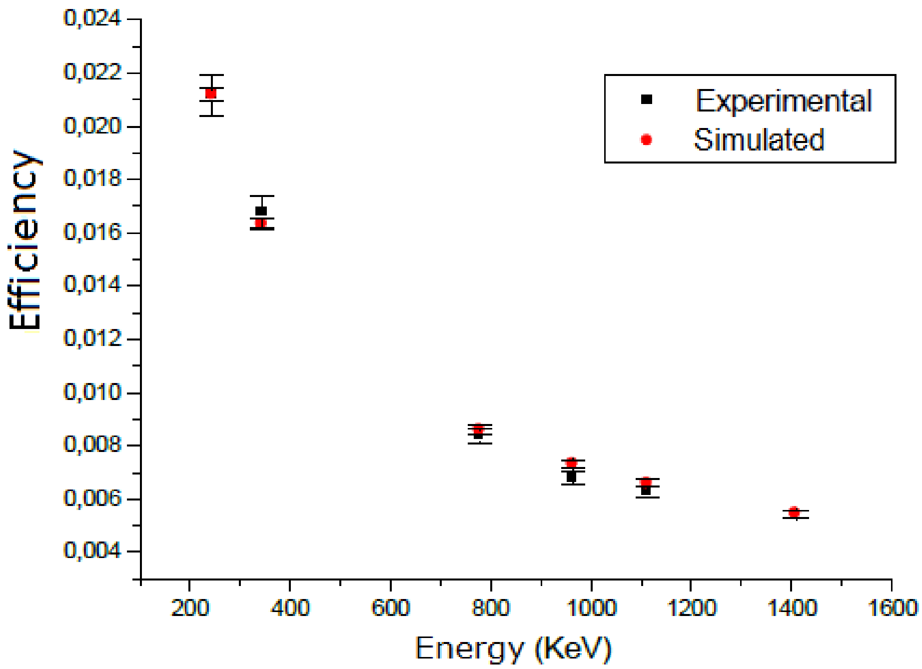

Figure 5. Comparison between the experimental and calculated efficiency in MCNP.

2.1.2. Determination of FGC (Collimator Geometric Factor)

The reduction in solid angle due to the introduction of the collimators can reduce up to 22 times the counts of photons of 277.6 keV from the decay of Neptunium 239. To correct this effect there have been ten pairs of simulations in which the HDS model was used previously. For each pair of simulations, the diameter of source is equal to one of the ten collimators. Figure 6 shows the pair of simulations.

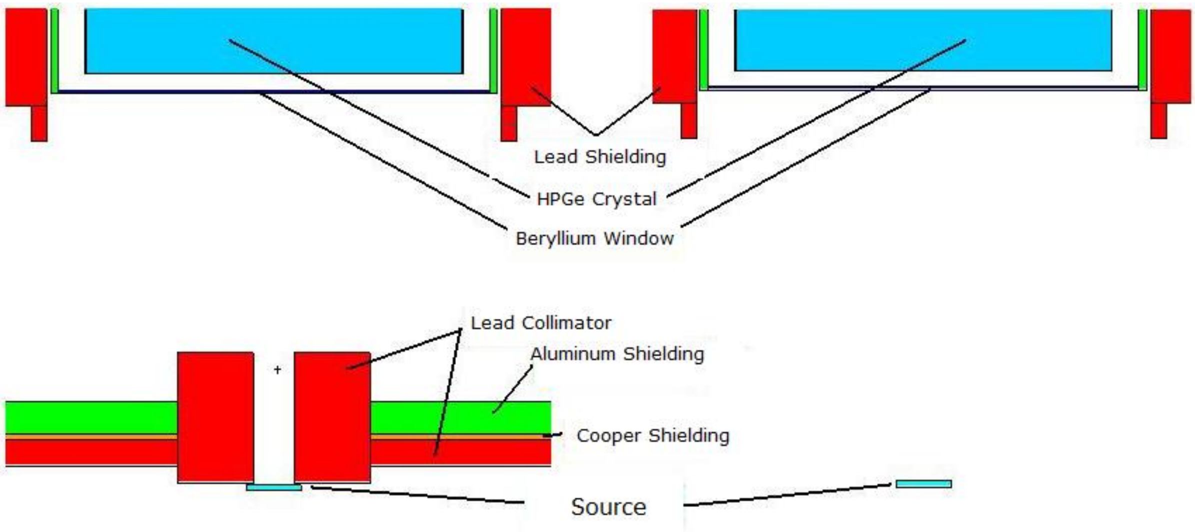

Figure 6. Geometry of pairs of simulations of HDS with and without collimator.

The efficiencies for both systems (with and without collimator) were obtained through the "f8 tally." The ratio of efficiency without collimator (*E(i)*) and with collimator (*EC(i)*) results in the correction factor FGC, which is used to correct the counts obtained during the gamma spectrometry of the irradiated disk. One should be careful when working with these corrections, minimizing their associated statistical uncertainty and increasing the number of stories generated, since MCNP does not take into account the uncertainty in the cross section of the nuclear libraries. In these simulations, it were analyzed the energies of 277.6 keV and 293.3 keV, since these are the ones of interest in measurements of capture and fission reaction rates.

2.1.3. Determination of FGA (Geometry Factor of the Rings)

The geometric factor of the rings (FGA) is the factor that corrects the undesired counts due to photons coming from the regions covered by collimators. To determine this, the UO_2 disk is divided into concentric rings with areas equal to the difference between two cavities sizes of the collimators (Figure 7).

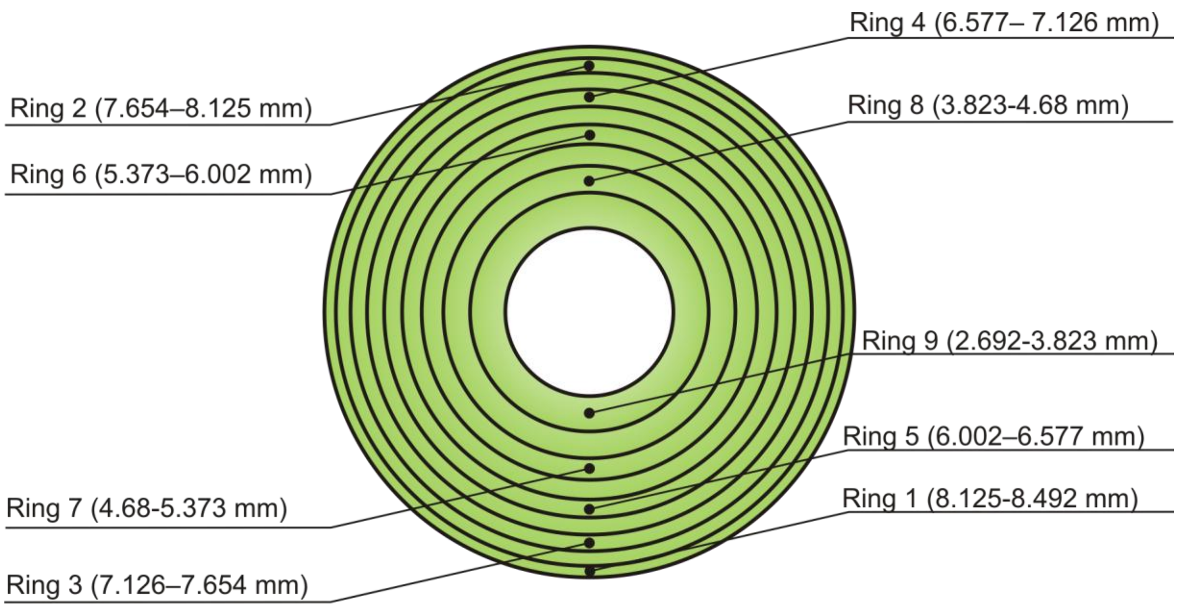

Figure 7. Distribution of concentric rings by diameter.

To determine the FGA of each collimator is necessary to obtain the efficiency of rings that are covered during spectrometry gamma. To this end, we used to model the HDS's again but this time with collimator. In these simulations the source is in the form of rings hidden by the collimator. Thus,is determined efficiency the HDS's for each region of Figure 7 with each collimator. An example of a ring geometry with source can be seen in Figure 8, where it was determined the detection efficiency of photons emitted by a ring source of the ring 2 (7.654 mm–8.125 mm) covered by the collimator with a cavity with 8.125 mm of diameter .

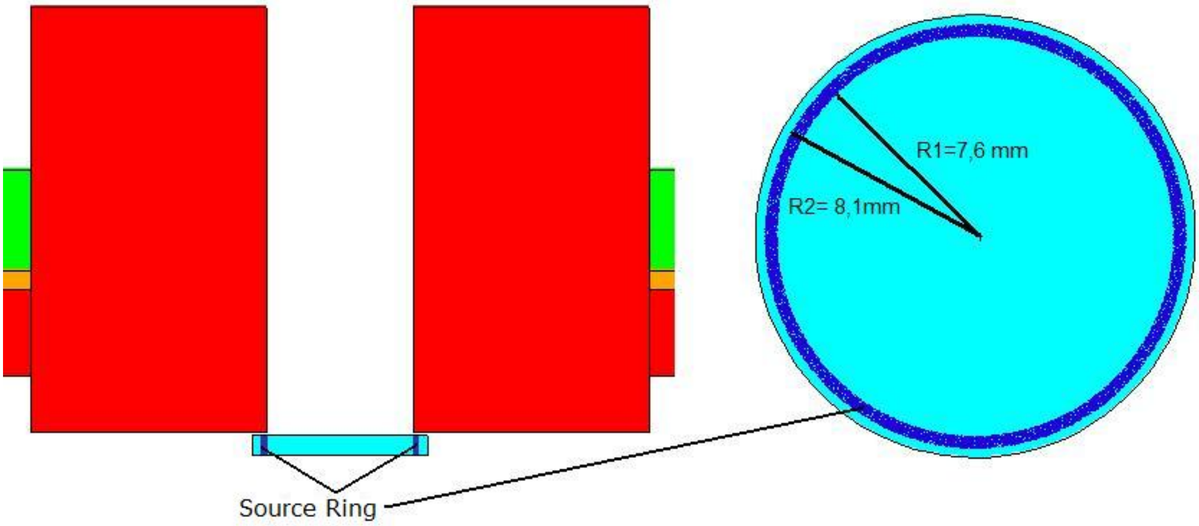

Figure 8. Geometry of the source ring 2 with the collimator with 8.125 mm of diameter.

Forty-six simulations were performed to determine the efficiencies of the ten rings hidden by collimators. For more internal rings (closer to the opening of the collimator) 16000000 histories were simulated, while for more external rings 8000000 histories were simulated resulting in uncertainties of 2% for regions with lower efficiency measure, ie, less significant. The number of stories used for the simulations of the rings from 1 to 8 covered with the collimator 3.823 mm in diameter can be seen in Figure 9.

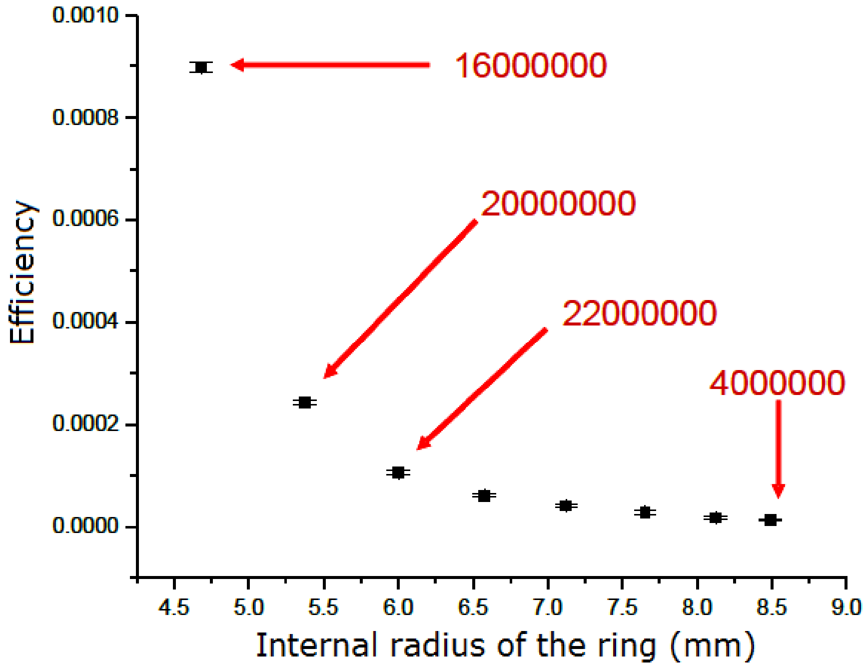

Figure 9. Profile distribution of efficiencies for each ring with collimator with 3.823 mm in diameter (Number of histories in each simulation in red).

2.1.4. Nuclear reaction rates with the correction factors FGC and FGA

For the corrected values of nuclear reaction rate relative units (Ty (i)) is used the following equation:

$$T_y(i) = FGC(i).\{C_0(i) - FGA(i)\} \quad (1)$$

Where,

$$FGA(x) = \sum_{a=i}^{10} \frac{E_{(a \to a+1)}(i).C_{(a \to a+1)}}{E(i)} \quad (2)$$

$T_y\,(i)$ is the nuclear reaction rate in the region uncovered by the collimator i and where y is the type of nuclear reaction;

$C_0\,(i)$ is the net score in the HDS for the irradiated disk with collimator i;

$E_{(a \to a+1)}\,(i)$ is the efficiency of the ring (a ⟶ a +1) with collimator i where a is the nominal value of the collimator;

$C_{(a \to a+1)}\,(i)$ is the net score of the ring calculated in MCNP and $E(i)$ is the efficiency of the disk uncovered by the collimator.

3. RESULTS

As a result of the twenty simulations were obtained efficiencies whose values are shown in Table 1 (energy equal to 277.6 keV) and Table 2 (energy equals 293.3 keV). These tables also shows the FGC.

Table 1. Correction efficiency due to the introduction of the collimators measurement system for energy 277.6 keV.

Diameter of Source (cm)	Efficiency without Collimator *E*(*i*)	σ *E*(*i*)	Efficiency with collimator *EC*(*i*)	σ *EC*(*i*)	*FGC* (*E*(*i*)/*EC*(*i*))
0.2692	1.96×10^{-2}	8.80×10^{-5}	8.81×10^{-4}	1.48×10^{-5}	22.2 ± 0.47
0.3823	1.96×10^{-2}	8.81×10^{-5}	1.76×10^{-3}	2.09×10^{-5}	11.1 ± 0.18
0.468	1.96×10^{-2}	8.80×10^{-5}	2.62×10^{-3}	2.56×10^{-5}	7.5 ± 0.11
0.5373	1.95×10^{-2}	8.79×10^{-5}	3.38×10^{-3}	2.91×10^{-5}	5.8 ± 0.08
0.6002	1.95×10^{-2}	8.80×10^{-5}	4.20×10^{-3}	3.23×10^{-5}	4.7 ± 0.06
0.6577	1.95×10^{-2}	8.79×10^{-5}	4.96×10^{-3}	3.52×10^{-5}	3.9 ± 0.05
0.7126	1.95×10^{-2}	8.79×10^{-5}	5.67×10^{-3}	3.74×10^{-5}	3.4 ± 0.04
0.7654	1.95×10^{-2}	8.79×10^{-5}	6.38×10^{-3}	3.96×10^{-5}	3.1 ± 0.03
0.8125	1.95×10^{-2}	8.79×10^{-5}	7.04×10^{-3}	4.22×10^{-5}	2.8 ± 0.03
0.8492	1.95×10^{-2}	8.79×10^{-5}	7.52×10^{-3}	4.36×10^{-5}	2.6 ± 0.03

Table 2. Correction efficiency due to the introduction of the collimators measurement system for energy 293.3 keV.

Diameter of Source (cm)	Efficiency without Collimator $E(i)$	$\sigma\ E(i)$	Efficiency with collimator $EC(i)$	$\sigma\ EC(i)$	FGC $(E(i)/EC(i))$
0.2692	1.87 X 10^{-2}	8.59 X 10^{-5}	8.61 X 10^{-4}	1.46 X 10^{-5}	21.7 ± 0.47
0.3823	1.87 X 10^{-2}	8.59 X 10^{-5}	1.78 X 10^{-3}	2.10 X 10^{-5}	10.5 ± 0.17
0.468	1.87 X 10^{-2}	8.59 X 10^{-5}	2.64 X 10^{-3}	2.56 X 10^{-5}	7.1 ± 0.1
0.5373	1.87 X 10^{-2}	8.59 X 10^{-5}	3.42 X 10^{-3}	2.91 X 10^{-5}	5.5 ± 0.07
0.6002	1.87 X 10^{-2}	8.58 X 10^{-5}	4.18 X 10^{-3}	3.22 X 10^{-5}	4.5 ± 0.05
0.6577	1.87 X 10^{-2}	8.58 X 10^{-5}	4.91 X 10^{-3}	3.48 X 10^{-5}	3.8 ± 0.04
0.7126	1.87 X 10^{-2}	8.58 X 10^{-5}	5.63 X 10^{-3}	3.77 X 10^{-5}	3.3 ± 0.04
0.7654	1.87 X 10^{-2}	8.58 X 10^{-5}	6.32 X 10^{-3}	3.98 X 10^{-5}	3 ± 0.03
0.8125	1.87 X 10^{-2}	8.58 X 10^{-5}	6.93 X 10^{-3}	4.16 X 10^{-5}	2.7 ± 0.03
0.8492	1.87 X 10^{-2}	8.58 X 10^{-5}	7.42 X 10^{-3}	4.31 X 10^{-5}	2.5 ± 0.03

To check the reliability of the geometric correction factor (FGC calculated) determined by the MCNP and presented in Tables 1 and 2. We performed an experimental measure of reaction rate capture with collimator with 8.492 mm in diameter and then measured without a collimator in HDS because this is the only collimator configuration possible to perform experimentally. Consequently, if the ratio between $FGC_{\text{experimental}}$ and $FGC_{\text{calculated}}$ is approximately 1, it is evident that $FGC_{\text{calculated}}$ corresponds to physical reality of the problem. The results obtained are shown in table 3.

Table 3. FGC values

$FGC_{experimental}$	2,53 ± 0,0106
$FGC_{calculated}$	2,60 ± 0,03
FGC ratio	1,028 ± 0,016

It is evident that within a confidence level within 95% (2σ), the *FGC* ratio has unit value proving that the calculated geometric correction factors are satisfactory. These will be applied to calculate the distribution of reaction rates nuclear.

The distribution of the ring efficiencies used to determine *FGA* in the ten collimators are presented in figure 10 in form of a graph. It can be seen that the effect of photons that emerged from the covered rings is more visible in collimators that have the bigger diameter cavities. Thus, the presence of *FGA* as a correction factor in measurements with these collimators is essential.

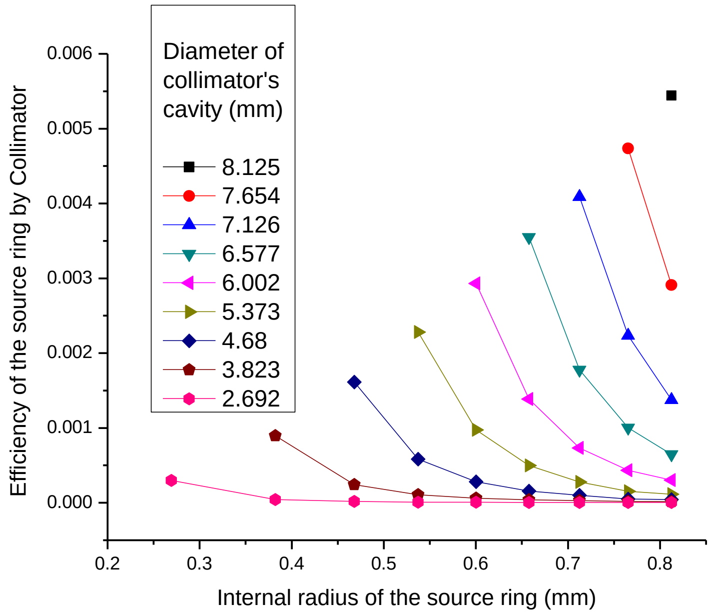

Figure 10. Profile distribution of efficiencies for each ring in function of collimator cavity diameter.

3.1. Final nuclear reaction rates with and without the correction factors

In the following figure, some measured radioactive capture reaction rates are presented in function of radius of the IPEN/MB-01 fuel pellet. This measured data is compared to calculated data using MCNP and ENDF/B-VII nuclear data library.

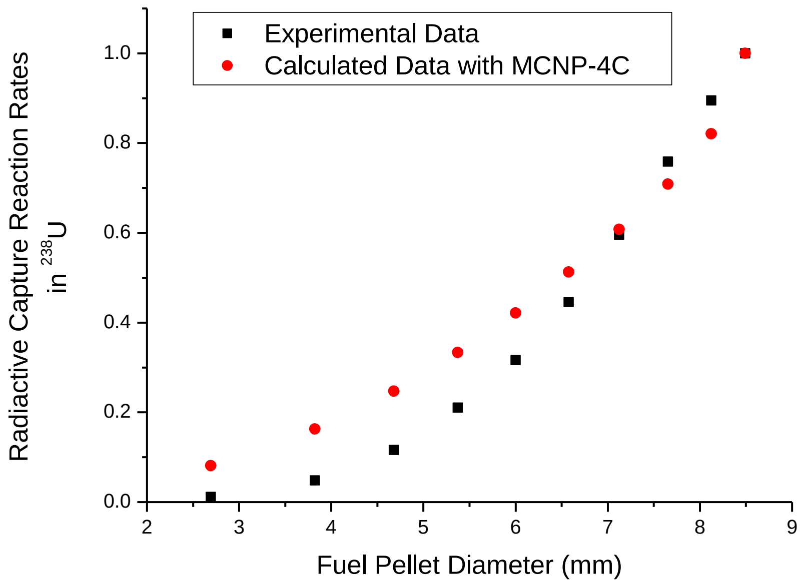

Figure 11. Radioactive capture reaction rates in ^{238}U without the correction factors (Relative Units).

Now we applied the *FGC* correction factor in the experimental data. The results can be seen in figure 12.

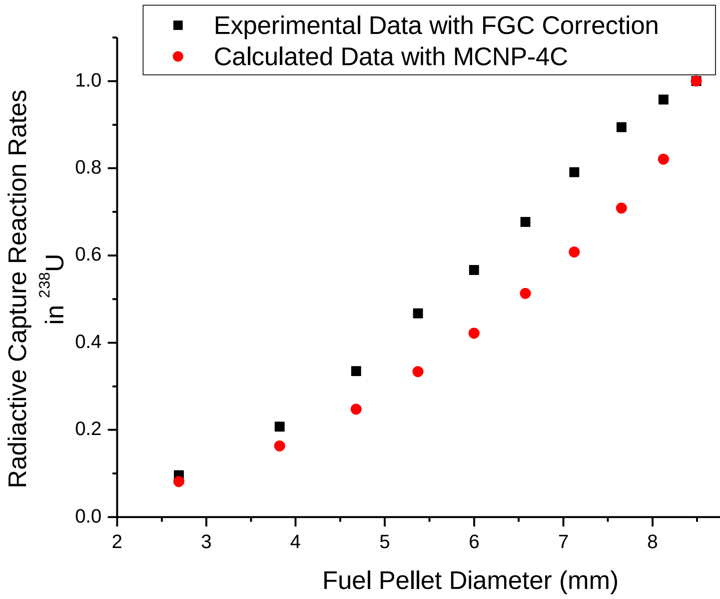

Figure 12. Radioactive capture reaction rates in ^{238}U with the *FGC* correction factor (Relative Units).

Finally we applied both the *FGC* and the *FGA* correction factors. The final results can be seen in figure 13.

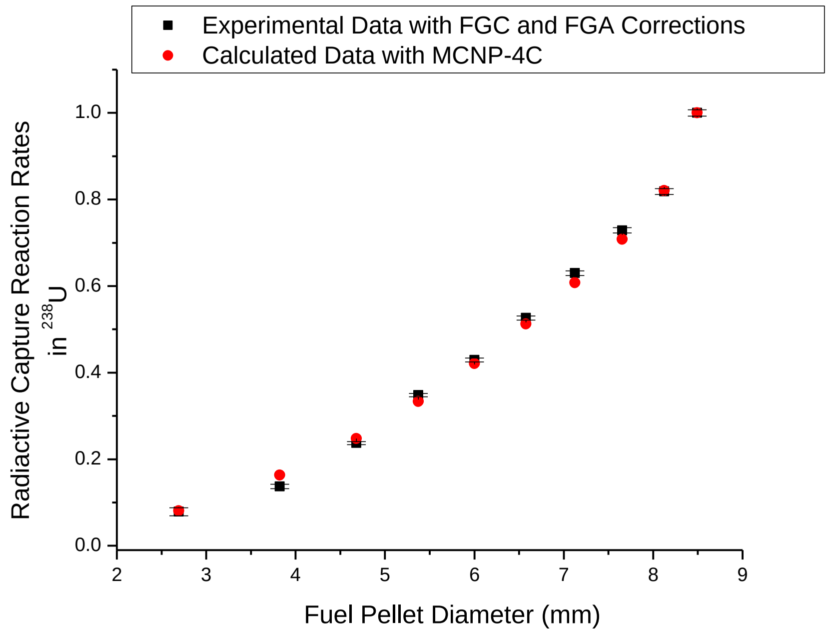

Figure 13. Radioactive capture reaction rates in ^{238}U with the *FGC* and *FGA* correction factors (Relative Units).

It appears that after the implementation of both correction factors, the experimental data reach a high degree of concordance with data calculated via MCNP. The main differences were found with measures 3.823 mm collimator which reached 14%.

4. CONCLUSIONS

The introduction of collimators in the HPGe detection system (HDS) makes necessary the application of geometric efficiency correction factors. Thus, the HDS used to make gamma spectrometry of the irradiated targets was modeled in the MCNP. Geometric efficiency correction factors (*FGC* and *FGA*) were determined and its behavior according to the variation of the collimator's cavity diameter. The correction factor for the collimator with 8.5 mm was determined experimentally. The calculated value showed 97.2% of consistency with the experimental value with an uncertainty of 1.6%, ie, demonstrating that calculated factors correction are according with physical reality of the problem.

In determining the correction factor FGA was found that the same has great relevance in determining the distribution of nuclear reaction rate. The contribution of the covered rings hidden by collimator's cavity showed elevated values of efficiency. With correction factors determined the geometric efficiency, we obtained the distributions of nuclear reaction rate of capture in ^{238}U showing that the efficiency correction factors are indispensable.

ACKNOWLEDGMENTS

We want to thanks the IPEN/MB-01 team for several operations to achieve some results presented in this paper and Leda C. C. B. Fanaro for calculated nuclear data with MCNP.

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