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COMPUTATIONAL METHOD FOR THE DETERMINATION OF INTENSE GAMMA-RAYS SOURCES ACTIVITY BY USING GEANT4

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Abstract. In this paper, a method for the determination of intense gamma-rays sources activity by using GEANT4 (Geometry And Tracking) is proposed. The method is recommended mainly for the cases when the activity of an intense gamma-rays source is unknown and there are no other classical activity determination methods available, or the existing ones are affected by higher uncertainties. The method is based on the fact that starting from an experimental determination of the absorbed dose rate value (well-knowing of all the exposure conditions), the activity of the involved gamma-rays source can be determined. The experimental absorbed dose rate determination can be performed by using a calibrated high performance dosimeter, in order to assure the traceability of the result.

Key words: GEANT4, activity determination, absorbed dose rate.

1. INTRODUCTION

In nuclear physics applications, the determination of the activity of a gamma-rays source is an important task to be fulfilled. There are some cases when the activity of an intense gamma-rays source is unknown and there are no other classical activity determination methods available, or the existing ones are affected by high associated uncertainties [1]. In this paper, an innovative method for the determination of intense gamma-rays sources activity by using GEANT4 (Geometry And Tracking) is proposed. The method is based on the fact that starting from an experimental determination of the absorbed dose rate value (well-knowing of all the exposure conditions), the activity of the involved gamma-rays source can be determined. The experimental absorbed dose rate determination can be performed by using a calibrated high performance dosimeter [2], in order to assure the traceability of the result, or by any other validated dosimetric systems [3].

In literature [4, 5], a well-known equation (Equation (1)) used to calculate an unknown absorbed dose rate value starting from a known activity value is available:

$$d = \frac{\Lambda \times \Gamma}{r^2} \quad (1),$$

where: Γ - specific gamma-ray constant for Co-60 (Gy m^2 s^{-1} Bq^{-1});
Λ - activity of the Co-60 source (Bq);
r - linear distance from source to the center of the sensitive volume of the detector (in this case, r = 1 m);
d - absorbed dose rate (Gy s^{-1}).

Even if Equation (1) can be transformed in Equation (2) in order to determine an unknown activity starting from the unknown absorbed dose rate value:

$$\Lambda = \frac{d \times r^2}{\Gamma} \quad (2),$$

it has some drawbacks, meaning it uses many approximations, leading to inexact results. For example, one of these approximations is the supposition that the source and the dosimeter are points in space, whereas in reality they are volumes having their own particular geometries. Another drawback is the fact that the values of the gamma-ray constant (Γ) found in literature are different for the same conditions and for the same radionuclide, as it can be seen in Table 1.

Table 1

Different values of Co-60 specific gamma-ray constant (Γ) found in literature.

Co-60 specific gamma-ray constant (air) (Gy m^2 s^{-1} Bq^{-1})	Reference	Average value of the Co-60 specific gamma-ray constant (Gy m^2 s^{-1} Bq^{-1})	Standard deviation of a single value (%)	Standard deviation of the average (%)
0.0856×10^{-15}	[6]	0.0860×10^{-15}	1.44	0.59
0.0868×10^{-15}	[7]			
0.0850×10^{-15}	[8]			
0.0848×10^{-15}	[5]			
0.0858×10^{-15}	[4, 9]			
0.0881×10^{-15}	[10]			

All these drawbacks can be avoided by using the method proposed in this paper, since by using GEANT 4, precise modeling of the exposure conditions involved in the experimental absorbed dose rate measurement can be performed.

2. EXPERIMENTAL CONDITIONS AND GEANT4 SIMULATION

The unknown activity of an intense gamma-rays source was determined by the method presented above, in the Introduction Chapter. The source was made of a 304 stainless steel capsule containing inside five Co-60 disks (20 mm diameter and 6 mm length each disk), as is shown in Fig. 1. The capsule is practically a cylinder with a (23.4 ± 0.2) mm external diameter and a (36.4 ± 0.2) mm total length.

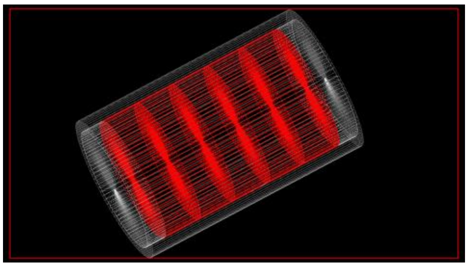

Fig. 1 – Geometry of the Co-60 source (GEANT4 export).

Co-60 is a radionuclide widely used in nuclear physics applications: nuclear medicine, industry, food processing etc. It is a beta-gamma emitter, having two main gamma-rays emissions at 1173.24 keV (99.85%) and 1332.51 keV (99.9826%), as it can be seen in Fig. 2. Its half-life time is of 5.2711(8) years, [11]. The electrons emissions (E_{max} = 317.32 keV; E_{mean} = 95.6 keV) were neglected due to their strong absorption in the source capsule and in the air.

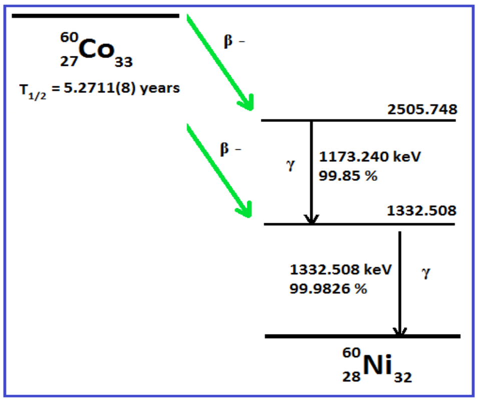

Fig. 2 – Co-60 simplified decay scheme.

The calibrated dosimeter used to determine the absorbed dose rate value, was a 30006 type “Farmer” ionization chamber (0.6 cm^3 active volume (air), 6.95 mm exterior diameter and 23.6 mm total length), as can be seen in Fig. 3. It is a waterproof standard chamber for absolute dosimetry (0.65 % combined standard uncertainty for a coverage factor $k = 2$, [2]). Chamber walls are made of 0.335 mm PMMA ($(C_5H_8O_2)_n$) supplemented with 0.09 mm Graphite layer. The chamber useful nominal energies range is between 30 keV and 50 MeV and it is equipped with a removable acrylic cap. The central (collecting) electrode is made of aluminum (1.1 mm diameter and 21.2 mm length).

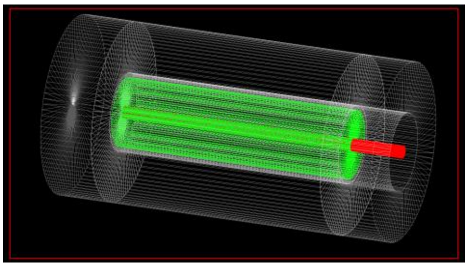

Fig. 3 – Geometry of the dosimeter (GEANT4 export).

The dosimeter was placed coaxially to the Co-60 source, at 1 meter distance from it, as it is shown in Fig. 4, the measured absorbed dose rate value being of 5.0694×10^{-4} Gy s^{-1}.

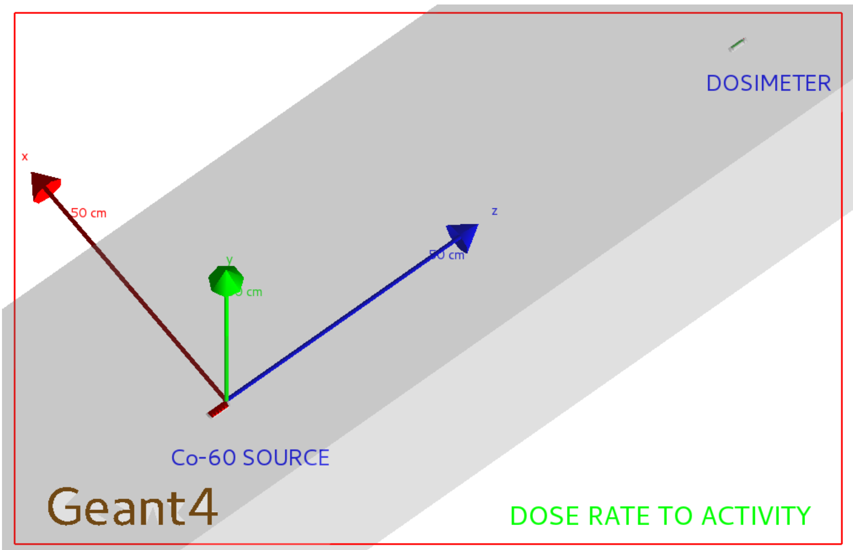

Fig. 4 - The experimental set-up of the exposure (GEANT4 export).

GEANT4 is a toolkit for the simulation of the passage of particles through matter, using Monte Carlo methods. It is the successor of the GEANT series of software toolkits developed by CERN, and the first to use C++ object oriented programming [12-16], its 10.03 release being used in this paper.

The geometry of the experimental set-up was built in the *Detector Construction class* using CSG (Constructive Solid Geometry) by assembling some solid 3D geometrical shapes. Boolean subtraction was also used. The G4 material database was used to define the composition of each material involved. The *Physics processes* taken into account were low-energy electromagnetic processes. Photon interactions include photoelectric effect, Compton scattering, pair production, Rayleigh scattering, and electrons interactions include bremsstrahlung, multiple scattering and ionization. Atomic effects as X-rays emission and Auger, following the photoelectric effect, were also included [17]. The Co-60 isotropically volume source was modelled using GPS (*General Particle Source class*).

3. RESULTS AND DISCUSSIONS

Using Equation (2), five different values of Co-60 source activity were calculated, corresponding to five different values of the gamma-ray constant (Γ) found in literature, as it can be seen in Table 2. Their mean value was used as a reference value for the value obtained by the GEANT4 method.

Table 2

Different values of the source activity, calculated with different values of Co-60 specific gamma-ray constant (Γ) found in literature.

d_{meas} - absorbed dose rate measured value, 1 m from the source ($Gy\ s^{-1}$)	Γ - specific gamma-ray constant ($Gy\ m^2\ s^{-1}\ Bq^{-1}$)	Reference	Calculated activity value, using Equation 2 (TBq)	Average value of the calculated activity (TBq)	Standard deviation of a single value (%)	Standard deviation of the average (%)
5.0694×10^{-4}	0.0856×10^{-15}	[6]	5.9222	5.8945	1.44	0.59
	0.0868×10^{-15}	[7]	5.8403			
	0.0850×10^{-15}	[8]	5.9640			
	0.0848×10^{-15}	[5]	5.9781			
	0.0858×10^{-15}	[4, 9]	5.9084			
	0.0881×10^{-15}	[10]	5.7541			

Using the simulation parameters mentioned above, 10^7 events were processed (10^7 decays in one second). The energy deposited in the detector (dosimeter) active volume was determined as being E_{dep} = 3860.74 eV (both Co-60 gamma quanta were considered). The total mass of the active region was m = 0.7225 mg. By dividing the E_{dep} (J) with the mass of the active volume of the dosimeter (kg), following Equation (3), an absorbed dose rate of 8.5614 x 10^{-10} Gy s^{-1} was determined (d_{sim}).

$$d_{sim} = \frac{E_{dep}}{m \times t} \tag{3}$$

where: E_{dep} - energy deposited in the active volume of the dosimeter (J);
m - mass of the active volume of the dosimeter (kg);
t - time in which the energy was deposited (1 s).

Knowing that this absorbed dose rate was obtained for 10^7 events, meaning actually a 10^7 Bq activity (Λ_{sim}), we can determine the activity value corresponding to our Co-60 source, using the Equation (4):

$$\Lambda_{unk} = \frac{\Lambda_{sim} \times d_{meas}}{d_{sim}} \tag{4}$$

where: Λ_{unk} - unknown activity of the Co-60 source (Bq);
Λ_{sim} - number of events simulated using GEANT4 (10^7 Bq);
d_{meas} - measured absorbed dose rate at 1 m from the Co-60 source (Gy s^{-1});
d_{sim} - absorbed dose rate at 1 m from the Co-60 source, GEANT4 (Gy s^{-1}).

By using the method proposed in this paper, a 5.9213 TBq activity value of the Co-60 source was determined. The relative difference between this value and the one calculated using Equation (2), 5.8945 TBq, is of 0.46 %. The good agreement between the two values, as it can be seen in Fig. 5, validates the proposed method. The small difference is resulted from the fact that the GEANT4 method is more precise because it simulates real life cases, when the source and the detector are not perfect points in space. However, as the results showed, in the case of the experimental condition used in this paper, because the source and the detector had relatively small dimensions reported to the large distance between them (1 m), a point approximation of them is acceptable.

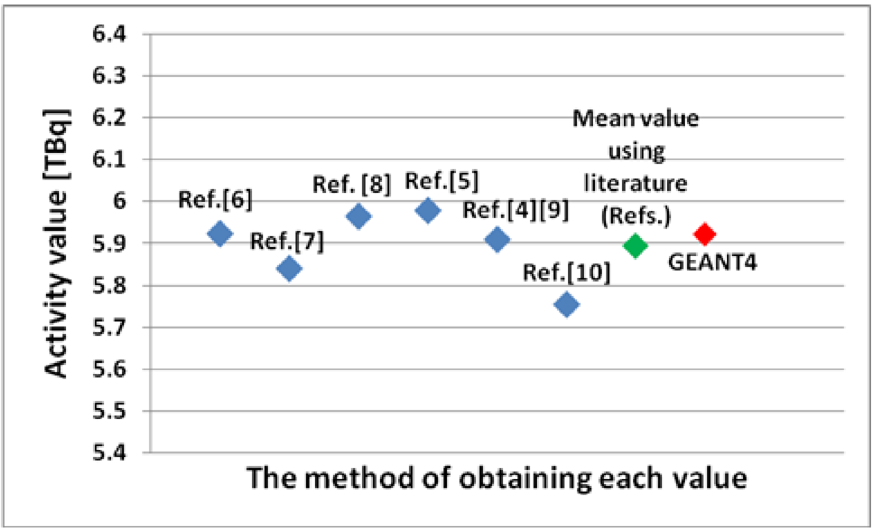

Fig. 5 - The activity value obtained by GEANT 4 method compared with the ones using Equation (2) and different values of the gamma-ray constant (Γ) found in literature.

The general form of the variance associated to the method proposed in this paper is presented in Equation (5):

$$\sigma^2_{\Lambda_{unk}} = \left(\frac{\partial \Lambda_{unk}}{\partial d_{sim}}\right)^2 \times \sigma^2_{d_{sim}} + \left(\frac{\partial \Lambda_{unk}}{\partial \Lambda_{sim}}\right)^2 \times \sigma^2_{\Lambda_{sim}} + \left(\frac{\partial \Lambda_{unk}}{\partial d_{meas}}\right) \times \sigma^2_{meas} \tag{5}$$

leading to its concrete form, Equation (6):

$$\sigma^2_{\Lambda_{unk}} = \left(\frac{d_{meas}}{d_{sim}}\right)^2 \times \left(\sigma^2_{\Lambda_{sim}} + \left(\frac{\Lambda_{sim}}{d_{meas}}\right)^2 \times \sigma^2_{d_{meas}} + \left(\frac{\Lambda_{sim}}{d_{sim}}\right)^2 \times \sigma^2_{d_{sim}}\right) \tag{6}$$

All the quantities from the Equation (6) and their associated uncertainties are known.

4. CONCLUSIONS

In this paper, a method for the determination of intense gamma-rays sources activity by using GEANT4 was proposed. As it is known, Equation (2) has some drawbacks, meaning it uses many approximations, leading to inexact results. All these drawbacks were solved by using the method proposed in this paper, since by using GEANT4, precise modeling of the exposure conditions involved in the experimental absorbed dose rate measurement can be performed.

The activity value obtained by the method proposed in this paper was 5.9213 TBq. The activity value calculated using Equation (2) was 5.8945 TBq. The relative difference between the two values is of only 0.46 %. The good agreement between the two values validates the method proposed. The small difference is resulted from the fact that the GEANT4 method is more precise because it simulates real life cases, when the source and the detector are not perfect points in space. However, as the results showed, in the case of the experimental condition used in this paper, because the source and the detector had relatively small dimensions reported to the large distance between them (1 m), a point approximation of them is acceptable. Another strong point of the proposed method is that it takes into account all the involved physical phenomena, including self-absorption and multiple scatterings. In the case of the proposed Monte Carlo method the angular distribution of the source is modeled with respect to the physical phenomena involved inside it, not being considered an ideal isotropically one.

The method can be applied starting from experimental absorbed doses rates determinations, as it was done in this paper, but it can also be used starting from absorbed dose values.

A new value of 0.0856 x 10^{-15} Gy m^2 s^{-1} Bq^{-1} for the Co-60 gamma-ray specific constant (Γ) (in air) was determined using the developed GEANT4 model, which is in a good agreement with the arithmetic mean of the ones found in literature of 0.0860 x 10^{-15} Gy m^2 s^{-1} Bq^{-1}.

Another important aspect of the method is that it can be used not only for isotropic radioactive sources, but it can also be extended in the case of bright gamma-rays beams, as those involved in Extreme Light Infrastructure – Nuclear Physics (ELI-NP) state-of-the-art European Research Facility [18, 19]. Is it also applicable in the cases of hard to be experimentally reproduced situations, as for example those when the activity of an intense gamma-rays source which is immersed in a water pool must be determined.

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