A HYBRID ANALYTICAL-NUMERICAL METHOD FOR EFFICIENCY CALCULATIONS OF SPHERICAL SCINTILLATION NaI(Tl) DETECTORS AND ARBITRARILY LOCATED POINT SOURCES

by

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The present work is essentially concerned to introduce a hybrid analytical-numerical method to calculate the geometrical, the total, and the full-energy peak efficiency of the spherical NaI(Tl) detector for using isotropic radiating γ-ray point sources. In addition, it calculates the average path lengths travelled by the photon inside the detector active medium, in order to study the characteristics of the source-to-detector configurations. This method was depended mainly on the calculation of the solid angle subtended by the radioactive point sources, which were situated at various locations from the detector surface and the photons path lengths through the detector active medium. Also, taking into account the attenuation coefficients of all the absorbers between the source and the detector material itself. The obtained results were compared against one data set published to show the method's possibility in the calibration process.

Key words: spherical NaI(Tl) detector, geometrical solid angle, detector efficiency, radioactive point source, hybrid analytical-numerical method

INTRODUCTION

In the pursuit of precision measurements, nothing is simple even when the equipment at work appears to be wholly uncomplicated. The γ-ray spherical detector design is considered as an instructive case in radiation measurements, where it can be used easily in several critical applications, including the medical therapy, radiation protection and environmental exposure monitoring. Therefore, the understanding of the full scope of the multidimensional calibration and measurement process must be done with a good accuracy even if the detector design seems less complex at first. In gamma ray spectrometry, knowing the solid angle Ω is the most important and widely used to calibrate the different detectors and determine their various efficiencies (geometrical, total and full-energy peak) [1-12]. Typically, the experimental calibration process for the gamma-ray detectors is not easy, due to the fact that it is a hard work to obtain the exactly calibrated γ-sources of various shapes and medium [13-15]. Therefore, there are many reports which were done and developed for gamma-spectrometries measurement systems, where some of them used Monte Carlo, semi-empirical, direct mathematical and efficiency transfer method in this calibration process [1-15]. The geometrical solid angle, Ω, calculation was presented by an isotropic radiating γ-ray source, for any given detector shape is looked to be the most difficult step [15-19]. The geometrical efficiency, ε_g $(=\Omega/4\pi)$, depends on the solid angle subtended by radiating γ-ray sources situated at different locations from the detector surface, which allows calculation of photon path lengths through any detector system.

Presently, the NaI(Tl) detectors have been commonly used in different detecting systems in the form of well-type, parallelepiped, cylindrical, hexagonal, borehole, sphere, *etc*., where it has relative simplicity, low cost of crystal preparation, high mass number, high efficiency and room temperature operation [20]. The spherical NaI(Tl) detector as a special design has a broad solid angle subtended to the isotropic radiating γ-ray point sources, if it is used for the calibration process [15]. This work will offer a new hybrid analytical-numerical (HAN) method to calculate by the integration of the geometrical, the total and the full-energy peak efficiency of the spherical NaI(Tl) detector, where an isotropic radiating γ-ray point sources situated at different positions were used, and this is considered as the main aim of this work. All the analytical integrations were solved numerically by using the

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trapezoidal rule, and the accuracy of the integration increases as the number of intervals, n, increasing at the side of the integration value converges fine at large value of n [7-12].

The calculation of the total and the full-energy peak efficiency of the spherical NaI(Tl) detector depends most strongly of two factors. First, the calculation of the photons path lengths through the detector active medium [1-5]. Second, the calculation of the attenuation of all absorbers materials between the source and the detector active medium [21-29]. Besides the study of the change of the average path lengths through the detector material as a function of the radioactive point source-to-detector distance, h. This method can be useful after some modifications in a forthcoming work with additional experimental evidence to determine the sample activity.

The arrangement of this paper is as follows. The mathematical model section presents the analytical calculation of the geometrical solid angle in details, the total and the full-energy peak efficiency in case of using an isotropic radiating γ-ray point sources. These sources were situated on the spherical detector major axis at a distance, h, from its end cap as shown in fig. 1. The results and discussion section contain several calculations and comparisons between this approach and some published data. The results of comparison showed the validity of the recent approach. The conclusions are given in last section.

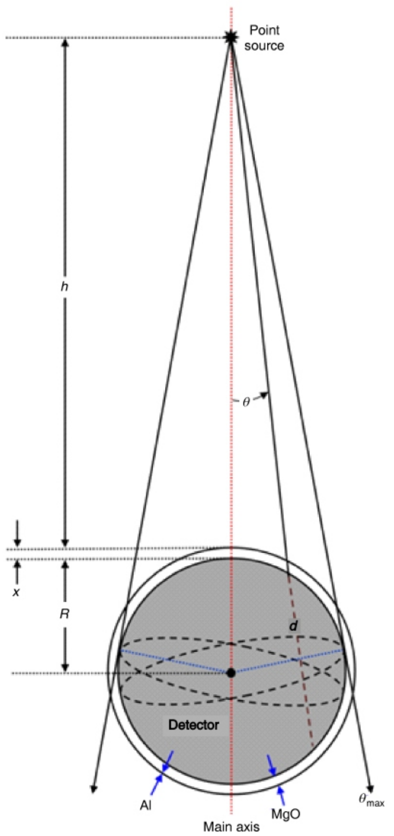

Figure 1. The point source is situated on the spherical detector main axis

MATHEMATICAL MODEL

Geometrical efficiency

This section gives an explanation about the new HAN method, which depends on the direct mathematical method [7-9]. The method will be useful to find the geometrical efficiency of the spherical NaI(Tl) detector of radius, R, with outer layers Al and MgO as shown in fig. 1. The geometrical efficiency, ε_g, for any specified source-to-detector configuration can be given by

$$\varepsilon_g = \frac{1}{4\pi}\int_{\Omega} \mathrm{d}\Omega, \quad \text{where} \quad \mathrm{d}\Omega = \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi \tag{1}$$

The polar angle, θ, and the azimuthal angle, ϕ, will control the direction of the incidence photons, while the geometrical solid angle, Ω, is subtended between the source and the detector and can be given by

$$\Omega = \int_{\phi}\int_{\theta} \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi \tag{2}$$

The geometrical solid angle, Ω, will be calculated for the isotropic radiating γ-ray point sources by the spherical co-ordinate system. The geometry is assumed to be axially as shown in fig. 1, where an isotropic radiating axial point source was used and located at a distance, h, from the detector surface. The azimuthal angle, ϕ, takes always the values from 0 to 2π. Considering all these conditions, the final expression of the detector geometrical efficiency, $\varepsilon_{g(\text{Point-Axial})}$, can be given by

$$\varepsilon_{g(\text{Point-Axial})} = \frac{1}{4\pi}\int_{0}^{2\pi}\int_{0}^{\theta_{max}} \sin\theta\,\mathrm{d}\theta\,\mathrm{d}\phi \tag{3}$$

where θ_{max} is the maximum extreme polar angle, that allows the photons to go into the detector active medium in case of axial isotropic radiating point source and it takes a certain value given by

$$\theta_{max} = \sin^{-1}\left(\frac{R}{R+h+x}\right) \tag{4}$$

where x is the spacing between the detector surface and the outer housing.

TOTAL AND FULL-ENERGY PEAK EFFICIENCY

The basic idea of this method is the fact that if the photon with incidence energy, E, from isotropic radiating point sources enters a detector active medium, then the probability fraction, P, of this photon to be recorded inside the detector from the solid angel element, dΩ, as a result of the emission of an electron (or electrons) is given by

$$P = \frac{1}{4\pi}\int_{\Omega}(1 - e^{-\mu d})\,\mathrm{d}\Omega \tag{5}$$

where d is the distance covered by the photon inside the detector active medium material, which depends on the source-to-detector geometry. The attenuation coefficient of the detector's material, μ, can be replaced by the total attenuation coefficient, μ_T, of the detector's material for gamma-ray energy, E, (excluding the coherent scattering portion) [30] to determine the total efficiency, ε_T, of the spherical NaI(Tl) detector based on the following cases:

– In case of an axial isotropic radiating point sources, the total efficiency, $\varepsilon_{T(Point\text{-}Axial)}$, of the spherical detector will be given as

$$\varepsilon_{T(Point-Axial)} = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\theta_{max}} f_{att} f_1 \sin\theta \, d\theta \, d\phi \tag{6}$$

The attenuation factor, f_{att}, is due to the reflector, the end-cap, the absorber between the source and the detector from the front and the side as well, which are described as the absorber layers with attenuation coefficients, $\mu_1, \mu_2, \ldots, \mu_n$, and the relevant thicknesses, t_1, $t_2, \ldots, t_n$, between the source-to-detector system [25] is given by

$$f_{att} = e^{-\sum_{i=1}^{n} \mu_i \delta_i} \quad \text{where} \quad \delta_i = \frac{t_i}{\cos\theta} \tag{7}$$

where the striking photon will enter the face of the spherical detector and emerge from the other side as shown in fig. 1.

The factor f_1, is expressed as $f_1 = (1 - e^{-\mu_T d})$ where d is the possible path length travelled by the photon within the detector active volume and can be given by

$$d = 2\sqrt{R^2 - (R + h + x)^2 \sin^2\theta} \tag{8}$$

– In case of the full-energy peak efficiency computation, the coefficient μ is replaced by the full-energy peak attenuation coefficient μ_P for the detector material, which represents the only part contributing to the full-energy peak (the photoelectric coefficient + the fractions of the incoherent and pair production cross-section leading to the full-energy peak) to determine the full-energy peak efficiency, ε_P, of the spherical NaI(Tl) detector, which depend on axial isotropic radiating point sources only as in [13]. The full-energy peak efficiency, $\varepsilon_{P(Point\text{-}Axial)}$, of the spherical detector will be given as

$$\varepsilon_{P(Point-Axial)} = \frac{1}{4\pi}\int_0^{2\pi}\int_0^{\theta_{max}} f_{att} f_1 \sin\theta \, d\theta \, d\phi \quad \text{where} \quad f_1 = (1 - e^{-\mu_P d}) \tag{9}$$

In order to get the peak attenuation coefficient μ_p, the measured efficiency values of an axial position using ^{137}Cs and ^{60}Co as a radioactive point sources [15] were compared with theoretical calculations using a new HAN method in eq. (9). The measured efficiency values were used in this approach to obtain the full peak attenuation coefficient μ_p, for this particular source-to-detector configuration, since the peak attenuation coefficient μ_p, cannot be determined directly. Changing the values of the attenuation μ_p, in eq. (9) a few times till reaching the small deviation of less than 2 % between the measured and the calculated efficiency. Once obtaining the suitable values of the attenuation μ_p, the mathematical method can be used to extend the calculated values of the attenuation μ_p, as a function of gamma-ray energy E. This can be done by plotting and fitting the values of the peak attenuation coefficient μ_p *vs*. the photon energy E, and the outcome will be an empirical formula given as

$$\mu_p = \left[0.06143 \ln\left(\frac{E - 0.5509}{2.215}\right)\right]^{-1} \tag{10}$$

At this time, the calculated values of the attenuation μ_p, can be used easily to build a calculated efficiency curve for the spherical detector with axial radioactive point source as a function of gamma-ray energy. Otherwise, it will be difficult to obtain the curve of the calculated full-energy peak efficiency in the absence of the full-energy peak attenuation coefficient μ_p, for this particular source-to-detector configuration.

The average distance, $\bar{d}$, travelled by the photon inside the spherical NaI(Tl) detector material depending on the position of the incident photon in general will be discussed later on and will be given as

$$\bar{d} = \frac{\int_\Omega d(\theta,\varphi)\,d\Omega}{\int_\Omega d\Omega} = \frac{\int_\Omega\int_\theta d(\theta,\varphi)\sin\theta \, d\theta \, d\varphi}{\Omega} \tag{11}$$

where θ and φ, are the polar and the azimuthal angles, respectively, and define the direction of the incidence photons as discussed before. The average distance of an isotropic radiating axial point source will be given as

$$\bar{d} = \frac{\int_0^{\theta_{max}} d_1 \sin\theta \, d\theta}{\int_0^{\theta_{max}} \sin\theta \, d\theta} = \frac{2\int_0^{\theta_{max}} \sqrt{R^2 - (R + h + x)^2 \sin^2\theta} \, d\theta}{\int_0^{\theta_{max}} \sin\theta \, d\theta} \tag{12}$$

RESULTS AND DISCUSSION

The new facility of the γ-ray spherical detector shape presents a few more challenges than other designed shapes, both in the manufacturing process and the subsequent volume measurement. The scientists have measured the full-energy peak of the spherical NaI(Tl) detector in [15], by allowing a beam of photons to from an isotropic radiating γ-ray point sources to enter the detector as measurement devices for a specific time at a specific distance. The measurements in [15] were done by using a 7.62 cm diameter spherical NaI(Tl) crystal with Al material of thickness 0.8 mm, as detector end cap housing and MgO material of thickness 3 mm as a reflector as shown in fig. 1. The point sources ^{137}Cs and ^{60}Co were positioned axially at 10 cm from the detector surface using 9 mm thick of acrylic holder [15].

The detector materials and dimensions were used realistically with the present HAN method, in order to estimate the geometrical, the total and calculate the full-energy peak efficiency of the spherical NaI(Tl) detector for using isotropic radiating γ-ray point sources. The true geometry is a sphere with a cylindrical connection to the photomultiplier tube. The study does not consider the effect of this extra volume of active material, and the average path lengths travelled by the photon inside the detector active medium are calculated. The calculations were done by situating the point sources axially from the detector major axis as shown in fig. 1. The calculated full-energy peak efficiency was compared with the measured and Monte Carlo data published in [15] to show the method's possibility in the calibration process.

The calculated axial geometrical efficiency of the spherical detector as a function of the source-to-detector distance h, which started from 1 up to 10 cm given by eq. (3) as shown in fig. 2. The geometrical efficiency was decreased exponentially as the source-to- -detector distance h increased. The calculated axial total efficiency of the spherical detector at a distance 10 cm from the detector surface, as a function of the photon energy from 0.1 up to 4 MeV given by the eq. (6) is presented in fig. 3. The total efficiency has a small value at 0.1 MeV, then increased with photon energy to its maximum at 0.2 MeV, and after that started to decrease exponentially. This behavior was happening as an effect of the

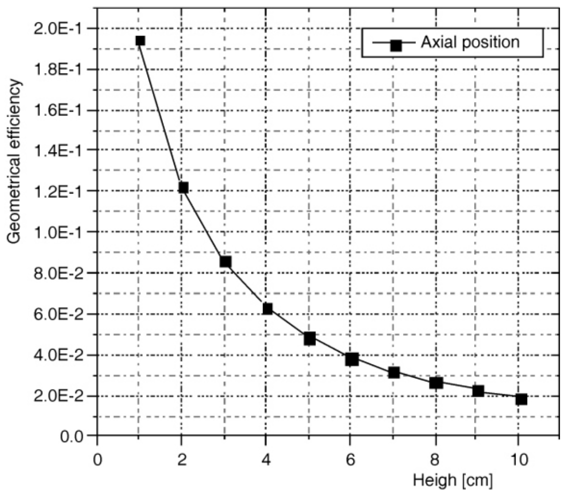

Figure 2. The calculated axial geometrical efficiency of the spherical detector as a function of the source-to-detector distance *h*, from 1 up to 10 cm

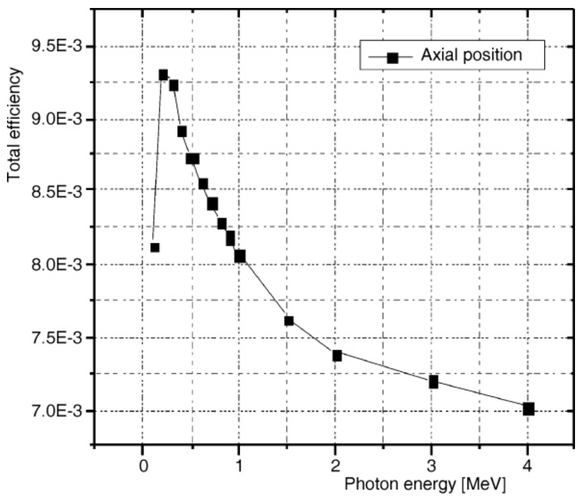

Figure 3. The calculated axial total efficiency of the spherical detector at a distance 10 cm from the detector surface as a function of the photon energy from 0.1 up to 4 MeV

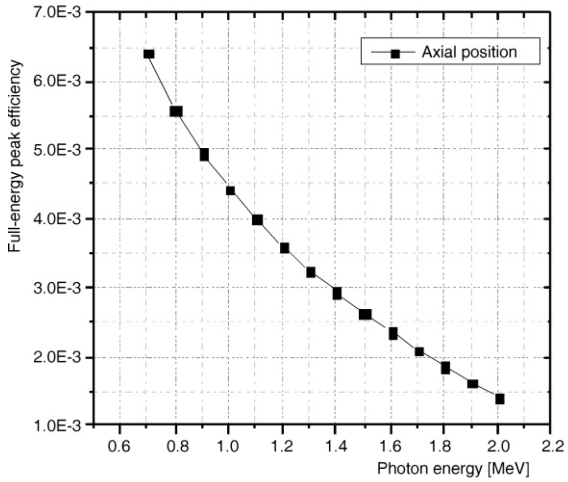

Figure 4. The calculated axial full-energy peak efficiency of the spherical detector at a distance 10 cm from the detector surface as a function of the photon energy from 0.7 up to 2 MeV

photon attenuation process, which is a function of the photon energy.

The calculated axial full-energy peak efficiency of the spherical detector at the source-to detector distance 10 cm as a function of the photon energy from 0.7 up to 2 MeV, was given by eqs. (9) and (10) is presented in fig. 4. The full-energy peak efficiency decreased exponentially with the source energy. The average path length as a function of the axial source-to-detector distance h from 1 up to 20 cm given by equation (12), was presented in fig. 5. The average path length was increased exponentially with the source-to-detector distance h increased, and reached an almost fixed value at distances higher than about 15 cm.

In tab. 1, the axial full-energy peak efficiency of the spherical detector for using the photons from ^{137}Cs and ^{60}Co sources was calculated by eqs. (9) and (10). Also, it was compared with the measured and Monte

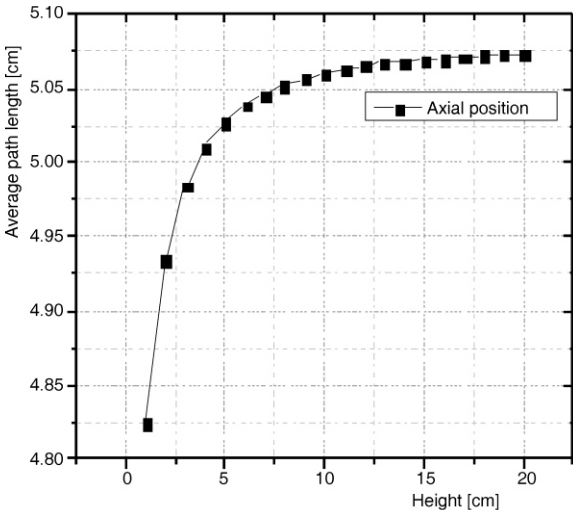

Figure 5. The average path length as a function of the axial source-to-detector distance *h* from 1 up to 20 cm

Carlo data published in [15]. Table 1 contains, as well, the calculated full-energy peak attenuation, μ_P, given by eq. (10) and the deviation $_1$ % and $_2$ % between the [$\varepsilon_{Calculated}/\varepsilon_{Measured}$ and $\varepsilon_{Calculated}/\varepsilon_{Simulated}$] based on the following equations, respectively

$$\Delta_1 \quad \frac{\varepsilon_{Calculated} \quad \varepsilon_{Measured}}{\varepsilon_{Calculated}} 100\%$$
$$\Delta_2 \quad \frac{\varepsilon_{Calculated} \quad \varepsilon_{Simulated}}{\varepsilon_{Calculated}} 100\% \qquad (13)$$

The comparison between the calculated efficiency values using the present HAN method, the published experimental and Monte Carlo data [15] needs the knowing of the uncertainty source for each method. Based on reference [15], the uncertainty of the measured full-energy efficiency depends on the uncertainty of following values: the net peak area in counts (statistical uncertainties of the measured peaks were in the range of 0.2 %), the activity of source at the time of standardization, the absolute γ-ray emission probability, the elapsed time since standardization, the decay constant and the measuring time (in seconds), in addition to the uncertainty of the source position, which was estimated to be within 3 mm. By combining all of these uncertainty components, the standard uncertainties of the measured values are less than 2.5 %.

In tab. 1, the Monte Carlo full-energy peak efficiencies for using the photons from ^{60}Co and ^{137}Cs sources are compared with the measured values, and by scoring the both photons of ^{60}Co successively in one simulation history, the peak are a reduction due to the coincidence summing was evaluated to be less than 1 % [15]. Errors involved in the peak area estimation were less than 2 %. The statistical uncertainty of the Monte Carlo calculations was less than 0.5 % and by combining all of these uncertainty components, the standard uncertainty of the efficiency calculations was obtained to be about 5 % [15]. On the other hand, the uncertainty of the present HAN method for calculating the full-energy peak and the total efficiencies in tabs.1 and 2 was found to be in the order 10-6 %, which is a very small value. The main reason for this phenomena is the uncertainty of the calculated efficiency and depends mainly on the energy uncertainty only, where the rest of the input factors are given without any accompanying errors. Therefore, due to the small value of the uncertainty, it can be neglected. The discrepancy

Table 2. The calculated axial total efficiency of the spherical detector for the photons from ^{137}Cs and ^{60}Co sources as a function of the source-to-detector distance *h*

Source-to-detector distance, *h* [cm]	Axial total efficiency		
	^{137}Cs	^{60}Co	
	(0.6617 MeV)	(1.1732 MeV)	(1.3325 MeV)
1	1.130E-01*	9.800E-02	9.600E-02
2	6.900E-02	6.100E-02	5.900E-02
3	4.700E-02	4.200E-02	4.100E-02
4	3.400E-02	3.000E-02	2.900E-02
5	2.500E-02	2.300E-02	2.200E-02
6	2.000E-02	1.800E-02	1.700E-02
7	1.500E-02	1.400E-02	1.400E-02
8	1.200E-02	1.100E-02	1.100E-02
9	1.000E-02	9.442E-03	9.278E-03
10	8.457E-03	7.892E-03	7.765E-03

*1.130E-01 means 1.130 10^{-1}

Table 1. The calculated axial full-energy peak efficiency of the spherical detector for the photons from ^{137}Cs and ^{60}Co sources compared with measured and simulated data by Monte Carlo method [15] beside the uncertainties

Source	Energy [MeV]	Axial full-energy peak efficiency		
		Measured [15]	Simulated [15]	Calculated (HAN)
^{137}Cs	0.6617	(6.84 0.11)E-03	(6.65 0.33)E-03	6.86E-3 0.00
^{60}Co	1.1732	(4.16 0.10)E-03	(4.03 0.20)E-03	4.16E-3 0.00
	1.3325	(3.69 0.08)E-03	(3.59 0.18)E-03	3.61E-3 0.00
Extension				
Source	Energy [MeV]	Calculated full-energy peak attenuation (μ_p)	Deviation percentage	
			$_1$ [%]	$_2$ [%]
^{137}Cs	0.6617	1.84E-01	0.35 0.11E-03	3.12 0.33E-03
^{60}Co	1.1732	7.80E-02	0.07 0.10E-03	3.19 0.20E-03
	1.3325	6.40E-02	–1.99 0.08E-03	0.77 0.18 E-03

in eq. (13) with uncertainty was calculated based on reference [31], as shown in tab. 1.

The calculated axial total efficiency of the spherical detector for using the photons from ^{137}Cs and ^{60}Co sources depends on the eq. (6) as a function of the source-to-detector distance h, which started from 1 up to 10 cm and will be presented in tab. 2, where the total efficiency decreased with the increase of the source-to-detector distance h. These phenomena related to that, the gamma-ray intensity emanating from a source falls off with the distance, according to the inverse square law. Also, the total efficiency decreased as the source energy increased related to the attenuation actions.

The average path length as a function of the polar angle, θ, from 9.0° up to 52° given by eq. (12) is presented in fig. 6. It decreased sharply from its maximum as the polar angle θ, increased. In that case, the polar angle θ, was calculated depending on eq. (4) equivalently by changing the axial source-to-detector distance h, from 1 up to 20 cm. The variation of the calculated full-energy peak attenuation of the spherical detector at a distance 10 cm from the detector surface, as a function of the photon energy is presented in fig. 7.

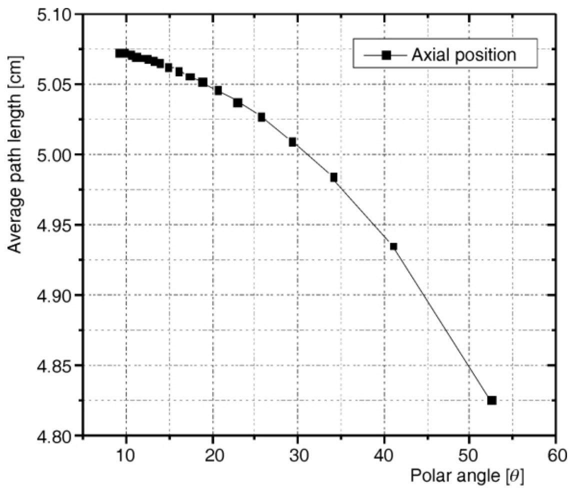

Figure 6. The average path length of gamma photon in the spherical detector as a function of the polar angle

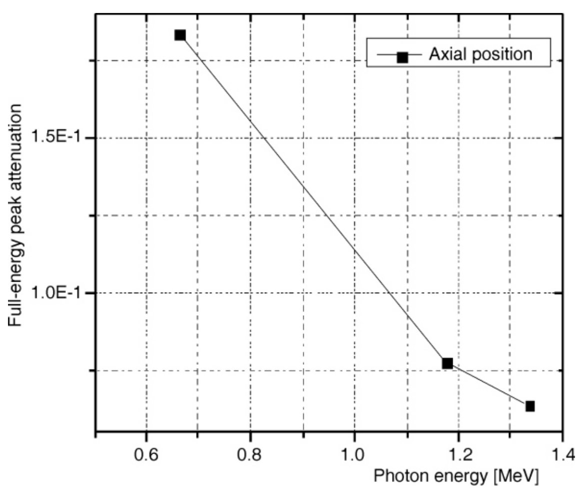

Figure 7. The calculated full-energy peak attenuation of the spherical detector at a distance 10 cm from the detector surface as a function of the photon energy

CONCLUSIONS

HAN method was developed in the present work to give larger facility in order to calculate the various efficiencies of spherical NaI(Tl) crystal based on the radial geometry. This mathematical approach is essentially numerical integration and needs only a few experimental events, then the calculations can be done within a reasonable time, even with a little central processing unit. It is an easy and very fast procedure for the computation process. This method can be also helpful after simple modifications to evaluate the full-energy peak efficiency using the efficiency transfer method as another method. This can be derived from knowing the change in efficiency under conditions of measurements and different sources used in the calibration process.

CONTRIBUTIONS

The theoretical work was done by S. F. Noureldine, M. S. Badawi, and M. I. Abbas. All authors took part in planning the work and in discussions during all phases of its elaboration. The manuscript was conceived, written, performed data elaboration and graphical representation of results by all authors.

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ХИБРИДНА АНАЛИТИЧКО-НУМЕРИЧКА МЕТОДА ЗА ПРОРАЧУН ЕФИКАСНОСТИ СФЕРИЧНОГ СЦИНТИЛАЦИОНОГ NaI(Tl) ДЕТЕКТОРА И ПРОИЗВОЉНО ПОСТАВЉЕН ТАЧКАСТИ ИЗВОР

Представљена је хибридна аналитичко-нумеричка метода за прорачун геометријске и укупне ефикасности, као и ефикасности детекције пика максималне енергије сферичног NaI(Tl) детектора, при примени изотропних тачкастих извора гама зрачења. Поред овога, ради изучавања карактеристика конфигурација извор-детектор, прорачуната је средња дужина пређених путања фотона унутар активне средине детектора. Ова метода највише зависи од прорачуна просторног угла наспрам тачкастих извора зрачења, који су постављени на различите локације у односу на површину детектора, као и од дужина путања фотона кроз активну средину детектора. Метода узима у обзир и коефицијенте слабљења свих апсорбера између извора и детектора. Добијени резултати упоређени су са објављеним сетом података како би се показала могућност примене методе у калибрационом поступку.

Кључне речи: сферични NaI(Tl) детектор, геометријски просторни угао, ефикасност детектора, тачкасти извор зрачења, хибридна аналитичко-нумеричка метода