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A Quick Method to Calculate NaI(Tl) Detector Efficiency Depending on Gamma ray Energy and Source-to-detector Distance

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Abstract

This paper examines and presents a simple computational Monte Carlo algorithm to determine the total, intrinsic and geometric efficiencies of NaI(Tl) gamma ray detectors for gamma rays emitted by isotropic radiating (point) sources with several energies in the range of 150-3000 keV. The code was used to compute efficiency values for various source-to-detector distances for each studied gamma ray energy. The comparisons with the data reported in the literature indicated that the present algorithm is useful in efficiency calculations for any source-detector and geometry configuration.
Keywords: Gamma ray, Detection, Total efficiency, Intrinsic efficiency, Geometric efficiency, Monte Carlo.

1. Introduction

A NaI(Tl) scintillation detector is one of the most fundamental instruments among the radiation detectors for health physics, industry, and environmental measurements [1]. In the radiation measurement, one of the most important characteristics of a detector is the efficiency of the detector for its practical and correct usage and to understand the operational behaviour of it. Because the experimental work is tedious and even difficult for extended sources, many researches have been focused on the development of computational techniques to determine the efficiencies [2]. One of these computational techniques is the Monte Carlo simulation method, and this method was applied before for different detectors and source-to-detector systems, and gamma rays with several energies by several researchers and calculation results have been reported [3-10]. The accuracy and the performance of this statistical method make it the most suitable and adapted to this kind of simulation [5]. Nevertheless, Monte Carlo simulations must be validated at least for the simple geometries by other methods, experiment, analytical calculations, etc.

In this study, we have tried to estimate the total, geometric and intrinsic efficiency values for cylindrical NaI(Tl) scintillation detectors, through Monte Carlo simulation procedure by an algorithm developed by us. Directions of photons emitted from the source are determined with the Monte-Carlo method. The photon path lengths within the detector are determined by analytic equations based on the directions obtained from the Monte-Carlo method [11]. The aim here was to describe an alternative method to experiment or analytical methods; provide a rapid way for efficiency calculations for any detector system and configuration.

2. Material and Methods

In the present work total, intrinsic and geometric efficiency values for a cylindrical NaI(Tl) detector 2.54 cm in radius and 5.08 cm in height were calculated for isotropic point sources with different gamma ray energies in the case of different source-to-detector distances (0.001, 5, 10 and 15 cm). These calculations have been carried out by using the simulation results that provide the number of photons striking the detector and the number of photons detected by the detector. The flow chart of the algorithm and a schematic diagram of the source-detector configurations have been already presented by Yalcin et al. [11] to explain the process of the program. In this model, attenuation due to the detector end cap material and detector holder has been neglected. Gamma ray interactions in the source container have also been neglected. Also, scattering of the gamma rays from the shielding and other surrounding materials back to the detector was assumed to be negligible [11]. 10^6 photons in the energy range of 150-3000 keV were followed. The direction of the photon emitted by any point source is determined by the polar angle in a point source-detector arrangement. The polar angle changes between 0 and $\pi/2$. For the next step it is determined whether the photon enters the detector or not, by checking some conditions based on the polar angle. If it is decided that the photon does not enter the detector, a new photon is considered. Otherwise, the photon is assumed to enter the detector, that assumption gives the number of detector impinging (reaching) gamma rays ($N_{impinging}$), and the distance it has to travel inside the detector is calculated as a function of cosine of the polar angle (cos θ). The absorption fraction for a gamma ray with energy E, traversing *l* path lenght inside the detector is given by

$$\mathrm{S(E)} = 1 - e^{-\mu(E)l} \qquad (1)$$

where $\mu(E)$ is the total linear attenuation coefficient (without coherent scattering) of NaI detector for photons with energy E. Attenuation coefficients for NaI were obtained by using the XCOM software [12]. The total S(E) values for all photons that traverse the detector is given by $\sum S(E)$. Total counting efficiency, ε(E), is calculated by using

$$\varepsilon(\mathrm{E}) = \frac{\sum \mathrm{S(E)}}{2\mathrm{N}} \qquad (2)$$

where N is the number of photons generated within a solid angle of 2π in the simulation. However, real sources emit photons in all directions, 4π solid angle. Ratio of the number of counted gamma rays by the number of gamma rays reaching the detector, intrinsic efficiency ($\varepsilon_{int}(E)$) is calculated by Eq. (3), and ratio of the number of gamma rays reaching the detector by the number of gamma rays emitted by the source, called geometric efficiency $\varepsilon_g(E)$, is calculated by Eq. (4).

$$\varepsilon_{int}(\mathrm{E}) = \frac{\sum \mathrm{S(E)}}{\mathrm{N_{impinging}}} \qquad (3)$$

$$\varepsilon_{g}(\mathrm{E}) = \frac{\mathrm{N_{impinging}}}{2\mathrm{N}} \qquad (4)$$

3. Results and Discussion

By the procedure based on the Monte Carlo method described above, we obtained total, intrinsic and geometric efficiency values of a cylindrical 2"×2" NaI(Tl) detector for gamma ray energies in the range of 150-3000 keV in the case of source-to-detector distances ranged from 0.001 to 15 cm. First of all, for testing the success of the written code for the used source-detector configurations, the code was run for a 3"×3" NaI(Tl) detector and gamma rays emitted at the distances of 0.001 cm and 10 cm from the cylindrical detector, and the obtained results were compared with the values available in the literature, see Table 1 and 2.

Table 1. Comparison of calculated efficiency values of 3"x3" cylindrical NaI(Tl) detector for gamma rays emitted from a point source at a distane 0.001 cm with literature.

Energy (keV)	Total efficiency					Intrinsic efficiency	Geometric efficiency
	This study	Vegors et al. [13]	Miller and Snow [14]	Nakamura [15]	Rehman et al. [16]	This study	This study
661	0.3652	0.362	0.370	0.367	0.3737	0.7306	0.4999
1332	0.2990	0.293	0.302	0.296	0.2974	0.5982	0.4999

Table 2. Comparison of calculated effciency values of 3"x3" cylindrical NaI(Tl) detector for gamma rays emitted from a point source at a distane 10 cm with literature.

Energy (keV)	Total efficiency						Intrinsic efficiency	Geometric efficiency
	This study	Heath [17]	Cesana and Terrani [18]	Nakamura (1972)	Belluscio et al. [19]	Rehman et al. [16]	This study	This study
661	0.0202	0.0198	0.0201	0.0183	0.0190	0.0207	0.6168	0.0328
1332	0.0168	0.0162	0.0165	0.0168	0.0164	0.0169	0.5116	0.0328

It is clear from the Tables 1 and 2 that our results are consistent with the literature, and the code is practical and sufficient (adaptable) for such kind of calculations. Table 3 presents the total, intrinsic and geometric efficiency values of a cylindrical 2"×2" NaI(Tl) detector for gamma rays with the energies of 150, 200, 300, 400, 500, 600, 661, 800, 1000, 1332, 2000, 3000 keV. To enlighten the researchers work experimentally, for the determination or selection of source-to-detector distance in their measurements, simulation results have been presented for distances smaller, nearly equal or bigger than the detector diameter.

Table 3. Total, intrinsic and geometric efficiency values of a 2"×2" NaI(Tl) detector for gamma rays emitted from point sources with several energies.

	D (cm)	Energy (keV) 150	200	300	400	500	600	661	800	1000	1332	2000	3000
Total efficiency	0.001	0.4988	0.4842	0.4192	0.3658	0.3318	0.3074	0.2940	0.2738	0.2509	0.2295	0.1964	0.1793
	5	0.0476	0.0435	0.0363	0.0315	0.0285	0.0267	0.0255	0.0238	0.0219	0.0200	0.0174	0.0157
	10	0.0141	0.0133	0.0117	0.0104	0.0096	0.0088	0.0086	0.0081	0.0074	0.0067	0.0059	0.0054
	15	0.0065	0.0064	0.0056	0.0051	0.0046	0.0044	0.0042	0.0040	0.0037	0.0033	0.0029	0.0027
Intrinsic efficiency	0.001	0.9980	0.9688	0.8387	0.7318	0.6639	0.6150	0.5882	0.5477	0.5019	0.4591	0.3930	0.3587
	5	0.8805	0.7999	0.6673	0.5816	0.5290	0.4908	0.4699	0.4384	0.4024	0.3693	0.3189	0.2905
	10	0.9233	0.8656	0.7530	0.6747	0.6158	0.5747	0.5550	0.5189	0.4793	0.4415	0.3829	0.3514
	15	0.9451	0.9040	0.8056	0.7228	0.6638	0.6270	0.5995	0.5662	0.5219	0.4803	0.4174	0.3843
Geometric efficiency	0.001	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998	0.4998
	5	0.0541	0.0544	0.0543	0.0542	0.0539	0.0543	0.0542	0.0542	0.0544	0.0543	0.0545	0.0542
	10	0.0153	0.0154	0.0155	0.0154	0.0156	0.0153	0.0155	0.0155	0.0154	0.0153	0.0154	0.0153
	15	0.0069	0.0071	0.0070	0.0070	0.0069	0.0071	0.0070	0.0070	0.0070	0.0070	0.0070	0.0070

As the detection efficiency of the NaI(Tl) detector can vary with the source-to-detector distance, in Figures 1-3 the geometric, total and intrinsic efficiencies of a 2"×2" NaI(Tl) detector have been presented as a function of source-to-detector distances, respectively. It can be seen from Figures 1 and 2 that the geometric and total efficiency values have decreased with the increasing distance from detector face.

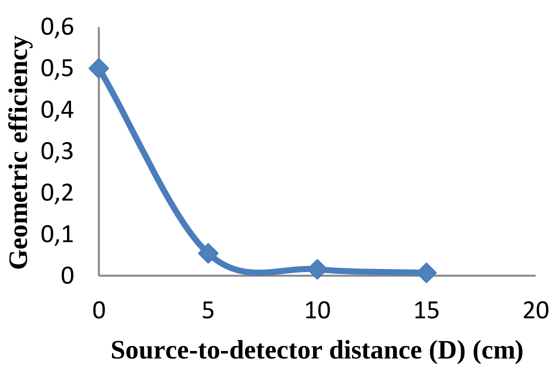

Figure 1. Variation of the geometic efficiency of a 2"×2" NaI(Tl) detector as a function of source-to-detector distance.

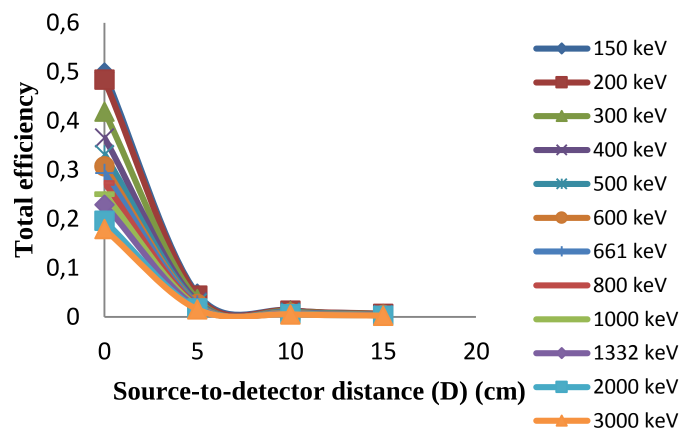

Figure 2. Variation of the total efficiency of a 2"×2" NaI(Tl) detector as a function of source-to-detector distance.

As it is seen in Figure 3, variation of the intrinsic efficiency of a NaI(Tl) detector for gamma rays emitted from several points at several distances is different from variations of geometric and total efficiencies as a function of source-to-detector distance. On the other hand, the results for the energy (incident gamma ray energy) dependency of intrinsic efficiency of the detector have been presented in Figure 4 for four different source-detector distances, 0.001, 5, 10 and 15 cm.

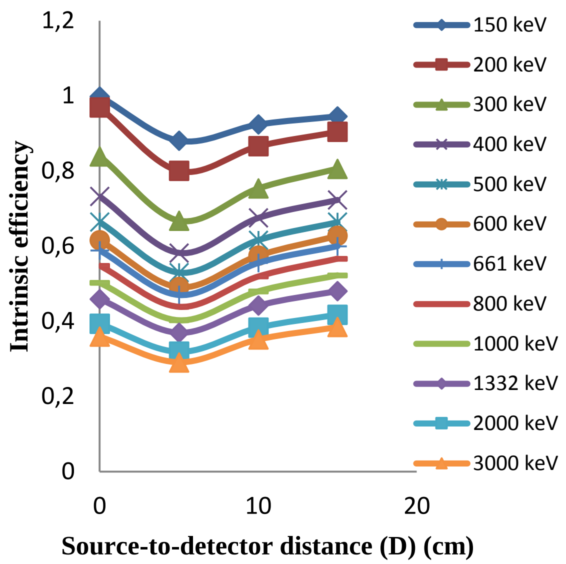

Figure 3. Variation of the intrinsic efficiency of a 2"×2" NaI(Tl) detector as a function of source-to-detector distance.

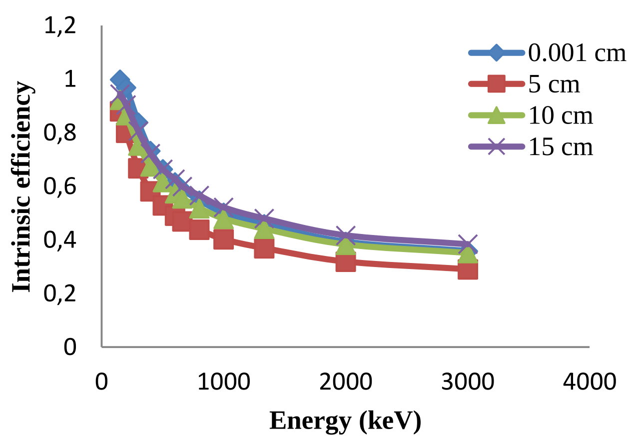

Figure 4. Energy dependency of intrinsic efficiency of the detector positioned at 0.001, 5, 10, 15 cm away from the source.

4. Conclusions

In this paper, total, intrinsic and geometric efficiencies of a cylindrical NaI(Tl) detector (2"×2") for gamma rays emitted from point sources have been obtained by Monte Carlo method which is presented here a direct rapid way to deduce the efficiency values. For the validation of the model developed in the code, some possible outcomes were compared with the literature and showed a good agreement. In addition, to draw useful conclusions in the preliminary stage for other researchers work on radiation detection, efficiency values were given depending on gamma ray energy and source-to-detector distance.

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