Evaluation of the total and intrinsic efficiencies of a 3 in × 3 in NaI(Tl) crystal by using the hybrid Monte Carlo method

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ABSTRACT

In this work, we developed a Fortran code (CalcTotEff) to calculate the intrinsic and total efficiencies of a 3 in × 3 in NaI(Tl) crystal by using the hybrid Monte Carlo method. To confirm the reliability of the results of the total efficiency calculated, an experimental arrangement was set up. The results showed the compatibility between the calculated and experimental data. We also used the hybrid Monte Carlo method to evaluate the dependence of the intrinsic efficiency on d/R ratio (d is the distance from the surface detector to point source and R is the radius of NaI(Tl) crystal).

Keywords: *Total efficiency, intrinsic efficiency, Hybrid Monte Carlo, NaI(Tl) detector*

INTRODUCTION

Scintillator detector using NaI(Tl) crystal was invented by Hofstadter in 1948. It was widely used in many radiation fields because of its high detection efficiency and especially, NaI(Tl) detector work at room temperature and thus are suitable for field measurements [7]. In radiation measurement, a high detection efficiency is one of important parameters.

Total efficiency of a 3 in × 3 in NaI(Tl) crystal for disk source was determined by analytical method by Nakamura [4]. After that, Younis S. Selim also used this method to determine the total efficiency of scintillator detector for coaxial disk sources [10].

In addition to analytical method, Monte Carlo method was also used to determine the total efficiency of NaI(Tl) crystal because of the simplicity of this method [2, 5].

In 2007, Yalcin et al. [9] combined two above methods to determine the total efficiency of NaI(Tl) detector. In their method, the Monte Carlo method was used to determine the direction of photons emitted from point source. The distance that photons travel in NaI(Tl) crystal was determined by analytical equations depending on photon directions. This was called the hybrid Monte Carlo method.

In our work, we developed a computer program using Fortran Programming Language (CalcTotEff) running on Plato program (Version 4.51, Copyright © Silverfrost Ltd 2012). The CalcTotEff computer code based on the hybrid

Monte Carlo method proposed by Yalcin was used to determine the total efficiency of NaI(Tl) versus distance from detector surface to coaxial point source. Experimental measurements were performed to recalculate the total efficiencies. These experimental results allowed us to evaluate the reliability of the hybrid Monte Carlo method.

Finally, we also used the hybrid Monte Carlo to calculate the intrinsic efficiency of a 3 in × 3 in NaI(Tl) crystal versus d/R ratio (where d is distance from detector surface to coaxial point source and R is radius of NaI(Tl) crystal).

MATERIALS AND METHODS

Determination of total efficiency of NaI(Tl) detector

The hybrid Monte Carlo method has the advantage of short calculated time. Furthermore, this method is flexible because we can easily change the parameters such as the distance from point source to detector surface (d), linear attenuation absorption factor (μ).

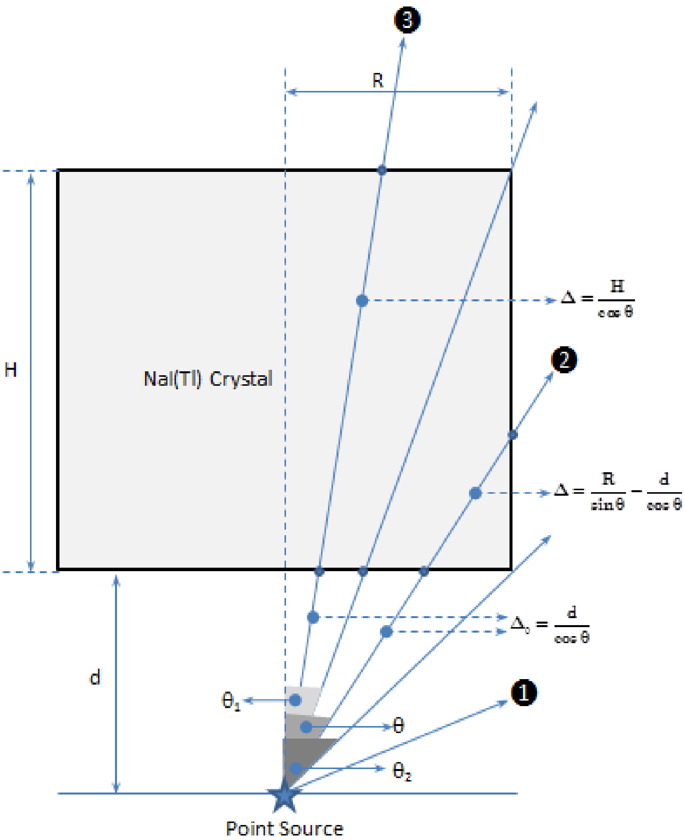

Figure 1. Paths of photon in NaI(Tl) crystal

While calculating the total and intrinsic efficiencies, we did not consider the attenuation of photon beam when photons travel in holder of NaI(Tl) crystal. The interaction of photons in the source volume as well as in source holder was not also considered. The interaction of photon with air was supposed not to be included.

A point source was located on symmetric axis of detector (Figure 1). The direction of photons emitted from the point source is determined by θ solid angle. It changes from 0 to π/2 (thus cosθ changes from 0 to 1). The emission of photons is a random process and thus the RANDOM_NUMBER (1) function of the Fortran program was used to create the random number in range from 0 to 1.

Photons emitted from source follow three cases:

If $\cos\theta \le \cos\theta_2$ (line 1): photon will not interact with NaI(Tl) crystal and thus detector do not record this photon.

If $\cos\theta_2 \le \cos\theta \le \cos\theta_1$ (line 2): the path length of photon in NaI(Tl) crystal is determined by following formula:

$$\Delta = \frac{R}{\sin\theta} - \frac{d}{\cos\theta}$$

If $\cos\theta \ge \cos\theta_1$ (line 3): the path length of photon in NaI(Tl) crystal is determined by following formula:

$$\Delta = \frac{H}{\cos\theta}$$

where θ_1 and θ_2 is determined as follows:

$\theta_1 = \tan^{-1}\left(\frac{R}{H+d}\right)$ and $\theta_2 = \tan^{-1}\left(\frac{R}{d}\right)$

When the photons travel in crystal via the path length (Δ) the absorption part of the photon having energy E is determined by:

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

where $\mu(E)$ is the total linear attenuation factor (without coherent scattering) for E energy photons when they travel in NaI(Tl) crystal.

In above calculations, photons emit from source in a 2π solid angle. However, real point source emit photons having the angle distribution is 4π. For this reason, the total efficiency of detector for the point source – detector arrangement was determined as follows [2]:

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

The diagram of algorithm for calculating the total efficiency of NaI(Tl) crystal was showed in Figure 2.

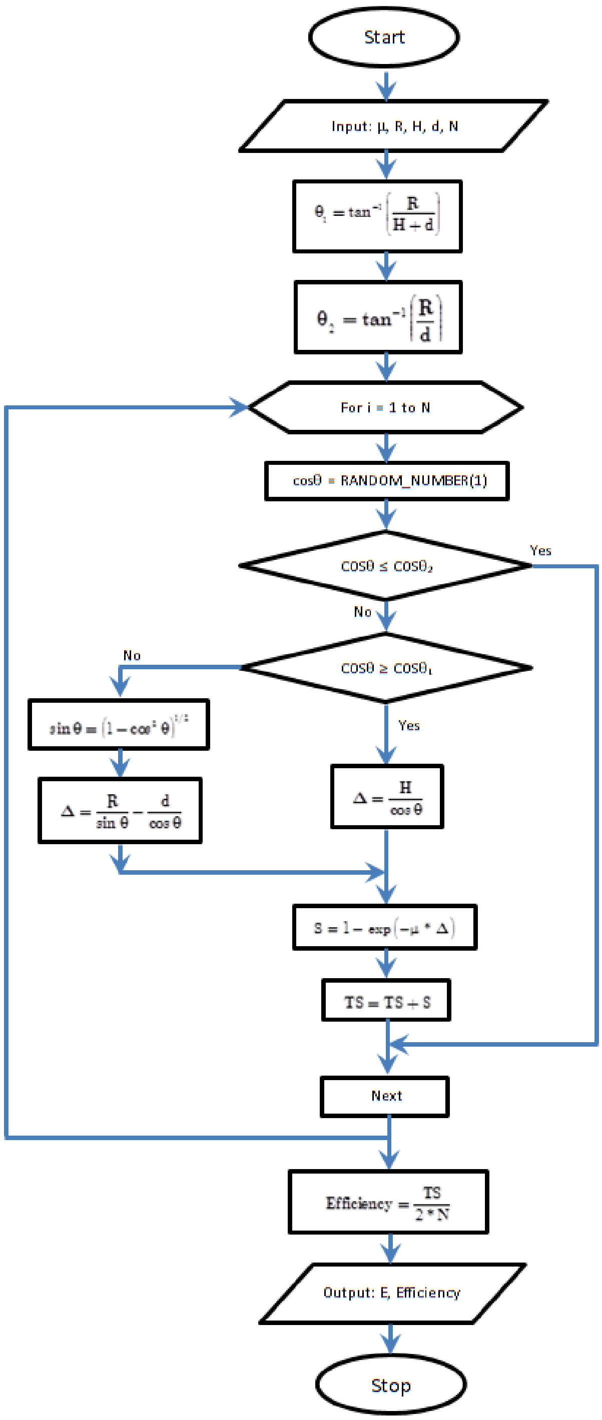

Figure 2. Diagram of algorithm for calculating the total efficiency.

Determination of the intrinsic efficiency of NaI(Tl) detector

Besides the total efficiency, the intrinsic efficiency was also one of important parameters for evaluating the detection ability of detector.

The intrinsic efficiency is defined as being the number of photons that the detector records compared with the number of photons that reach the detector. The intrinsic efficiency is calculated by the following formula:

$$\varepsilon_i = \frac{2\varepsilon_T}{1 - \frac{d/R}{\sqrt{(d/R)^2 + 1}}} \qquad (3)$$

In this work, we used the hybrid Monte Carlo method in order to calculate the intrinsic efficiency of detector versus the practical geometrical parameters and then we study the dependence of the intrinsic efficiency versus d/R ratio (where d is the distance from point source to detector surface and R is radius of detector).

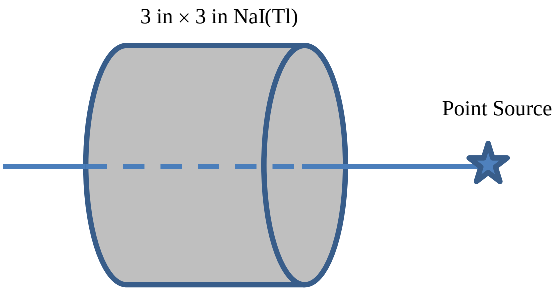

Figure 3. Experimental arrangement for determining the total efficiency

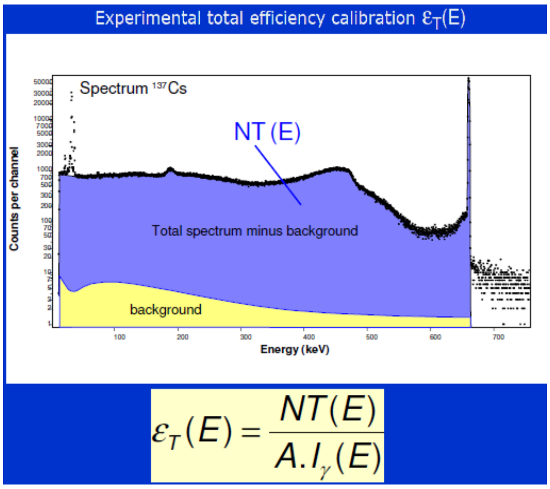

Figure 4. Cs-137 Spectrum [3]

For evaluating the reliability of results of the total efficiency from CalcTotEff code, we arranged the experimental set-up in Figure 3.

^{137}Cs spectrum was recorded by ADMCA software. To get high accuracy, the net counts were used for calculation.

MCA (Multichannel Analyzer) was set up at 8192 channels scale. The total count was taken from channel 0 to the right position of photo-peak (661.66keV). In low energy range of ^{137}Cs spectrum there is a X-ray peak of ^{137}Ba. This peak was not included in our calculations.

To get the total efficiency from experimental data, we use the following formula:

$$\varepsilon_T(E) = \frac{NT(E)}{AI_\gamma(E)} \qquad (4)$$

Table 1. Information of the source and the NaI(Tl) detector

NaI(Tl) Detector	Radiation source
Scintillator material type: NaI(Tl)	Source Type: ^{137}Cs standard source
Dimensions of crystal: diameter: 3 in, length: 3 in	Activity: 1 μCi
Supplier: Amptek, Inc., USA	Date of production: December, 2007
	Supplier: Spectrum Techniques LLC, USA

where $NT(E)$ is the net count-rate; A is the activity of source at the measured time and $I_\gamma(E)$ is the intensity of 661.66 keV photons of ^{137}Cs nuclide.

The relative uncertainty of total efficiency is computed according to the law of propagation of uncertainty as:

$$\frac{\sigma_{\varepsilon_T}}{\varepsilon_T} = \sqrt{\left(\frac{\sigma_N}{N}\right)^2 + \left(\frac{\sigma_{I_\gamma}}{I_\gamma}\right)^2 + \left(\frac{\sigma_{A_0}}{A_0}\right)^2 + (ln 2)^2\left(\frac{\sigma_\tau}{T}\right)^2} \quad (5)$$

RESULTS AND DISCUSSION

To evaluate the reality of the total efficiency calculated by CalcTotEff, we compared our resulsts with that of another authors. The results were showed in Table 2 and 3.

Table 2. The total efficiency of a 3 in × 3 in NaI(Tl) detector with point source located at d = 0.001cm away from the front surface and on the symmetric axis of detector

Energy (keV)	Total Efficiency		
	Our work	S. Yalcin (2007)	Nakamura (1972)
661	0.3640	0.3646	0.367
1332	0.2924	0.2930	0.296
2620	0.2470	0.2476	0.249

Table 3. The total efficiency of a 3 in × 3 in NaI(Tl) detector with point source located at d = 10 cm away from the front surface and on the symmetric axis of detector

Energy (keV)	Total Efficiency		
	Our work	S. Yalcin (2007)	Nakamura (1972)
661	0.0199	0.0202	0.0183
1332	0.0163	0.0164	0.0168
2620	0.0139	0.0140	0.0132

The results in Table 2 and 3 showed that the total efficiency calculated by CalcTotEff are suitable to others.

In CalcTotEff code, the input parameters are the number of photons emitted from point source and the total linear attenuation factor. The number of photons used was 199821691. This number was chosen because it was related to the experimental measurements. The total linear attenuation factor of the 661.66 keV energy photon in NaI(Tl) material is 0.27124 cm^{-1} [1].

Table 4 showed the results of the total efficiency calculated by CalcTotEff and experimental measurements.

Table 4. The total efficiency of NaI(Tl) detector was calculated by CalcTotEff and experimental measurements

d (cm)	**Total efficiency (ε_T)**		
	CalcTotEff	**Experimental**	**Relative uncertainty of measurement (%)**
5	0.05482	0.04682	2.02326
10	0.02004	0.02053	2.02366
15	0.01024	0.01008	2.02439
20	0.00620	0.00594	2.02540

25	0.00415	0.00404	2.02655
30	0.00297	0.00294	2.02789
35	0.00223	0.00220	2.02954
40	0.00174	0.00175	2.03124
45	0.00139	0.00142	2.03318
50	0.00114	0.00124	2.03468

There was a good agreement of the total efficiency calculated by CalcTotEff with the experimental measurements. However, at the distance of 5 cm the difference of the total efficiency values is significant because of the influence of dead time when source is located nearly the detector.

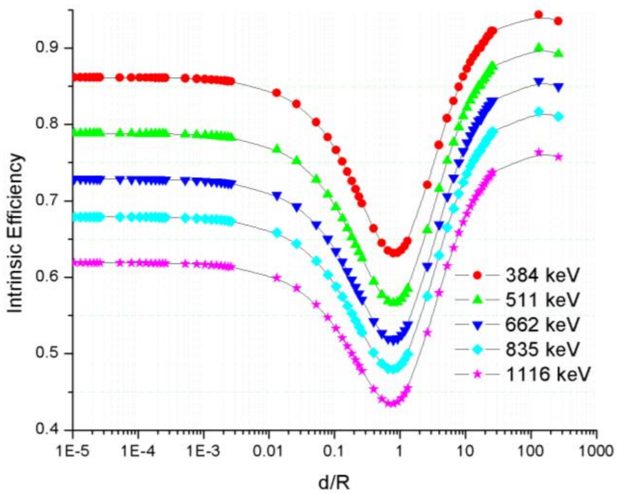

Figure 5. The dependence of the intrinsic efficiency on d/R ratio corresponding to the different energies

Figure 5 showed the dependence of the intrinsic efficiency versus d/R ratio for a 3 in × 3 in NaI(Tl) detector. When d/R increases, the intrinsic efficiency decreases, and after passing through minimum, it increases again. Similar results have been reported by Jehouani [8] and Ogundare [6].

CONCLUSION

For evaluating the total efficiency of NaI(Tl) detector, we use both of hybrid Monte Carlo and experimental methods. The results showed that there were a good agreement between two methods. Only at the distance of 5 cm, the difference of the total efficiency values was significant due to the influence of dead time when source is located nearly the detector.

Besides total efficiency, we also use the hybrid Monte Carlo method to calculate the intrinsic efficiency of NaI(Tl) detector versus d/R ratio corresponding to the different energies of photons. The results showed that, the intrinsic efficiency achieved the minimum value when d/R ratio equal 1 and values are saturated when d/R ratio is lower than 0.01 or higher than 100.

Đánh giá hiệu suất tổng và hiệu suất nội của Đề-tếc-tơ NaI (Tl) kích thước 3 in × 3 in bằng phương pháp Môn-te Các-lô lai

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TÓM TẮT

Trong công trình này, chúng tôi viết một đoạn code sử dụng phương pháp Môn-te Cac-lô lai (hybrid Monte Carlo) để tính toán hiệu suất tổng của detector NaI(Tl) kích thước 3 in × 3 in. Để khẳng định độ tin cậy của kết quả tính toán, các thí nghiệm với đề-tếc-tơ NaI(Tl) và nguồn chuẩn ^{137}Cs đã được tiến hành để xác định hiệu suất tổng này. Kết quả cho thấy sự phù hợp tốt giữa tính toán và thực nghiệm. Trên cơ sở đó, chúng tôi sử dụng phương pháp Môn-te Cac-lô lai để đánh giá sự phụ thuộc của hiệu suất nội theo khoảng cách.

Từ khóa: *Hiệu suất tổng, hiệu suất nội, Môn-te Các-lô lai , đề-tếc-tơ NaI(Tl).*

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