CALCULATION OF RADIATION DETECTORS EFFICIENCY IN A WIDE PHOTON ENERGY RANGE BY USING DETECC

Nurul Farhah Nazirah Zamzuri[1], Suffian Mohamad Tajudin[1*], A. M. Abdel-Monem[2], Adila Hanim Aminordin Sabri[1], Devendra Raj Upadhyay[3,4] and Raju Khanal[4]

[1] *Faculty of Health Sciences, Universiti Sultan Zainal Abidin (UniSZA), Terengganu, Malaysia.*

[2] *Faculty of Sciences and Arts, Department of Physics, Jouf University, Al-Jouf, Saudi Arabia.*

[3] *Department of Physics, Amrit Campus, Tribhuvan University, Kathmandu, Nepal.*

[4] *Central Department of Physics, Tribhuvan University, Kathmandu, Nepal.*

suffian@unisza.edu.my

ABSTRACT

This study evaluated the peak efficiency of gamma detectors using Detecc and validated as a reliable tool in the study of detector efficiency. HpGe, NaI(Tl), and BGO detectors are widely used in gamma detection and measurement due to their high atomic number and high density, which lead to high detection efficiency. Evaluation of HPGe, NaI(Tl) and BGO detector's peak efficiency and total efficiency in a wide photon energy range is important to understand the properties of various radiation detectors. Calculating the detector efficiency using Monte Carlo simulation through Detecc is more convenient as it can produce the detector response accurately similar to gamma ray spectrometry technique besides facilitating researchers when calibration of radiation detectors is impossible. Detecc programme had been developed based on EGS5 code but not yet tested and verified by any publication. BGO detector has the highest detection efficiency among HpGe, NaI(Tl), and BGO detectors. In simulations of low-energy photons, the optimum detector thickness of HpGe, NaI(Tl), and BGO is 0.3 cm, 0.2 cm, and 0.4 cm, respectively. Detecc is highly accurate to be used for evaluation of peak efficiency of detectors with low energy photons. As energy increased, the accuracy of Detecc reduced. Consequently, the results from the developed Detecc comparable with the database verified our programme to be used for radiation detectors study.

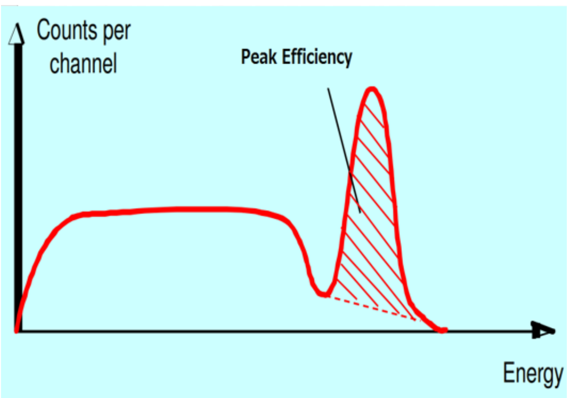
ABSTRAK

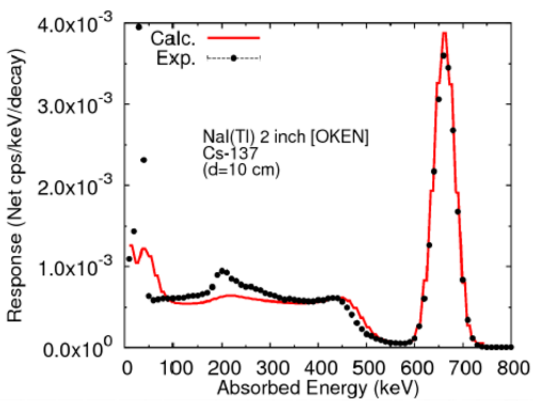
Kajian ini menilai kecekapan puncak pengesan gamma menggunakan Detecc dan disahkan sebagai alat yang boleh dipercayai dalam kajian kecekapan pengesan. Pengesan HpGe, NaI(Tl) dan BGO digunakan secara meluas dalam pengesanan dan pengukuran gamma kerana nombor atomnya yang tinggi dan ketumpatan tinggi, yang membawa kepada kecekapan pengesanan yang tinggi. Penilaian kecekapan puncak pengesan HPGe, NaI(Tl) dan BGO dan kecekapan jumlah dalam julat tenaga foton yang luas adalah penting untuk memahami sifat pelbagai pengesan sinaran. Pengiraan kecekapan pengesan menggunakan simulasi Monte Carlo melalui Detecc adalah lebih mudah kerana ia boleh menghasilkan tindak balas pengesan dengan tepat sama dengan teknik spektrometri sinar gamma selain memudahkan penyelidik apabila penentukuran pengesan sinaran adalah mustahil. Program Detecc telah dibangunkan berdasarkan kod EGS5 tetapi belum diuji dan disahkan oleh mana-mana penerbitan. Pengesan BGO *mempunyai kecekapan pengesanan tertinggi antara pengesan HpGe, NaI(Tl) dan BGO. Dalam simulasi foton tenaga rendah, ketebalan pengesan optimum HpGe, NaI(Tl), dan BGO ialah 0.3 cm, 0.2 cm, dan 0.4 cm, masing-masing. Detecc sangat tepat untuk digunakan untuk penilaian kecekapan puncak pengesan dengan foton tenaga rendah. Apabila tenaga meningkat, ketepatan Detecc berkurangan. Akibatnya, keputusan daripada Detecc yang dibangunkan setanding dengan pangkalan data mengesahkan program kami untuk digunakan untuk kajian pengesan sinaran.*

Keywords: HpGe, NaI(Tl), Detecc, gamma ray, Monte Carlo simulation

INTRODUCTION

When radiation from gamma sources deposits its energy within a detector, energy spectra will be produced or measured. The two main properties of energy spectra are peak efficiency and total efficiency. In Figure 1 (a), the shadow part of the energy spectra represents the peak efficiency while the whole region spectra are the total efficiency. The efficiency for each gamma ray measurement would depend on the detector's geometrical conditions and the photons' energy [1]. The geometrical conditions of the detector include its shape, size, materials, and source-to-detector distance. Figure 1 (b) shows the comparison of measured and calculated (EGS5 code) pulse height spectra for the Cs-137 source [2]. For the case of NaI(Tl), the measured and calculated absolute peak efficiency (PE) are in good agreement within 3.5 %. In addition, the full energy peak, Compton edge and Compton area are in agreement where they appeared at the correct value and intensity. Such agreement is important as the basis for developing Detecc for radiation detectors based on the same Monte Carlo code. Previously, we had successfully developed Simu-Rad [3] as a learning tool for photon interactions.





(a) (b)

Figure 1. The typical detector spectra for gamma measurement as shown in (a) [1]. Fig. (b) is an example of measured and calculated absorbed energy spectra of Cs-137 source by NaI(Tl) detector [2].

A radiation detector's most crucial features are total and peak efficiency. The evaluation of the total and peak efficiency helps to improve understanding regarding the ability and performance of the detector [2]. The total efficiency is the ratio of the number of counts recorded by the detector to the number of gamma rays emitted by the source. Meanwhile, the peak (or photopeak) efficiency is for producing full-energy peak pulses only, rather than a pulse of any size, for the gamma ray [4]. The formula for total efficiency is as follows;

$$\sum T(E) = NT(E)/F(E) \qquad (1)$$

where, $\varepsilon T(E)$ is the total efficiency, $NT(E)$ is the total number of counts in the spectrum and the number of photons with energy E emitted by the source $F(E)$. The formula for peak efficiency is as follows;

$$\sum P(E) = NP(E)/F(E) \qquad (2)$$

where, $\varepsilon P(E)$ is the peak efficiency, $NP(E)$ is the number of counts in full-energy peak corresponding to energy, $F(E)$ is the number of photons with energy emitted by the source.

The peak efficiency of a radiation detector can be explained as the probability that the photon will deposit all of its initial energy in the detector. The total efficiency of a detector is almost always higher than the peak efficiency because the incident photons can deposit only a portion of their energy and then escape from the detector [5]. In addition, higher density detectors and larger detector sizes increase the probability of the gamma-ray being absorbed [6].

Vassiliev [7] described Monte Carlo simulation as a statistical approach to studying differential equations or integro-differential equations that occur in various branches of the natural sciences. For example, Monte Carlo consists of several codes widely used to study radiation detectors, such as GEANT4 [8], FLUKA [9], PENELOPE [10], and EGS5 [11]. For example, the EGS5 Monte Carlo code is commonly applied in radiation measurement, detector design [12 -14], and radiation shielding [15 – 18].

Detecc programme, a Monte Carlo simulation based on the Electron Gamma Shower Vers. 5 (EGS5), will be used to study for HpGe, NaI(Tl) and BGO detector's efficiency for several energy of gamma sources. The interactions of the photons, such as photoelectric absorption, Compton scattering, and pair productions, were considered. EGS5 code was developed at the High Energy Accelerator Research Organization (KEK), Japan [19].

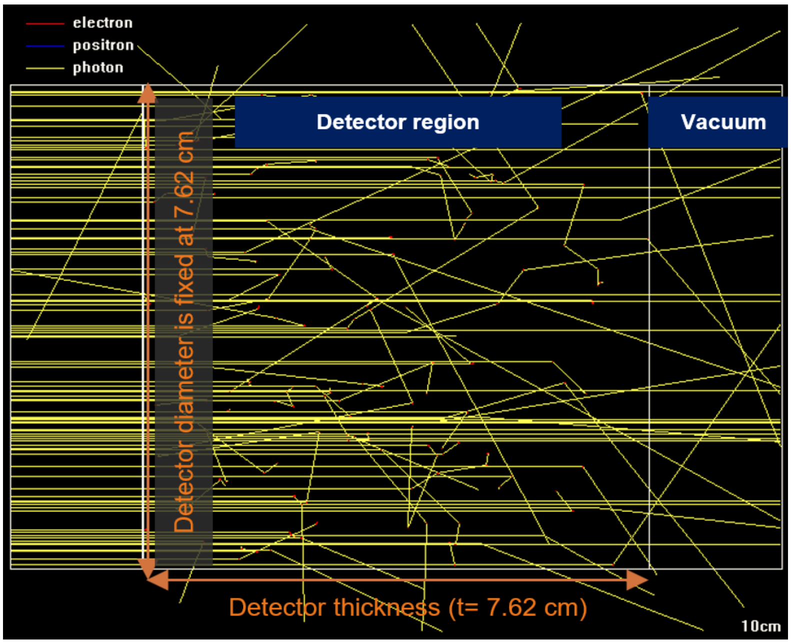


Figure 2. The example of photon interactions within a detector simulated using Detecc programme. The detector material is NaI with an incident photon energy of 662 keV.

CALCULATED PEAK EFFICIENCY FOR VARIOUS DETECTORS

Detecc programme is relatively simple software and easy-to-use interface for radiation detector efficiency. Detecc programme had been developed based on EGS5 code, but not yet tested and verified by any publication. The detector geometry in this programme was designed as a cylindrical shape (Figure 2), representing the shape of HPGe, NaI (Tl), and BGO detectors. This software has several fixed variables, such as detector diameter which is 7.62 cm, and source to detector distance, which is 10 cm. The number of photons are limited up to 5000. In order to reduce the error, the number of incident photons simulated needs to be increased, particularly to obtain reliable research data. In real case of simulation, we normally simulated millions number of photons for better statistics point of view.

In this study, the peak and total efficiency of HpGe, NaI(Tl) and BGO is calculated using Detecc programme at energies of 59.5 keV, 662 keV, 1173 keV and 1333 keV. The detector thickness is 7.62 cm for all detectors and energy levels. The data of peak efficiency were tabulated in Table 1.

Table 1. The peak efficiency of radiation detectors for various photon energies.

Source	**keV**	**Peak Efficiency (%)**		
		NaI	BGO	HpGe
Am-241	59.5	90±6.49	99±6.50	98±6.90
Cs-137	662.0	46±4.78	91±6.54	51±4.14
Co-60	1173.0	36±4.00	79± 6.89	35±3.92
Co-60	1333.0	28±3.29	72±5.49	26±3.10

Based on Table 1, all detectors recorded a decrease in peak efficiency with increasing photon energy. It is due to higher energy photons will be unlikely to deposit their energy in the detector and pass through the detectors.

Among the detectors, BGO seem to have the highest peak and total efficiency value, followed by HpGe and NaI in the detection of various range of photon energies. It is due to the BGO having the highest density which is 7.13g cm^{-3}, and the atomic number of 83 [20]. The high density and atomic number of the bismuth in the BGO scintillator led to a higher probability of gamma ray absorption, resulting in the BGO scintillator having the highest peak detection efficiency [21] as in Table 1. Compared to BGO, HpGe has a density of 5.33 g cm^{-3} and the atomic number of 32, while NaI has a density of 3.67 g cm^{-3} and an Iodine atomic number of 53 [5]. In addition, in higher energy levels, the peak efficiency of NaI is higher than HpGe. This indicates that HPGe is effective at detecting nuclides with lower energies but is less effective at detecting nuclides with higher energies [22]. For gamma rays, it is impossible for the photons to completely transfer their initial energy to the detectors unless in very low-energy photons. The photons will likely deposit only part of their energy and then leave the detectors. These events do not contribute to peak efficiency.

CALCULATED PEAK EFFICIENCY FOR DIFFERENT DETECTOR THICKNESS

The peak efficiency of NaI(Tl), BGO and HpGe detectors were calculated for detector thickness of 0.1 cm, 0.2 cm, 0.3 cm, 0.4 cm and 0.5 cm for low energy photon of 59.5 keV, and thickness of 2 cm, 4 cm, 6 cm, 8 cm and 10 cm for the high photon energy of 1333 keV.

In the simulation of gamma photons with low energy, at a detector thickness of 0.1 cm, all detectors have the lowest detection efficiency. From the photon trajectory, there are still a number of photons that can pass through the scintillation or semiconductor region within the detector. Therefore, increasing the thickness has increased the value of peak efficiency of the detectors. Since photons energy of 59.5 keV is used, the photon can be completely deposited within the scintillator although the thickness is less. The optimum thickness of the detector to achieve an optimum value of peak efficiency for NaI, BGO and HpGe is 0.3 cm, 0.2 cm and 0.4 cm, respectively. Therefore, designing a thicker thickness than these values for energy of 59.5 keV is not necessary or economical for diagnostic radiology application.

Table 2. The peak efficiency of radiation detectors at a fixed energy of 59.5 keV (a) and 1173 keV (b) and different detectors' thickness.

Peak Efficiency (%)					
Detector	Thickness (cm)				
	0.1	0.2	0.3	0.4	0.5
NaI	73±5.54	89±6.43	90±6.49	90±6.49	90±6.49
BGO	91±6.54	99±6.95	99±6.95	99±6.95	99±6.95
HpGe	66±5.12	89±6.43	94±6.70	98±6.90	98±6.90

(a)

Peak Efficiency (%)					
Detector	Thickness (cm)				
	2	4	6	8	10
NaI	9±2.0	22±2.69	28±3.29	40±4.32	43±4.56
BGO	29±3.39	60±5.75	75±5.66	79±5.89	79±5.89
HpGe	11±2.32	16±3.00	32±3.66	35±3.92	44±4.63

(b)

Increasing the detector thickness will result in increase the likelihood that the entire energy of the incident photons will be photoelectrically absorbed. At 10 cm of detector thickness, NaI(Tl) and HpGe still recorded a low value of peak efficiency as tabulated in Table 2 (b). This is because of these detectors have lesser atomic number compared to BGO. So less photoelectric absorption occurs in NaI(Tl) and HpGe detectors. Some photons may only deposit part of their energy thus affecting the value of peak efficiency.

COMPARISON OF PEAK EFFICIENCY OF NAI(TL) WITH THEORY

Monte Carlo simulation was implemented through Detecc programme to calculate the peak efficiency of NaI(Tl). The diameter and thickness of the detector were set at 7.62 cm, and seven different energy levels based on previous study [23]. The results obtained were tabulated in Table 3. Based on the table, the percentage of difference between Detecc and literature increased as the photon energy increased. Therefore, it seems the programme is suitable for diagnostic radiology application, but not suitable for high energy photons such as in radiotheraphy whenever high accuracy of less than 5 % is needed.

The peak efficiency value obtained from the Detecc programme is lower than in the literature as in Table 3. This is because the lower energies gamma that are ignored in Detecc are mostly absorbed within the detector, contributing to high peak efficiency value in literature. Therefore, the peak efficiency value of the programme is lower than literature. For photon energies ranging from 59.54 keV to 1332 keV, the results that were calculated for the NaI(Tl) detectors by using Detecc programe are in good agreement with the results that were obtained through literature. However, when it comes to photon energy higher than 661.7 keV, the percentage difference between the results calculated and those found in the literature is quite significant. This means that Detecc is highly accurate to be used for the evaluation of peak efficiency of detectors with low energy photons. Above 1000 keV, the percentage difference is more than 10 % thus, we could summarize that the accuracy of Detecc programme reduced.

Table 3. The percentage difference of peak efficiency between Detecc and literature.

Energy (keV)	**Peak efficiency (%)**		**Percentage difference (%)**
	Detecc	Literature [23]	
59.54	89.64±1.34	90	0.40
165.8	96.76±1.39	96	0.79
391.7	78.62±1.25	77	2.08
500	66.74±1.16	69	3.33
661.7	54.68±1.05	57	4.15
1115.5	35.88±0.85	42	15.72
1332	31.74±0.80	38	17.95

CONCLUSION

The peak efficiency values for the HpGe, NaI(Tl) as well as BGO detectors were evaluated by using a Monte-Carlo simulation through Detecc programme that has been developed. All energy values in the range can be calculated using this computer method, which makes it simple and easy to determine the total efficiency.

Among HpGe, NaI(Tl) and BGO detectors, BGO detector seems to have the highest detection efficiency, followed by HpGe and NaI(Tl) detectors. However, in energy over 1000 keV, HpGe detectors recorded lower peak efficiency compare to NaI(Tl). In simulation of photons with low energy, the optimum thickness of detector of HpGe, NaI(Tl) and BGO in order to achieve the optimum total efficiency are 0.3 cm, 0.2 cm and 0.4 cm respectively.

The results calculated for the NaI(Tl) detectors by using the Detecc program are in good agreement with the results obtained through literature for photon energies ranging from 59.54 keV to 1332 keV. However, the difference is quite significant when it comes to photon energies greater than 661.7 keV. This demonstrates that Detecc is a precise tool that can be used to evaluate the peak efficiency of detectors when dealing with low-energy photons. However, as the energy level increased, the accuracy of Detecc became less precise. Nevertheless, the programme could be a tool for radiation detector education for the radiation workers including students of radiation sciences.

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