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Calculation of Full Energy Peak Efficiency for HPGe Detector Using Monte Carlo Method

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Abstract
This research presents results on the full energy peak efficiency of a high purity germanium (HPGe) detector from point source as a function of photon energy and source-detector distance. The directions of photons emitted from the source and the photon path lengths in the detector were determined by Monte Carlo technique. A major advantage of this technique is the short computation time compared to the experiments. Another advantage is the flexibility for inputting detector-related parameters (such as source–detector distance, detector radius, length and attenuation coefficient) into the algorithm developed, thus making it an easy and flexible method to apply to other detector systems and configurations. It has been designed and written the program for this computational. The results of the full energy peak counting efficiency were compared with the published results. It appears in a good agreement with quantity and behavior.

Keywords: Efficiency, High Purity Germanium (HPGe) Detector, and Solid-State Detectors.

استخدام طريقة مونتِ كارلو لحساب كفاءة قمة الامتصاص الكلي لكاشف الجرمانيوم عالي النقاوة

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الخلاصة
يقدم هذا البحث نتائج عن حسابات كفاءة ذروة الامتصاص الكلي لكاشف الجرمانيوم عالي النقاوة ولمصدر اقرب ما يكون نقطي كدالة لطاقة الفوتون والمسافة بين المصدر و الكاشف. تم تحديد اتجاهات الفوتونات المنبعثة من المصدر وأطوال مسار الفوتونات بواسطة تقنية مونت كارلو. الميزة الرئيسية لهذه التقنية هو الوقت القصير اللازم للحساب بالمقارنة مع التجارب العملية. ومن المميزات الاخرى هي المرونة لإدخال المعلومات ذات الصلة بالكاشف (مثل المسافة بين المصدر و الكاشف،نصف قطر الكاشف، طول الكاشف، معامل التوهين الكاشف و اختيار الطاقات) في الخوارزمية المتقدمة، مما يجعل منها وسيلة سهلة ومرنة لتطبق في نظم اخرى من الكواشف.قورنت نتائج حساباتنا مع نتائج حسابات ابحاث سابقه (بقياسات عملية وحسابات مونت كارلو). من خلال مقارنة نتائج الحسابات، لوحظ ان حساباتنا توافقت بشكل جيد مع حسابات الابحاث السابقة.

Introduction

Gamma-ray spectrometry with germanium detectors is one of the most widely used techniques to determine the concentration of natural and artificial radionuclides in environmental samples [1]. In 1948, Hofstadter reports the detection of gamma-rays using NaI(Tl) crystals. This crystalline material has remained for almost twenty years the most important detector medium for gamma-ray spectrometry [2]. In the 1960's, the first semi-conductor gamma-ray detectors became commercially available. Semi-conductor detectors soon became widely used because of their superior energy

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resolution. The primary semi-conductor materials used in these detectors were either germanium or silicon [3]. Germanium became the preferred choice for gamma-ray spectroscopy because it had a higher atomic number than silicon, and thus yielded higher efficiencies at typical gamma-ray energies for a given crystal size. Germanium was also easier to manufacture to the low level of impurities needed to achieve the proper depletion depths [3]. Detector efficiency is a key parameter in the design of gamma-ray spectrometers and imaging devices such as cameras and scanners [4].
Detector efficiency depends upon [5]:

- the type of detector (scintillation, solid-state)
- the detector size and shape (larger areas and volumes are more sensitive)
- the distance from the detector to the radioactive material
- the radioisotope and type of radiation measured (alpha, beta and gamma radiation and their energies)
- the backscatter of radiation toward the detector (the denser the surface, the more scattering)
- the absorption of radiation before it reaches the detector (by air, and by the detector covering)

Determination of detector efficiency is very important in various scientific and industrial fields. Four techniques are commonly employed for determining detector efficiencies. These are [6]:

1. Direct measurement using relative or absolute intensity standards.
2. Empirical calculations.
3. Semi-empirical calculations based on various detector parameters or interaction processes.
4. Monte Carlo computations

In the past, efforts have been made for theoretical determination of the values of gamma-ray detector efficiency for a variety of situations. Because the theoretical calculations of efficiency are at present so complex, it is important to determine reliable experimental techniques for measuring efficiency [7]. Monte Carlo simulation is nowadays a powerful method for solving problems concerning radiation transport. Its application for the computation of detection efficiency has dramatically increased in the last period. The method is powerful and flexible, as it can be applied to any semi-conductor and scintillation detectors [8].

Several papers have appeared recently discussing the experimental and theoretical aspects of determining the efficiency of different types of detectors. The experimental full energy peak efficiency curve of a 5.8 cm^3 planar Ge (Li) detector was compared by Seyfarth (1974) with the curve obtained from the corrected semi-empirical formula of Paradellis and Hontzeas [9].

Park et al. (2003) calibrated the full energy peak efficiency of a high purity germanium (HPGe) detector in a wide energy range from 0.06 to 11 MeV. Both the experimental technique and the Monte Carlo method were used for the efficiency calibration. The calculated efficiency agreed with the measured within about 7% [10]. Karfopoulos and Anagnostakis (2010) investigated the effect of various simulation parameters on the full energy peak determination of a Ge detector [11]. Selim et al. (2011) introduced a new mathematical model to calculate directly photopeak efficiency of HPGe detector with an axial point source at different distances from the detector surface [12]. McNamara et al. (2012) investigated a model based on Monte Carlo simulation to calculate the apparent full energy peak efficiency (FEPE) [13]. Challan (2013) calculated the full energy peak efficiency of the coaxial 120 m^3 closed high purity germanium (HPGe) detectors. The calculated efficiencies obtained were in good agreement with the experimental data [14].

Monte Carlo Simulation Efficiency Program

The program is designed mainly for a cylindrical shaped detector that is considered along with a point isotropic source. The front face of detector is at distance "d" from the origin along z-axis in the axial direction. The detector has radius "r_d" and length "t_d". The configuration of this detector is illustrated in Figure-1.

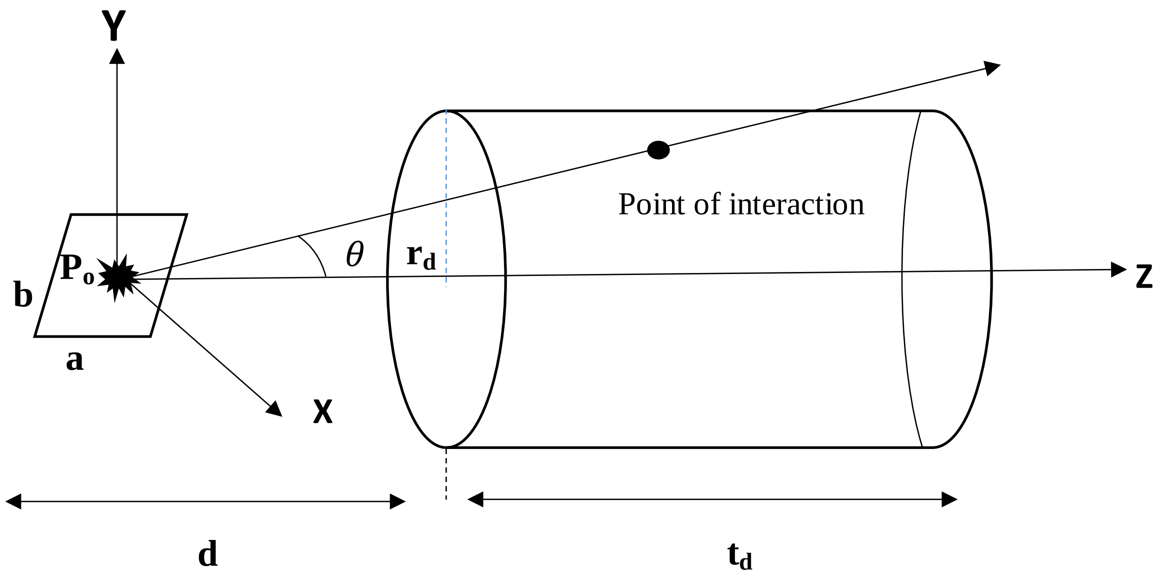


Figure 1- Geometric arrangement for a point source-detector, where r_d: radius of the detector window, t_d: detector length, d: distance between the detector and the source

The main way of the work program for this research is to follow the path of the photon until detected or absorbed or escaped from the material. If a large enough number of particles is simulated, a picture of how system behaves emerges.

The photon's path length and its attenuation value at the same source has been neglected on the assumption that the source is close to be a point source (where the value of a and b was considered equal to 0.001 cm).

Also, any attenuation of the photon energy emitted from the source before colliding with a detector window because the air is considers as a medium between the source and the detector, besides neglecting the attenuation of the detector window because it is very thin [15].

The flowchart is shown in Figure-2.

Symbol	Definition
E	Photon energy emitted from the source.
N	Number of photons emitted from the source ($N=10^6$).
D	Distance between the detector and the source.
$\mathbf{r_d}$	Radius of the detector.
$\mathbf{t_d}$	Detector length.
a, b	The dimensions of the radioactive source in the x and y axis respectively.
P	Density.
$\mathbf{n_i}$	Number of photons incident on the detector.
$\mathbf{n_a}$	Number of photons absorbed in the detector.
$\mathbf{n_o}$	Number of photons exiting the detector without interaction.
$\mathbf{n_s}$	Number of photons exiting from the side of the detector.
$\mathbf{n_b}$	Number of photons exiting from the bottom of the detector.
$\mathbf{Z_g^b}$	Distance from the source to the bottom of the detector ($z_g^b = d + t_d$).

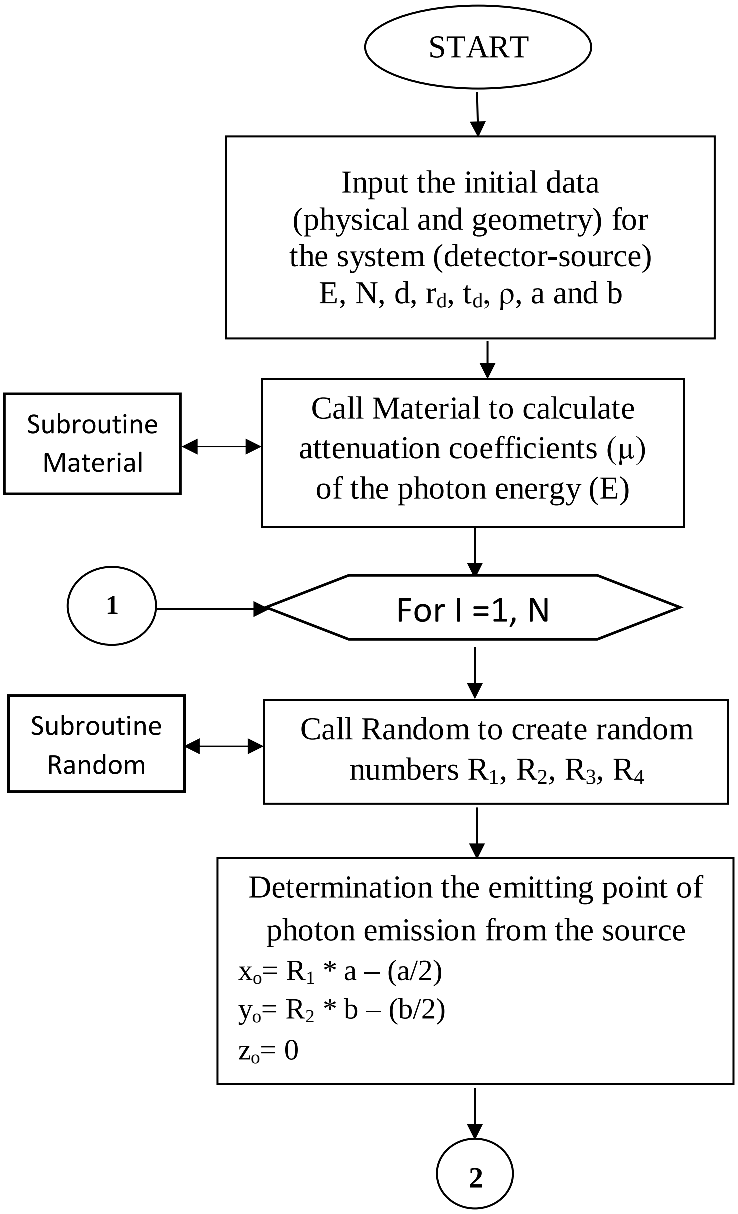
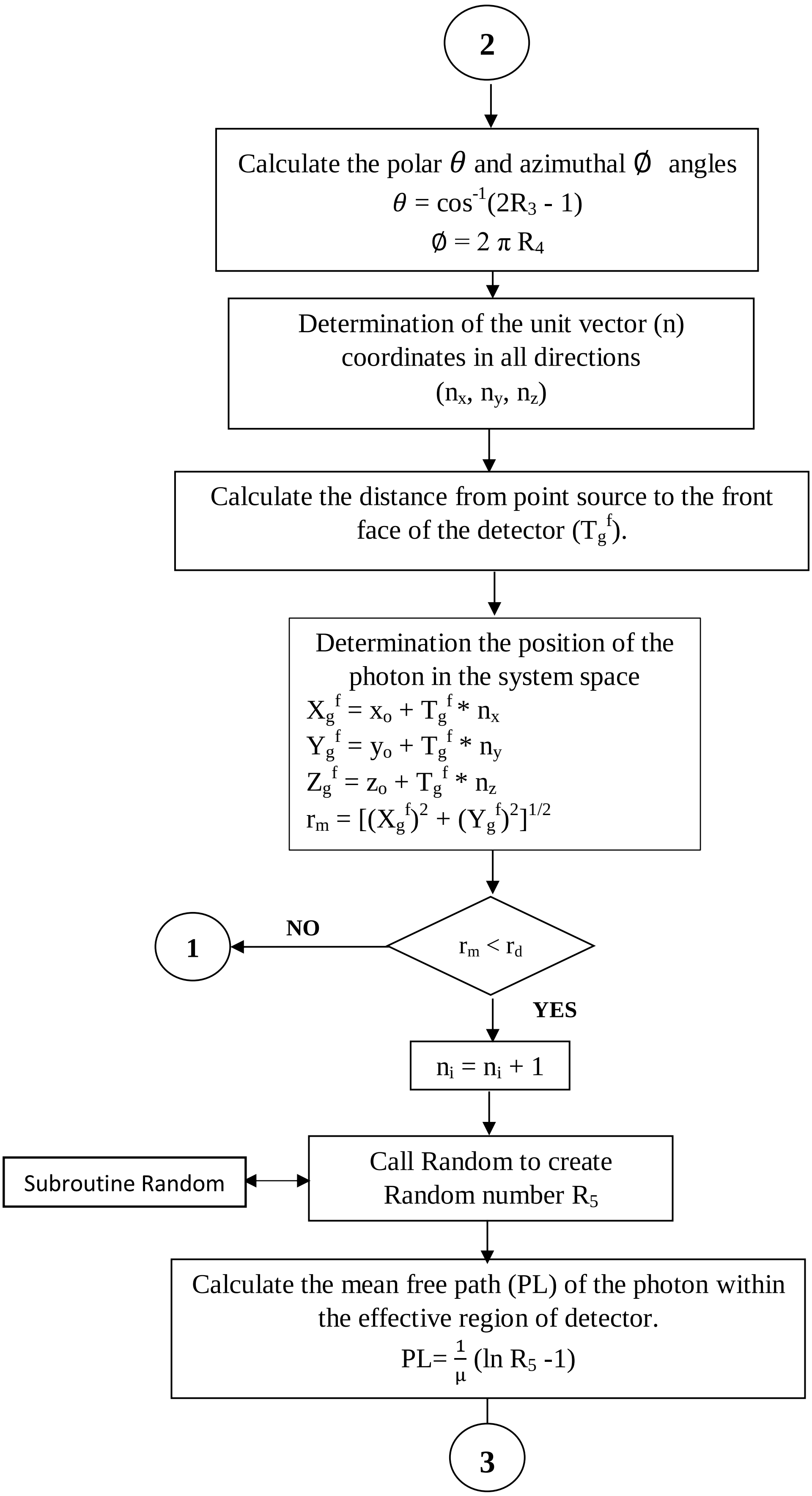
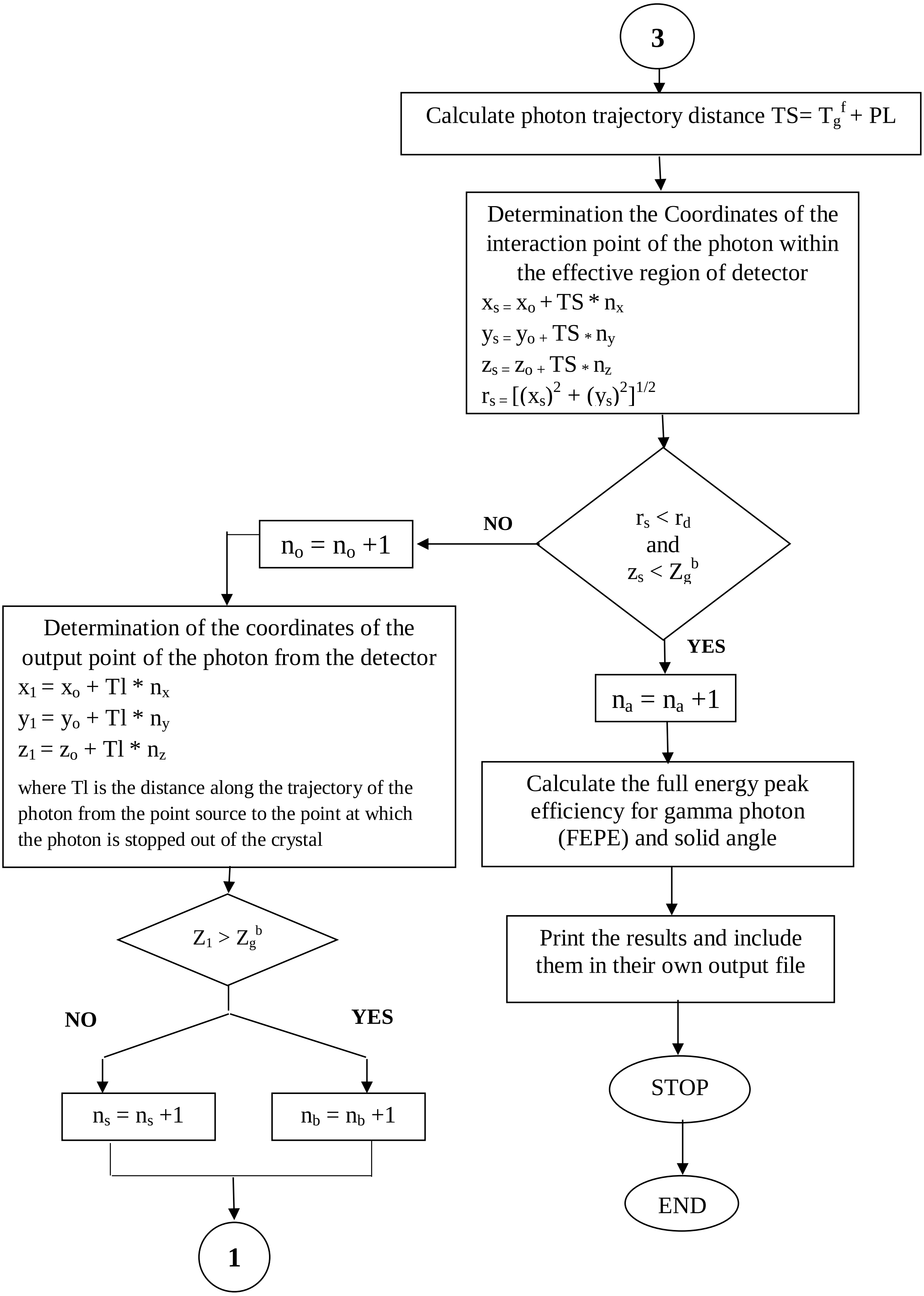


Figure 2- Flowchart of the FEPE program to simulate the history of the photon.


2
Calculate the polar θ and azimuthal $\emptyset$ angles
$\theta = \cos^{-1}(2R_3 - 1)$
$\emptyset = 2\pi R_4$
Determination of the unit vector (n) coordinates in all directions
(n_x, n_y, n_z)
Calculate the distance from point source to the front face of the detector (T_g^f).
Determination the position of the photon in the system space
$X_g^f = x_o + T_g^f * n_x$
$Y_g^f = y_o + T_g^f * n_y$
$Z_g^f = z_o + T_g^f * n_z$
$r_m = [(X_g^f)^2 + (Y_g^f)^2]^{1/2}$
NO
1
$r_m < r_d$
YES
$n_i = n_i + 1$
Subroutine Random
Call Random to create Random number R_5
Calculate the mean free path (PL) of the photon within the effective region of detector.
$PL = \frac{1}{\mu}(\ln R_5 - 1)$
3


3
Calculate photon trajectory distance TS= T_g^f + PL
Determination the Coordinates of the interaction point of the photon within the effective region of detector
$x_s = x_o + TS * n_x$
$y_s = y_o + TS * n_y$
$z_s = z_o + TS * n_z$
$r_s = [(x_s)^2 + (y_s)^2]^{1/2}$
$r_s < r_d$ and $z_s < Z_g^b$
NO
YES
$n_o = n_o + 1$
$n_a = n_a + 1$
Determination of the coordinates of the output point of the photon from the detector
$x_1 = x_o + Tl * n_x$
$y_1 = y_o + Tl * n_y$
$z_1 = z_o + Tl * n_z$
where Tl is the distance along the trajectory of the photon from the point source to the point at which the photon is stopped out of the crystal
Calculate the full energy peak efficiency for gamma photon (FEPE) and solid angle
Print the results and include them in their own output file
$Z_1 > Z_g^b$
NO
YES
STOP
$n_s = n_s + 1$
$n_b = n_b + 1$
END
1

Results and Discussion

Monte Carlo techniques are used to calculate the full energy peak values of the HPGe detector (radius (r_d), length (t_d)) for photons were obtained for point source. A compute program has been written to carry out their calculations and it can use for different sizes and types of gamma detectors since the input parameters can be controlled.

The results of this simulation comprise the several runs with variable numbers of initial photons ranging from 10^5 to 10^6. The largest number of the initial photons was used for the simulations in order to improve the statistical uncertainty. The full energy peak efficiency value, depend on the geometries of the detector and source, and on the distance between the detector and the source.

The function which adequately represents the FEPE values has the form:

$$\text{FEPE} = \frac{N_a}{N} \quad (1)$$

The full energy peak efficiency values of HPGe detector for different gamma energies have been compared with the values previously reported for point sources. The comparison with the ones obtained by Monte Carlo N-Particle Code (MCNP) and also with the experimental values for point source with (r_d = 2.455, t_d = 4.99 cm) detector for source-detector distances (d = 1.7 and 12.6 cm) are given in Figures-3 and -4, it can be seen that agreement was obtained. The differences with some considerations among researchers causes the deviations where some of them takes into account a certain point that is not taken by others, such as the attenuation in the source itself and the attenuation of the detector window and dead layer of the detector specially for low gamma ray energy or the following photon for more than one or two scatters and pair production specially for high energies. Obviously, the neglected of inactive detector component in the calculations caused the deviations in the FEPE values. The FEPE values calculated for (r_d = 2.3, t_d = 5.2 cm) detector for different source-detector distances (d = 5, 9, 13 and 17cm) are given in Figures -5, -6, -7 and -8.

In this case the experimental and the simulated values show good agreement at high energies but deviate at lower energies. The discrepancies at lower energies are most likely due to inaccuracies in the detector model. Low energy gamma ray photons would be more susceptible to absorption in the inactive detector component (e.g. dead layer). If these components are not modelled it can affect the simulated efficiencies. Also, the number of incident photons could strongly affect the simulated results.

Table 1- The comparison between the experimental results, calculated MCNP results and present results of the FEPE of the HPGe detector (r_d=2.455 t_d=4.99) cm.

Distance	d = 1.7 cm			d = 12.6 cm		
Energy (MeV)	**MCNP FEPE [16]**	**Exp. FEPE [16]**	**Present work FEPE**	**MCNP FEPE [16]**	**Exp. FEPE [16]**	**Present work FEPE**
0.1221	0.1126	0.0757	0.07895	0.0065	0.0054	0.00982
0.1365	0.1073	0.0720	0.06343	0.0064	0.0053	0.00772
0.2792	0.0579	0.0424	0.02618	0.0039	0.0033	0.00318
0.32	0.0525	0.0363	0.02342	0.0034	0.0030	0.00286
0.661	0.0238	0.0168	0.01559	0.0017	0.0015	0.00202
1.115	0.0155	0.0103	0.01198	0.0011	0.0009	0.00166

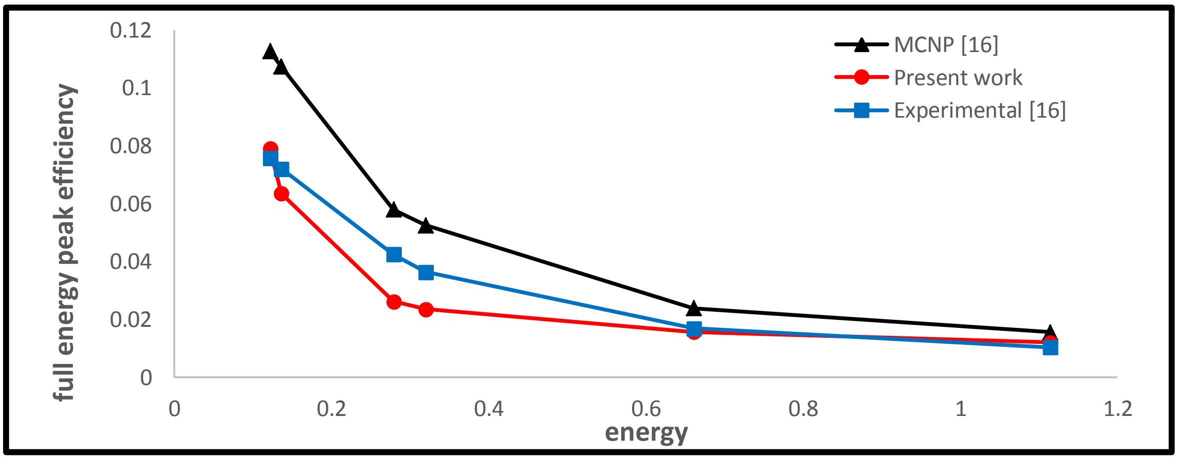


Figure 3- The Comparison between the calculated efficiency (present work), experimental and the calculated MCNP efficiency at 1.7 cm distance as a function of energy (MeV)

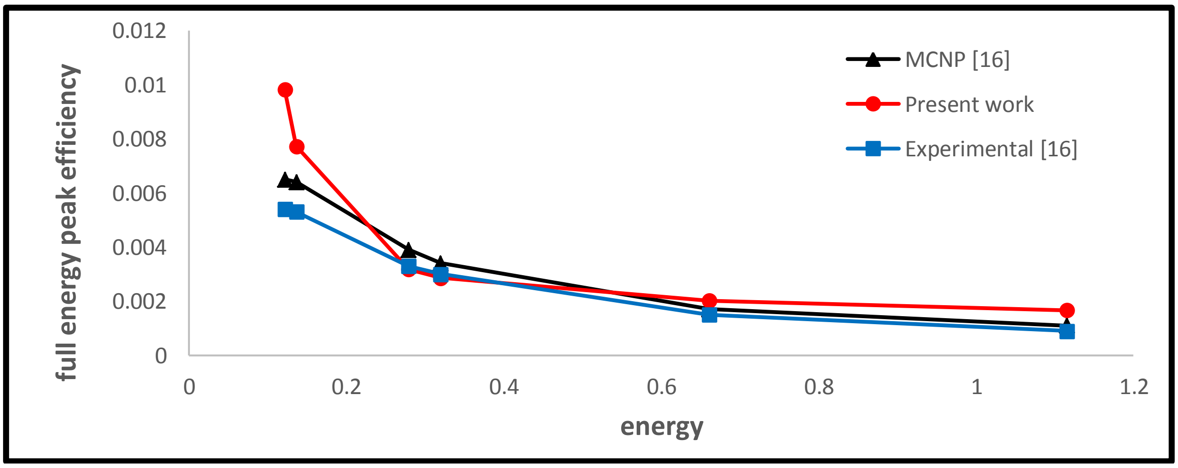


Figure 4- The Comparison between the calculated efficiency (present work), experimental and the calculated MCNP efficiency at 12.6 cm distance as a function of energy (MeV)

Table (2): The comparison between the experimental results and present results of the FEPE of the HPGe detector (r_d=2.3 t_d=5.2) cm, at d=5 cm.

Energy (MeV)	Experimental FEPE [17]	Present work FEPE	Mean Squared Error of Efficiency Present work and Experimental
0.13	0.03	0.02524	2.26576E-05
0.17	0.02	0.01631	1.36161E-05
0.33	0.014	0.00873	2.77729E-05
0.4	0.011	0.00775	1.05625E-05
0.5	0.0086	0.00687	2.9929E-06
0.66	0.007	0.006	0.000001
0.88	0.006	0.00523	5.929E-07
1.3	0.0045	0.00433	2.89E-08
Average of the Mean Squared Error = 8.80264E-06			

Table (3): The comparison between the experimental results and present results of the FEPE of the HPGe detector (r_d=2.3 t_d=5.2) cm, at d=9 cm.

Energy (MeV)	Experimental FEPE [17]	Present work FEPE	Mean Squared Error of Efficiency Present work and Experimental
0.13	0.013	0.01244	3.136E-07
0.17	0.009	0.00847	2.809E-07
0.33	0.0059	0.00494	9.216E-07
0.4	0.005	0.00447	2.809E-07
0.5	0.0038	0.00399	3.61E-08
0.66	0.0035	0.00351	1E-10
0.88	0.0026	0.00313	2.809E-07
1.3	0.0021	0.00262	2.704E-07
Average of the Mean Squared Error = 2.64944E-07			

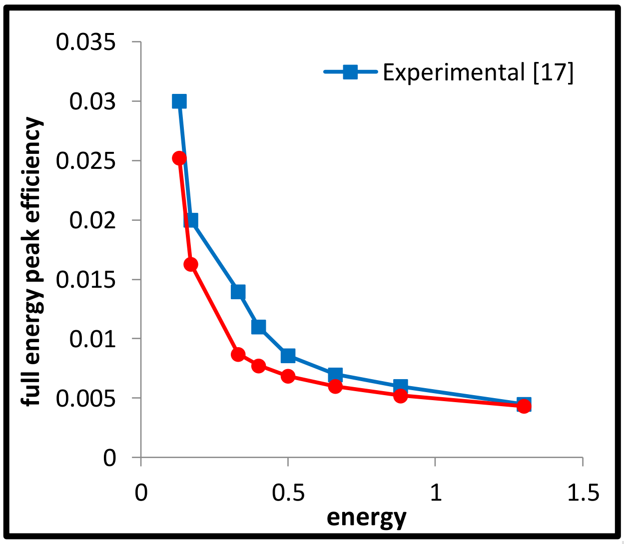


Figure 5- The Comparison between the calculated efficiency (present work) and the measured efficiency at 5 cm distance as a function of energy (MeV)

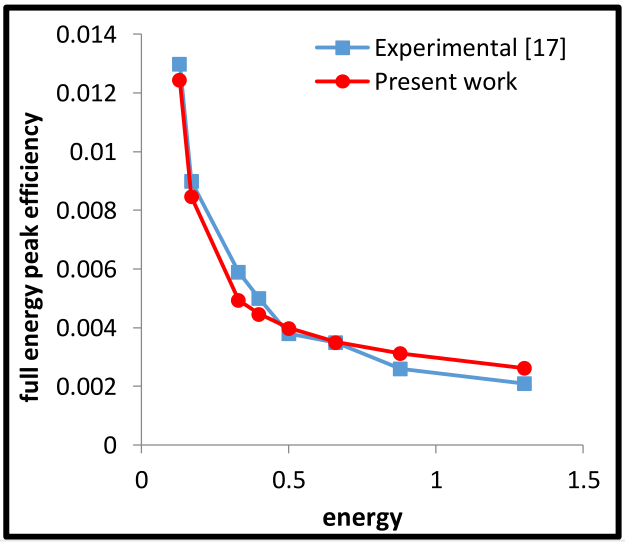


Figure 6- The Comparison between the calculated efficiency (present work) and the measured efficiency at 9 cm distance as a function of energy (MeV)

Table 4- The comparison between the experimental results and present results of the FEPE of the HPGe detector (r_d=2.3 t_d=5.2) cm, at d=13 cm.

Energy (MeV)	Experimental FEPE [17]	Present work FEPE	Mean Squared Error of Efficiency Present work and Experimental
0.13	0.0068	0.00705	6.25E-08
0.17	0.0051	0.00449	3.721E-07
0.33	0.0034	0.00263	5.929E-07
0.4	0.0029	0.00239	2.601E-07
0.5	0.0022	0.00216	1.6E-09
0.66	0.00185	0.00192	4.9E-09
0.88	0.0016	0.00171	1.21E-08
1.3	0.0012	0.00147	7.29E-08
Average of the Mean Squared Error = 1.53233E-07			

Table 5- The comparison between the experimental results and present results of the FEPE of the HPGe detector (r_d=2.3 t_d=5.2) cm, at d=17 cm.

Energy (MeV)	Experimental FEPE [17]	Present work FEPE	Mean Squared Error of Efficiency Present work and Experimental
0.13	0.0044	0.00517	5.929E-07
0.17	0.0033	0.00355	6.25E-08
0.33	0.0021	0.00226	2.56E-08
0.4	0.002	0.00204	1.6E-09
0.5	0.0015	0.00189	1.521E-07
0.66	0.0012	0.00168	2.304E-07
0.88	0.001	0.00152	2.704E-07
1.3	0.00075	0.00133	3.364E-07
Average the of Mean Squared Error = 1.85767E-07			

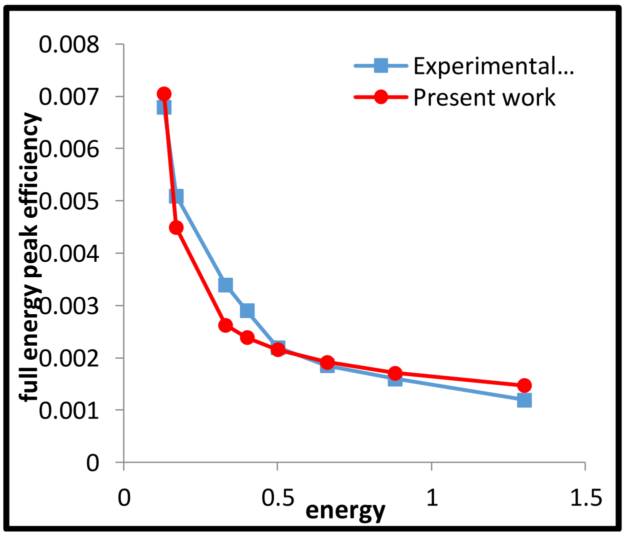


Figure 7-The Comparison between the calculated efficiency (present work) and the measured efficiency at 13 cm distance as a function of energy (MeV)

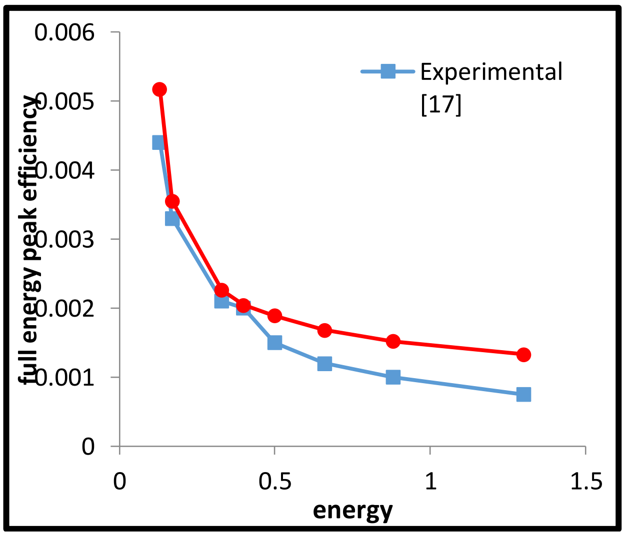


Figure 8- The Comparison between the calculated efficiency (present work) and the measured efficiency at 17 cm distance as a function of energy (MeV)

Conclusions

1. The present Monte Carlo program requires a rather short computing time, with a good statistical counts.
2. The method can also be applied to other detector systems in a simple manner since detector-distance, detector and source dimensions and energy dependent linear attenuation coefficients are all controllable input parameters.
3. The results can be used in gamma spectroscopy and determining the activity of sources.
4. Our program allows a simple, easy and elastic calculation of full energy peak efficiencies for all the energy values in the range because it is difficult to determine detector efficiencies for all gamma energies experimentally since there are a rather limited number of single energy gamma emitting radioisotopes.

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