The Treatment of Efficiency of NaI(Tl) Detector By Using Monte Carlo Simulation

Dr.A. B. Kadhem* & A. N. Mohammed**

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Abstract

An efficient Monte Carlo computer program for simulation and calculation of the total and full energy peak efficiency (absolute and intrinsic) of the cylindrical NaI(Tl)detector (with different volumes, source-detector separation and gamma rays energies) is described. All the fundamental physical processes (photoelectric effect, compton scattering effect and pair production effect) occurring inside the detector are taken into account. Very fast analytical expressions for the absorption coefficients are obtained. The same program can be used to calculate the response function of the detector to gamma ray. The results show quite well agreement with experimental data and with other calculations within error rate less than 2%.The results can be used in gamma spectroscopy and determining the activity of sources.

Keywords: Gamma Detection Efficiency, NaI(Tl) detector, Monte Carlo Simulation, Gamma Ray Spectroscopy.

معالجة كفاءة كاشف NaI(Tl) بإستخدام محاكاة مونتِ كارلو

الخلاصة

تم تصميم برنامج يعتمد طريقة مونتِ كارلو، كفوء في محاكاة وحساب الكفاءة الكلية وكفاءة الإمتصاص الكلي (المطلقة والذاتية) لكاشف NaI(Tl) الإسطواني (بحجوم ومسافات بين المصدر والكاشف وطاقات أشعة گاما ، مختلفة) . لقد أُخِذتْ بنظر الإعتبار جميع العمليات الفيزيائية الرئيسة (الثأثير الكهروضوئي وتأثير إستطارة كومبتن وتأثير إنتاج الزوج) التي تحدث في الكاشف عند تفاعل أشعة گاما معه. ولزيادة فاعلية البرنامج ، فقد تم موائمة معاملات الإمتصاص لأشعة گاما في مادة الكاشف بتعابير رياضية كدالة للطاقة. ومن الممكن أيضاً إستخدام البرنامج لحساب دالة الإستجابة للكاشف لأشعة گاما. لقد أظهرت النتائج توافق عالي مع القياسات العملية والحسابات النظرية الأُخرى بنسبة خطأ لاتتجاوز 2%. من الممكن إستخدام النتائج في قياسات طيف أشعة گاما وحساب فعالية المصادر المشعة.

* College of Sciences, University of Baghdad / Baghdad
** College of Sciences, University of Al Mustanseriyah / Baghdad

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2412-0758/University of Technology-Iraq, Baghdad, Iraq

1. Introduction

NaI(Tl) detectors are commonly used to identify and measure activities of low-level radioactive sources. They have high detection efficiency and operate at room temperature [1]. One of the most important parameters in the calculation of the gamma activity of environmental radioactive sources is detection efficiency. It is usually determined by using calibrated standard sources. Gamma detection techniques are widely used in gamma ray spectroscopy for nuclear physics, medical radiography [2, 3], neutron activation analyses [4, 5], well logging [6], and study of cosmic rays [7].

Monte-Carlo simulation used to calculate the total (absolute and intrinsic) efficiency and (absolute and intrinsic) full energy peak efficiency of detectors such as NaI(Tl), HpGe and Ge(Li) have been presented [8,9]. This approach is impossible to use calibrated sources are obviously limited as concerns their sizes and compositions. By the Monte Carlo method, one can reproduce in a flexible way any experimental physical situation. For example, it is not difficult to treat cases in which the gamma-ray sources has a non-negligible energy width, or even to simulate cases where the energy spectrum is rather complex. Moreover, the sizes and dimensions of both sources and detectors, and the geometrical configuration of the experimental apparatus, can easily be reproduced to fit every particular case.

The present work describes an accurate Monte Carlo computer program had been designed by us. It reconstructs the efficiency of cylindrical detectors (in particular NaI(Tl) crystal) to gamma-radiations coming from punctiform sources, having energies include in the range to 10 MeV. Our program can deduce any kind of information on efficiencies, solid angles etc. to minimized the execution times, appropriate analytical expressions for the absorption coefficients in the NaI(Tl) crystal (photoelectric effect, coherent & incoherent compton scattering and pair production) have been obtained.

2. Description of the program

Our Monte Carlo computer program is, step by step, the story of a prefixed number of photons, starting from their creation in the source (with various emision angles θ), up to their possible complete absorption in the detector or their escape from it. Our program has a modular structure, to favour a wide range of possibilities in the choice of the geometry (Fig.1). It assumes the existence of a point source, which only "sees" the front face of a cylindrical detector (with radius r_d), place at a fixed distance (d).

From the geometrical point of view, the only restriction is due to the cylindrical size of the detector, which, on the other hand, can be a NaI(Tl) crystal (the two cases are obviously characterized by different absorption coefficients, the calculation of which is developed in suitable fast subroutine. The Z-axis is the symmetry axis of the detector (oriented from the source to the detector). The XY plane is tangent to the source at its point most remote from the detector itself.

The values of physical and geometrical properties must be read as input data such as, the geometrical characteristics and positional variables of source and detector. The photons are usually assumed to be isotropically emitted, with a Gaussian energy distribution (of prefixable width). However, it is easily possible to arrange the program to simulate preferential-emission directions and more complicate energy distributions.

The different steps followed the program, to simulate the story of each photon, are schematically described (see fig. 2).

Step A. each photon is emitted from a random chosen point inside the volume of the source, it has a random direction in the half space containing the detector. The emission point and the direction of the trajectory are referred to the frame described in fig. 1. The self-absorption inside the source is negligible. Otherwise the program goes on with the following step.

Step B. The photon exit path from the source is extended up to the interception point with the plane containing the front face of the detector. If the interception is outside this face, a specific counter is increased(this number allows the calculation of the solid angle) and the program starts again from *step A.* when, on the other hand, the photon goes into the detector, the "virtual" path l_d is evaluated (l_d is the distance which the photon would cover inside the detector in the case of missing interaction).

Step C. To establish the possible interaction point and the type of process which the photon actually undergoes, the relevant absorption coefficients as a function of the gamma energy *E* must be known. To this end, suitable analytical expressions have been obtained, which reproduce to a very good approximation the absorption coefficient values of ref.10. The whole energy range up to 20 MeV has been divided into four intervals only, in order to minimize the computing time. It is then possible to calculate the total probability that any one of the three considered processes may occur: $W = (1 - e^{-\mu l_d})$ where $\mu=\mu_{ph}+\mu_c+\mu_{pp}$. Starting from this expression for W, the program chooses first of all whether or not photon interacts inside the detector. In the negative case a particular counter is increased and the calculation starts again from *step A*, otherwise, the probabilities concerning the various processes are separately evaluated, and the actual processes together with the coordinates of the interaction point are selected.

<u>Step D.</u> Each interaction process is then treated as follows:

Photoelectric effect: In this case the photon is totally absorbed, the event is recorded and a new photon is considered.

Compton scattering: The new direction and corresponding energy of the photon are calculated, on the basis of the Compton angular distribution. The so-defined new photon is followed again, with the same procedure described from *step B*.

Pair production: the energy E of the incoming photon is totally absorbed into the detector, except the energy of the tow photons following the annihilation of the positron at rest, $E_{\gamma\gamma} = 1.022\ MeV$. Each one of these photons is then followed inside the detector, starting from *step B*, their possible energy losses are then added to the already transferred energy.

<u>Step E.</u> An important point is that the energy (partially or totally) transferred to the detector by each photon is separately recorded, so that all the above process have been treatment for access to the total and full energy peak probability of interaction.

3. Results and Discussion

Our program has been designed to calculate the total (absolute and intrinsic) detector efficiency and (absolute and intrinsic) full energy peak efficiency of NaI(Tl) detectors for punctual sources emit different energy photons by employing a Monte-Carlo technique. It can be used for different sizes and types of gamma detectors since the input parameters can be controlled. For a good statistical distribution, 5,000,000 photons have been followed. The error on the total efficiency value was found to be less than ± 2% from repeated calculations for a certain energy value.

The total efficiency values of NaI(Tl) detectors for different gamma energies have been compared with the values previously reported for point sources [9, 11, 12, 13, 14, 15, 16, 17, 18]. Total efficiency values calculated for a 3"×3" NaI(Tl) detector for source–detector separation of d = 0.001 cm, d = 0.5 cm and d = 10 cm are given in Figs. 3–5, respectively, and for different separations of d from 0.003 to 300 cm for three values of gamma ray energy (0.2, 1, 10) MeV are given in fig.6. There is a very good agreement between our values and values reported in the literature.

The total efficiency of NaI(Tl) detectors is dependent on the source-detector distance and photon energy. As the gamma energy increases, the total detector efficiency decreases given that the possibility of a photon being absorbed inside the detector decreases. The total detection efficiency has a maximum value at low gamma energies and decreases as the photon energy increases.

For a cylinder of NaI, 1.5" in diameter, and 1.5" in height, Five million γ –rays were then fired randomly in all directions from a point 9.3 cm away from the detector, to compare with the results of the simulation of GEANT4 code, a package created at CERN to determine the absolute efficiency [18] as shown in fig.7.

4. Conclusion

The total and Full Energy Peak detection efficiency (intrinsic and absolute) values for the NaI(Tl) scintillation detectors were evaluated by using Monte Carlo simulation that has been designed by us. Our program allows a simple, easy and elastic calculation of total 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.

The method can also be applied to other detector systems in a simple manner since detector–source distance, detector and source dimensions and energy dependent linear attenuation coefficients are all controllable input parameters. This means that the method of which foundations were presented here can be extended to volume sources and applicable to any medium and energy value as long as linear attenuation coefficients are known.

The results can be used in gamma spectroscopy and determining the activity of sources.

References

[1] Perez-Andujar, A., Pibida, L., "*Performance of CdTe, HpGe and NaI(Tl) detectors for radioactivity measurements*", Appl. Radiat. Isot. 60 (1), pp. 41–47, 2004.

[2] Wagenaar, D. J., Chowdhury, S., Engdahl, J. C., Burckhardt, D. D., "*Planar image quality comparison between a CdZnTe prototype and a standard NaI(Tl) gamma camera*", Nucl. Inst. Meth. A505, pp. 586-589, 2003.

[3] Goriletsky, V. I., Bondarenko, S. K., "*Production of preset quality large NaI(Tl) single crystals for detectors used in medical instrument building*", Materials Science and Engineering A288, pp. 196–199, 2000.

[4] Gardner, R. P., Sayyed El-Zheng, Y., Hayden, S. and Mayo, C. W., "*NaI(Tl) detector neutron activation spectra for PGNAA applications*", Appl. Radiat. Isot. 53, pp. 483- 497, 2000.

[5] Palomba, M., D'Erasmo G., Pantaleo A., "*An application of the CSSE code: analysis of pileup in NaI(Tl) detectors used for TNA*", Nucl. Inst. Meth. A498, pp. 397- 414, 2003.

[6] Ellis, D.V., "*Well logging for earth sciences*". Elsevier, New York, 1987.

[7] Nagai, Y., Kikuchi, T., Kii, T., Suzuki, T. S., Murakami, T., Shima, T., Ohsaki, T., "$^{127}I(n,\gamma)^{128}I$ *reaction in NaI(Tl) due to cosmic-ray muon capture by Pb*", Nucl. Inst. Meth. A368, pp. 498-502, 1996.

[8] Kadhem, A. B., Mohammed, A. N., "*The efficiency treatment of semiconductor detectors for HPGe & Ge(Li) using Monte Carlo method*" Sci. J. Iraqi Atomic Energy Commission, 2 (2), 66 – 74, 2000.

[9] Yalcin, S., Gurler, O., Kaynak, G., Gundogdu, O., "*Calculation of total counting efficiency of a NaI(Tl) detector by hybrid Monte-Carlo method for point and disk sources*". Appl. Radiat. Isot., 65 (10), p.p. 1179–1186, 2007.

[10] Berger, M.J., Hubbell, J.H., XCOM Version 3.1. NIST Standard Reference Data Base, 1999.

[11] Nakamura, T., "*Monte-Carlo calculation of efficiencies and response functions of NaI(Tl) crystals for thick disk gamma-ray sources and its application to Ge(Li) detectors*". Nucl. Instrum. Methods 105, 77, 1972.

[12] Miller, W.F., Snow, W.J., "*NaI and CsI efficiencies and photofractions for gamma-ray detection*". Nucleonics 19 (11), 174, 1961.

[13] Vegors Jr., S.H., Marsden, L.L., Heath, R.L., **1958**. USAEC Report IDO- 16370.

[14] Cesana, A., Terrani, M., "*Gamma-ray activity determination in large volume samples with Ge(Li) detector*". Anal. Chem. 49 (8), 1156–1159, 1977.

[15] Heath, R.L., Scintillat. Spectrom.1, IDO-16880-1, 1964.

[16] Belluscio, M., DeLeo, R., Pantaleo, A., Vox, A., "*Efficiencies and response functions of NaI(Tl) crystals for gamma-rays from thick disk sources*". Nucl. Instrum. Methods 118 (2), 553–563, 1974.

[17] Mowlavi, A. A., Izadi Najafabadi R., Koohi Faygh R., Private Communication, 2005.

[18] University of Guelph, Department of Physics, integrated laboratory. "Gamma-Ray Spectroscopy Usingan NaI(Tl) Detector". Available at: http://www.physics.uoguelph.ca/.detong/phys3510-4500/low-res-gamma-ray%20 fall07.pdf

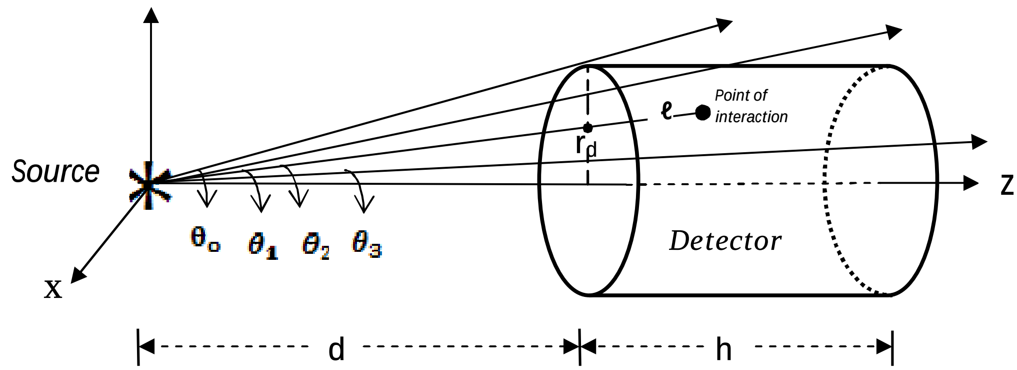
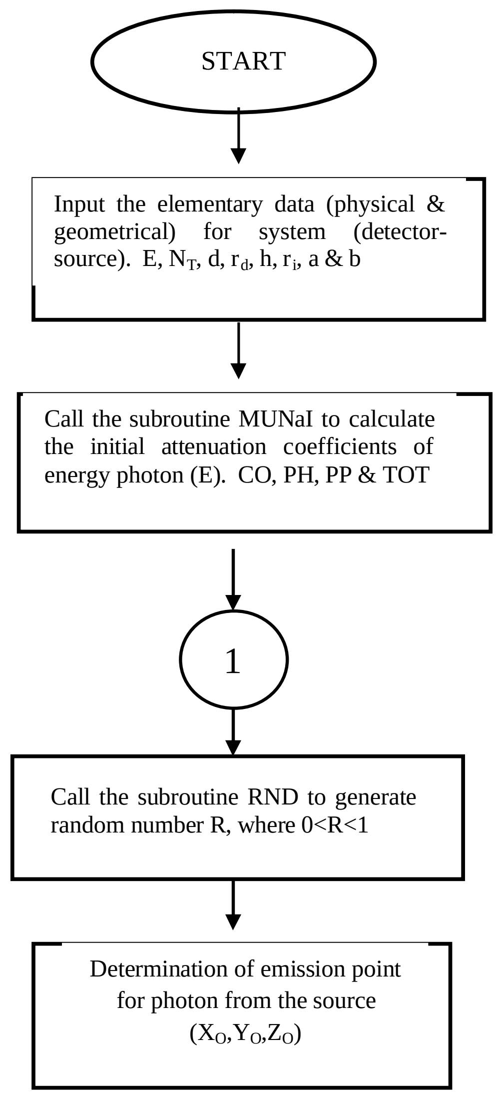
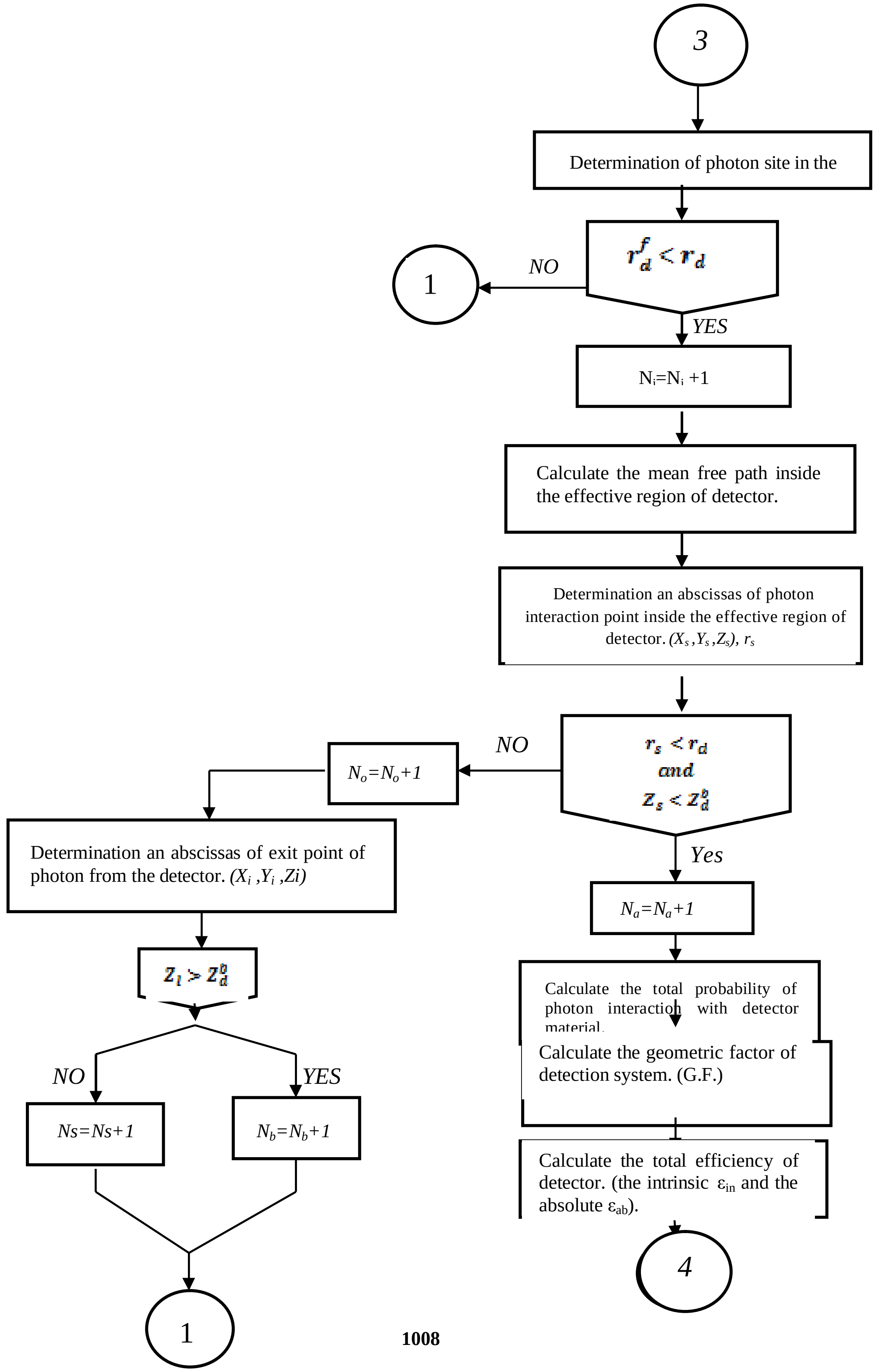


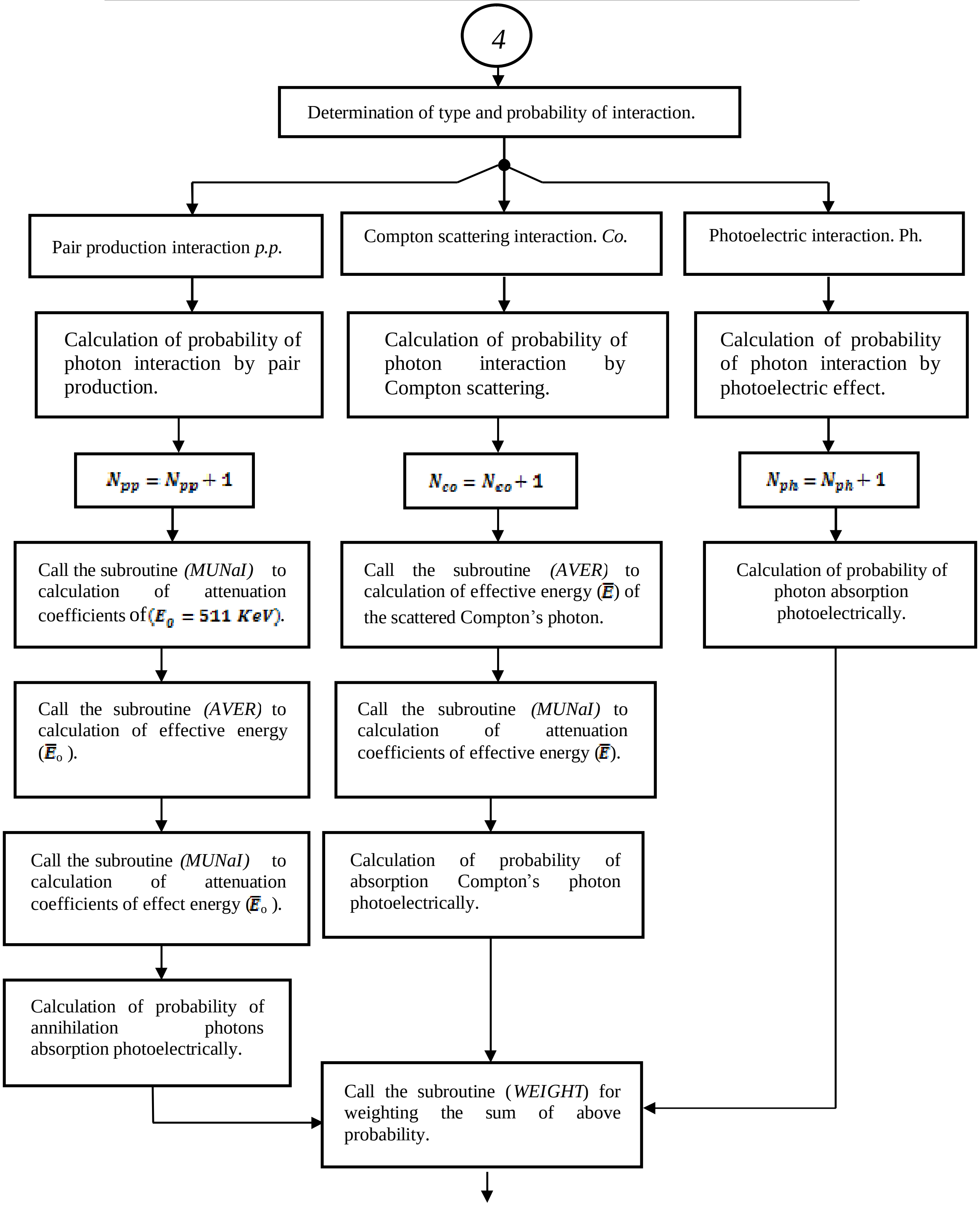
Figure (1) Geometrical configuration simulation by the Monte Carlo computer program.

Definitions

E : Energy of emitted photon from source.
N_t: Number of emitted photons from source.
d : separation between the source & detector.
r_d: radius of detector window.
h: height of detector.
r_i: interior radius of detector.
a,b: dimensions of source with x-axis & y-axis respectively.
CO: Compton scattering attenuation
PH: photoelectric attenuation coefficient.
PP: pair production attenuation coefficient.
TOT: total attenuation coefficient.
N_i : number of incident photons on detector.
N_a : number of interacted photons with matter of detector.
N_o : number of photons leaving the detector without interaction.
N_s : number of photons leaving the detector from side.
N_b : number of photons leaving the detector from behinds.
Z_d^b: the distance from the source to behinds of detector. $(Z_d^b = d + h)$




3
Determination of photon site in the
$r_d^f < r_d$
NO
1
YES
$N_i = N_i + 1$
Calculate the mean free path inside the effective region of detector.
Determination an abscissas of photon interaction point inside the effective region of detector. (X_s, Y_s, Z_s), r_s
$r_s < r_d$ and $Z_s < Z_d^b$
NO
$N_o = N_o + 1$
Yes
$N_a = N_a + 1$
Determination an abscissas of exit point of photon from the detector. (X_i, Y_i, Zi)
$Z_i > Z_d^b$
NO
YES
$Ns = Ns + 1$
$N_b = N_b + 1$
1
Calculate the total probability of photon interaction with detector material.
Calculate the geometric factor of detection system. (G.F.)
Calculate the total efficiency of detector. (the intrinsic ε_{in} and the absolute ε_{ab}).
4


4
Determination of type and probability of interaction.
Pair production interaction *p.p.*
Compton scattering interaction. *Co.*
Photoelectric interaction. Ph.
Calculation of probability of photon interaction by pair production.
Calculation of probability of photon interaction by Compton scattering.
Calculation of probability of photon interaction by photoelectric effect.
$N_{pp} = N_{pp} + 1$
$N_{co} = N_{co} + 1$
$N_{ph} = N_{ph} + 1$
Call the subroutine *(MUNaI)* to calculation of attenuation coefficients of $(E_0 = 511\ KeV)$.
Call the subroutine *(AVER)* to calculation of effective energy $(\overline{E})$ of the scattered Compton's photon.
Calculation of probability of photon absorption photoelectrically.
Call the subroutine *(AVER)* to calculation of effective energy $(\overline{E}_o)$.
Call the subroutine *(MUNaI)* to calculation of attenuation coefficients of effective energy $(\overline{E})$.
Call the subroutine *(MUNaI)* to calculation of attenuation coefficients of effect energy $(\overline{E}_o)$.
Calculation of probability of absorption Compton's photon photoelectrically.
Calculation of probability of annihilation photons absorption photoelectrically.
Call the subroutine (*WEIGHT*) for weighting the sum of above probability.

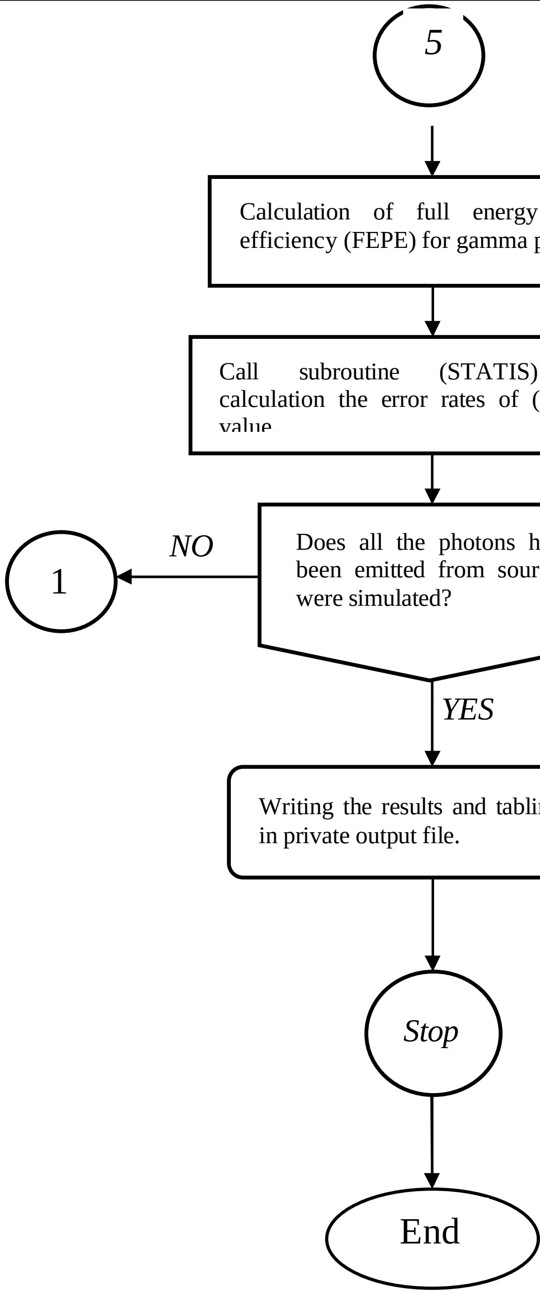


Figure (2) Flowchart for successive stages of program for simulation of photon history

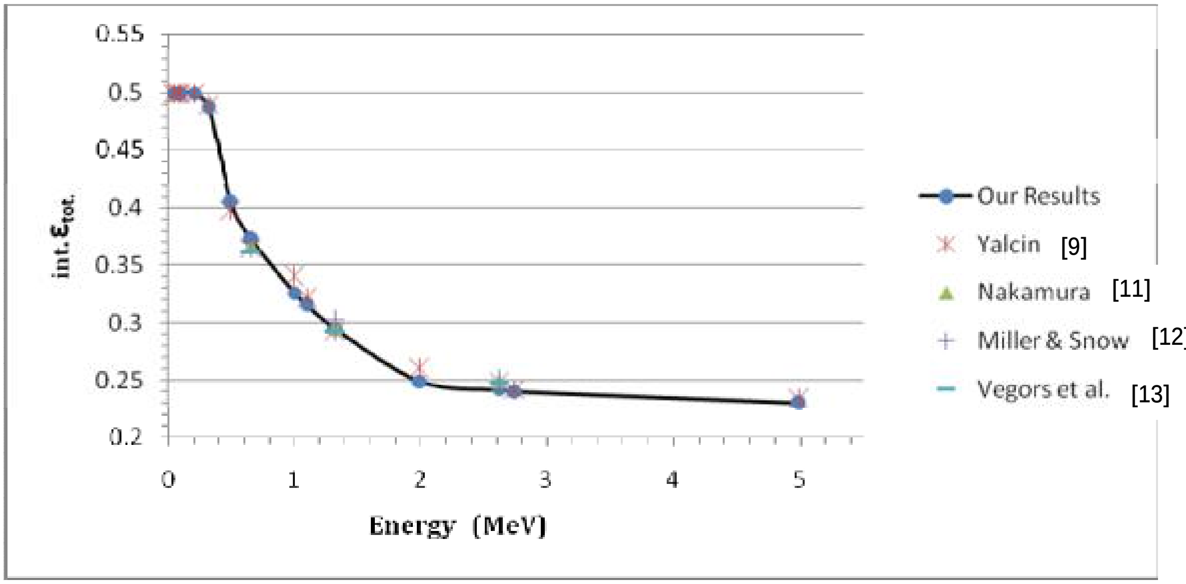


Figure (3) Intrinsic total efficiency for a 3 in×3 in NaI(Tl) detector with a point source located at d = 0.001 cm away from the detector on its symmetrical axis

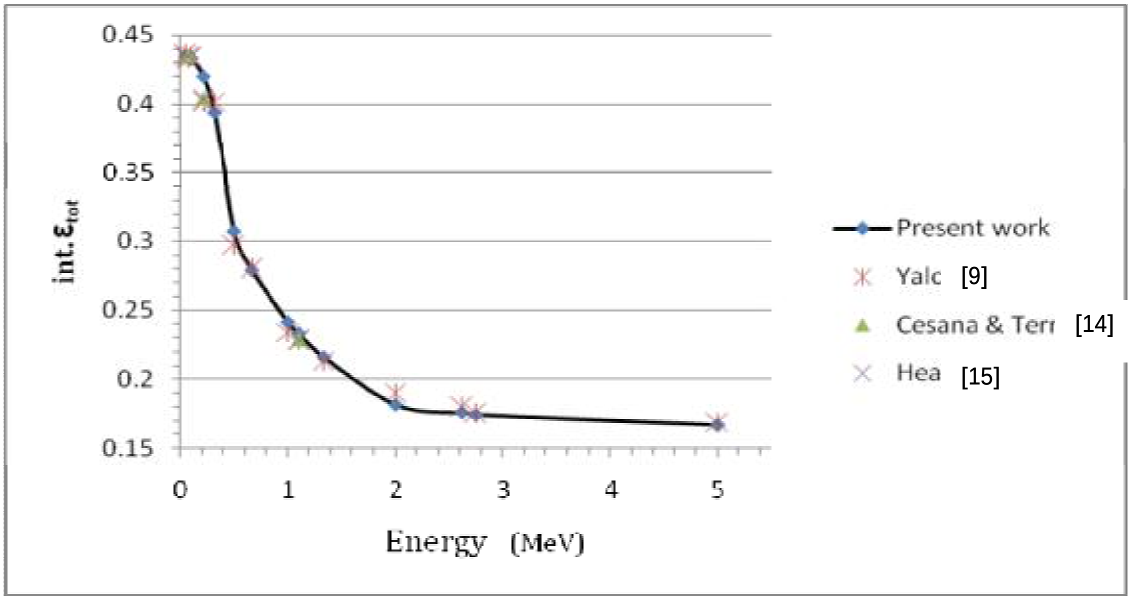


Figure (4) Intrinsic total efficiency for a 3 in×3 in NaI(Tl) detector with a point source located d = 0.5 cm away from the detector on its symmetrical axis

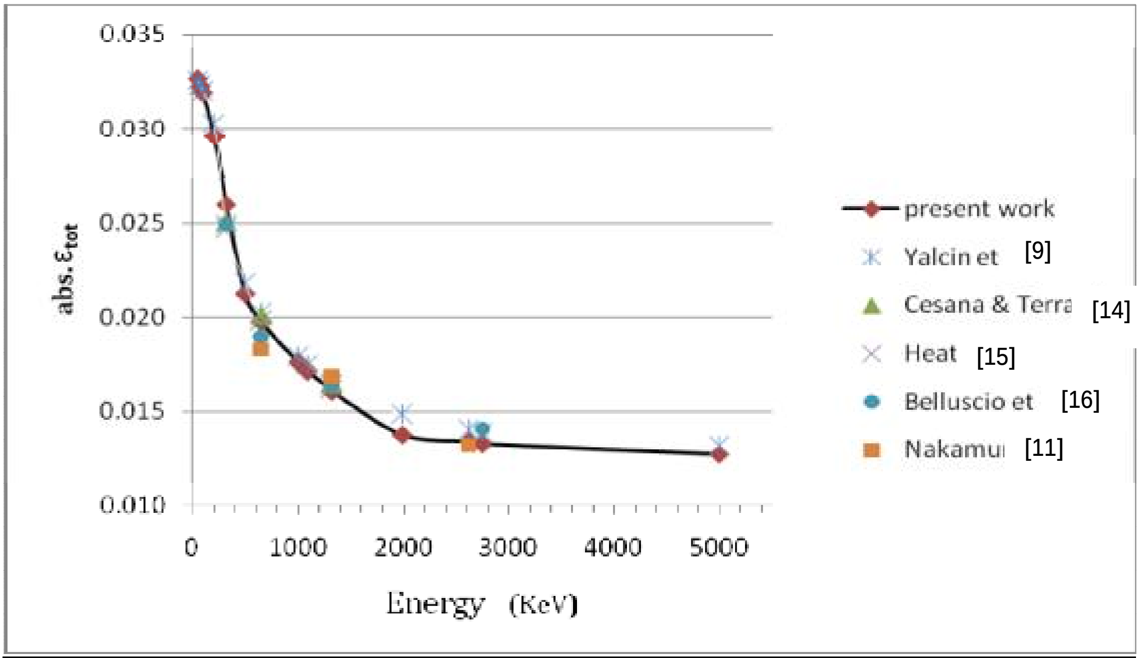
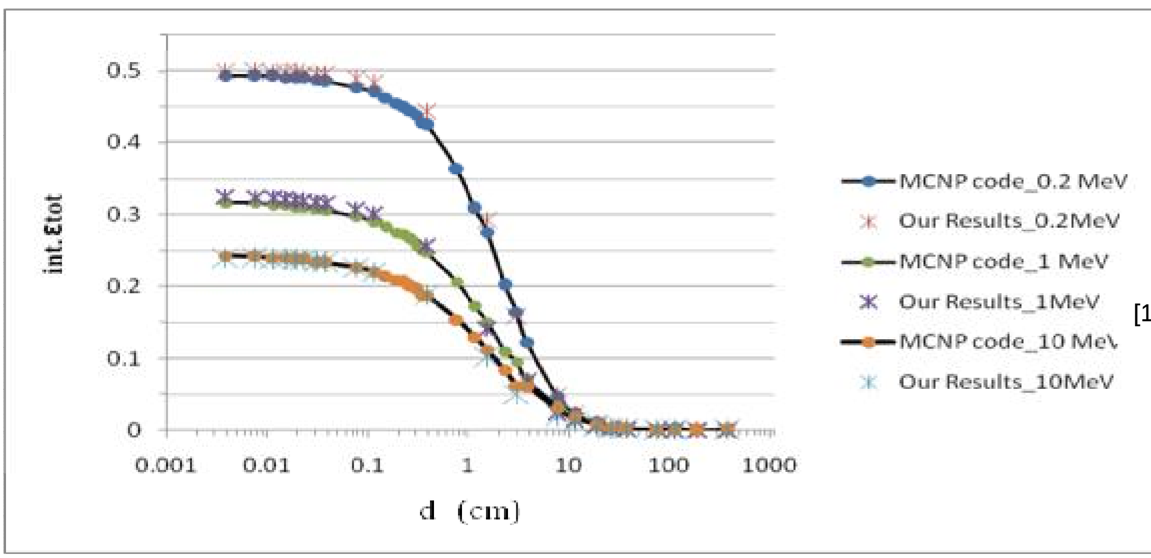


Figure (5) Absolute total efficiency for a 3 in×3 in NaI(Tl) detector with a point source located d = 10 cm away from the detector on its symmetrical axis.



Figure(6) Intrinsic total efficiency for a 3 in×3 in NaI(Tl) detector with a point source located at a different distances (d) away from the detector on its symmetrical axis

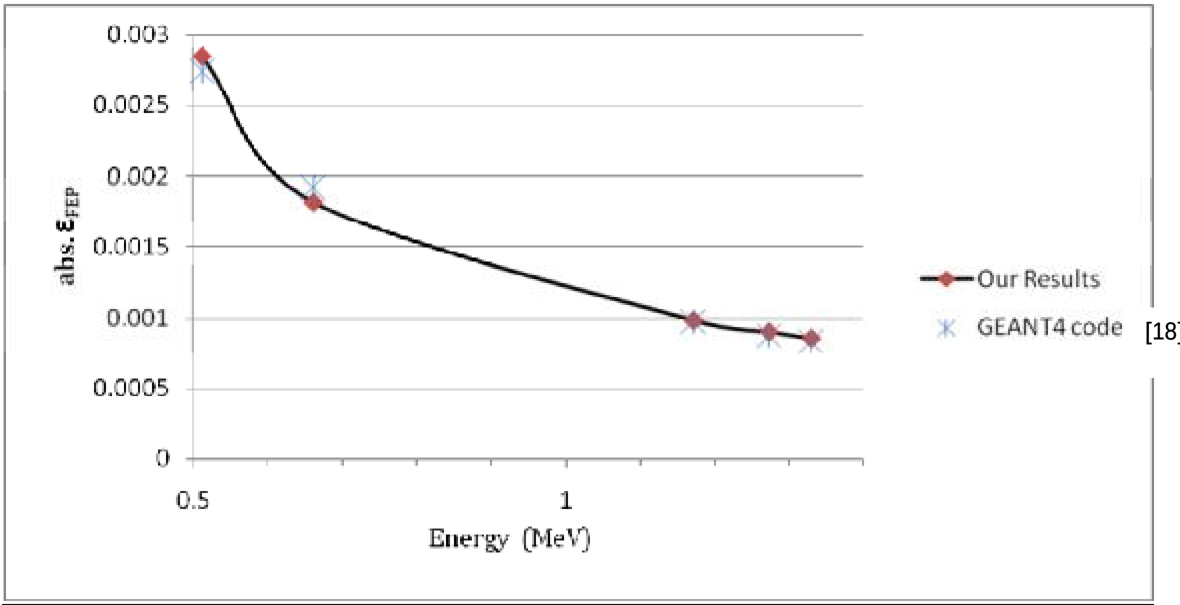


Figure (7) Absolute full energy peak efficiency for a 1.5×1.5" NaI(Tl) detector with a point source located d = 9.30 cm away from the detector on its symmetrical axis.