Monte Carlo Simulation of the Backscattering Gamma Ray System

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Abstract

A Monte Carlo simulation has been used to design program which simulate gamma rays backscattering system. Gamma ray backscattering is very important to get useful information about shielding, absorption and counting problems. Simulation was done of a 661.6 KeV from a collimated point source of ^{137}Cs. When increasing the scattering angle of photon which emerging from Iron target , as the incident gamma beam angles of 15°, 45° and 75°, the results showed that the single scattering count decreases. Whereas, this count increased by increasing the incident angle. In addition, the single scattering peak (count) increases according to the sample thickness until ‘saturation thickness’. Our simulation results are useful to evaluate the optimal configuration of systems using Compton backscattered radiation and to access the feasibility for setting up experimentally this system. Also, it will be used to determine the best conditions under which this method can be applied to testing electron densities or to assess the thickness of sample to locate defects in them.

Keywords: *Gamma rays backscattering, Gamma rays, Compton backscattered radiation, Monte Carlo, Compton single scattering, Saturation thickness.*

محاكاة مونت كارلو لمنظومة أشعة گاما المرتدة

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الخلاصة

إستُخدِمتْ محاكاة مونت كارلو لتصميم برنامج يحاكي نظام الاستطارة الخلفية لأشعة كاما. تكمن أهمية الاستطارة العكسية في أنها تعطي معلومات مفيدة عن مسائل التدريع والامتصاص والعد. تم تنفيذ المحاكاة لمصدر السيزيوم–137 النقطي والمسدد ليبعث فوتونات أشعة كاما بطاقة 661.6 KeV. بينت النتائج نقصان العد بزيادة زاوية الاستطارة عند زاوية سقوط معينة ولقيم °15 و °45 و °75 من جهة، و ازدياده مع زياده قيمة زاوية السقوط من جهة أخرى. كما يزداد عد الفوتونات المستطارة بزيادة سمك العينة ولغاية سمك معين يدعى "سمك الاشباع". يمكن الاستفادة من نتائج محاكاتنا في تقييم الترتيب المثالي للأنظمة التي تعتمد مبدأ استطارة كومبتن الخلفية للاشعاع و بمثابة مدخل لامكانية الاعداد التجريبي لهذا النظام. كذلك، من الممكن استخدامها في تحديد أفضل الشروط التي بموجبها يمكن تطبيق هذه الطريقة في عملية اختبار الكثافات الالكترونية أو تخمين سمك العينة لتحديد مكان العيوب فيها.

1. Introduction

Simulation uses a model to develop conclusions providing insight on the behavior of real-world elements being studied. Computer simulation uses the same concept but requires the model be created through computer programming. Computer simulation can be an expensive, time consuming and complicated problem solving technique. The Monte Carlo method is used to represent simulations that are a scheme employing random numbers, which is used for solving certain stochastic or deterministic problems where the passage of time plays no role [1]. The random numbers can be used to simulate events which are not completely predictable but occur according to particular probabilities.

Backscattering is a phenomenon in which photons colliding within the material are scattered backward compared to their original direction. The backscattering (or reflection) of gamma rays from the surface of a material is a fundamental importance in radiation shielding, radiation absorption and non-destructive testing of finite samples in industrial, medical and agricultural interest[2, 3]. At present, gamma backscattering method is applied in industry to measure the thickness of light materials, such as in the paper [4]. The number of backscattered photons increased according to the target thickness, eventually reaching saturation.

In this work, we designed program to simulate the system of gamma rays backscattering from a different materials (elements or compounds) and for various geometries. Based on this simulation, we investigated the photons backscattered from Iron $\left({}^{56}_{26}Fe\right)$ with density equal to 7.873 gm.cm^{-3} by rotating the detector collimator from 5° to 85° using a ^{137}Cs source at 661.6 keV of energy to determine where the contribution of single scattering was greatest. We then fixed the scattering angle and changed the thickness of Iron substance to find the needed results. Our goal is to optimize several design parameters that are of importance for the Compton backscattering system. Such parameters include the dimensions of the source-sample (Fe), sample-detector and source-detector (sonde length), in addition to optimizing these parameters, we also performed the incident and scattering angles of gamma rays photons.

2. Procedure of the simulation

Monte Carlo based codes have proved to be a valuable tool in experimental design because they allow the testing of experimental conditions which would be difficult or expensive to perform otherwise.

In our Compton model, we use backscatter mode which allow source and detector to be located on the same side of the target (Fe substance).

The configuration proposed for the simulation is showed in Figure1 including a collimated ^{137}Cs source, a collimated backscattering detector and an Iron substance with particular thickness.

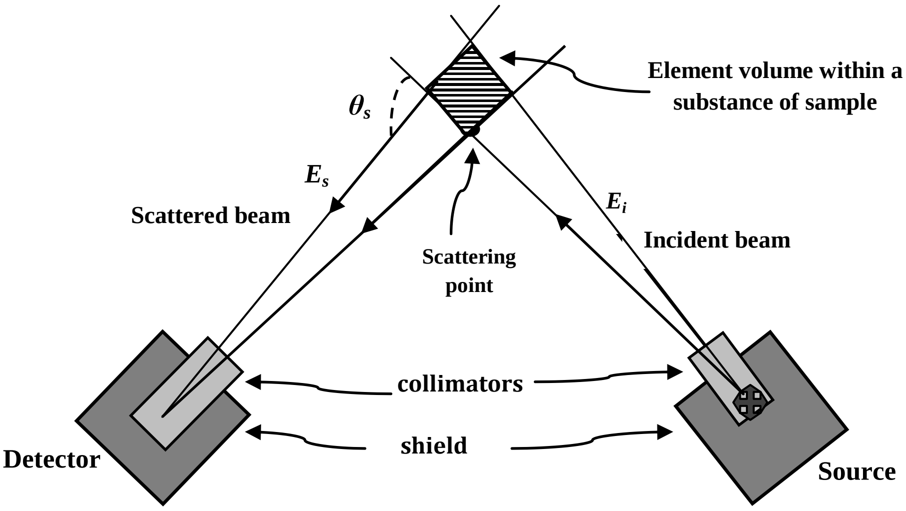


Figure 1- Schematics of the backscattering geometry.

The distance between the source-sample, the detector-sample and the source-detector (sonde length) can be changed. Based on the proposed configuration, we have developed Monte Carlo simulation to describe the interaction processes occurred when the photon beam coming in the sample, the results of which are that only the photons that are backscattered within a solid angle covered by the detector collimator are to be registered (counted). The registered back-scattered events allowed then us to study "virtually" the characteristics of the experimental backscattering system, concerned characteristics of geometrical system or/and substance of the sample to determine the needed results about them. The predicted history of photon in our simulation is defined during the following steps:

a. For simplicity, assumed that the emitted photons from the source undergo only one scattering. Also it ignores the small attenuation by the air between the sample and the source-detector system.

b. The path length of photon (*x*) traverses to interact is randomly chosen (sampling) using the below equation:

$$x = -\frac{1}{\mu}\, ln(1 - R_n) \quad \cdots\cdots\cdots\cdots (1)$$

Where: R_n is the random number $(0 \le R_n \le 1)$, and, μ: is the linear attenuation coefficient of γ-radiation (with the energy E_γ) in the material.

XCOM program [5] have been used to calculate the mass attenuation coefficients $(\mu_m = \mu/\rho)$, where ρ is the bulk density.

c. According to the value of a distance x and an incident angle ($\theta_{inc.}$), if the location of interaction is outside the dimensions of the sample, the history of photon will end. So the energy absorbed into the material is considered zero, counter concerned this process will increase (N_{out}), and the program starts from beginning for another photon.

d. If the location of an interaction is inside the material, counter concerned this process will increase ($N_{int.}$), and the type of interaction is sampled (i.e. forward- or back- scattering) using Kahn's method [6] (a non-uniform rejection method). The final result of this step is the scattered photon energy.

e. In the Compton scattering process, by which an incoming photon is deflected by an angle θ with respect to its origin direction after transferring a part of its energy to an electron, the energy of scattered photon $E_\gamma^{'}$ is given by [7]:

$$\cos\theta_{scat.} = 1 + \left(\frac{1}{E_\gamma} - \frac{1}{E_\gamma^{'}}\right) m_o c^2 \quad \cdots\cdots\cdots\cdots (2)$$

Where: $m_o c^2 = 511\, KeV$ is the rest mass of the electron, and

E_γ: is the energy of the incident photon (the electron is assumed initially at rest).

In order to use this relation our virtual set up allows a clear determination of this single scattered process. So, both the radiation source and the detector are strongly collimated.

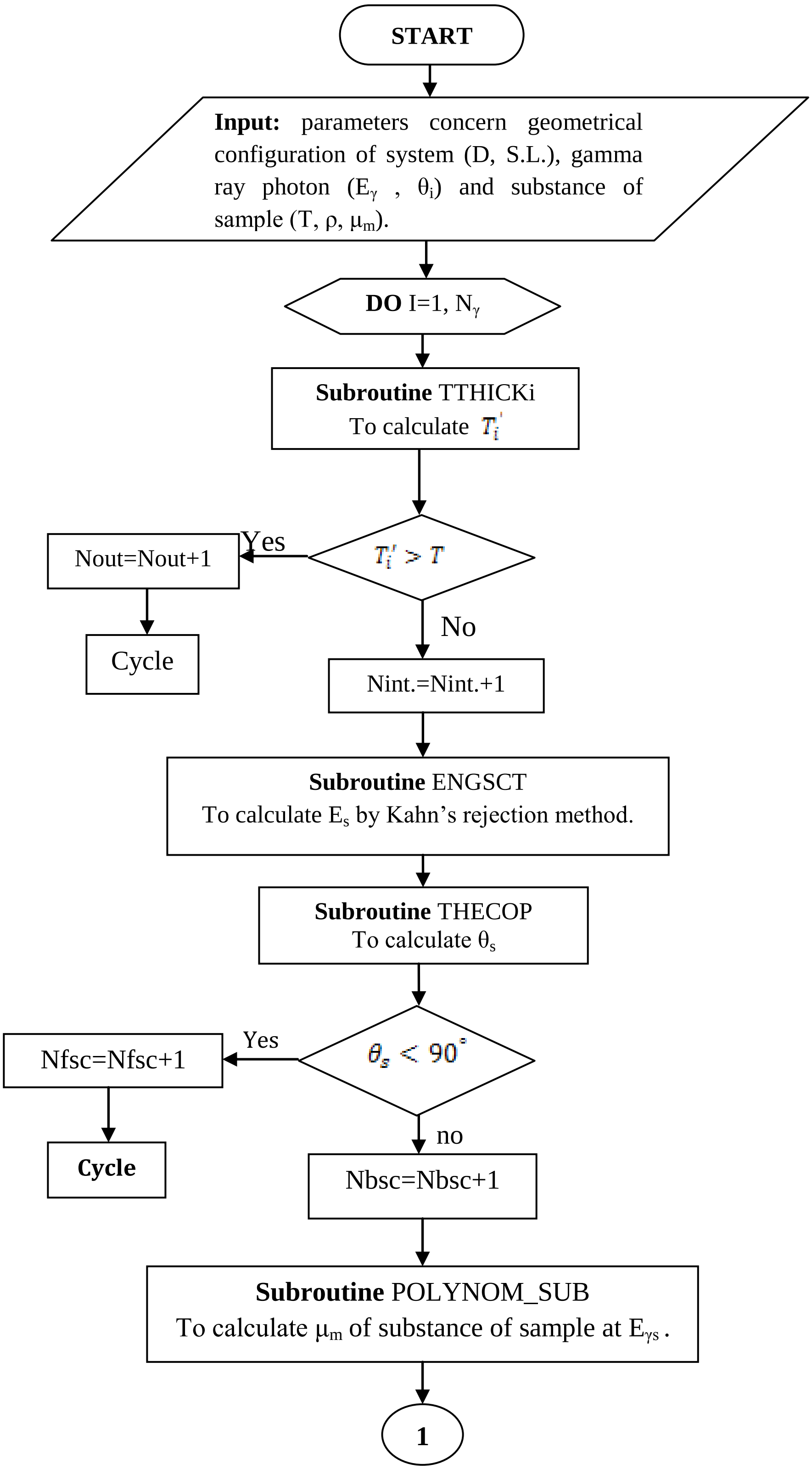
f. Respect to the scattering angle, if the type of scattering is forward, a counter concerned this process will increase ($N_{fsc.}$), and the history of photon will end.

g. Whereas, if the type is backscattering, a counter concerned this process will increase ($N_{bsc.}$), and the new scattered photon trajectory is determined.

h. The path length of this trajectory determined the scattered photon is still within the dimension of sample or escape from it toward the detector.

i. The escaped scattered photon trajectories lies within a solid angle, covered by the detector collimator, are to be counted ($N_{bsc.\_counted}$).

A program has been written for this purpose in FORTRAN language (90-95). The flowchart of this program can be, briefly, shown below:


START
Input: parameters concern geometrical configuration of system (D, S.L.), gamma ray photon (E_γ , θ_i) and substance of sample (T, ρ, μ_m).
DO I=1, N_γ
Subroutine TTHICKi
To calculate T_i'
$T_i' > T$
Yes
Nout=Nout+1
Cycle
No
Nint.=Nint.+1
Subroutine ENGSCT
To calculate E_s by Kahn's rejection method.
Subroutine THECOP
To calculate θ_s
$\theta_s < 90^\circ$
Yes
Nfsc=Nfsc+1
Cycle
no
Nbsc=Nbsc+1
Subroutine POLYNOM_SUB
To calculate μ_m of substance of sample at $E_{\gamma s}$.
1

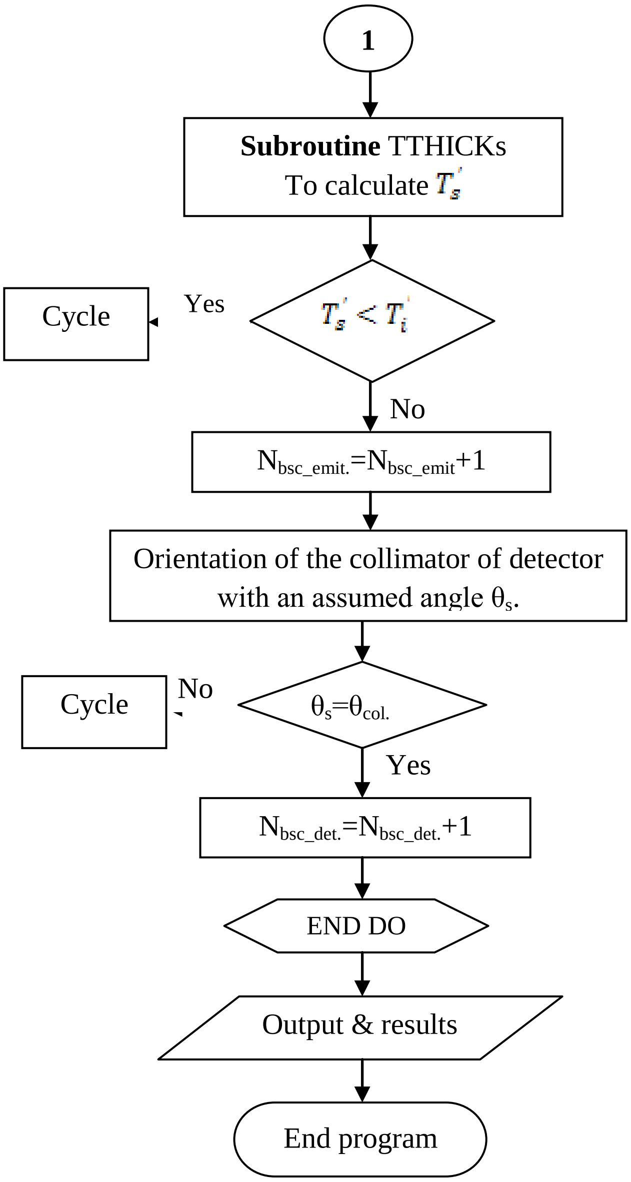


Figure 2- Simplified flowchart of present simulation.

3. Results and Discussion

An investigation of the backscattering gamma rays while changing the angle between the radioactive source (^{137}Cs) and the NaI(Tl) detector, θ, was perfo-rmed in the first set of simulations. An iron target with a thickness of 2 cm was placed at, where an angles of the incident beam be (15°, 45°, 75°). When the NaI(Tl) detector with collimator 0.86 mm was rotated by changing θ up to 180°, the backscattering peak shifted to a lower scattering angle, as shown in Figure 3.

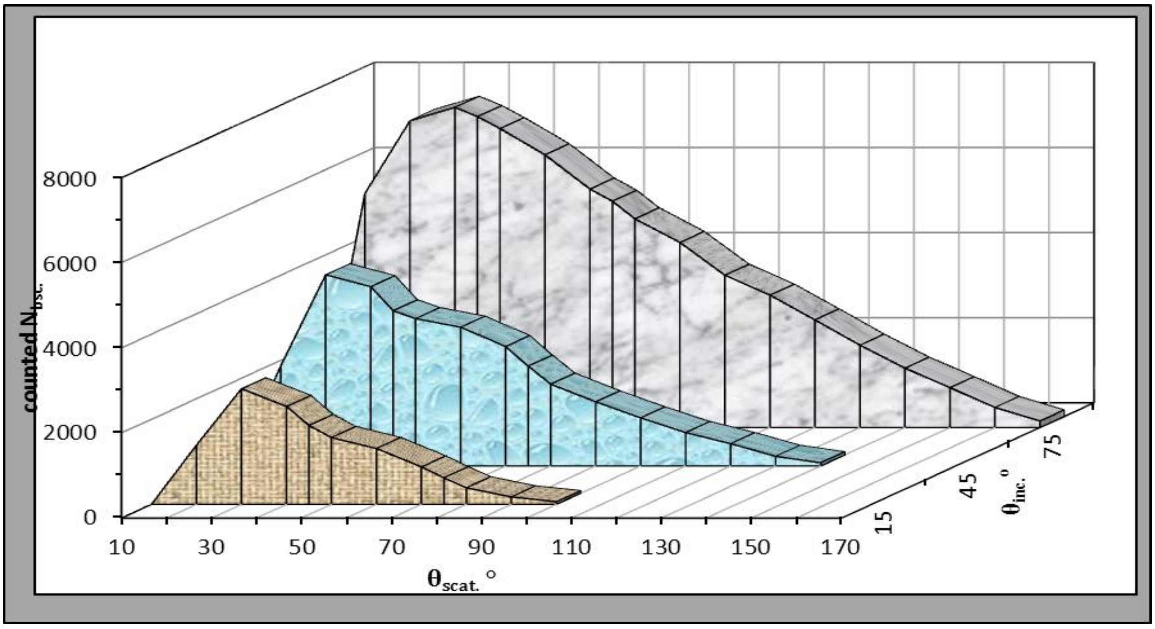


Figure 3- The dependence of the single scattering peak on the scattering angle compared to the incident beam**.**

So, we achieved to the location at which the contribution of single scattering was the largest (for example: if (θinc.=75°, then: θscat.=45°). This agrees with Compton scattering equation (eq. 2), since the scattered photon energy is inversely dependent on the scattering angle as shown in Figure 4. By other meaning, the value of scattered photon path length within dimension of the sample, toward the detector, is inversely too dependent on the scattered photon angle as shown in Figure 5. And we can see in Figure 5 how influence of the increase of the value of the scattered photon angle on a value of the counted backscattered photons. According to this say, we can explain, at particular incident angle, the downhill of the curves showing in Figure 3.

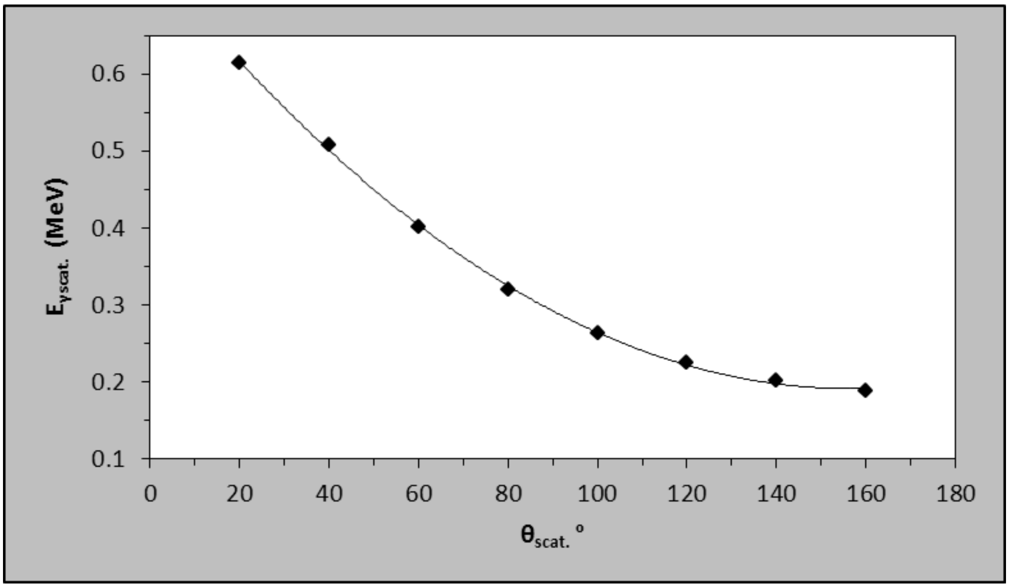


Figure 4- The inverse dependence between the scattered photon energy and the scattering angle.

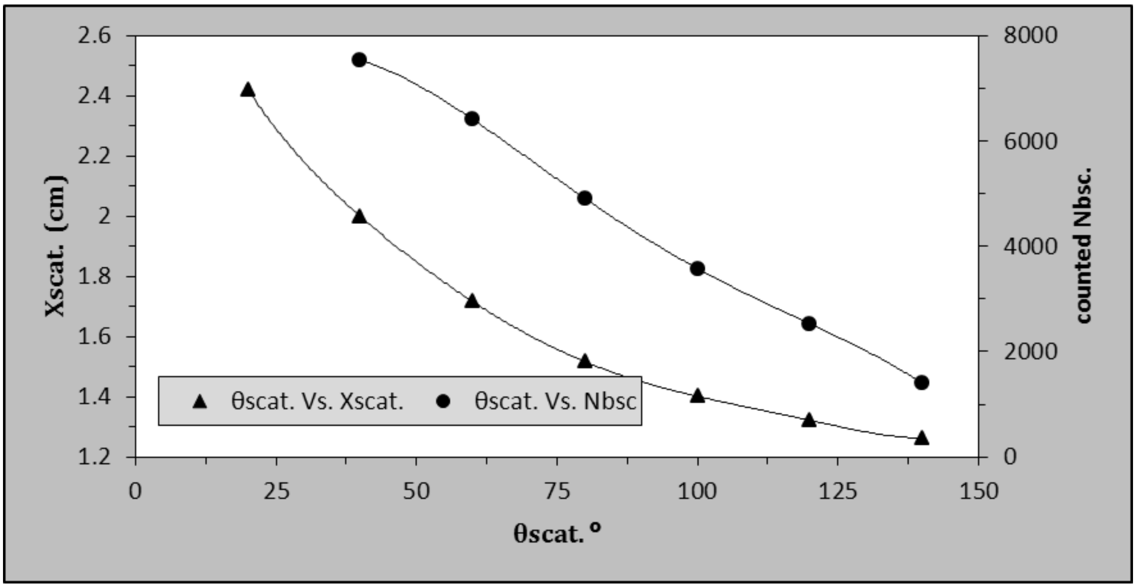


Figure 5- The inverse dependence between the scattered photon angle and, firstly, the scattered photon path length and, counted backscattered photons.

Concerning Figure 6, it shows a ratio of the vertical depth of an interaction point, within the sample, about the surface of sample for incident and scattered photon T_i' *and* T_s' respectively. This ratio is determined the chance or probability to escape the scattered photon far away the sample toward of the front face of the detector. So the behavior of curves shows in Figure 6 is explaining the increase of scattering peak with increase of the incident angle as shown in Figure 3.

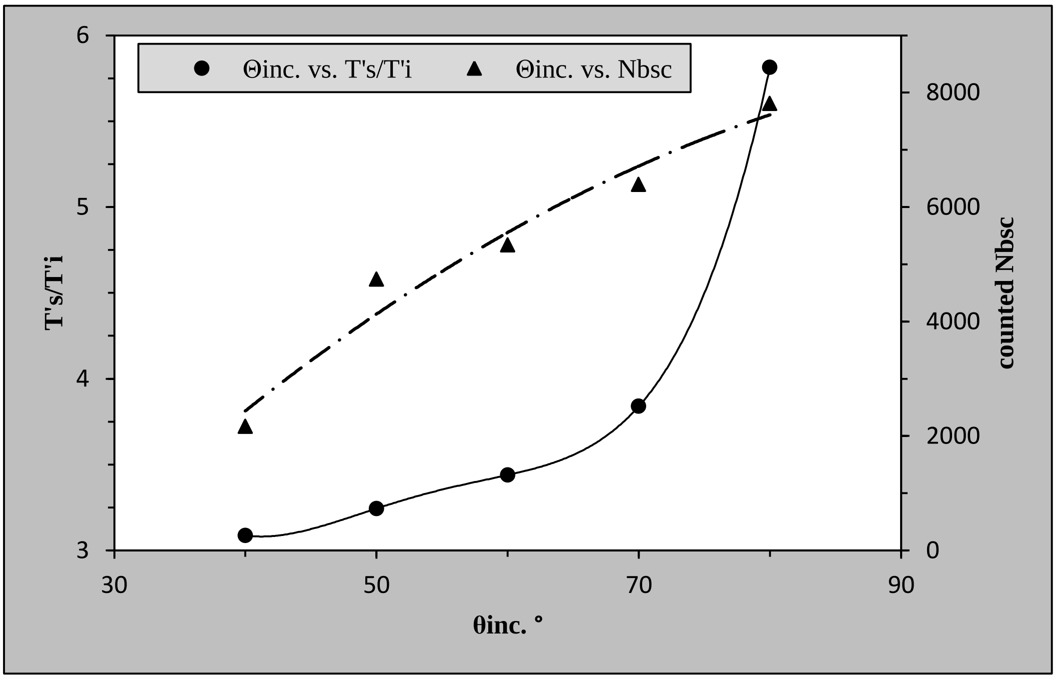


Figure 6- Correlating of number of counted photons with the photon incident angle on the sample and ratio of the vertical depth of an interaction point, within the sample, from the surface of sample for incident and scattered photon T_i' *and* T_s' respectively.

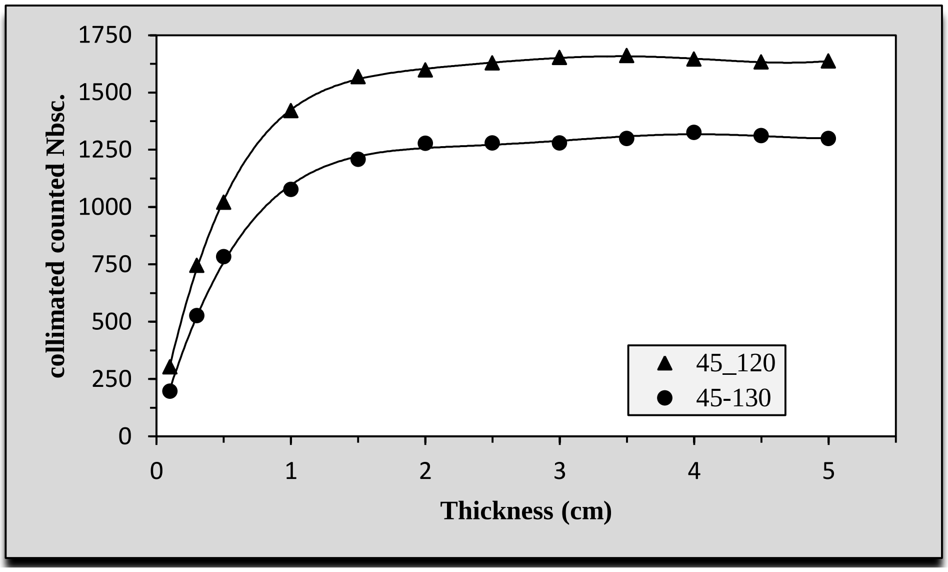


Figure 7- The dependence of the single scattering count on the iron thickness respect to incident angle 45° at scattering angle 120° and 130° respectively.

Concerning the thickness, we changed the thickness of iron target from (0.1-5) cm when the NaI(Tl) detector was fixed at 75° compared to scatter gamma rays emanating from the target. Fiq.7 shows the dependence of the single scattering count on the iron thickness respect to incident angle 45° at scattering angle 120° and 130° respectively. The results show that intensity (count) of single backscattering photons increases according to the increase in the target thickness. However, the count of the backscattered photons increases up to an Iron thickness of 3.0 cm. We consider a thickness of 3.0 cm as the saturation depth of the backscattering inside the iron sample target for the given energy and backscattering angle, and these results agree with the experimental results reported by G. Singh and et al. [8] This is explained by the fact that gamma rays have a higher probability of scattering, while a backscattered gamma ray must fly a longer distance before escaping the target surface when the gamma ray penetrates at a deeper distance into the target. Hence, the absorbing and scattering process offset each other. Finally, a stage is reached when the thickness of iron target becomes sufficient to counter balance two these process, resulting in the reaching of the saturation depth.

4. Conclusions

In this study, a Monte Carlo simulation has been used to design the geometry of a backscattered gamma rays system. The simulation was run at 661.6 KeV from a ^{137}Cs radioactive source. Virtually, the ^{137}Cs radioactive source was placed inside a collimator with angles (15, 45, and 75) degrees respect to an iron substance target. For various geometries, the properties of back-scattering system were then investigated while changing the thickness of iron substance and the scattering angle. The results showed that the single backscattering photons increase according to the scattering angle. When the iron substance thickness was increased, the single backscattering photons increased and reach saturation value at a thickness, approximately, 3.0 cm.

These results will be utilized to obtain the optimized conditions with which this method can be applied to an investigation of electron densities or the thickness of material samples determine whether defects are present. In addition, the results of this research have also been very useful in the training staffs and students in the field of applications of nuclear technique.

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