Proceedings of the Second International Workshop on EGS, 8.-12. August 2000, Tsukuba, Japan
KEK Proceedings 200-20, pp.216-223

EGS4 Simulation of Compton Scattering for Nondestructive Testing

N. Shengli, Z. Jun, and H. Liuxing

Northwest Institute of Nuclear Technology,
P. O. Box 69, No.15, Xi'an, 710024,CHINA

Abstract

This paper presents the principle of nondestructive testing based on the measurement of Compton-scattered photons. When a well-collimated beam of 0.662MeV gamma rays from Cs-137 isotope source is radiated vertically into a concrete wall, scattered photons can be detected at the same side of the wall by a NaI detector. The intensity of single Compton scattered photons is proportional to the electron density at the point where the scattering occurs. However, most of the incident photons are scattered more than one time. The single and multiple scattering are studied by Monte Carlo program package EGS4. This paper presents the flow of single and multiple scattered photons before reaching the NaI detector when a iron block is buried in the wall or not. Based on the results, it can be concluded that this system can detect the iron block buried in the concrete wall. In this process, the difference between ion and no ion for the single scattered photons is more obvious than that for the multiple scattered photons. The system can also be used to detect any non-iron object in other material with different electron densities.

1 Introduction

The CSI technique is based on the measurement of Compton scattered photons. In contrast to the conventional transmission tomography, this process relies on measuring of the back-scattered radiation from the interior of an object surface to achieve a three-dimensional image of the object interior. So CSI is useful in imaging on extended industrial objects or in cases where access to two opposite sides of the object is not possible[1, 2, 3, 4].

The objection of this paper is to theoretically analyze the feasibility of NDT technique to massive extended structure. The emphasis of the study was to investigate the feasibility of detecting defects or foreign object in concrete structures. The Compton scattering process is simulated using Monte Carlo program package EGS4. Owing to EGS4's open-architecture, the intensity and energy spectrum of the single and multiple scattering photons can be given separately. Meanwhile, program MCNP is used to simulate the total scattered photons. The two results agreed very well. So the simulation method is valid and the results are believable.

The paper is organized as follows. In section 2, a brief discussion of the CSI theoretical model is presented. A description of the Monte Carlo simulation is contained in section 3. Section 4 summarizes and concludes this paper.

2 Theoretical Model

An isotope source Cs-137 is assumed to be placed beside a concrete wall. Around the source, there is an annular NaI detector with its axis vertical to the wall. The well-collimated gamma ray from the source is radiated vertically into the wall, and then the detector will detect the scattered photons. Before entering the NaI, photons will pass through a narrow collimator, which is used to determine the particular point to focus at. The geometry sectional drawing of the structure is given in Figure 1. Assume there is a foreign object buried 60mm below the surface of the wall. It is a cylindrical block of iron, 5mm in height, and 5mm in diameter. Out of the concrete wall 40mm in distance there is an iron double-frustum-of-cone-shape collimator. The conical angle is 120°, and the vertical height of collimator is 100mm.

The energy of isotope Cs-137's gamma ray is 0.662 MeV. When it emits into the concrete, the main interactions are photoelectric effect and Compton scattering. The energy of electrons ejected in the two interactions is too low to create new photons. So all of the photons detected by NaI are Compton scattered photons.

The Compton scattering process is strictly an interaction between a photon and an individual electron. In the interaction, the photon does not disappear (Figure 2). In stead, it is deflected through a scattering angle and part of its energy is transferred to the recoil electron. The energy loss in the process depends on the initial photon energy as well as on the scattering angle. Under the assumption that the electron is free and stationary before collision, the energy change of the incident photon and the scattering angle is related to each other by

$$E_{\gamma'} = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)} \tag{1}$$

where $E_{\gamma'}$ is the energy of scattered photon, E_γ is the energy of incident photon, $m_0 c^2$ is the rest mass energy of electron, and θ is the scattering angle.

The Compton photons is not isotropically scattered. The differential total Compton scattering cross sections are given by the formula[5]

$$\frac{d\sigma_c}{d\Omega}(E, \theta) = \frac{\gamma_0^2}{2}\left[\frac{E_{\gamma'}}{E_\gamma}\right]^2 \left[\frac{E_{\gamma'}}{E_\gamma} + \frac{E_\gamma}{E_{\gamma'}} - \sin^2\theta\right] \tag{2}$$

where $d\sigma_c/d\Omega$ is the differential scattering cross section, and r_0 is the classical electron radius (cm).

The intensity of the single scattered photons can be written as

$$N_d = N_0 \frac{d\sigma_c}{d\Omega} \triangle\Omega n \triangle Z \exp\left(-\int_{l1} \mu dl\right) \exp\left(-\int_{l2} \mu' dl'\right) \tag{3}$$

where, N_0 is the number of photons in the source collimator, $d\sigma_c/d\Omega$ is the differential Compton scattering cross section, $\triangle\Omega$ and $\triangle Z$ are solid angle and depth focused by collimator of NaI, n is the electron density at the focus point, $\exp(-\int_1 \mu dl)$ and $\exp(-\int_2 \mu' dl')$ are respectively the attenuation rate of incident photons and scattered photons. It can be concluded that N_d is proportional to the electron density at the focus point if the geometry and source are given.

However, in the equation 3, we have just talked about the single scattered photons. There will be more photons scattered more than one time before reaching the NaI detector. Only the intensity of single scattered photons entering detector is the designed signal. The intensity of multiple scattered photons is the background. The aim of our study is to restrain the multiple scattering background. And then increase the signal-to-noise ratio. By adopting narrow collimator, the high signal-to-noise ratio can be achieved.

3 Monte Carlo Simulation

The single and multiple scatterings are studied by Monte Carlo radiation transport simulation. In order to distinguish the single and multiple scattered photons, the Monte Carlo program package EGS4 is adopted. The physical mechanism in the problem is only concerned with the shower of electron and gamma ray, so the package EGS4 is feasible. Because the whole configuration, geometry condition, information needed and the structure of source have not been determined, the open-architecture EGS4 is preferred[6]. The most important, the EGS4 can easily tell the information of particles' interactions, so we can distinguish the multiple and single scattered photons.

The main program is edited by user in EGS4, thus the simulation process can be controlled well. To distinguish the single and multiple scattering, we didn't choose the auxiliary subprogram already in EGS4, like WATCH. By setting the appropriate flag IAUSFL (19) from 0 to 1 in the main program, call AUSGAB with IARG=18 if a Compton interaction has occurred. An arithmometer is used to record the number of Compton scattering. The arithmometer adds 1 if a Compton scattering occurs except in the NaI detector. When this photon is terminated, the arithmometer can show how many times of Compton-scattering have occurred.

In order to verify the simulation of EGS4, the Monte Carlo program MCNP [7] is also used to calculate the total scattered photons.

4 Results and Conclusions

First, three cases are simulated, namely, no block, aimed (source rays emitted along the axe of block cylinder), and deviated. Table 1 gives the intensities and energy deposited in NaI.

Table 1: Intensity and Energy Deposited

	Intensity		Energy Deposited(10^{-6} Mev/photon)			Relative Error of EGS & MCNP
	Single Scattered	Total	Single Scattered	Total	MCNP Total	
No Block	136	2455	0.2544	3.338	3.347	0.3%
Deviated	126	2459	0.2362	3.342	3.427	2.5%
Aimed	294	2887	0.5806	4.083	3.983	2.5%

It can be seen from the table that the intensity of total photons obtained by EGS4 is close to that of MCNP. So the results of the simulation are believable. The single scattered photons are only the small fraction of the total photons. But they can distinctly tell if there is a change of electron density at the focus point. Because the scattered photons are attenuated by the deviated iron block, the intensity of photons in deviated case is lower than that of no iron block.

Then, we change the width of the collimator at the front of NaI. We choose the width as 0.2cm, 0.6cm, or 2.0cm. The counts of single and multiple scattered photons detected by NaI are listed in table 2. The pulse-height distribution of the three cases can be seen respectively in Figures 4, 5, and 6.

Table 2: Counts at different Collimator Width

Width (cm)	Single	multiple	Single/multiple
0.2	283	2491	0.114
0.6	1929	23497	0.082
2.0	21079	263032	0.080

When the width is 0.2cm, the counts of detected photons are very low. But the signal-to-noise ratio is high. It takes a long time to get enough counts. As shown in figure 4, there is a peak at 0.225MeV. It just equal to the energy of scattered photon when scatter angle is 120° and incident photon energy is 0.662MeV in Eq.1.

When the width is 0.6cm or 2.0cm, the counts of detected photons are high, but the signal-to-noise ratio is low. Because the background is high, the counts of detected photons cannot tell the change of electron density exactly. The broader collimator makes the larger of scattering angle, thus the energy range increase. It is shown in Figure 6, energy peak is wider than that in Figure 4.

According to all of above analysis, one should prefer narrow collimator as possible, especially in detecting small foreign body. We suppose the collimator width should be 0.2cm. The results and analysis can be used as reference on this kind of experiment and apparatus.

In summary, this kind of complete process is easy to be simulated using EGS4.The results obtained by MCNP shows that the EGS4 simulation is believable.

References

[1] J. Wehlburg, S. Keshavmurthy, Y. Watanabe, E. Dugan, and A. Jacobs, "Image restoration technique using Compton backscatter imaging for the detection of buried landmines ", *SPIE Proceedings*, 1995, Vol.2496:336-347.

[2] S. J. Norton, "Compton scattering tomography", *J. Appl. Phys.* **76(4)**(1994)2007-2015.

[3] G. Harding, and J. Kosanetzky, "Scattered x-ray beam nondestructive testing", *Nucl. Insru. Meth.* **A280**(1989)517-528.

[4] S. Anghaie, L. L. Humphries, and N. J. Diaz, "Material characterization and flaw detection, sizing, and gamma scattering spectroscopy technique", *Nucl. Tech.* **91**(1990)361-387.

[5] R. L. Morin, Monte Carlo Simulation in the Radiological Science, CRC Inc., 1988.

[6] W. R. Nelson, H. Hirayama, and D. W. O. Rogers, "The EGS4 Code System". *SLAC-265* (1985).

[7] J. F. Briesmeister, "MCNP–A General Monte Carlo N-Particle Transport Code", America La-12625-M.

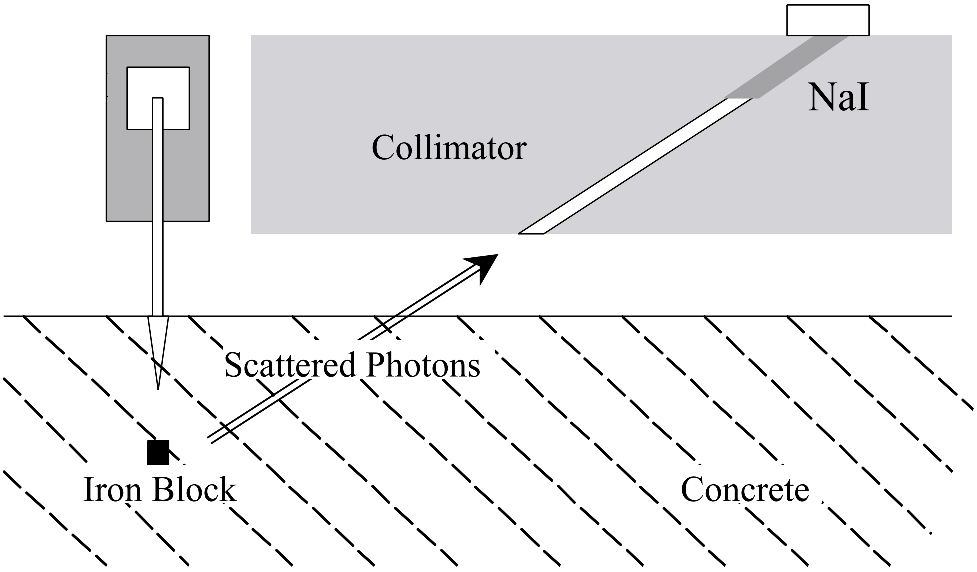

Figure 1: Geometry sectional drawing

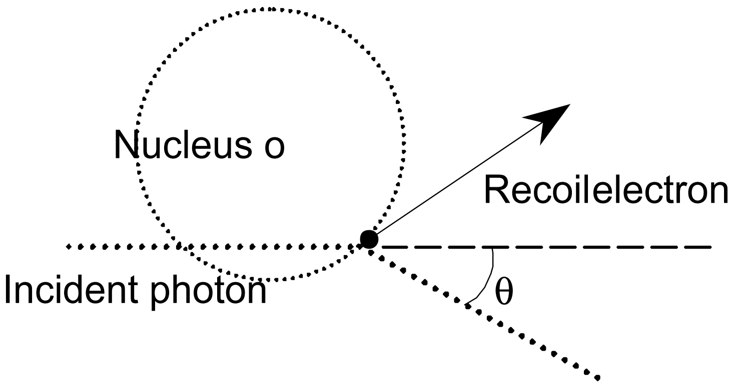

Figure 2: Compton scattering.

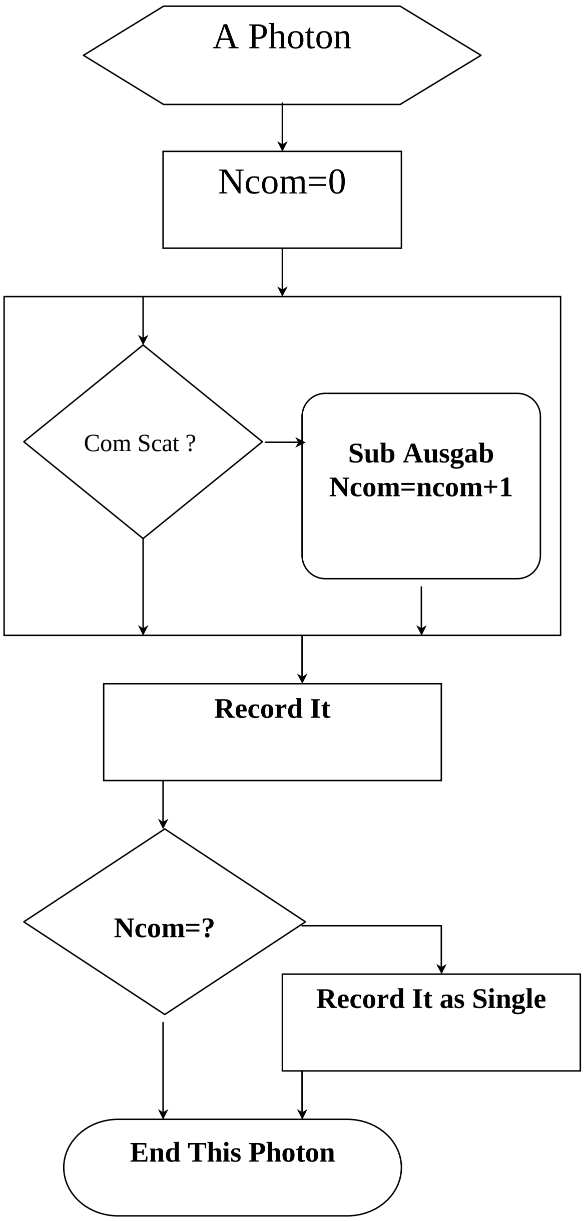

Figure 3: Block Diagram used to Distinguish Single and Multiple Scattering.

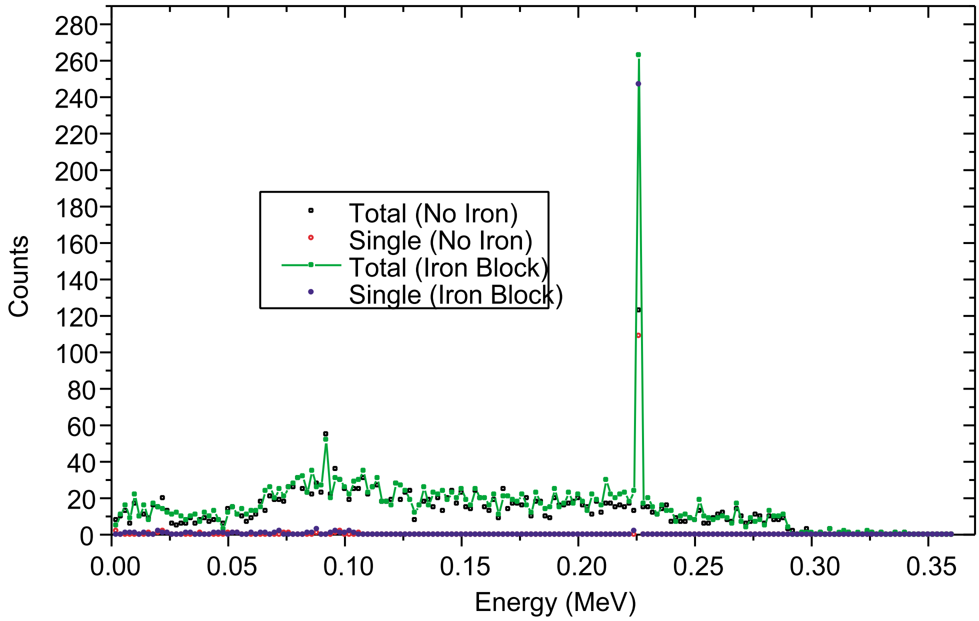

Figure 4: Pulse-height Distribution of the Detected Photons (Width=0.2cm).

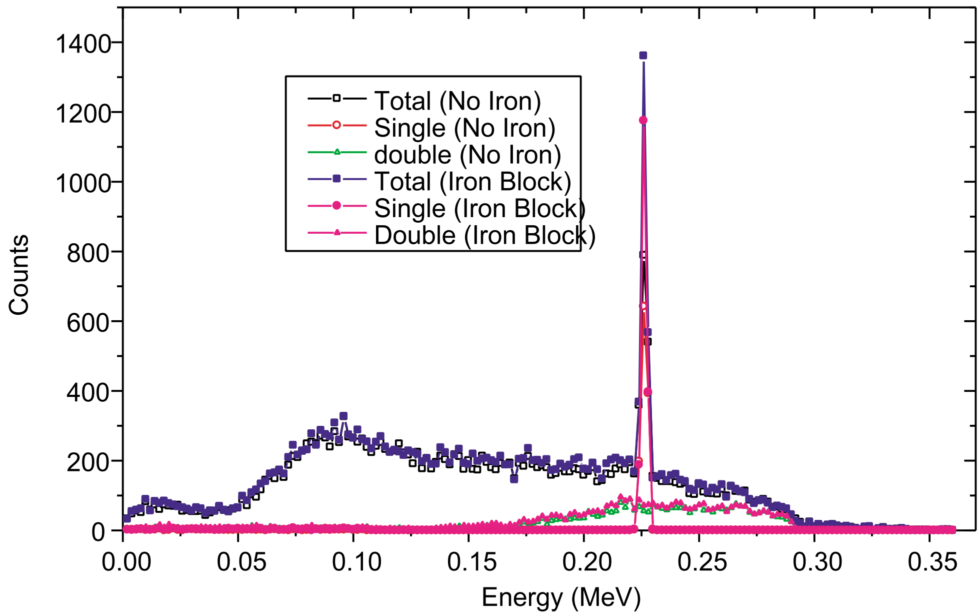

Figure 5: Pulse-height Distribution of the Detected Photons (Width=0.6cm).

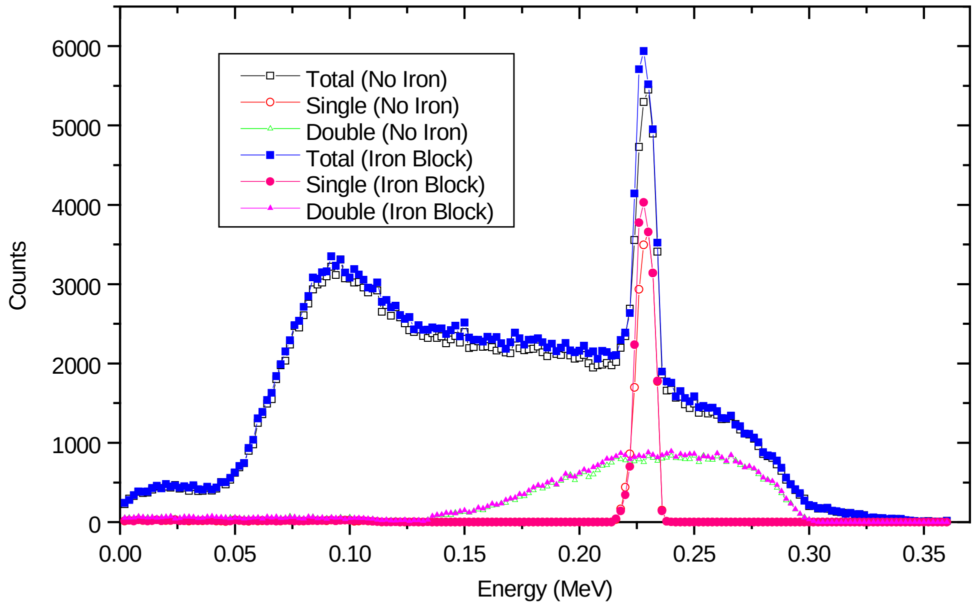

Figure 6: Pulse-height Distribution of the Detected Photons (Width=2.0cm).