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A Design of the Thickness Gauge Using the Compton Gamma-ray Backscattering

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Abstract

In this paper, we describe the results of various calculations performed for a design of the thickness gauges that use the gamma-ray backscattering method. The radiation source is assumed to be the ^{241}Am(60keV gamma-ray) and the detector is a single crystal scintillator in a cylindrical form. The source is located at the center of the detector with the collimator of a cylindrical shape. First, when gamma-rays are incident on a material with a constant angle, we compute the variations of the spectrum for the photons scattered into different angular intervals. Next, we compute for an optimal size for the collimator cylinder for a fixed detector size and an optimal distance from the detector to the material. Finally, we compute the number of observed photons for different thickness of two different materials, a plastic film and an Al foil.

Key Words : thickness gauge, gamma-ray backscattering, EGS4 simulation, scattered photon spectrum, plastic film and Al foil

1. Introduction

The thickness-measuring devices using radioisotopes can be classified into either as a backscattering or as an absorption type on the basis of the measuring principle. The absorption type operates in such a way that the radiation source and the detector are physically separate, and they are usually located on the different sides of the object to be measured. In the backscattering type, on the contrary, the source and the detector are located on the same side. The backscattering type is used effectively in those cases where the detector cannot be located in the opposite side of the source relative to the material whose thickness is to be measured due to the mechanical layout of the processing equipment[1,2]. This method is based on the analysis of the radiation which is backscattered from the test object after the Compton scattering. The information regarding thickness of the test object will be obtained by measuring the intensity and the energy of the

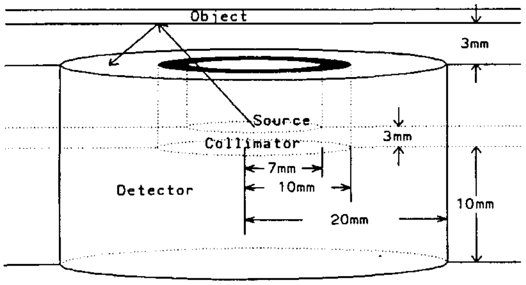

Fig. 1. Architecture of the Thickness Gauge Being Considered

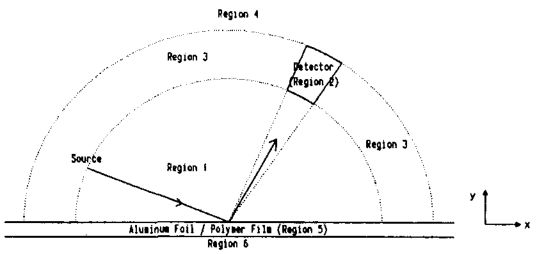

Fig. 2. Detector Location to Measure Scattered Photons

scattered photons[3,4,5].

The Compton scattering refers to a collision between a photon and a free electron. Under normal circumstances, all the electrons in an atom are bound to the nucleus. However, if the energy of the photon is of the order of keV or higher, the bound electron can be considered to be a free electron, because the binding energy of the electron is of the order of eV. When a Compton scattering occurs, the direction and energy of the incident photon will change after a collision with an electron. The energy of the photon is reduced by the amount that is given to the electron. The energy of the scattered photon depends on the scattering angle θ and is calculated by the following equation;

$$E_s = \frac{E_i}{1+(1-\cos\theta)E_i/mc^2} \tag{1}$$

where m is the rest mass of an electron, c the speed of light, E_i the energy of an incident photon, and E_s the scattered photon energy[6].

In the following, we will describe the results of various simulations performed for a design of a thickness gauge using the Monte Carlo method. The architecture of the thickness gauge being considered is shown in Fig. 1. The outer cylindrical shell represents a scintillator crystal and the inner shell whose top is shaded represents a collimator. We assume the radioactive gamma-ray source is located at the center of the collimator, and the collimator material is tungsten. The thickness of the tungsten shell will be assumed to be 2.5mm which is found to be enough for shielding 60keV photons directly reaching the scintillator crystal. We are to determine a set of optimal values for various design parameters such as the activity of radioactive isotope source, the scintillator size, the collimator size, and the distance between the detector and the test object etc..

2. Spectrum of Gamma Rays Scattered in Different Angles

In this section, we describe the results of computations performed by using EGS4[7] to investigate the changes of the spectrum for the scattered photons in different angular directions. We made calculations for two different cases. The first case is with the geometry shown in Fig. 2 where the gamma-ray beam is incident on the object(region 5) in a fixed direction and the location of the detector(region 2) varies on the circumference of a half circle. The objective here is to confirm the validity of our user programs written for EGS4 and to determine the angular

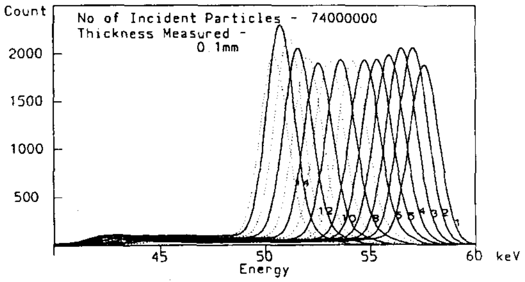

Fig. 3. Angular Variation of Backscattered Photon Spectrum

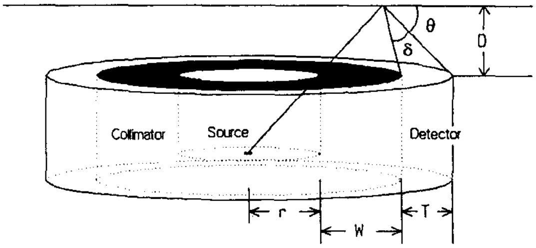

Fig. 4. Source-Detector Layout to Compute Angular Dependency of Scattered Photons

dependency of the Compton scattered photons for the 60keV energy. The second case is using the geometry shown in Fig.1 where the diameters of the detector and the shield material are varied so that only the photons scattered into desired angular intervals can be detected.

To make the geometrical part of the EGS4 user program for the first case, we take a coordinate system with the origin at the point where the particles hit the material(Fig. 2) and the positive x-axis toward the right-hand side of the figure. The detector is assumed to be a part of a cone with the polar angle span of $\pi/32$ and is cut off by two cylinders (or circles in x-y plane) with radii 20cm and 22cm each. The equation for the boundaries of the detector when it is located on the positive x-axis can be written as

$$y^2 + z^2 \le cx^2, \quad c=\tan^2(\delta) \qquad (2)$$
$$r_1^2 <= x^2 + y^2 <= r^2_2$$

with $\delta = \pi/32$, $r_1 = 20$cm and $r_2 = 22$cm. In general, one can rotate the cone by an angle α so that we have

$$(-x \sin(\alpha)+y\cos(\alpha))^2 + z^2 \le c(x\cos(\alpha)+y\sin(\alpha))^2 \qquad (3)$$

for the cone part of the detector boundary.

We assume all the photons start from a fixed point and hit the material at the origin as shown in Fig. 2 and compute the spectrum of the gamma rays measured by the detector located at angles $\alpha = \pi/64 + i\pi/32$ for $i=1, 2, 3, \cdots 15$. The results are shown in Fig. 3, where the labels1,2,3···, represents the detector location corresponding to the angle $\alpha = \pi/64 + i\,\pi/32$, $i=1, 2, 3, \cdots$, respectively. We confirmed from Fig. 3 that the angular distribution of the scattered photons is nearly isotropic as is expected from Klein-Nishina formula.

For the second case, we use the arrangement of the source-detector set and the object as shown in Fig.1 where 'Object' indicates the object whose thickness is to be measured. To count the number of photons scattered from the object into a fixed angular interval, we use different sizes of the detector and different thicknesses of the collimator.

Let r be the inner radius and h be the length of the collimator. If W is the thickness of the tungsten collimator, T is the thickness of the CsI crystal surrounding the tungsten, then from Fig. 4, we have the following relation

$$W= D\left(\frac{r}{h} + \cot(\theta+\delta)\right), \quad T = D\left(\cot(\theta)-\cot(\theta+\delta)\right) \qquad (4)$$

where D is the distance from the detector to the

Table 1. Sizes of the Collimator and the Detector

$\theta = \frac{i\pi}{32}$	W(cm)	T(cm)	$\theta = \frac{i\pi}{32}$	W(cm)	T(cm)
0.0982	5.5273	5.1258	0.8836	1.1682	0.1525
0.1963	3.7966	1.7308	0.9817	1.0345	0.1337
0.2945	2.9142	0.8823	1.0799	0.9142	0.1203
0.3927	2.3709	0.5433	1.1781	0.8033	0.1109
0.4909	1.9966	0.3743	1.2763	0.6989	0.1044
0.5890	1.7195	0.2781	1.3744	0.5985	0.1004
0.6872	1.5000	0.2185	1.4726	0.5000	0.0985
0.7854	1.3207	0.1793			

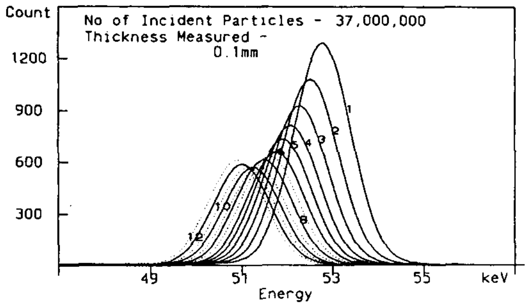

Fig. 5. Energy Spectra Calculated when Incident Angle is 90°

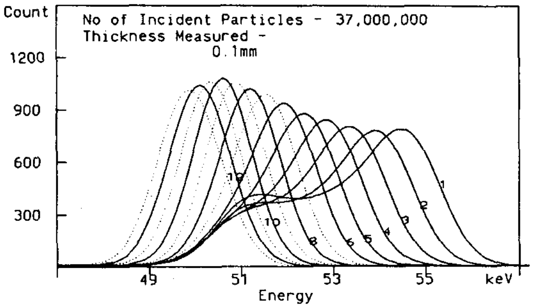

Fig. 7. Energy Spectra when Incident Angle is 63.4°

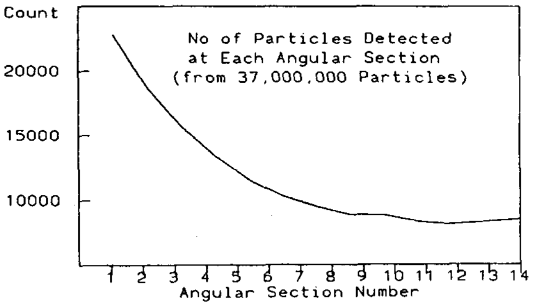

Fig. 6. Number of Gamma Rays Scattered in Different Angular Directions

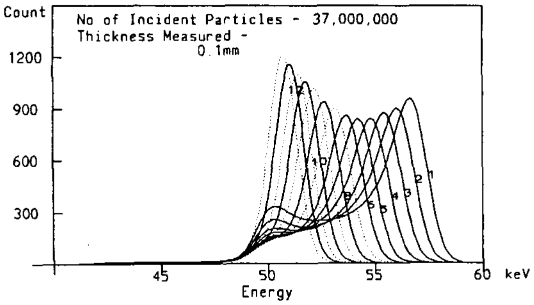

Fig. 8. Energy Spectra when Incident Angle is 45°

object whose thickness is to be measured, θ is the starting angle, and $\theta + \delta$ is the ending angle for the counting. We divided the 90 degree angle into 16 angular intervals so that we have $\delta = \frac{\pi}{32}$. When we take $D=1cm$, $r=1cm$, $h=2cm$ and compute W and T, we obtain the values shown in table 1.

We assume that the material whose thickness is to be measured is a plastic film of density $1g/cm^3$ and the thickness of 0.1mm. When 60keV

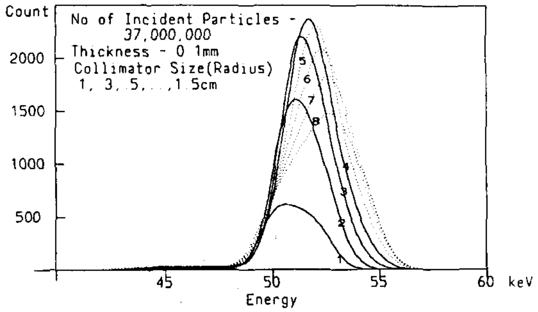

Fig. 9. Spectra of Backscattered Photons Depending on the Collimator Size

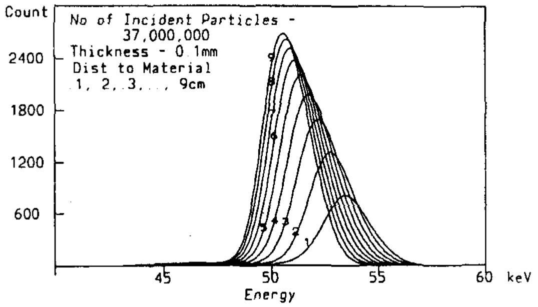

Fig. 10. Spectra of Backscattered Photons at the Distances from 0.1cm to 0.9cm with a 1cm Diameter Collimator

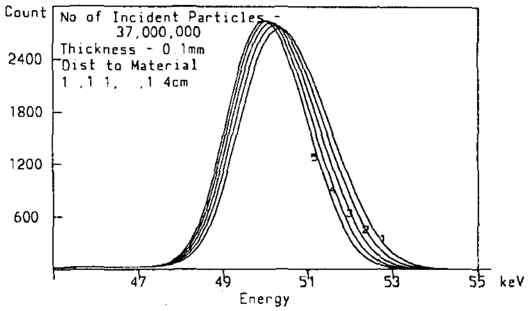

Fig. 11. Spectrum of Backscattered Photons at the Distances of 1.0, 1.1, ···,1.4cm with a 1cm Diameter Collimator

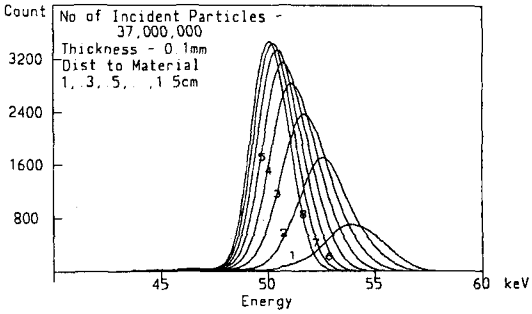

Fig. 12. Spectrum of Backscattered Photons Depending on the Distance with a 1.4cm Diameter Collimator. Spectrum 1,2,···,8 show the Result for Distance 0.1cm, 0.3cm,···, 1.5cm, Respectively

gamma rays from a point source located at the center of the collimator are all incident perpendicularly upon the object, the EGS4 calculation produces the energy spectra as shown in Fig. 5. Fig. 6 shows the number of particles as a function of the scattering angle.

When the photons are incident on the material with an angle of 63.4° and 45° instead of the 90°, the spectra we have obtained are as shown in Figs. 7 and 8, respectively. Note that from Fig. 1, the gamma rays scattered from the object can arrive at the detector only when the scattered angle is within a certain angular interval. Since the usual size of the detector crystal(NaI or CsI) used in thickness gauges is one inch in diameter, we restrict our attention to crystals of size less than 2 inches in diameter, i.e., 2.5cm in radius. Now from Table 1, we compute $r+W+T = 1.0 + 1.3207+0.1793 \simeq 2.5$cm when i=8, i.e., $\theta = \frac{\pi}{4}$. Using this and the results shown in Figs. 7 and 8, we find that the angular distribution of gamma rays scattered from the object is nearly isotropic in the interval where the detector is located. Thus, we conclude that the photons have nearly the same probability to be measured in an arbitrary direction as long as we are concerned with designing a thickness gauge using 60keV gamma rays of ^{241}Am source with the geometrical

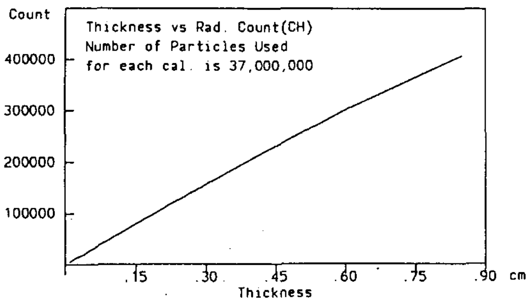

Fig. 13. Relation Between Plastic Film Thickness and Calculated Total Counts

arrangement of Fig. 4.

3. An Optimal Radius of the Source Collimator for a Fixed Size CsI Scintillator

In this section, we assume that the size of the detector and the thickness of the shield material are fixed. We also assume that the source is in the form of a disk whose radius is 80% of the inner-radius of the collimator. We hope to determine the optimal radius of the collimator with which the detector efficiency becomes maximum.

We assume that the diameter of the CsI crystal is 5cm, which is a typical size used for most thickness gauges. The height of the crystal is assumed to be 1.5cm. The thickness of the shield material (tungsten) is assumed to be 2.5mm since it is sufficient for completely shielding 60keV photons of the ^{241}Am source. When calculations are performed for collimators of radius 0.1cm, 0.2cm, ⋯, 1.5cm, each with 37million particles, we obtain the results shown in Fig. 9. Note that higher peaks with lower variations in the spectrum curves are attained when the radius of the cylindrical collimator ranges from 0.5cm to 0.8cm. Thus, we take any value in this range to be an optimal value for the radius of the collimator.

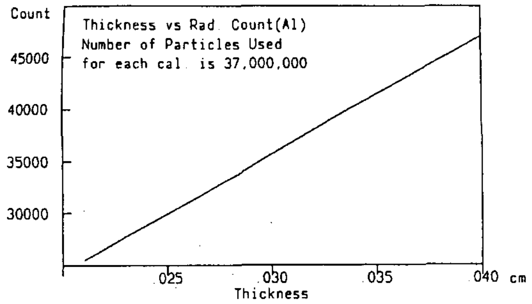

Fig. 14. Relation Between Al Foil Thickness and Calculated Total Counts

4. An Optimal Distance from the Detector to the Material

In this section, we describe the results of calculations performed to find how the spectrum changes as the distance from the detector to the object material varies. Again, we fix the size of the detector to be 5cm in diameter and 1.5cm in height, while the thickness of the shield material is set at 2.5mm. We first consider the case with a collimator of 1cm in diameter. A set of calculations has been carried out for the 14 different cases with distances ranging from 1mm to 14mm, each with 37 million particles. The spectrum for first 9 cases are shown in Fig. 10 and the cases from 10mm to 14mm are shown in Fig. 11.

Next, we performed a set of calculations with 1.4cm in diameter for the collimator. The computed results for the cases of distances 1mm, 3mm, ⋯, 15mm to the material to be measured are shown in Fig. 12.

From the calculated results shown in figures Fig. 10, Fig. 11, and Fig. 12, we may conclude that the relatively lower energy photons tend to be detected and the FWHM of calculated peak decreases as the distance increases. This is due to the fact that the backscattered photons with larger scattering angles are detected and the solid angle of detector decreases when the distance gets larger. Note also that the total number of detected particles, i.e. the area of peak, is saturated when the distance from the detector to the material is around 1cm for the given geometry. Hence, we take this distance to be our optimal value.

5. The Thickness Versus the Radiation Count

In order to see how the number of detected particles changes as the thickness of the material increases, we performed a series of calculations for two different materials. The first material is a plastic film whose chemical composition is assumed to be CH, and whose density is assumed to be 1g/cm^3. We computed for the cases of thicknesses from 0.1mm to 20mm using 3.7×10^7 gamma rays each. From the results for the distances from 0.1mm to 0.9mm shown in Fig. 13, one can see that the total number of photons measured by the detector is increasing as the thickness increases and the relation is fairly linear when the thickness range is in that interval. The second material is an Al foil and the results in Fig. 14 also show a similar linear relation between thickness and calculated counts.

6. Conclusions

Using the Monte Carlo method, we have studied the design parameters for the thickness gauge based on the principle of Compton gamma-ray backscattering. We used ^{241}Am as a radioisotope source positioned at the center of the cylindrical scintillator crystal, and 2.5mm thick tungsten as its shielding material. The simulation results show that the peak position of the backscattered photon spectrum varies depending on the scattering angle, which is what was expected. We find also that the photons have nearly the same probability to scatter in an arbitrary direction in case of 60keV gamma rays. The results also show that all of the peaks are located inside an interval of 30 to 60keV which is away from 20keV, the noise boundary for scintillation detectors. An optimal radius of the source collimator for a 5cm diameter detector is determined to be in the range of 5mm to 8mm. An optimal distance from the detector to the material is determined to be around 1cm for our geometry. And the total counts of photons measured by the detector are found to be fairly proportional to the thickness of the object for both cases of a CH film and an Al foil. From these results, we conclude that the designed thickness gauge based on the gamma-ray backscattering can be used for thickness measurements of plastic films and aluminum foils when the thickness is in the range of 0.1mm to 20mm.

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