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Full Length Research Paper

Compton scattering of 662 keV gamma rays by aluminium and copper materials using NaI(Tl) detector

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A rotating NaI(TI) scintillator detector and a collimated Cs^{137} source producing gamma rays with an energy of 662 keV scattered incoherently by aluminum (Al) and copper (Cu) scatterers through the angles from 0 to 120° are used to study Compton scattering. The Compton scattering effect is investigated and found that the energy of scattered gamma ray decreases as the scattering angles increases. The differential scattering cross-section as a function of scattering angles is also measured. The experimental results of differential scattering cross-sections for Al and Cu scatterers were compared as a function of scattering angle and found to coincide at the higher angle region, although scattering cross-section for Cu are larger than Al scatterer at the lower angles region.

Key words: Incoherently, scatterers, cross-section, energy.

INTRODUCTION

Arthur Compton in 1923 was the first to observed Compton effect and this discovery led to the award of the 1927 Nobel Prize in Physics. The discovery is very important, because it demonstrates that light cannot explicitly be explained purely as a wave phenomenon. Compton's work convinced the scientific community to accept light as a stream of particles (photons), the energy of which is proportional to the frequency (Nicholas, 1995).

Gamma ray scattering by individual atomic electrons is known as Compton scattering if the simplifying approximation invoked that the target electrons are initially free and at rest, in this case, the differential and integral scattering cross sections can be computed using the compact analytical expressions (Hubbell, 1997; Klein and Nishina, 1929). In practical cases where the scattering electrons are always bound, the application of this formula restricts the momentum transferred to the struck electron which must be large compared to the square root of the binding energy of the electron (Acharya et al., 1981).

The interaction process of Compton scattering occurs between incident gamma ray photons and electrons in the absorbing material. It is predominant interaction mechanism of radioisotopes emitting energy in the range of few hundreds keV (Acharya et al., 1981). Compton scattering has been subject to many investigation ever since it was first introduced. The observation and explanation was of course a great importance to the development of modern physics. To determine the cross section for the elastic scattering of gamma ray, knowledge of the energy of Compton scattered photons is vital. For high gamma ray energy and low atomic numbers at small angles, Compton and elastic peaks overlap. Theoretical calculation of Compton scattering of 662 keV gamma rays proposed by Klein-Nishima formula was reported (Hossain et al., 2011). Recently heavy metals in hair samples of sanitation workers were analysed using energy-dispersive X-ray fluorescence (Khudzari et al., 2011). Theoretical calculation of isomers around ^{68}Ni was reported Abdullah et al., 2011; Hossain et al., 2011). The radioactivity levels in various types of rice in Malaysia were measured using hyper pure germanium detector (Saeed et al., 2011). Incoherent scattering of 59.5 and 661.6 keV gamma ray by elements with 13 ≤ Z ≤ 82 was investigated by a number of groups (Krishnaveni and Gowda, 2005; Erzeneoglu et al., 1980).

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This experiment involves gamma ray spectrometers that determine the energy and the counts rate of gamma rays emitted by radiation. A clear spectrum with a high resolution is needed to make it easier to analyze the experimental data. In this study, ^{137}Cs is chosen as the source because it is commonly used in gamma-ray spectroscopy, medicine and many others area of sciences. In this paper, Compton scattering of 662 keV gamma rays for aluminium (Al) and copper (Cu) scatters is investigated at the angles in the range from 0 to 120°.

COMPTON DIFFERENTIAL CROSS SECTION BY EXPERIMENTS

The $(\frac{d\sigma}{d\Omega})_{experimental}$ can be measured experimentally by knowing about the geometry and type of scattering material, detector's solid angle, the source activity and incident flux from the source. The Compton differential cross section can be calculated as follow:

$$(\frac{d\sigma}{d\Omega})_{experimental} = \frac{\Sigma\gamma'}{K\,\Delta\Omega\,I} \quad (1)$$

In the foregoing expression (Equation 1), $\Sigma\gamma'$ can be found from the sum of counts under the full energy peak, $N_{\gamma'}$ for each angle from 0 to 120° over the time taken 't' to collect the readings. The equation for $\Sigma\gamma'$ is:

$$\Sigma\gamma' = \frac{N\gamma'}{t} \quad (2)$$

K is the number of electrons in the scattering sample, given by equation:

$$K = \frac{mZN_0}{A} \quad (3)$$

where m is the mass of the sample (scatterer), Z is the atomic number of the sample, N_0 is the Avagadro's number and A is the atomic weight of the sample.

The solid angle of detector is expressed in steradians, sr. The calculation of the solid angle is possible if the area of the detector 'G' and the distance 'd' from the scattering sample to the detector is known. The area of detector G is calculated using the equation:

$$G = 2\pi r^2 \quad (4)$$

where r is the radius of detector. So, the solid angle of detector is expressed by the equation:

$$\Delta\Omega = \frac{G}{d^2} \quad (5)$$

The flux of gamma rays 'I' incident at the scattering sample means, the number of gamma rays impinging the surface area of detector. The number can be calculated from known values of the activity 'A' of the source and the distance 'R' between the sources and sample. The calculation of I can be done using the equation:

$$I = \frac{A}{4\pi R^2} \quad (6)$$

EXPERIMENTAL DETAILS

For this study, the incident gamma rays from ^{137}Cs (662 keV) with an activity of 13.73 mCi (508.3 MBq), NaI(Tl) detector with photomultiplier (PM) tube, high voltage supply, amplifier, multichannel amplifier, lead shield and the computer based gamma acquisition system available in Nuclear Physics Laboratory, Universiti Teknologi Malaysia are used. The collimator in front of the NaI(Tl) detector is tapered to define the better scattering geometry, but results with simple shielding have been of adequately good quality.

A block diagram of a typical system for gamma ray spectroscopy is presented in Figure 1. The gamma source, ^{137}Cs was housed at the centre of a cylindrical lead shield. High-purity elementals rods of Al and Cu, were used as scatterers. The Al and Cu rods as scatterer were placed at 36 cm from the ^{137}Cs source. The lead shield covering the collimator was removed. High voltage (HV) was applied to the photo multiplayer tube (PMT) detector. The power was turned on and the HV was set at 1.00 kV. The angle of the detector was adjusted at 0°. The voltage pulse by the photomultiplier in a NaI(TI) detector was shaped by a multichannel analyzer (MCA). The MCA takes a very small voltage signal produced by the NaI(TI) detector, reshapes it into a Gaussian or trapezoidal shape, and then converts it into a digital signal. The data was recorded for 300 s by a 1024 channel analyzer. The MCA output was sent to a computer to store, display and analyzes the data. In the energy calibration, the peak of ^{137}Cs with the energy of 662 keV was calibrated. This calibration was used to determine energy E_γ. The detector's angle was increased by 5° in step until 120°.

RESULTS AND DISCUSSION

Energy determination

The values of scattered photon energy, $E_{\gamma'(experimental)}$ are calculated at various angles ranging from 0 to 120° using Equation 1 for aluminum and copper scatterers. It is seen that, as the scattering angle increases, the photo peak of gamma spectrum obtained is slowly going to the lower channel numbers. Thus, as the scattering angle increases, the energy of gamma ray decreases, ecause the gamma ray looses energy, when it interacts with the matter. The comparative studies of experimental scattering angles of gamma rays for scatterers Al and Cu are presented in Figure 2. It can be seen that the scattered energy decreases when the scattering angle increases. The results demonstrate that the experimental values of Al are smaller than Cu, especially at larger scattering angles. The scattered energy $E_{\gamma'}$ as a function scattering angle θ shows non-linear curve.

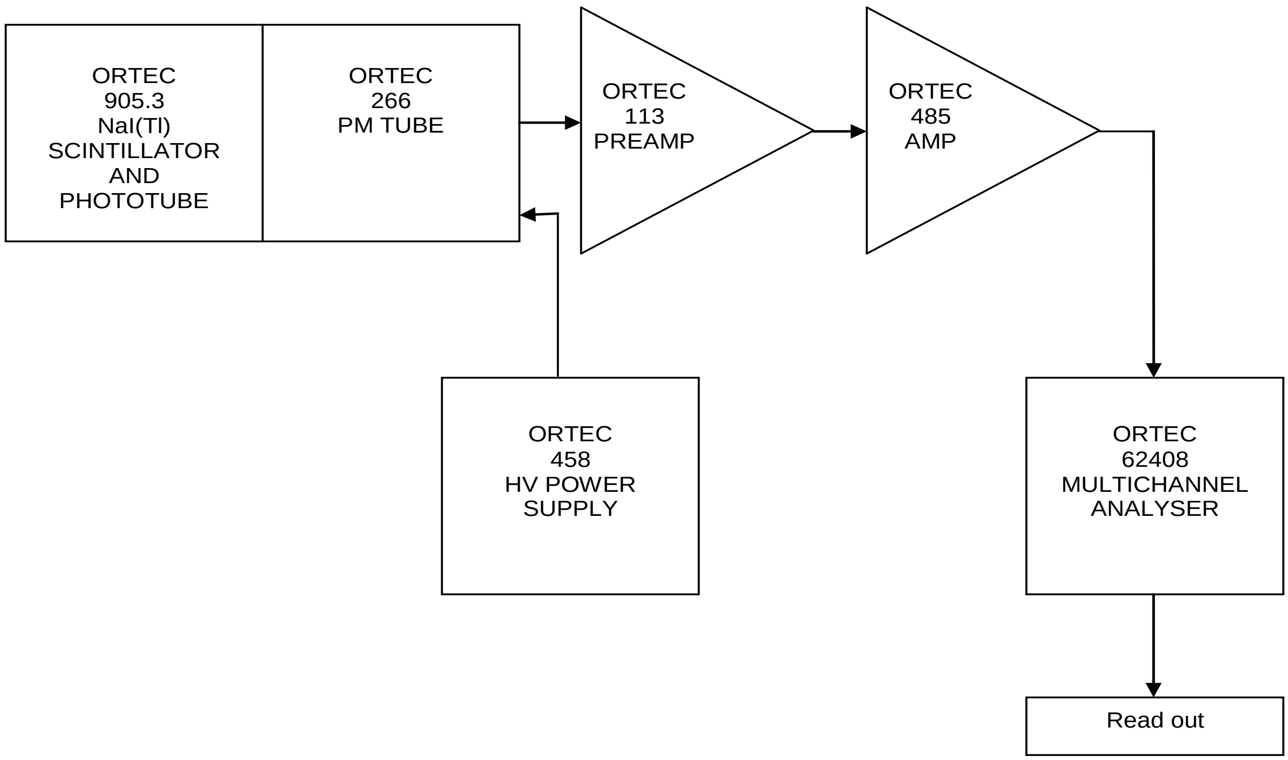

Figure 1. A block diagram of a typical system for γ-ray spectroscopy.

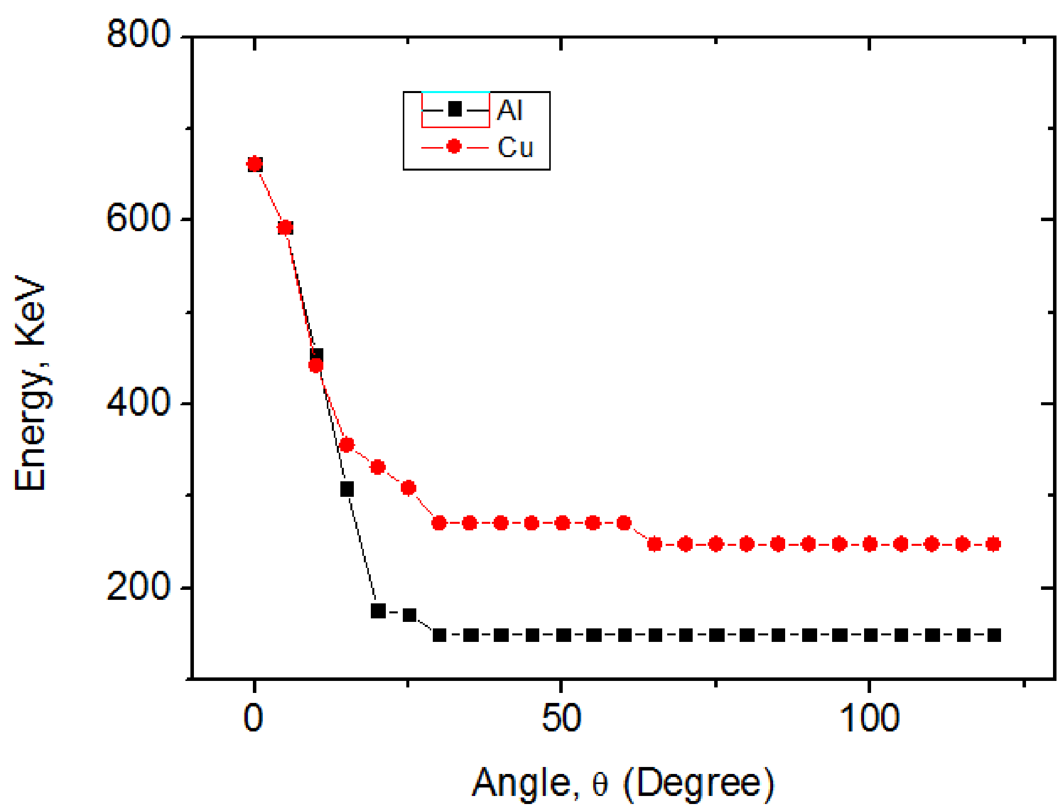

Figure 2. Photon energies versus scattering angle θ for Al and Cu.

Table 1. The mass, atomic number, atomic weight and number of electrons for Al and Cu.

Type of sample	Aluminium	Copper
Mass of sample	19.9 g	29.83 g
Atomic number of sample	13	29
Atomic weight of sample, A	26.98 g	58.93 g
The number of electrons, K	5.77×10^{24}	8.84×10^{24}

It is found that the measured values of scatterers Al and Cu decrease with the scattering angles and overlap to each other at the angles from 0 to 15°, and then the values of Al rapidly decrease as compared to Cu from 15 to 30°. The scattering energy is almost constant at the angles from 30 to 120° for both scatters Al and Cu. When gamma-rays undergo a Compton interaction, a fraction of the energy escapes from the detector without being absorbed resulting in the background rate increase in the spectrum. Larger volume of detector is required to reduce an effect.

In the Compton formula, it is assumed that the electrons in the outer orbital are loosely bound. In reality, the electrons were initially in a strongly bound initial state, therefore causing significant deviation from the case of a free initial state. Compton scattering is strongly affected by the scattering electron's binding. It's also noteworthy to mention that all the scattered photons do not reach the photomultiplier, thus making it hard for the detector to detect the scattered energy precisely.

^{137}Cs activities

In calculation of Compton differential cross-section, experimental activity of the source is needed. The activity of the source decreases with time due to radioactive decay. The current activity, A of the ^{137}Cs source is 508.3 MBq.

Other parameters involved in the calculation are number of electrons in scattering sample, K and the sum under the photo peak, $\Sigma\gamma'$. The value of $\Sigma\gamma'$ can be calculated using Equation 2 and it is as shown in Table 2. The Avogadro's number is 6.022×10^{23} mol^{-1}. Using Equation 3, Table 1 shows the values of K.

Solid angle of the detector

In order to calculate the solid angle of the detector, the calculation of the area of the detector is needed. The detector used in this study was in cylindrical form with a diameter of 5.8 cm. Based on Equation 4, the area of detector, G is 52.84 cm^2 and the distance, d from the scattering sample to the detector is 24 cm. Using the value of G and d in Equation 5, the solid angle of detector, $\Delta\Omega$ is calculated and found to be 0.092 sr.

Incident gamma rays

The flux of gamma rays incident at the scattering sample can be calculated using Equation 6. From calculation, the activity, A of ^{137}Cs is found to be 508.3 MBq and the distance, R between the sources and sample is 36 cm. Thus, the calculation provides the flux of gamma rays, 312.11×10^{-26} Bqm^{-2}.

As all the parameters have been calculated, the experimental values of Compton differential cross-section are determined based on the expression in Equation 1. The determined Compton differential cross-sections are listed in Table 2.

The comparison of experimental data of differential cross-sectional area for both the scatterers Al and Cu is as shown in Figure 3. By plotting both data in the same graph, it is easier to compare the results of experimental data between Al and Cu. From the graphs, it is clearly seen that there is a qualitative agreement between the experimental results of scatterers Al and Cu which demonstrate almost similar pattern. It is observed from the Figure 3 that the experimental results are systematically lower for Al than that for Cu at the lower angles from 0 to 25°, but the experimental results are almost overlapped to each other at the higher angles from 25 to 120°. There are many factors that can affect the experimental results of cross-section, such as geometrical shape of the detector, activity of the source, incident gamma rays that hits the detector and number of counts.

Conclusion

Using NaI(Tl) scintillation detector, the effect of Compton scattering of 662 keV gamma rays is investigated for Al and Cu materials. The shift in energy and differential cross-section as a function of scattering angle is experimentally observed. The experimental results of Al and Cu, demonstrate a correlation that the energy of the scattered gamma ray decreases with the increase in scattering angle for the both scatterers. The differential cross-sections for Al and Cu materials by gamma ray photons scattering indicate very good agreement at the higher angles showing similar fashion at the lower angles.

Table 2. Experimental data $\Sigma_{\gamma'}$, $K\Delta\Omega I$ and $\left(\frac{d\sigma}{d\Omega}\right)_{exp}$ obtained from this study.

Angle, (θ) degree	Aluminium			Copper		
	$\Sigma_{\gamma'}$ (Counts/s)	$K\Delta\Omega I$ × E+28	$\left(\frac{d\sigma}{d\Omega}\right)_{exp}$ (cm^2/sr) × E-26	$\Sigma_{\gamma'}$ (Counts/s)	$K\Delta\Omega I$ × E+28	$\left(\frac{d\sigma}{d\Omega}\right)_{exp}$ (cm^2/sr) × E-26
0	1160.33	1.65	7.03	2554.10	2.53	10.0
5	1071.98	1.65	6.50	2466.63	2.53	9.75
10	1023.73	1.65	6.20	2390.53	2.53	9.45
15	961.32	1.65	5.83	2357.14	2.53	9.32
20	944.21	1.65	5.72	2095.31	2.53	8.28
25	808.13	1.65	4.90	1254.26	2.53	4.96
30	710.66	1.65	4.31	999.42	2.53	3.95
35	633.39	1.65	3.84	903.32	2.53	3.57
40	586.30	1.65	3.55	807.50	2.53	3.19
45	545.56	1.65	3.31	774.44	2.53	3.06
50	518.04	1.65	3.14	750.61	2.53	2.97
55	491.49	1.65	2.98	742.07	2.53	2.93
60	461.64	1.65	2.80	761.63	2.53	3.01
65	458.04	1.65	2.78	722.80	2.53	2.86
70	454.64	1.65	2.76	736.16	2.53	2.91
75	450.72	1.65	2.73	721.42	2.53	2.85
80	453.98	1.65	2.75	708.46	2.53	2.80
85	452.91	1.65	2.74	726.74	2.53	2.87
90	449.57	1.65	2.72	739.01	2.53	2.92
95	440.52	1.65	2.67	730.64	2.53	2.89
100	448.93	1.65	2.72	718.09	2.53	2.84
105	443.36	1.65	2.69	725.17	2.53	2.87
110	431.37	1.65	2.61	692.82	2.53	2.74
115	427.76	1.65	2.59	679.85	2.53	2.69
120	427.89	1.65	2.59	672.66	2.53	2.66

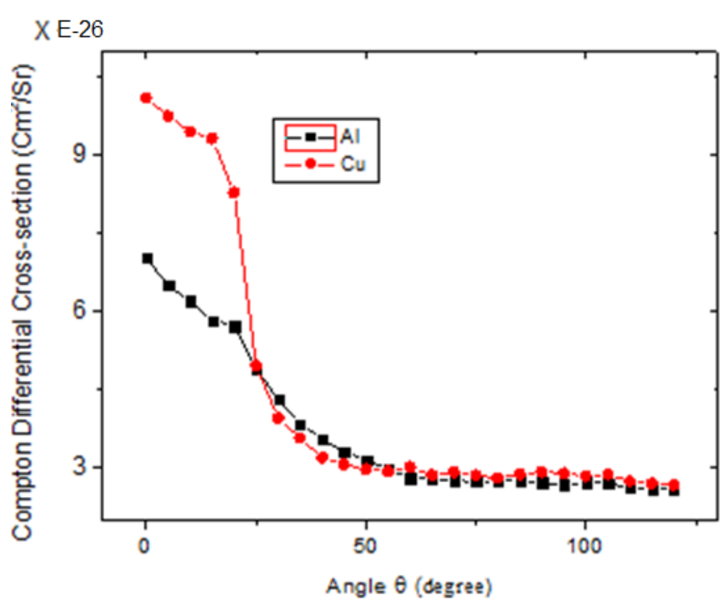

Figure 3. Compton differential cross-section (Cm^2/Sr) versus scattering angle θ for Al and Cu.

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