Compton scattering off an Aluminum target at angles of approximately 180^0 and 90^0

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An experiment was designed to measure the incident and scattered energies of photons from a ^{137}Cs source interacting with electrons in an aluminum target at angles of approximately 180^0 and 90^0. These energies were then compared to theoretical values produced from the Compton equation. The energies of the backscattered photons were found to be (0.197 ± 0.027) MeV, which is within experimental error of the theoretical value of 0.184MeV. The energy of the approximately 90^0 scattered photons were found to be (0.279 ± 0.048) MeV, which is within experimental error of the theoretical value of 0.288MeV.

INTRODUCTION

Discovered in the late 1800s, x-rays became a popular branch of physical study.[1] It was soon shown that the x-ray was a light beam of shorter wavelength than that of visible light, and several experiments were then used to scatter x-rays off certain materials. In these scattering experiments, it was noticed that the scattered x-rays were more readily absorbed than the incident x-rays from the same source.[2] These results were mostly apparent with high energy x-rays (about 0.1 MeV and above)[1] and meant that the more readily absorbed x-ray photons had less energy than the photons emitted from the source. This energy loss of the scattered x-rays remained a mystery until work by Compton showed the ultimate example of light behaving as a particle. [1]

Compton imagined that photons striking the electrons in the target material behaved like other "classical" objects colliding with each other. In this assumption, an incoming photon of a certain energy and momentum would glance off a stationary electron and send the electron recoiling at an angle away from the incident angle of the approaching photon.[2] The photon would scatter off at a different angle and would lose some amount of energy in the collision, corresponding to a change in wavelength of the photon. The collision would happen in a plane, and therefore a two-dimensional model in which the electron was at the origin and the photon was incident on the x-axis was used. Compton was then able to apply the laws of energy and momentum conservation to derive an equation for the change in wavelength of the scattered photon,[2]

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_o c}(1-\cos\alpha) \qquad (1)$$

where $\Delta\lambda$ is the change in wavelength of the photon, h is Planck's constant, m_o is the rest mass of an electron, c is the speed of light, and α is the photon's angle of scattering.

The purpose of this experiment is to measure Compton scattering from a radioactive source of (^{137}Cs) producing photons that can scatter from effectively free electrons in an aluminum target at angles of approximately 180^0 and 90^0, and compare these experimental energies to the theoretical energies using the Compton equation. ^{137}Cs has a half-life of 30 years and undergoes β decay producing $^{137}Ba^*$, an electron, and an electron neutrino. $^{137}Ba^*$ has an unstable nucleus that emits[3] photons of energy 0.661 MeV. These gamma rays are the source of the photons that strike the aluminum target.

Using the expression[2]

$$\lambda = \frac{hc}{energy} \qquad (2)$$

you are able to manipulate equation 1 to solve for the energy of the deflected photon E_α (Eq.(3)).

$$\frac{1}{E_\alpha} = \frac{1}{E_\gamma} + \frac{(1-\cos\alpha)}{m_o c^2} \qquad (3)$$

Where E_γ is the energy of the incoming photon prior to the collision, and $m_o c^2$ is the energy of the electron (0.511 MeV). For ^{137}Cs, the energy of the incident photon is equal to 0.661 MeV. This yields theoretical values of E_α when $\alpha = 180^0$ and

$\alpha = 90^0$ of 0.184MeV and 0.288 MeV respectively.

EXPERIMENT

The experiment used a gamma source of ^{137}Cs to produced photons that were then scattered off an aluminum target at different angles. When the gamma rays hit the electrons in the Al target, they were scattered at different angles in accordance with Compton scattering. The energy of the deflected photons were then determined using a photomultiplier tube (PMT) with a NaI crystal scintillator and a pulse height analyzer (PHA).

Since the PHA gives a channel scale and not an energy scale as needed for analysis of data for the experiment, an energy calibration of the channels had to first be completed. This was done by collecting intensity measurements on three radioactive sources of ^{60}Co, ^{22}Na, and ^{137}Cs. These sources have known energies of radiation represented by peaks in their energy spectrum. The known energies that corresponded to the channel peaks were fit to a line to form an expression that converted channel numbers to a specific energies.

The source was constantly emitting radiation at all angles, and therefore it hit the Al target at several angles. It was impossible to only view scattering from a specific angle with this experimental design, because photons scattered off the Al target could enter the PMT at angles within a range of values. For this reason, all measured Compton scattering angles were labeled as approximate. The range of angles that can be detected is a function of the width of the Al target, the distance the target is from the PMT, the diameter of the PMT, and the height at which the incident gammas hit the Al target. This gives a very complicated 3 dimensional equation for the uncertainty of the angle. During the experiment, the incident gamma rays were estimated to strike the middle width of the Al target and at a height near the height of the center of the PMT detector. The Al target's center was lined up with the center of the PMT's circular detector at a distance less than 3 cm away. By centering the Al target, the radiation source, and the PMT as much as possible, the desired angle became the highest probable angle of detection. This meant that for any given number of pulses counted per channel of the expected Compton scattering angle, the majority of those pulses were coming from scattering of the centered angle. Thus, the peak pulse heights corresponded to the energies of the centered angle.

With a channel to energy conversion equation, the intensity of radiation from the ^{137}Cs source was collected with and without the Al target in place at the angles of approximately 180^0 and 90^0. It was important to keep the preset time the same so the number of counts could be compared for equal time. Since the source is always radiating energy, the two energy spectrums looked identical except for the area represented by the energy change of the scattered photon. By looking at the differences between the energy intensities with and without the Al target present, the scattered photon energy was observed. This value was then compared to the theoretical value for that scattering angle.

ANALYSIS AND INTERPRETATION

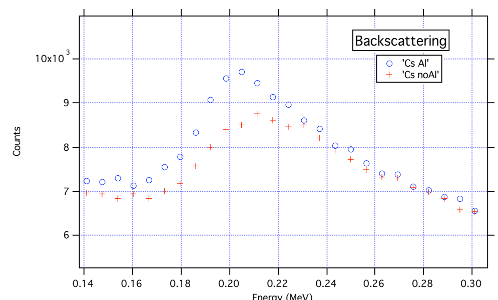

Figure 1: ^{137}Cs plot of backscattering. (180^0)

Figure 1 clearly shows a difference between measured intensities in the energy range of (0.17 –0.22) MeV. To better analyze the energy value associated with the backscattering, a plot of the number of pulse counts with the data sets of Al not present was subtracted from the number of pulse counts with the data set of Al present. If there is no scattering effect, then the count number should remain the same for each of the energies, and the change in counts will be zero. In an area where scattering has occurred, the change in counts will appear as a hump in that energy range. The center of this hump represents the energy value of the scattered photon.

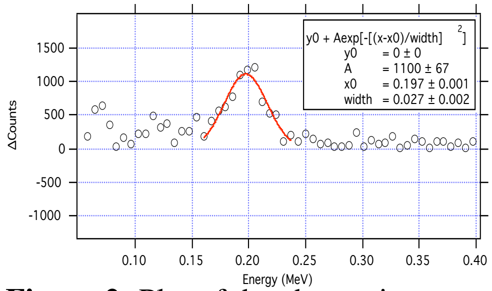

Figure 2: Plot of the change in counts versus energy for ^{137}Cs backscattering. A Gaussian fit was produced over the range of the hump associated with changing energies.

Figure 2 shows the expected hump in the region between (0.16 – 0.24) MeV. A Gaussian fit with the y-intercept held to zero was added to this region and shows that the maximum energy deviation occurs at an energy of (x0 ± width) MeV. This gives a value of (0.197 ± 0.027) MeV for the energy of the back-scattered photons, which is within experimental error of the theoretical value of 0.184MeV. The experimental value has a percent error of 7.1% from the theoretical value. Also shown in this graph is the near flatness of the change in counts for energies where no backscattering occurred.

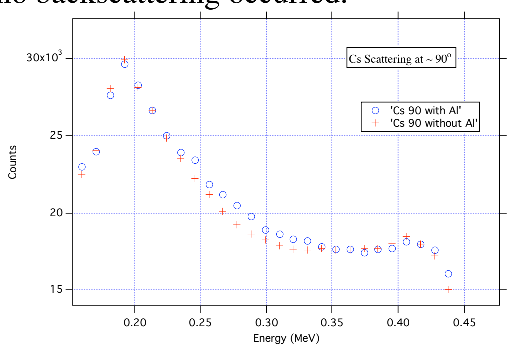

Figure 3: Expanded plot of ^{137}Cs for scattering at approximately 90^0.

Figure 3 shows an area of discrepancy in counts per energy between (0.24 – 0.34) MeV for Compton scattering at 90^0. Figure 4 is a plot of the change in count versus energy over this energy range.

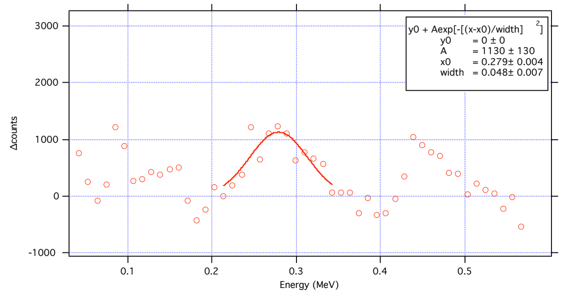

Figure 4: Plot of the change in counts versus energy for ^{137}Cs scattering at approximately 90^0. A Gaussian fit was produced over the range of the hump associated with changing counts.

Figure 4 shows the expected hump in the region between (0.21 – 0.34) MeV. The Gaussian fit over this range gives a value of (0.279 ± 0.048) MeV for the energy of the scattered photons, which is within experimental error of the theoretical value of 0.288MeV. The experimental value has a percent error of 3.1% from the theoretical value.

CONCLUSION

Compton's equations were confirmed in this experiment for a ^{137}Cs gamma source was observed at angles of approximately 180^0 and 90^0. The energy of the backscattered photons was found to be (0.197 ± 0.027) MeV, which is within experimental error of the theoretical value of 0.184MeV. The experimental value has a percent error of 7.1% from the theoretical value. The energy of the approximately 90^0 scattered photons was found to be (0.279 ± 0.048) MeV, which is within experimental error of the theoretical value of 0.288MeV. The experimental value has a percent error of 3.1% from the theoretical value.

[1]Tipler, Paul A. and Llewllyn, Ralph A. Third Edition Modern Physics, (W. H. Freeman and Company, New York, NY, 1999)p.136-149

[R]Richards, Sears, Wehr, and Zemansky. Modern College Physics,(Addison-Wesley Publishing Company, Inc., 1964) p.796-825

[3]Melissinos, Adrian C. Experiments in Modern Physics, (Academic Press,Inc. New York, NY, 1966) p.524 and 526

[4]McGraw-Hill Encyclopedia of Science and Technology Vol. 13, (McGraw-Hill Inc.,1992) p.335-437

[5]McGraw-Hill Encyclopedia of Science and Technology Vol. 16, (McGraw-Hill Inc.,1992) p.119-120

[6]Moore, Davis, and Coplan. Building Scientific Apparatus third edition , (Westview Press, 2003) p.470 and 472