The Compton Effect

Nicholas Johann Harmon

Physics Department, The College of Wooster, Wooster, Ohio 44691

May 1, 2003

In this lab the Compton Effect was verified. Backscattering data from a Cesium 137 radioactive source emitting high-energy photons were collected by a NaI scintillator and processed by a Pulse Height Analyzer (PHA). After converting the units of the PHA to units of energy, the difference in energy between the prominent intensity peak from gamma rays and the lesser intensity peak from scattered gamma rays of lesser energy. As expected from Compton's equation, the scattered gamma rays had less energy than the non-scattered gamma rays. The difference in energy was measured to be $\Delta E = 0.460\ MeV \pm 0.016\ MeV$. The theoretical value for this quantity is *0.477 MeV*. The discrepancy is *3.6%*.

INTRODUCTION

In the year 1900, Max Planck amazingly solved the riddle of the so-called 'ultra-violet catastrophe' that predicted the average energy density of the spectral distribution to be infinity.[1] The novel assumption that Planck made was to surmise that the energy of the photons was discrete in nature – not continuous as previously assumed.[1] This claim was mathematically described by Planck to be

$$E_n = nhf \tag{1}$$

where E_n is the energy, n is a non-negative integer, h is Planck's constant, and f is the frequency of the photon.[2] In 1905, Albert Einstein extended Planck's inference to include not only black body radiation but all electromagnetic waves! Therefore, Einstein hypothesized that light is quantized with energy proportional to its frequency.[3] The obvious principle to be deduced from these discoveries is that light possessed attributes of waves *and* particles!

In 1922, Arthur Holly Compton solidified Planck's assumption and therefore firmly established a new era of physics. Compton theorized and then experimentally demonstrated that electromagnetic waves had the properties of particles. Classically, x-rays would shake the electrons of a target material at the same frequency of the x-ray. Hence, the wavelength of radiation from the oscillating electrons would be identical to the wavelength of the incoming x-rays.[1] However, it was observed that x-rays were more easily absorbed by materials than waves of longer wavelength. In other words, the scattered x-rays were of longer wavelength.[4] This was contrary to the predictions of classical physics. Compton realized though, that if the interaction was modeled as a collision between two particles (electron and photon), the scattered x-rays would be of longer wavelength (compared to the incident x-rays) because the recoiling electron would acquire some of the energy and momentum of the incoming x-ray.[4] Since wavelength is inversely proportional to frequency, the frequency of the scattered x-rays was less. From eq. (1), it is seen that the energy would also be decreased. When Compton carried out this experiment in 1922 using molybdenum as his target, he verified his theory and provided even more evidence that light also possessed a massless particle nature.

THEORY

The Compton effect can be derived[4] theoretically by using the laws of conservation for energy and momentum to produce Compton's equation:

$$\lambda_2 - \lambda_1 = \frac{h}{mc}(1 - \cos\theta) \tag{2}$$

where λ_1 and λ_2 represent the initial and final wavelengths of the photons respectively, m is the mass of an electron, and θ is the angle between the photon's initial and final momentum vectors. A photon's wavelength is increased when it collides with a particle because some of the incident energy is imparted to the particle. In this lab, it is more useful to express the Compton equation in terms of energy instead of wavelength.

Also in this lab, only backscattering was investigated where $\theta = 180^{o}$ so eq. (2) becomes:

$$\Delta E = (E_1 - E_2) = E_1 \frac{2E_1}{mc^2 + 2E_1}. \qquad (3)$$

For the gamma rays used in this experiment, E_1 is equal to *0.661 MeV*.[1] The quantity mc^2 is the rest energy of an electron and is *0.511 MeV*. Entering those values into eq. (3) gives an energy change of *0.477 MeV* resulting from Compton backscattering.

The difference in energies is most noticeable when the scattering angle is 180º because of the cosine function's minimum at that angle. Compton used x-rays when he first performed this experiment because of their short wavelength. Visible light is not a good candidate to test the Compton effect because its wavelength is too large and when it is collided with a free electron, the change in wavelength is too small in proportion to the initial wavelength to be accurately measured. For this reason, in the following lab, radioactive sources that emitted gammas were used to measure the Compton effect at an angle of 180º.

EXPERIMENTAL

To measure the Compton effect, Cesium 137 was used as a radioactive source of gamma rays at an energy *0.661 MeV*. A Nucleus Bicron 37830 NaI scintillator was used to detect the high energy photons. The scintillator detects the incident photons. A photomultiplier tube converts light into and a Multichannel Pulse Height Analyzer (PHA) 800 analyzes the pulses by organizing them according to their energies into bins. A Sanyo VM 4509 monitor then displays the intensity of photons at the different current pulses which are called channel numbers. A relationship must be found to convert channel number to energy. Sodium 22 source was also used to have another accepted energy value in order to convert channel number to energy.

An aluminum rod was placed behind the radioactive source to cause backscattering. The NaI scintillator was placed directly in front of the emitting source. Lead blocks surrounding the source and scintillator had little or no effect on the quality of data. It was expected that a large peak signifying large number of photons at gamma ray energy would be seen around *0.661 MeV*. Then it was expected that a smaller peak resulting from Compton backscattering would be seen *0.477 MeV* from the gamma peak.

DATA AND ANALYSIS

First the channel numbers which are obtained from the PHA must be converted into energy by using accepted values. The known values were the gamma ray peaks for Cs 137 and Na 22 and the x-ray peak for Cs 137. The relationship is linear and is shown in Figure 1.

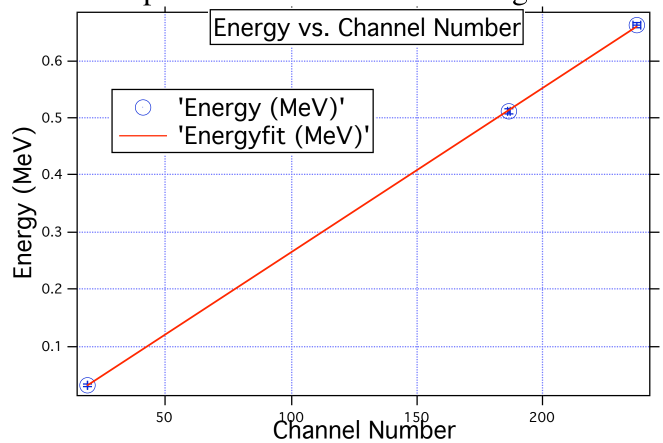

FIG. 1. Weighted fit for energy and channel number.

The line of best fit is

$$E = (0.0029 \pm 2 \times 10^{-5})(C\#) - (0.023 \pm 0.003) \quad (4)$$

where E is the energy and $C\#$ is the channel number. The four trials conducted without backscattering (no Al) and the four trials conducted with backscattering (with Al) had to be converted to energy using eq. (4).

Figure 2 shows a comparison between the averages of the four trials with backscattering and without backscattering. The Compton peak (on the left) is higher when backscattering ocurrs. However, even when no aluminum is placed behind the source, backscattering still occurs at a lesser degree from the surroundings. The error for energy and intensity was the standard deviation from the four trials. There was also an inherent error in energy from the channel number bin size. Error bars are not shown in order for the Compton peak to be seen adequately.

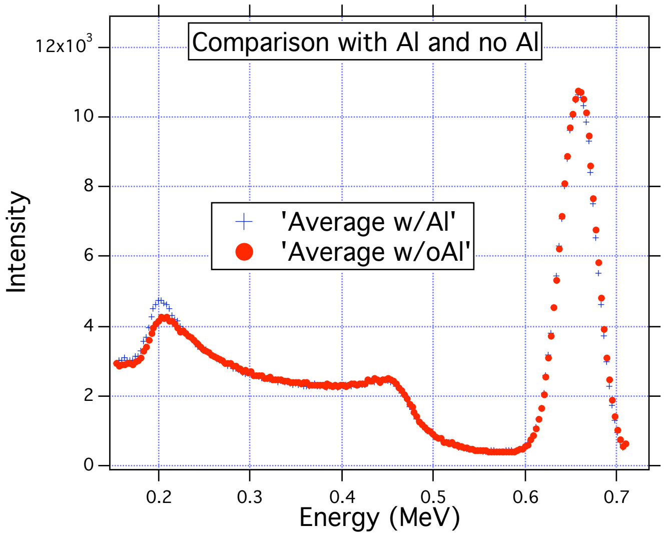

FIG. 2. Comparison between backscattering and not backscattering. The high peak on the right is the gamma peak corresponding to 0.661 MeV. The smaller peak on the left is the Compton peak. The two scenarios match well except at the Compton peak where the backscattering scenario measures more photons than when no backscatter is implemented.

Taking the difference between the two cases is shown in Figure 3. The difference between the two instances is obvious because of the positive values around *0.20 MeV*.

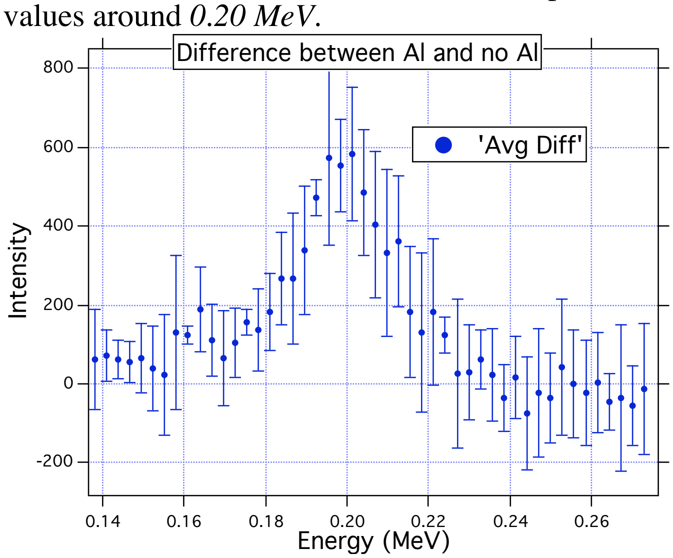

FIG. 3. The difference in the plots of Figure 2 over a restricted range of energies. The peak in the middle is from Compton scattering. The energy at which the peak occurs is estimated from this plot.

The peak of Figure 3 is estimated to be a *0.201 ± 0.016 MeV*.

RESULT AND DISCUSSION

Since the initial energy is known to be *0.661 MeV* and the final energy is measured to be *0.201 ± 0.016 MeV* for the gamma rays, the energy difference is *0.460 ± 0.016 MeV*. The theoretical value for the change in energy is *0.477* MeV, a discrepancy of *3.6 %*. The theoretical value also just barely lies beyond the upper error bound of the measured value.

By using eq. (6) and eq. (7), the energy difference can be seen in the wavelength difference. The initial wavelength is $\lambda_1 = 1.88 \times 10^{-12}\ m$ and the final wavelength is $\lambda_2 = 6.17 \times 10^{-12} \pm 4.91 \times 10^{-13}\ m$.

As expected the final energy of the photons was less than the initial energy due to the collision with the electrons of the aluminum bar. Consequently, the wavelength after the collision was longer than the incident wavelength. The longer wavelength signifies less energy.

CONCLUSION

The Compton effect was verified by observing backscattering from aluminum by a Cs 137 gamma radiation source. The energy difference of *0.460 MeV* was ascertained in the experiment with a discrepancy of only 3.6 % from the theoretical value of *0.477 MeV*. Further work should be done investigating other radioactive sources and other scattering angles. The utilization of different scattering targets would also be an interesting alteration to the existing experiment.

ACKNOWLEDGMENTS

I would like to thank Dr. Jacobs for his endless help through all of Jr. I.S. I would also like to thank Clinton Braganza for his help in this lab.

REFERENCES

[1] Paul A. Tipler and Ralph A. Llewellyn, Modern Physics, 3rd ed. (W.H. Freeman and Company, New York, 1999), p.131.

[2] Ibid. p. 132-133.

[3] Ibid. p. 138.

[4] Ohanian, Hans C., Modern Physics. (Prentice Hall, Inc., Englewood Cliffs, NJ, 1987), p. 123.

[5] R.L. Heath, Scintillation Spectrometry : Gamma-Ray Spectrum Catalogue, 2nd edition, (Phillips Petroleum Company August 1964), 55-137-1.