Experiment Note: Exploring Compton Scattering Using the Spectrum Techniques Universal Computer Spectrometer

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Objective

The objective of this experiment is to demonstrate the influence of the Compton Effect on gamma-spectrum measurements of gamma-emitting radioisotopes. This demonstration is easily conducted using a Universal Computer Spectrometer (UCS) by Spectrum Techniques (www.spectrumtechniques.com), a small scintillation probe, and safe-to-handle radioactive sources available from Spectrum Techniques. Despite its simplicity, the results of this experiment clearly show that, although massless, photons are particles that have and convey momentum.

Background

The common unit "keV" (kilo-electronvolts) used to describe a spectral line of gamma-ray emission from a radioisotope relates to the energy of the high-frequency gamma-ray photons. By definition, one electronvolt (eV) is equal to the amount of kinetic energy gained by a single electron when it accelerates through an electric potential difference of one Volt. Thus, one electron volt is equal to 1.602×10^{-19} J. The energy E of a photon is related to its wavelength λ or its frequency f through Planck's formula $E = hf = \dfrac{hc}{\lambda}$, where h=6.626×10^{-34} J·s is Planck's constant, and $c \approx 3 \times 10^{8}$ m/s is the speed of light. The wavelength of a photon in nm is thus: $\lambda[\mathrm{nm}] \approx \dfrac{1,240[\mathrm{eV \cdot nm}]}{E[\mathrm{eV}]}$. So, for example, the photons emitted by the radioisotope Cesium-137 (^{137}Cs) at 662 keV have a wavelength $\lambda = 1.87 \times 10^{-12}\,\mathrm{m}$.

One matter that often confuses students beginning to conduct experiments using a gamma spectrometer is that although discrete gamma lines are listed for a gamma-emitting radioisotope, a spectral measurement commonly shows many other features besides these expected lines. For example, ^{137}Cs is known to produce discrete lines at 30 and 662 keV.

However, as shown in Figure 1, other features and peaks are present in the gamma spectrum measured from a ^{137}Cs source, most importantly a plateau that extends to 480 keV and a peak at 180 keV.
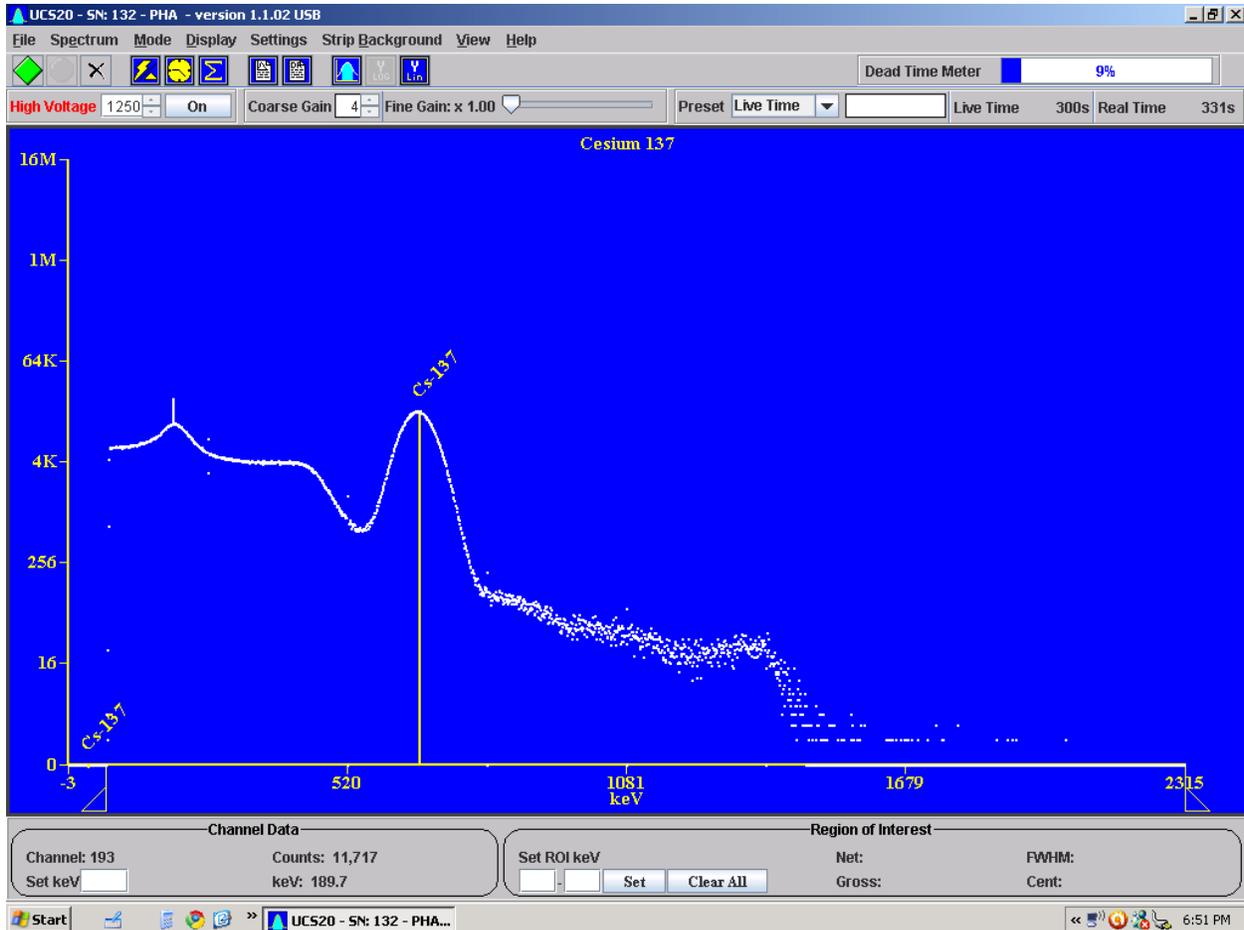

Figure 1 - Spectrum of Cesium 137 gamma-emitting radioisotope source measured using a NaI(TI) crystal scintillator and a Spectrum Techniques UCS-20 MCA. [137]Cs produces discrete lines at 662 keV and 30 keV, yet other features and peaks are present in the gamma spectrum.

To understand the origin of these experimentally-measured spectral features, we need to review an important experiment conducted by Dr. Arthur Compton at Washington University in St. Louis in 1923. In this experiment, light (in the form of gamma-rays) was made to interact with virtually free electrons. Classical Physics predicted that the electron should absorb energy from the gamma-ray, and then re-emit the gamma-ray at the same frequency. However, Compton's experiments actually showed that the gamma-ray bounces off the electron with lower energy, just as if the gamma-rays were a stream of particles (photons) colliding with the

electrons. That is, gamma-ray photons are able to transfer momentum to another particle. This new understanding about the particle-nature of light (gamma-rays in this case) won Compton the 1927 Nobel Prize in Physics.
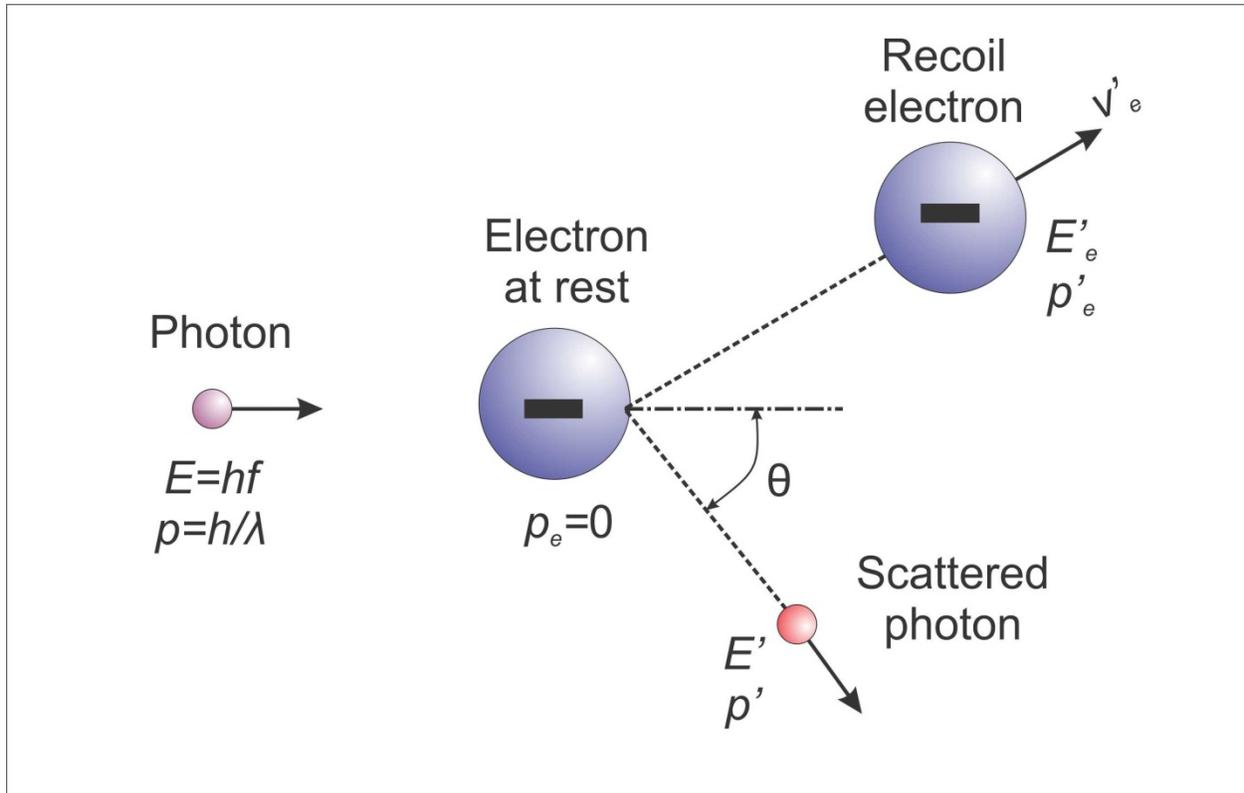

Figure 2 - Compton Effect. A photon with momentum $p_{photon} = \dfrac{E}{c} = \dfrac{hf}{c} = \dfrac{h}{\lambda}$ approaches an electron at rest. After the collision, the photon transfers momentum to the electron, which results in a proportional decrease in the photon's frequency.

Let's take a look at the geometry of Compton scattering shown in Figure 2. A photon of frequency f collides with an electron at rest. Before the collision, the energy of the photon E is given by Planck's formula $E=hf$, where $h=6.626\times10^{-34}$ J·s is Planck's constant and f is the photon's frequency. Upon collision, the photon bounces off the electron, giving up some of its energy, while the electron gains momentum. But the photon cannot lower its velocity (the speed of light c), so instead the loss of energy by the photon shows up as a decrease in the photon's frequency f (or, conversely by an increase in its wavelength λ) since $E=hf$.

As we can see, the photon loses some energy after the collision, bouncing off at an angle θ with a new energy E' and momentum p', which translate into a decrease in frequency to f'. Of course, the initial photon's wavelength is λ, and its wavelength after the collision is λ'.

The photon's momentum is:

$$p_{\text{photon}} = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda}$$

So if the change in the photon's wavelength is $\Delta\lambda = \lambda' - \lambda$, the electron (that has a mass $m_e = 9.1 \times 10^{-31}$ kg) gains the momentum lost by the photon:

$$\Delta\lambda = \lambda' - \lambda = \frac{h}{m_e c}\left(1 - \cos(\theta)\right)$$

The maximum change in wavelength for the photon happens when it transfers as much momentum as possible to the electron. That is, when $\cos(\theta) = -1$. The maximum change in wavelength is thus:

$$\Delta\lambda = \frac{h}{m_e c}\left(1 - (-1)\right) = \frac{2h}{m_e c} = \frac{2 \times (6.626 \times 10^{-34}[\text{J} \cdot \text{s}])}{9.1 \times 10^{-31}\ [\text{kg}]\ \times\ 3 \times 10^{8}[\text{m}/\text{s}]} = 4.86 \times 10^{-12}\,\text{m}$$

Even this maximum shift in wavelength would be insignificant for visible light with $\lambda \approx 10^{-7}\text{m}$, but not for gamma-rays with $\lambda < 10^{-10}\text{m}$ (4.1×10^{-11} m and 1.87×10^{-12} m for ^{137}Cs). Please note that this is the maximum change, which doesn't mean that all the photons will recoil at 180° (to give $\cos(\theta) = -1$). In fact, most of the photons will bounce at much smaller values of θ.

The mysterious peak at 180 keV is thus the result of 662keV photons that are Compton-scattered by free electrons in the source's vicinity and in the detector crystal.

Experiment

Setting up the experiment is straightforward. As shown in Figure 3, couple a photomultiplier (PMT) to a small NaI(Tl) scintillation crystal (e.g. 1" diameter by 1" long). Power the PMT probe from the highly stable, low-noise, high-voltage power supply within the Spectrum Techniques Universal Computer Spectrometer. Feed the PMT probe's output directly to the UCS' "Preamp

In" connector. Run the Spectrum Techniques MCA software on a PC to display the pulse-height spectra collected by the UCS.
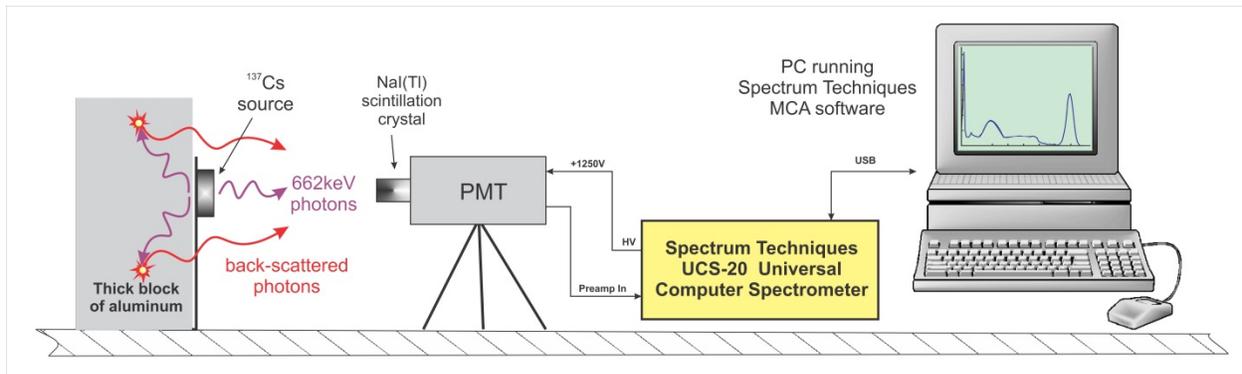
After calibrating the instrument according to Spectrum Techniques' instructions, place the scintillation probe and ^{137}Cs source facing each other at some distance above the work surface and away from any solid objects as shown in Figure 4-a. You should place the source far enough away from the detector so that the multichannel analyzer yields a clean spectrum. You should be able to see the 662 keV line produced by the ^{137}Cs source, as well as the "Compton Plateau," which is produced by Compton scattering of gamma rays within the NaI(Tl) scintillation crystal. Note that when the scattered gamma photon escapes from the crystal, only the energy deposited on the recoiling electron is detected. The upper edge of the plateau (the "Compton Edge") results from the most inelastic collisions – that is, those where the photon is scattered by 180°. You can use the equations that we saw before for explaining the Compton Effect and calculate the energy at the Compton Edge from:

$$\frac{1}{E'} - \frac{1}{E} = \frac{(1 - \cos(180°))}{m_e c^2} = \frac{2}{m_e c^2}$$

where E is the energy of the original gamma photon (662 keV for ^{137}Cs), and E' is the energy of the back-scattered photon. The Compton edge thus sits at $E_e = E - E'$.
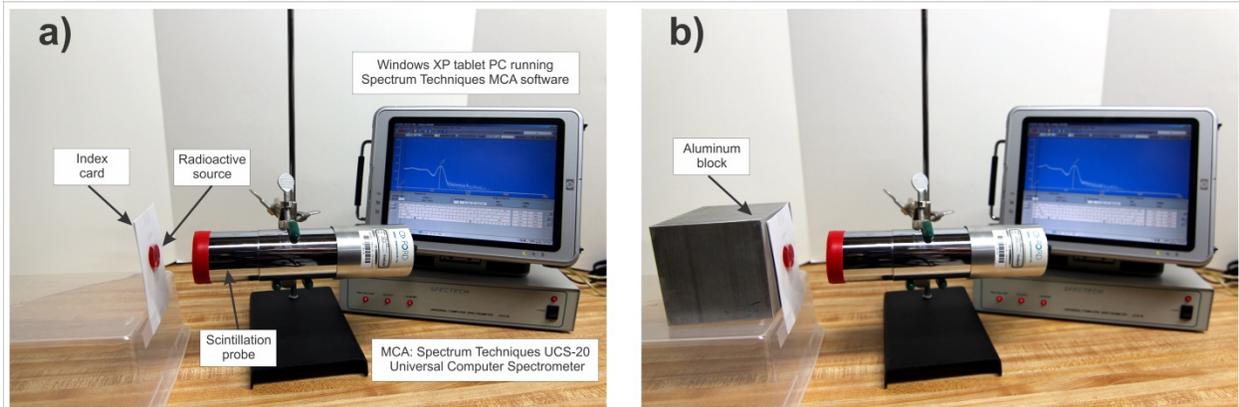

Figure 4 - The scintillation probe and ^{137}Cs source should face each other at some distance over the work surface, and away from any solid objects. a) You should be able to see the 662keV line produced by the ^{137}Cs source, as well as the "Compton plateau," which is produced by Compton scattering of gamma rays within the NaI(Tl) scintillation crystal. b) Adding a thick aluminum block behind the source enhances the effect by providing more free electrons to cause Compton Scattering of the 662keV photons.

Although that in itself is a demonstration of the Compton Effect, it is much more dramatic to place a thick aluminum block (e.g. 3" thick) behind the source as shown in Figure 4-b. This will cause a large number of photons with energy E' to be back-scattered by electrons in the aluminum block. You can thus verify the Compton Effect by comparing the location of the Compton peak (E') and Compton edge (E_e) in relationship to the 662 keV ^{137}Cs line. You should see the Compton edge E_e at around 480 keV, and the backscattered peak E' at around 180 keV as shown in Figure 5. This may be repeated with other gamma emitters such as Spectrum Techniques' [60]Co, [57]Co, and [133]Ba exempt sources. In addition, the 511 keV gamma-rays produced by positron/electron annihilation when using positron-emitting sources such as [22]Na are also appropriate to observe Compton Scattering.
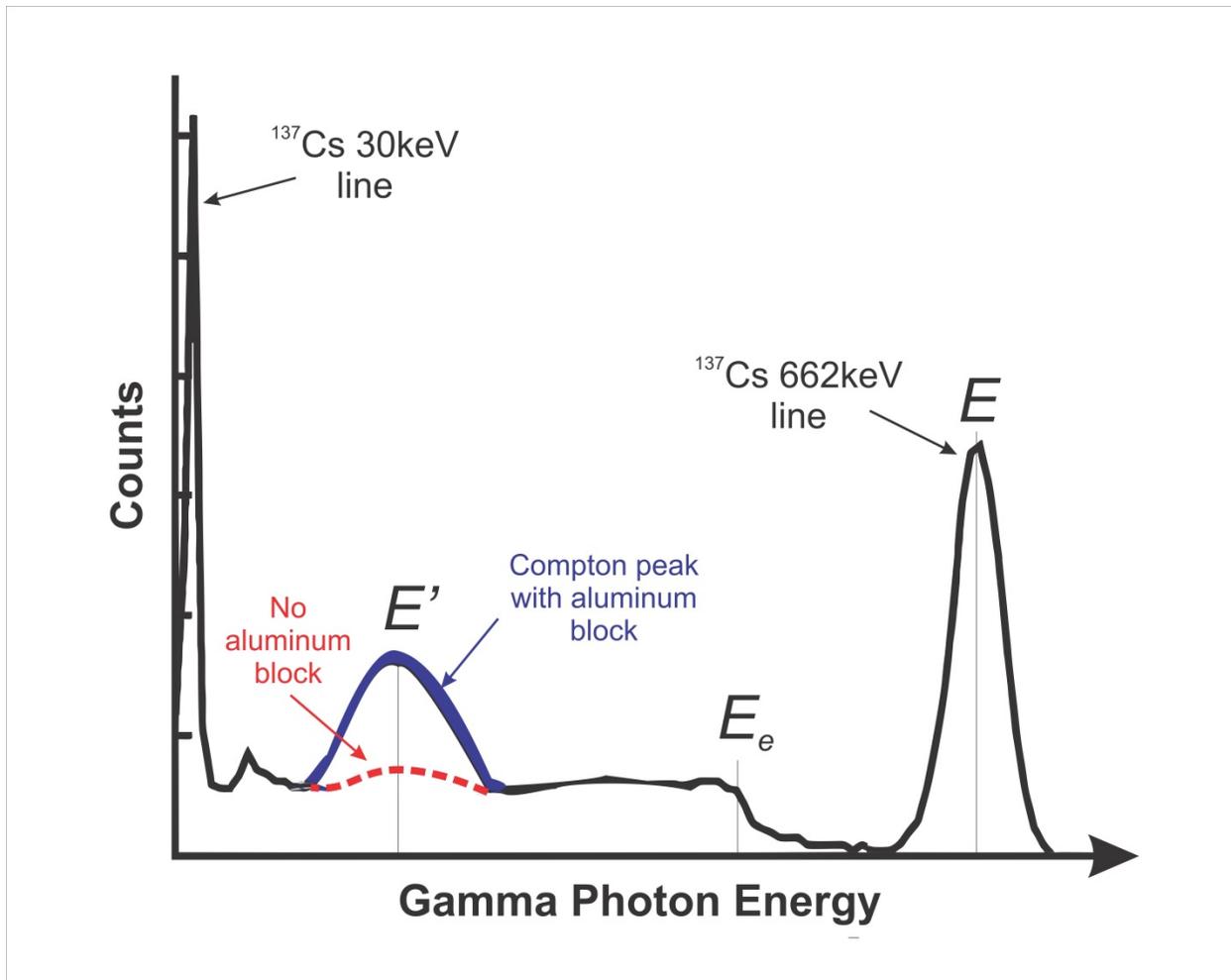
Figure 5 – Placing a thick aluminum block behind the gamma-ray source provides many free electrons from which the photons can recoil, as evidenced by an increase in the amplitude of the Compton peak.

Results and Discussion

Table 1 shows sample Compton Scattering measurements obtained from spectra measured with the Spectrum Techniques Universal Computer Spectrometer. The calibration was performed using only two points, and values for E, E', as well as the Compton edge were obtained by visual approximation, which probably account for the variation from the predicted values. This was done on purpose to encourage students to perform a three-point calibration, as well as to use the peak-finding feature of the Spectrum Techniques MCA software.

Source	Expected E (keV)	Predicted E' (keV)	Predicted Compton Edge (keV)	Measured E (keV)	Measured E' (keV)	Measured Compton Edge (keV)
Cs-137	662	180	482	659	185	469
Co-60	1,170	204	966	1,166	209	965
	1,330	208	1,122	1,266	209	965
Na-22	511	167	344	503	170	333
Ba-133	356	146	210	343	147	213

Table 1 – Predicted and measured values for Compton Scattering of gamma photons from various radioisotopes.

Conclusions

Although the origin of spectral features in the gamma spectrum of a pure radioisotope is a common source of confusion among beginner physics students, its explanation is simple and touches on one of the most important ideas about the nature of light.

This experiment directly demonstrates the transfer of momentum by photons as described by Compton. It also teaches students about important practical factors affecting gamma-ray spectrum analysis using scintillation probes and MCAs.

Acknowledgements

We are grateful to Spectrum Techniques and to George Dowell for lending us equipment to conduct the experiments described in this tutorial.

Further Reading and Experiments

For a more detailed discussion on the demonstration of the Compton Effect, as well as for additional experiments in Modern and Quantum Physics, see our book:

D. Prutchi and S.R. Prutchi, *Exploring Quantum Physics Through Hands-On Projects*, J. Wiley and Sons, 2012.

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