How do different Gamma-Ray Interactions within a Gamma-Ray Detector affect the uncertainty on the Spectrum of a Source?

U1810833, 79.

In this experiment a Sodium Iodide Scintillator was used in tandem to a Multi Channel Analyser to determine which processes dictate the uncertainty of a Gamma-ray spectrum the most; using three sources of Caesium-137, Barium-133 and Sodium-22. It was found that different mechanisms impacted the spectra under different circumstances and that there is not one underlying process that will always impact the spectrum the most.

1 Introduction

Gamma-ray spectroscopy is a very useful part of modern day physics, for instance astrophysicists use it to analyse gamma rays from distant systems. The importance of a precise and accurate spectrum for uses such as this is hugely important in validating the discoveries of the forefronts of physics.

One of the ways in which a gamma-ray spectrum can be made more uncertain is the Compton scattering of the gamma photons within the crystal. Compton scattering is when a photon collides with an electron, transferring part of its energy and scattering itself over an angle (θ). The resultant energy from the scattered photon is given by the following equation[1]:

$$hv' = \frac{hv}{1 + (\frac{hv}{m_0 c^2})(1 - cos\theta)} \qquad (1)$$

Where h is Planck's constant, c is the speed of light in a vacuum, v is the speed of the photon and m_0 is the rest mass of an electron. This process can cause these photons of less energy to be picked up by the Multi Channel Analyser (MCA), leading to a wide, low energy peak called a backscatter peak. However, Compton scattering can cause photons to scatter from 0 to π radians; this means that there will be a 'Compton Continuum' that spans a large

section of the spectrum caused by the scattered photons. The edge of this continuum is called the Compton edge, and represents where the photons start to scatter through an angle higher than π radians and thus will go undetected[1, 2].

Another mechanism that impacts the uncertainty, and also the accuracy, of a spectrum is pair production: This is when a gamma photon has an energy at least twice as much of the rest mass of an electron (1.022 MeV) which causes the production of an electron-positron pair in the intense electric field near the protons in the nuclei of the sodium iodide crystal. If the positron slows down enough, so that its kinetic energy is similar to that of the electrons in the crystal, it will annihilate with one of these electrons and produce a pair of photons. If one of these photons escapes the crystal without any interaction, this will create a single escape peak at an energy of 0.511 MeV below the photopeak expected for the original photon. A double escape peak (another 0.511 MeV below the single escape peak) will be produced if both annihilation photons escape without interaction. In cases where the gamma-ray energy is substantial, the single and double escape peaks can be higher than the initial photopeak[1]. This is not usually a problem if the source you are using produces gamma photons of a low enough energy, however; if this is not the case then the escape peaks can interfere with actual photopeaks from the source. Not only can this decrease the precision of measuring this peak, but it can also skew this accuracy if the escape peak is close enough to the photopeak.

The position of such photopeak is dictated by the photoelectric effect. This mechanism is arguably the most important process within gamma-ray spectroscopy since it will create most of the photopeaks. The main, high energy photopeak is created by the absorption of a gamma-ray into the scintillator crystal, this causes a photoelectron to be emitted with an energy according to the following equation[1]:

$$E_{e-} = hv - E_b \tag{2}$$

Where E_{e-} is the energy of the photoelectron, hv is the energy of the gamma photon and E_b is the binding energy of the scintillator material. Since there is now a vacancy in the electron shell due to the photoelectron emission, electrons from higher binding energy states will 'drop down' into this vacant shell and emit a characteristic x-ray in the process. This x-ray will most likely absorb into another loosely bound electron, causing another photoelectron emission meaning that this whole process leads to 2 photoelectron emissions; one of high energy in accordance to the initial gamma-ray, and one of lower energy from the secondary x-ray.

My aims for this experiment are to investigate how these mechanisms that are undergone within the detector impact a spectrum and by how much. I am also looking to see if there are any other mechanism that do not necessarily happen within the detector from which a spectrum will be made more uncertain.

2 Materials and Methods

To obtain the relevant data for this experiment I have used a combination of non-standard equipment. 3 gamma sources were used, each directed into a Sodium Iodide scintillator crystal which will absorb the gamma photons through the photoelectric effect. These absorbed photons will convert into visible photons by exciting electrons in the deliberate Thallium impurities in the crystal, these photons are then incident on the photocathode of a photomultiplier tube causing photoelectrons to accelerate towards the anode. These electrons are now multiplied and collected, with the total charge being proportional to the initial photon energy. From this, the Multi Channel Analyser (MCA) will receive the pulse of electrons and convert this into a digital count which is inputted into a form of multichannel pulse height analysing software where the spectrum will be shown. Each spectrum was measured for 6 minutes, however this number can be altered.

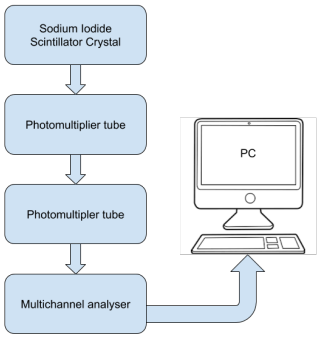

Figure 1: Block diagram illustrating the detector equipment.

Software of this kind will sometimes output a voltage instead of an energy and will require calibration. This can be done using 2 sources with distinct peaks and known values for these peaks: By obtaining a spectrum for each source you will have 2 voltage values of known energies and will then be able to translate between the two.

In this experiment, errors of different peaks on a spectrum were determined by fitting the 'curve' in a form of graphing software and obtaining the standard deviation. This was used for the error[3].

3 Experimental Results

4 Discussion

4.1 Figure 2

In Fig.2 there is one distinct photopeak that is caused by the photoelectric effect, peak 2.4. The accepted value for this photopeak is 662 keV[4] which is within one

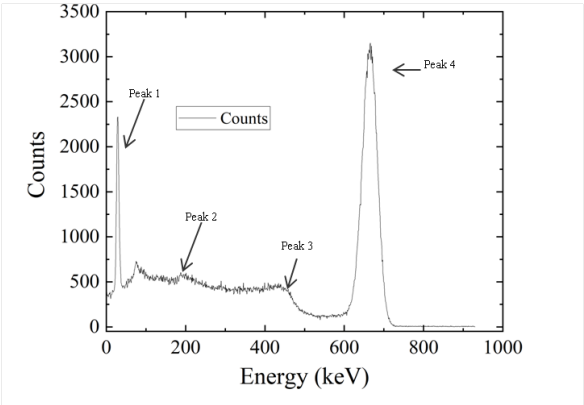

Figure 2: Caesium-137 Spectrum.
Peak 2.1 = 30 ± 1 keV
Peak 2.2 = 186 ± 4 keV
Peak 2.3 = 465 ± 18 keV
Peak 2.4 = 680 ± 30 keV

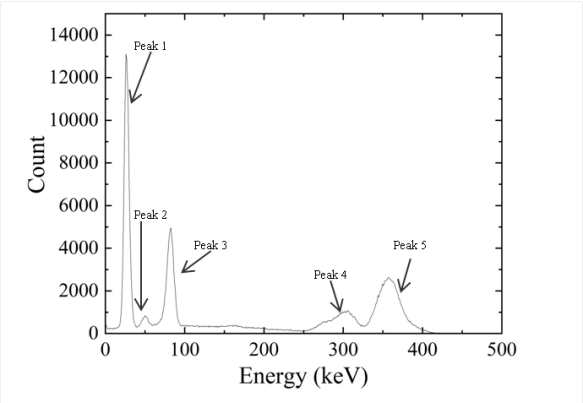

Figure 3: Barium-133 Spectrum.
Peak 3.1 = 27 ± 6 keV
Peak 3.2 = 50 ± 7 keV
Peak 3.3 = 80 ± 10 keV
Peak 3.4 = 300 ± 40 keV
Peak 3.5 = 360 ± 30 keV

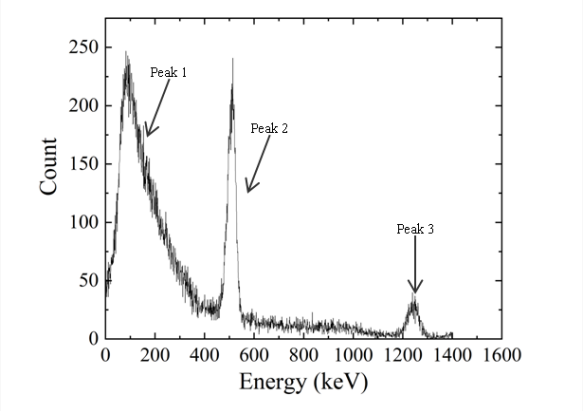

Figure 4: Sodium-22 Spectrum.
Peak 4.1 = 110 ± 110 keV
Peak 4.2 = 510 ± 30 keV
Peak 4.3 = 1240 ± 50 keV

standard error of my experimental value, and thus my value is in strong agreement with it. All of the other peaks are from other processes: Peak 2.1 is a result of the daughter nuclei of Caesium-137 (Barium-137) releasing a gamma photon. Peak 2.2 is the backscatter peak and peak 2.3 is the Compton edge; both of these are a result of Compton scattering.

As you can see none of the first three peaks seem to influence the uncertainty or accuracy of the final, main photopeak. This suggests that there is another source of error in the main photopeak. Even though it is well defined, it's error is still substantial. The source of error is unlikely to be due to the digital nature of the MCA, which leads to the thought that the high energy of the photopeak is the source of the error. If this is to be true, then the detector must be less efficient at higher energies[5]. The reason behind this is that there is a slight non-linear relationship between the output of the scintillator into the MCA and the energy of the gamma photon, if this was completely linear an almost impossibly steep photopeak would form instead of peak 2.4. The reason behind this slight non-linearity is that when the gamma rays are fully absorbed, there are many varied combinations of secondary photoelectrons that will increase the error (width) in the fi-

nal photopeak, without necessarily impacting the final accuracy of the result. Not only this, but the scintillator has a more varied response to higher energy electrons which adds to the argument that these two ideas are the driving factors behind the error in the main photopeak[1].

4.2 Figure 3

In Fig.3, peak 3.1 is a result of the K electron transition. Peaks 3.2, 3.3, 3.4 and 3.5 are all photopeaks; however 3.4 and 3.5 are, individually, two photopeaks merged into one due to the proximity of such peaks meaning that there are actually 4 photopeaks within the two peaks. Each of the peaks in this Figure are in strong agreement (one standard error) of the given values for each. The accepted values are as follows[4]: Peak 3.1 is 30 keV, Peak 3.2 is 52 keV, peak 3.3 is 80keV, peak 3.4 is a combination of 276 keV and 303keV with 3.5 being a combination of 356 keV and 384 keV.

The only perceived inaccuracies in this figure is that the higher energy peaks seem to have less counts than expected. This could be similar to the reasons why the main photopeak on Fig.2 had a higher uncertainty, however it could be to do with the source itself. The Caesium-137 source had a half life of 30.17 years, whilst the Barium-133 source has a half life of 8-10 years[6]. This means that, in a 30 year period, the Caesium's activity will decrease by a half; whilst the Barium's activity will decrease by, at least, 8 times. This leads to thought that the activity of the Barium has fallen considerably, leading to a low count rate and less accurate photopeaks for the higher energy photons. This, coupled with the idea that higher energy photopeaks inherently have a higher uncertainty for this apparatus, all adds to the less defined higher energy peaks for this figure.

4.3 Figure 4

In Fig.4 the peak 4.1 is a result of the daughter nuclei of Sodium-22 decaying (as with peak 2.1), peak 4.2 is the first photopeak and is in strong agreement with the accepted value of 511 keV (since it is within one standard error). Peak 4.3 is another photopeak and is also in strong agreement with its accepted value of 1275 keV[4].

Initially, it looks as though peak 4.1 is much larger than it should be, however when you look at the scale it is the second two peaks which are much lower than expected. Each of the spectra were taken over the same period of time (6 minutes) and this figure showed activity around 250 counts compared to many thousands of counts for the other sources. Again, the reason for this lack of activity is likely to be the source. Sodium-22 has a half life of 2.60 years[6] which strongly suggests that this

source has gone through many half life's causing its activity to decrease significantly. This has lead to the higher energy peak to be less defined, thus leading to a higher error in this measurement.

5 conclusion

From all of these figures, it is clear to see that there is a plethora of potential factors that will impact the uncertainty of a gamma-ray spectrum. Not all of these are interactions within the detector, as I alluded to previously: The properties of the source (such as the half life) can be just as important a factor when analysing the causes of the errors.

In terms of the mere processes going on within tho detector however, the Compton effect had a very minimal impact on the uncertainty of the main photopeak for Fig.2; whilst the photopeaks through which the photons interacted with the scintillator to produce the main photopeaks, the photoelectric effect, had the most impact because of the nature of the randomness of this process.

All in all, the processes that dictate the uncertainty of a spectrum will vary from source to source, with many processes involved that will only affect the spectrum circumstantially.

References

[1] G. F. Knoll, *Radiation Detection and Measurement* (Wiley, 1979).

[2] P. Cooper, *Introduction to Nuclear Radiation Detectors* (Cambridge, 1986).

[3] I. G. Hughes and T. P. Hase, *Measurements and their Uncertainties* (Oxford, 2010).

[4] D. Poole, X-ray absorption edges, characteristic x-ray lines and fluorescence yields, Kaye and Laby, http://www.kayelaby.npl.co.uk.

[5] I. Akkurt, K. Gunoglu, and S. Arda*Detection efficiency of NaI (Tl) detector in 511-1332 keV energy range* Vol. 2014 (Hindawi, 2014), Science and Technology of Nuclear Installations.

[6] D. Parker, Radioactive sources, Kaye and Laby, http://www.kayelaby.npl.co.uk.