Properties of Gamma radiation

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This experiment was performed in collaboration with Hannah Riley

Abstract

The aims of this experiment were to use a NaI(Tl) scintillation detector to find the strength of a source and to investigate the attenuation of gamma rays through various materials. The strength of the ^{22}Na source was found to be 194 ± 9 kBq and the attenuation coefficients for aluminium and steel at both 511 and 1275 keV were found to be 0.978 ± 0.097, 0.068 ± 0.004 and 0.097 ± 0.001, 0.065 ± 0.003 g/cm ^{2} respectively.

1. Introduction

Gamma rays are a form of radiation expelled by an atom during radioactive decay. Radiation has many applications in various fields such as medical imaging, sterilization of food and medical instruments and even measuring the thicknesses of materials such as paper [1]. Exposure to radiation is harmful as it can cause burns and lead to long term conditions such as cancer [2]. Therefore, it is important to understand the interaction between gamma rays and matter so that precautions can be taken to ensure safety.

Scintillation counting was one of the first methods of gamma ray detection and they are still used to this day. Scintillation detectors are often used due to the fact that they are cheaper and easier to maintain than other detectors such as semiconductors. While they do not have a high energy resolution they have a high counting efficiency which is desirable for this experiment [3].

In this experiment a scintillation detector was used to investigate the strength of a ^{22}Na source and the attenuation of the gamma rays through aluminium and steel.

2. Theory

2.1. Detecting gamma rays

Gamma rays mainly interact with matter through the photoelectric effect, Compton scattering and pair production. The photoelectric effect occurs when an atomic electron fully absorbs a photon and is released from an atom. During Compton scattering a photon is scattered off an atomic electron so a photon with less energy and a scattered electron are the result of this interaction, both are emitted at an angle to the initial photon such that momentum is conserved. The energy of the scattered photon is given by

$$E'_\gamma = \frac{E_\gamma}{1 + (\frac{E_\gamma}{mc^2})(1 - cos\theta)}, \tag{1}$$

where E_γ is the energy of the original photon, E'_γ is the energy of the scattered photon, θ is the angle at which the photon is scattered and m and c are the electron rest mass and the speed of light respectively. Pair production is when a high energy gamma ray spontaneously produces a particle and an antiparticle. Pair production will be ignored in this report as the gamma rays used do not have sufficient energy to undergo pair production [4].

The NaI(Ti) detector used in this experiment detects gamma rays through scintillation. Incident gamma rays interact with the electrons in the crystal through Compton scattering which excite electrons which then emit light close to the visible part of the spectrum as they transition back into lower energy levels and are said to 'fluoresce'. The number of photons is proportional to the initial energy of the photon [3].

These photons are then converted to a digital signal by a PMT (photomultiplier) tube where a photocathode emits an electron for each incident photon. These electrons then pass through a focusing electrode and a series of dynodes which amplify the signal by emitting a number of

secondary electrons when an electron strikes the surface. This current is then detected by an anode. This signal is then digitally analysed [5].

There are three measurements of the time associated with the detector: the real time, the live time and the dead time. The live time is the time which the detector is available to process the pulses produced by the detector. The dead time is the minimum time in which the detector can detect two separate events or the time where the detector can not process information. Any information arriving during the dead time will be lost. The main contribution to the dead time is due to the electronics in the PMT. The real time, which is the sum of the dead time and the real time, is the total time which the detector is running [3].

2.2. Source strength

The activity of a radioactive source, A is defined to be the rate at which a source decays. The activity of a source is given by,

$$A = A_0 e^{-\lambda t}, \tag{2}$$

where A_0 is the activity at a known time, $\lambda = \frac{ln(2)}{t_{1/2}}$ is the decay constant, $t_{1/2}$ is the half life of the source and t is the time between the time that the activity was known and the current time.

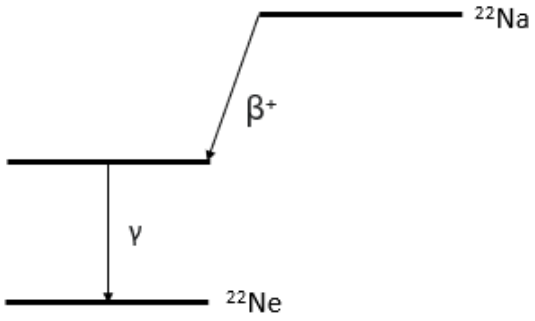

Figure 1: Decay scheme of ^{22}Na. ^{22}Na decays by emitting a positron forming ^{22}Ne which then emits a gamma ray to expel excess energy.

As seen in Figure 1, ^{22}Na decays via β^+ decay. This will almost immediately annihilate and produce two gamma rays at an energy 511.0 keV (the rest mass of an electron) which will travel in opposite directions. The ^{22}Na atom has then become an ^{22}Ne atom which emits another gamma ray at 1274.5 keV [5].

The detector will only measure a fraction of the decay events due to the direction in which the gamma ray is emitted and the efficiency of the detector (as some gamma rays will simply pass through without detection). From this it is clear to see that the counts expected for the ^{22}Na source is given by,

$$R_{1274.5} = S\Omega\varepsilon(1275) \tag{3}$$

$$R_{511.0} = 2S\Omega\varepsilon(511) \tag{4}$$

$$R_{sum} = 2S\Omega^2\varepsilon(511)\varepsilon(1275), \tag{5}$$

where R is the counts per second, S is the source strength or activity, Ω is the solid angle and ε is the efficiency at a specific energy. Note that for the gamma rays at 511.0 keV the efficiency must be doubled as two gamma rays are emitted and therefore the detector is twice as likely to detect an gamma ray at 511.0 keV than 1274.5 keV [3].

Using Equations 3, 4 and 5, the efficiency and solid angle can be eliminated from the equation such that the source strength is given by,

$$S = \frac{R_{511} R_{1275}}{R_{sum}}. \tag{6}$$

The solid angle is the angle made by the detector and the source. When the distance between the source and the detector is much larger than the angle the solid angle can be approximated by

$$\Omega \simeq \frac{\pi a^2}{d^2} \tag{7}$$

where a is the radius of the detector and d is the distance between the source and the detector [3].

2.3. Attenuation

When a beam of gamma rays passes through a material they can be attenuated via photoelectric absorption, Compton scattered away from the detector or undergo pair production. This is quantified by the total linear attenuation coefficient, μ which is the probability per unit length of a photon being attenuated [4].

The intensity of a beam of gamma rays of a given energy can be calculated using

$$I = I_0 e^{-\mu x} \tag{8}$$

where I is the intensity after attenuation, I_0 is the intensity before attenuation, μ is the attenuation coefficient and x is the thickness of the material [4] [5].

3. Experimental method

The detector consists of a thallium activated sodium iodide (NaI(Ti)) crystal, a PMT tube, an amplifier and multichannel analyser (see Figure 2). A gamma photon is incident on the scintillation crystal and excites electrons which emit light at a lower energy as they transition into lower energy levels. The light is then converted into a digital signal by the PMT, amplified then analysed by a multichannal analyser.

To measure the source strength of ^{22}Na the source was placed on the source plate and left for an hour while the spectra was being taken. The counts and the live time were given by the software used to analyse the spectra. The count rate was calculated by dividing the counts by the live time. A theoretical value was calculated using Equation 2 and an activity previously measured for the source.

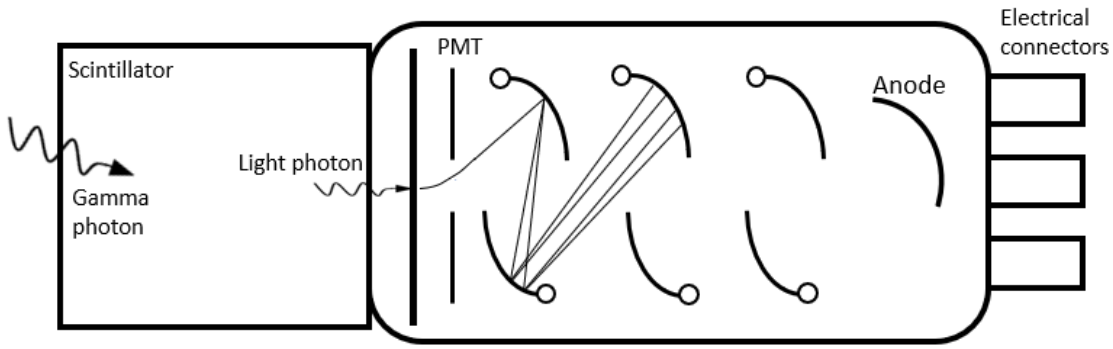

Figure 2: A schematic diagram of the detector consisting of a NaL(Ti) scintillation crystal and a photo-multiplier tube. The amplifier and multichannel analyser are not shown.

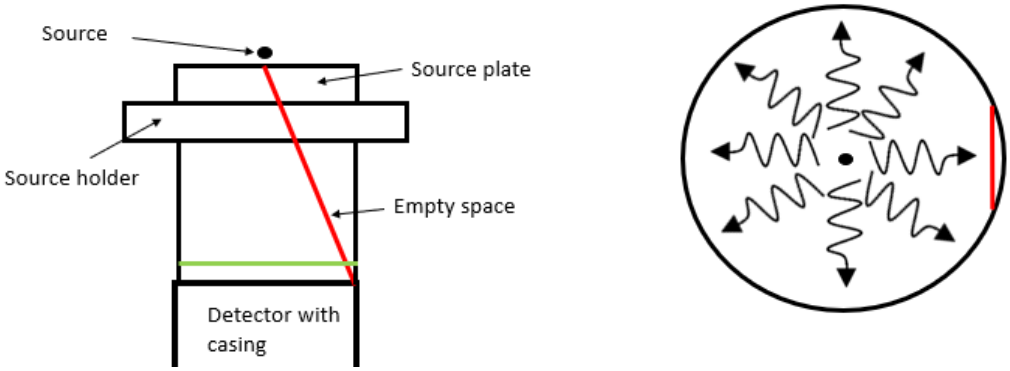

Figure 3: The experimental set up showing the source held above the detector. The red line shows the distance taken to be the distance between the source and the detector and the green line shows the distance taken to be the radius (left). A diagram demonstrating that the detector only detects a fraction of the emitted gamma rays. The black circle shows the area which the radiation covers and the red line shows the area that the detector covers (right).

The solid angle was found using Equation 7. The dimensions (see Figure 3) were measured with a ruler with a precision of 1 mm. The distance between the detector and the source was taken to be the sum of the distance between the surface of the detector to the source holder, the thicknesses of the source holder and the thickness of the source plate. The distance between the detector and the source was considered to be much larger than the radius of the detector and the area that the detector covers was approximated as a circle rather than the section of the surface area of a sphere. The mean free path of the photons inside the detector was also considered to be negligible.

The attenuation coefficients for aluminium and steel were invested by placing plates of the attenuating material between the source and the detector and measuring the count rate for a fixed time which remained constant for all the measurements. Attenuating the gamma rays will broaden the peak so the largest thickness of material was measured first so the regions of interest on Maestro (the software used to analyse the spectra) could be chosen to include the whole peak and then be kept constant for the rest of the measurements. The distance to

the source and the detector was also kept constant by inserting the plates into the empty space shown in Figure 3. The plates were measured using vernier calipers with a precision of 0.1 mm and averaged across all the plates. The live time of the measurement was kept constant by entering the time into Maestro so that data would stop being recorded after the specified time. The plates were removed one by one to decrease the thickness. A spectrum was also taken with no attenuating material.

4. Results and analysis

4.1. Source strength

The source strength was measured to be 194 ± 9 kBq which is consistent with the theoretical value of 198 kBq. The error was propagated from the error in the counts as the error in the live time is negligible. The error in the counts was obtained by taking the square root of the counts as the detection is a Poisson process.

From this, the solid angle was calculated using the measured value for the source strength resulting in $\Omega = 5.0 \pm 0.2$ %. The error in the solid angle was propagated from the error in each of the measurements.

The relative efficiency for each energy was also calculated by substituting back into Equations 3 and 4. The relative efficiencies were found to be $\varepsilon(511) = 0.168 \pm 0.007$ and $\varepsilon(1275) = 0.0576 \pm 0.003$. The errors in the efficiencies were taken to come from the errors in the source strength, the counts and the solid angle.

4.2. Attenuation

To find the attenuation coefficient, Equation 8 is rearranged to plot $ln(\frac{I}{I_0}) = -\mu x$ so that the graph of $ln\frac{I}{I_0}$ against x should be a straight line through the origin with gradient $-\mu$ (see Figure 4) . The results can be seen in Table 1. Steel was considered to act as a soft iron in order to be able to compare the measured attenuation to an accepted value.

It is difficult to compare the values for the attenuation as the values were not found for the exact energies measured in this experiment. So the trend of attenuation against energy was plotted in the region of energies with the measured values (see Figure 5).

5. Discussion

It is worth noting that scintillation detectors have a worse energy resolution than other detectors [5] and therefore have a large error in the energy. However, this does not affect the results in

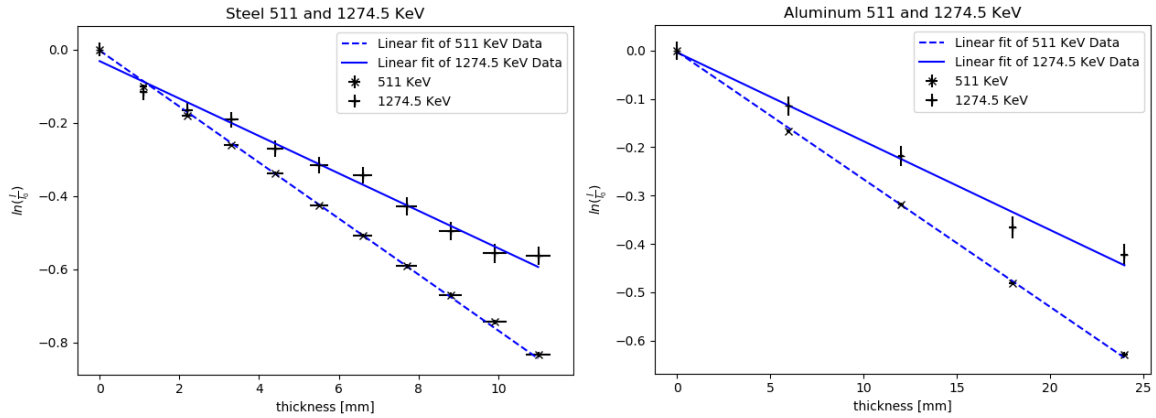

Figure 4: Linear fits of the attenuation for a specific energy from a ^{22}Na source for steel and aluminium.

Gamma ray [keV]	Measured attenuation [cm/g ^{2}]	χ^2_{red}	Comparable value [cm/g ^{2}]
Al 511	0.9778 ± 0.097	1.12	0.08445
Al 1275	0.068 ± 0.004	0.96	0.05496
Steel 511	0.097 ± 0.001	0.53	0.08414
Steel 1275	0.065 ± 0.003	0.92	0.05350

Table 1: Results for the attenuation coefficients for aluminium (Al) and steel at both 511 keV and 1275 keV. The Comparable values are taken at 500 keV and 1250 keV. The values for steel are being compared to iron (Fe) [6].

this experiment as the energy of the detected gamma rays was not used for any part of this experiment.

5.1 Source strength

The error in the counts was taken to be the statistical error due to the Poisson nature of the curve. However, Maestro removes the background counts by fitting a linear fit to the fist and last three channels and subtracting the counts under the line. However, the background should fall with the efficiency of the detector which is not linear. So the background is systematically overestimated meaning that the net counts is systematically underestimated in all of the measurements. Therefore the source strength has a systematic error associated with it which is not included in the error presented though it should not have a significant effect on the size of the error.

The error given on the solid angle is due to the random errors from the measurements of the dimensions of the detector. This is not representative of the actual error. There is a systematic overestimation in the radius of the detector as the diameter was measured while the detector was in an insulating casing. There is also an error associated with all of the assumptions made. Mainly it was assumed that the distance between the source and the detector was much larger than the radius of the detector though they were found to be comparable values. This means that approximating the area of the detector as flat circle may no longer be a valid approximation. Also, the source-detector distance was underestimated as the exact position of the source and mean free path were ignored, but this error can be considered negligible compared to other

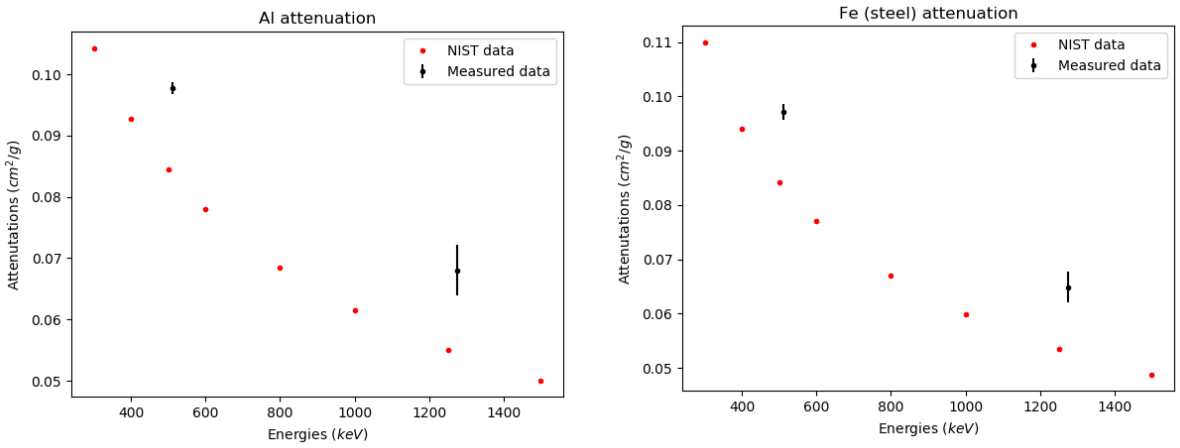

Figure 5: Graph of the accepted attenuation coefficients for different materials (red) and the measured attenuation coefficients (black). Note that error bars have been plotted on all the measured (black) points though they are not always visible on this scale.

errors as it only acts as a small correction to the source-detector distance.

The error given for the efficiency is also not representative of the actual uncertainty as the solid angle was used to calculate it. It is difficult to compare the relative efficiencies to a theoretical value as the efficiency of the detector is dependant on the dimensions of the detector though it is expected that the efficiency should be about 10 % [3] which is a similar order of magnitude to the calculated value.

5.2 Attenuation

Looking at the χ^2_{red} in Table 1, it can be seen that the linear fit was successful both energies in both aluminum and steel (see Figure 4). This suggests that the attenuation coefficient well represents the data.

It is difficult to compare the measured attenuation coefficients to accepted values as the accepted values are not measured at the same energies. So the accepted attenuation coefficients were plotted against energy along with the measured coefficients to see if they matched the trend followed by the accepted values (see Figure 5). It is clear to see that the attenuation coefficients for both aluminum and steel do not fit the trend as there appears to be a systematic error which increases the attenuation. This could be due to extra attenuation from other materials between the detector and the source such as air or the detector casing. Conducting this experiment in a vacuum and using thinner shielding to remove extra attenuation may improve these results. Alternatively, the attenuation of the shielding could be investigated to allow for corrections to the results.

6. Conclusion

In conclusion the source strength was found to be 194 ± 9 kBq which agreed with the expected value. The solid angle and efficiency are a reasonable magnitude but the errors do not well describe the actual error on the value. The attenuation coefficients for aluminium, steel and lead at both 511.0 and 1274.5 keV were found to be 0.0978 ± 0.097, 0.068 ± 0.004, 0.097 ± 0.001 and 0.065 ± 0.003 g/cm. These results are all inconsistent with accepted values so the experiment should be reproduced with thinner shielding between the source and the detector to reduce this systematic error.

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