Gamma ray coincidence and angular correlation

HLNNHL005

September 19, 2021

Abstract

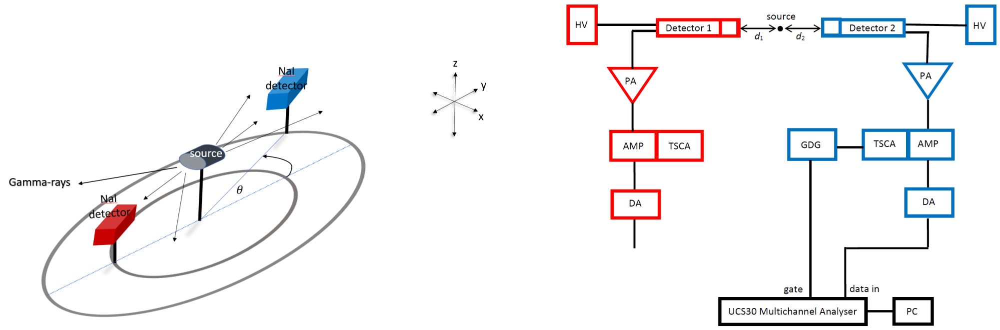
Electron-positron annihilation results in the emission of two 0.511MeV gamma rays. Coincidence counting has various applications some of which are listed in the introduction section. Using Na(IT) detectors one of which is found to have an efficiency of 45% in this report the angular correlation of these gamma rays is found to be strongly peaked at 180°. The TSCA settings (described in the experiment section) and radial distances from the radiation source have advantages and disadvantages in determining the angular correlation function. Larger detector distances result in lower coincidence counts but with a reduced width of uncertainty for the angular correlation function.

1 Introduction

Radioactive decay (also known as nuclear decay) is the random process in which a nucleus loses energy by emitting radiation. This is usually in the form of alpha particles, beta particles, or gamma rays. A positron produced in a nuclear decay will rapidly annihilate with an electron, resulting in a pair of 0.511MeV gamma rays which are emitted almost back-to-back [**1**]. This experiment investigates the gamma rays detected in time coincidence and the efficiency of two Rexon 50 mm x 50 mm NaI(Tl) scintillator detectors for detecting 0.511 MeV coincident gamma rays emitted by a ^{22}Na radiation source. In nuclear physics applications, coincidence systems are used to detect and identify weak detection signals or to distinguish a physics signal from background signals. In high-energy or particle physics, detection systems consisting of thousands of detectors and electronics channels are all operated in coincidence when two accelerated beams collide to search for newly formed particles or new decay pathways[**2**]

1.1 Experiment

With the NaI(Tl) detectors mounted on tracks so that their radical distances from the source can be varied, the ^{22}Na source was placed on a stand in the center of the platforms. The detectors can also rotate on the platform so that their angular separation may be varied as shown in figure 1a below. Each detector was connected to a Ortec 556 HV power supply and a Ortec 113 preamplifier (PA). Signals from the detectors through the preamplifiers were further processed in the Ortec 590A Amplifier (AMP) and timing single channel analyser (TSCA) combo units as shown in figure 1b below. A Ortec 416A gate and delay generator (GDG) unit was used to stretch the signal by about 3 μs. Signals were also sent from the amplifier to the Ortec 427A delay amplifiers (DA) and through to the UCS30 multichannel analyser unit which sorts these pulses (by voltage or "height") into the 1024 channels of the pulse height spectrum.[**1**]



(a) Experimental setup: Source and detectors

(b) Experimental setup: Electrical components

Figure 1: The two figures above (a and b) show different parts of the experimental set up. Figure a shows the radiation source in the center of the two NaI(TI) detectors (red and blue as indicated by the colors in both figures). Each detector can rotate independent of the other detector around the source as shown by the blue detector in the diagram. The radial distance of each detector can also be varied independently. Black arrows from the source indicate the gamma rays emitted by the source. figure b shows the electrical connections made to each detector. These connections are described in detail in section 1.1 above.

2 Results & Analysis

With the AMP fine gain set to 0.95 for the red detector signal and 0.8 for the blue detector, figure 2 displays the calibrated pulse height spectra of the ^{22}Na source as detected by the red and blue detectors. The sources used to calibrate the spectra are ^{137}Cs, ^{60}Co and ^{22}Na. To obtain the spectra seen in figure 2 the detectors were set at an approximate distance of 10cm from the source at an angle of 0^o relative to the source as shown in figure 1a. More details on electrical parameter settings are tabled in the appendix section.Both detectors display photopeaks at 1.27MeV and 0.511MeV (characteristic of electron-positron annihilation) as well as a compton edge just above 1keV. A feature that distinguishes the spectra besides the colours is the heights of the spectra. In particular, the red detector detected nearly 12000 gamma rays in the region around 0.511MeV, compared to the blue detector which detected about 4000 counts, this is a significantly large number. The detectors were placed at approximately the same distance so any influences due to slight differences in distance from the source could not have been this significant. The extra amplification of the signals in the red detector is the only other variable that is different about these detectors. The amplification in the red detector results in more signals being identified and counted compared to the signals in the blue detector. This is also observed in the regions around 0.25MeV and the 1.27MeV photopeak.

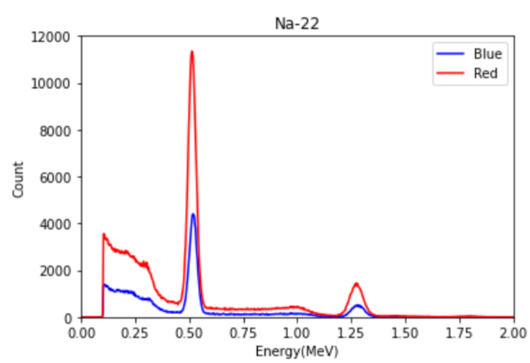
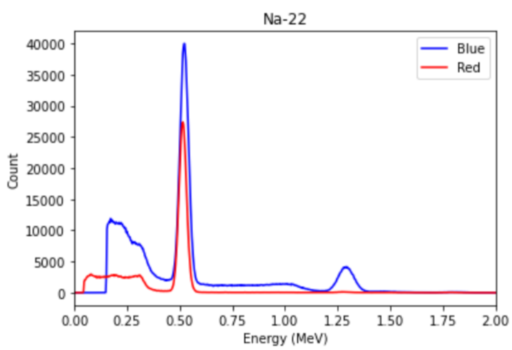


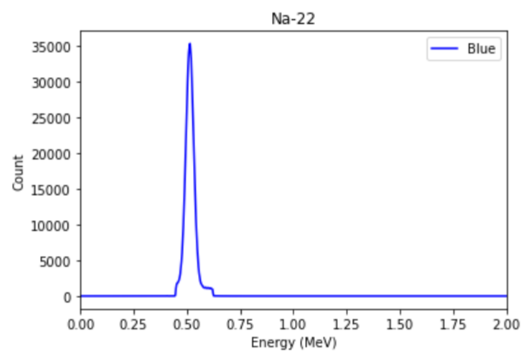
Figure 2: Calibration spectra of the detected gamma ray counts displayed on the vertical axis while the energy of the corresponding gamma ray is displayed on the horizontal axis.

2.1 Coincident gamma spectra

The TSCA function allows a user to set a window on the amplifier pulses and outputs a logic pulse every time there is an amplifier pulse in this window.[**1**] The pulses are further stretched and delayed by the GDG and DA units respectively as shown in figure 1b. Figure 3a displays the Gamma-ray spectra for each detector with different TSCA settings. The TSCA settings on the blue detector was set to be as wide as possible, with the lower level at 0.10 and the window opened to a maximum (10.00). Note how the blue gamma ray spectrum in figure 3a is similar to the one found in figure 2.The TSCA window was then set very tightly around the 0.511MeV photopeak (lower level = 0.18; window = 0.06) to obtain the red spectrum. Figure 3b displays the gamma ray spectrum obtained with TSCA settings similar to that of the red spectrum in figure 3a.



(a) Gamma-ray spectra of ^{22}Na source.



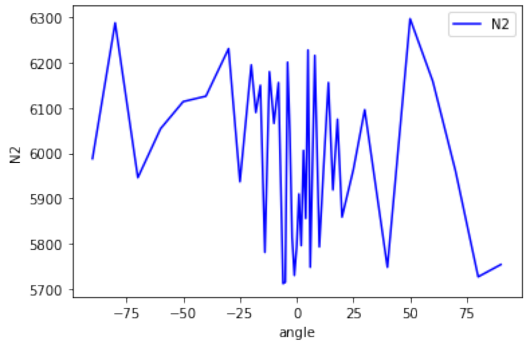
(b) Gamma-ray spectra of a ^{22}Na source.s

Figure 3: Gamma-ray spectrum obtained with TSCA window opened to a maximum (10.00) for the blue detecttor signals shown in figure 3a. The TSCA window was then set very tightly around the 0.511MeV photopeak of ^{22}Na on the red detector(lower level = 0.18; window = 0.06). Figure 3b was obtained using the same TSCA settings used for the red spectrum on the blue detector signals.

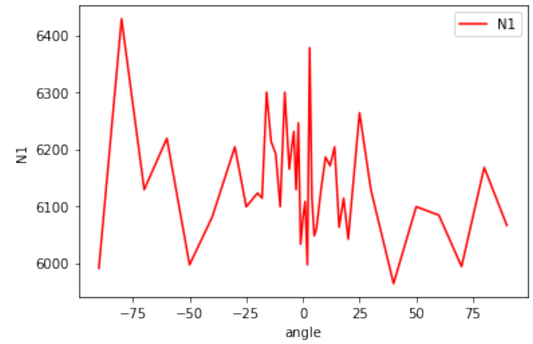
2.2 Angular correlation measurements

The gamma rays produced by annihilation travel in opposite directions. Hence, for 0.511MeV photons from ^{22}Na we expect P(θ) to be strongly peaked at $\theta = 180^o$. The angular correlation function P(θ) of two gamma rays, γ1 and γ2 may be defined as the relative probability of γ1 and γ 2 being emitted at relative angle θ. A universal coincidence (UCO) was introduced with the outputs from the two TSCAs as the two inputs. Replacing the GDG and the multichannel analyser. The UCO only outputs a logic pulse (5V, 500ns) only when the two input pulses overlap in time, either partially or fully. A scaler unit was introduced to which counts logic pulses. All the pulses from the TSCA servicing each detector were recorded (N1 and N2) as well as the number of coincidences (Nco). The scaler was set to record singles counts from each detector (N1 and N2) and coincidences (Nco) in a pre-set time. The angle was varied, and N1, N2 and Nco measured for 30 seconds intervals.[**1**] Figures 4 displays the counts from each detector as a function of the relative angle between the detectors. Figure 5 shows the number of coincidences obtained under various conditions over the the same time period used for figures 4a and 4b.

the red spectrum in figure 3a.

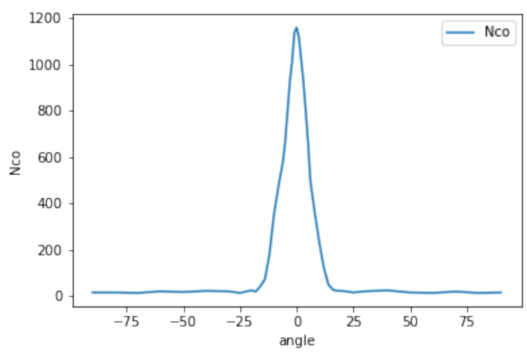


(a) Gamma ray counts from the blue detector as a function of the relative angle θ.

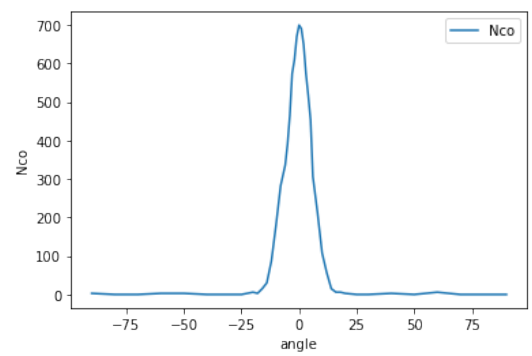


(b) Gamma ray counts from the red detector as a function of the relative angle.

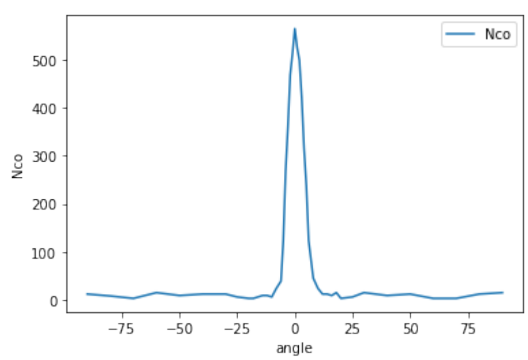
Figure 4: Gamma ray counts as a function of the relative angle between the two detectors on the platform. The detectors were placed at a distance of 15cm from the source. Both TSCA windows were set to be wide open.



(a) Coincidences as a function of the relative angle with the red and blue detectors 15cm away from the source. Both TSCA windows were widely open.



(b) Coincidences as a function of the relative angle with the red and blue detectors 15cm away from the source. Both TSCA windows were set tight around the the 0.511MeV photopeaks.



(c) Coincidences as a function of the relative angle with the red detector located 15cm away and the blue detector located 30cm away from the source. Both TSCA windows were widely open.

Figure 5: Coincidence counts as a function of the relative angle between the detectors under different TSCA settings and radial distances.

Figures 4a and 4b display the gamma ray counts as a function of the relative angle between the detectors. Slight changes in the angle near θ=0^o - this is can also be interpreted as θ=180^o between the detectors - result in rapid changes consisting of very steep gradients. This implies that a different process occurs near θ=0^o compared to angles further away. The detectors detect on average roughly the same number of counts as they move around the source meaning that the source radiates in different directions on average in the same way. This is further evidence that an interesting phenomena occurs at θ=180^o.

Figure 5 shows the coincidence counts as a function of the relative angle between the detectors for various radial distance and TSCA settings. As expected, The gamma rays produced by annihilation travel in opposite directions, this is seen by coincidence peak at $\theta = 180^o$. Changing the TSCA settings affects the number of coincidences more than the shape of the distribution as seen in figure 5a and 5b. More counts were detected in figure 5a, which has its TSCA widow wide open, than in 5b which has it's TSCA tight around the 0.511MeV photopeak. In figure 5c, the blue detector is placed 30cm away from the source and the TSCA is wide open. The difference between figures 5a and 5c is the distance of the blue detector and this has an influence on the distribution as well as the number of coincidences detected. Increasing the distance of the detectors from the source decreases the uncertainty of whether a particular coincidence was from the 0.511MeV gamma rays. Although the uncertainty is decreased, a smaller number of coincidence is detected.

2.3 Absolute efficiency (ϵ) determination

The number of photons emitted by the radioactive source is always larger than the number of photons observed by the detector, and the ratio of the number of photons detected or observed by the detector with respect to the number of photons emitted by the source is known as the detection efficiency. [**2**] This section seeks to determine the efficiency of the red detector (detector 1) for detecting 0.511MeV gamma rays. The detectors were positioned at 180^{o} with a ^{22}Na source between them. The red and blue detectors were placed 8cm and 24cm away from the source respectively. Since the efficiency of the detector is the ratio of the detected gamma ray to the emitted, it is sufficient to approximate the efficiency of the red detector as the ratio of the total gamma ray counts detected with the TSCA window tight on the 0.511MeV photopeaks to the total gamma rays detected with the TSCA window wide open.

$$\epsilon = \frac{Total\ counts\ with\ TSCA\ tight\ on\ the\ 0.511MeV\ photopeak}{Total\ counts\ with\ TSCA\ window\ wide\ open}$$

The table below lists the total counts and coincidences, each measure over a time interval of 600 seconds, as detected by the red (N1) and blue (N2) detector at different TSCA settings

	N1	N2	Nco
Both TSCA windows wide open	253901	79100	12607
Both tight on the 0.511MeV photopeaks	115940	32444	7871
Tight on the 0.511MeV photopeak on blue detector	258432	31578	12236

Table 1: Gamma ray counts as a function of the TSCA setting

From the values given in table 1 above, two efficiency approximations for the red detector can be calculated. The window for the red detector in the third row of table 1 was kept wide open. Using these values, the efficiency of the red detector is calculated as follows.

$$\epsilon_1 = \frac{115940}{253901} \approx 0.4566; \ \epsilon_2 = \frac{115940}{258432} \approx 0.4487$$

The average efficiency is $\epsilon = \frac{\epsilon_1+\epsilon_2}{2}$=0.45265. Since the events are random, the uncertainty in the total number of counts for each of the values in table 1 is given by the square root of the value.

$$u(N1) = \sqrt{N1};$$

the uncertainty $u(\epsilon_1) = \frac{115940}{253901}\sqrt{(\frac{\sqrt{115940}}{115940})^2 + (\frac{\sqrt{253901}}{253901})^2} \approx 0.0016$

In a similar way $u(\epsilon_2) \approx 0.0016$

Therefore, the uncertainty in the mean of the detector efficiency is given by $u(\epsilon) = \frac{1}{2}\sqrt{u(\epsilon_1)^2 + u(\epsilon_2)^2}$

Substituting in the values for the uncertainty, the red detector efficiency is found to be

$$\epsilon = 45 \times 10^{-2} \pm 0.001$$

Therefore, of the total gamma rays entering the red detector, approximately 45% of them are detected.

2.4 The activity of the ^{60}Co source

The detectors were then placed at an angle of 180° with a ^{60}Co source between them in an attempt to measure the activity of a ^{60}Co source. Table 2 displays the total ^{60}Co gamma ray counts obtained (in a time interval of 1200 seconds) with the TSCA widows wide open.

	N1	N2	Nco
Both TSCA windows wide open	231123	223368	4582

Table 2: Total gamma ray counts and coincidences detected

The activity of a ^{60}Co source gives a measure of the total number of disintegrations per second and is given by

$$\mathrm{R}=\frac{R_1 R_2}{R_{co}}$$

where R_1 and R_2 are the count rates of the red (1) and blue (2) detectors respectively. R_{co} is coincidence count rate. Dividing each value in table 2 by the total time interval (1200 seconds) gives the count rates (counts per second) and substituding these values into the equation for the activity of the ^{60}Co source gives $R \approx 9389.2$ disintegrations per second. The uncertainty of each value in table 1 is given by the square root of the value therefore the uncertainty in the activity u(R) is give by

$$\mathrm{u(R)} = \frac{R_1 R_2}{R_{co}} \sqrt{(\frac{u(R_1 R_2)}{R_1 R_2})^2 + (\frac{u(R_{co})}{R_{co}})^2}$$

where $u(R_1 R_2) = R_1 R_2 \sqrt{(\frac{u(R_1)}{R_1})^2 + (\frac{u(R_2)}{R_2})^2} \approx 106.37$
$\mathrm{u(R_1)} = \sqrt{R_1}$ and $u(R_2) = \sqrt{R_2}$
Using the values given in table 1, the activity of ^{60}Co is R = 9389.2 ± 28.1 disintegrations per second. The (2010) stamp on the source says that the source radiates 1 Ci which is 37 billion disintegrations per second. 11 years later, the activity of the ^{60}Co source has drastically decreased to approximately 9389 disintegrations per second.

2.5 Discussion & conclusions

The diagrams in figure 5 show how changing the TSCA window affects the number of gamma rays detected. The shape of the gamma ray distribution is not affected as much as the maximum number of gamma rays detected. Changing the distance from the source affects both the shape of the distribution and the maximum number of gamma rays detected. increasing the distance from the radiation source as seen in figure 5c results in a narrower distribution and has a smaller maximum gamma ray count compared to figures 5a and 5b. From this we can conclude that increasing the distance of the detector from the source results in smaller uncertainty for the coincidence. Coincident gamma rays are detected far better away from the source compared to detectors located closer. However, although the uncertainty is decreased further away from the source, the number of gamma rays detected decreases and this may reduce the reliability of the result in the case where a detector is place too far from the source in a distance. Coincident gamma rays are strongly peaked at 180○ as shown in Figures 4 and 5 this is a result of electron-positron annihilation.
The activity of a radiation source decreases over time, this is seen by the comparison of a activity of a ^{60}Co source in a time interval of 11 years. The 1Ci ^{60}Co source decreased to 3.5×10^{-6}Ci in 11 years.

References

[1] A. Buffler, *Gamma ray coincidence and angular correlation*, accessed September 2021, (https://vula.uct.ac.za/access/content/group/275677d7-258c-4507-b368-7cb674c91ca0/Laboratory/Lab%206%20Gamma%20coincidence/PHY3004W_gglab_instructions_do_at_home_2021.pdf)

[2] Miron Technologies, *Gamma-ray efficiency calibration*, accessed September 2021, (https://www.mirion.com/learning-center/lab-experiments/gamma-ray-efficiency-calibration-lab-experiment)

A Appendix

The table below lists the module settings.[**1**]

	Detector 1 (red)	Detector 2 (blue)
HV	+600V	+600V
PA capacitance	1000μF	1000μF
AMP course gainn	X 20	X 20
AMP fine gain	0.95	0.80 TSCA lower level
0.10	0.10 TSCA window	10.00
10.00		

Table 3: Module settings