Study of Gamma-Gamma coincidence using Na^{22}

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Sodium-22 is an excellent source of simple $\gamma - \gamma$ coincidence experiments. The decay of the isotope occurs through a process[a] that includes positron emission or electron capture through the 1.274 MeV state of ^{22}Ne. In this experiment, solid-state detectors are used to keep track of the coincidence events occurring during the whole time of the experiment. Then, we tried to study the coincidence events that occur between $\gamma - \gamma$ produced by our sample source ^{22}Na. Using the source, we first calibrated the Counts vs energy curve and plotted the heat map corresponding to different results[b] using the CNSPEC software. The whole experiment is performed for different angles, to show some angular dependence of the associated coincidence events.

Keywords: Positron emission, Electron capture, $\gamma - \gamma$ coincidence, scintillation

I. OBJECTIVES

To study the angular dependence of $\gamma - \gamma$ coincidence using ^{22}Na radioactive source.

II. THEORY

A. Scintillation based solid state detectors

Generally, a γ detector consists of a scintillator[1] mated with a device capable of measuring the quanta of scintillation photons emitted from it as a result of an incident γ. In this case, a $10mm \times 10mm \times 8mm$ scintillator is mated to a semiconductor PN junction connected in reverse bias mode. Thus, the depletion region acts as an ionization medium that converts the scintillation photons into a corresponding number of electron-hole pairs. The small amount of charge generated as a result of one gamma ray depositing, its entire energy in the scintillator which then gets converted into a charge pulse by the PN junction results in an event in the photopeak[2] region. Other types of interactions such as Compton scattering[3] result in different energies being detected. This charge pulse is then fed to the signal-processing electronics, followed by the multi-channel analyzer(MCA) which generates a spectrum.

B. Signal Processing electronics and MCA

1. Pre-Amplifier

A charge-sensitive preamplifier converts the charge generated by an incident bunch of scintillation photons into a correlating output voltage. The preamp's primary function is to ensure impedance matching between high impedance on the detector side (i.e.input), with the post-processing electronics' low output impedance. This improves the SNR[4].

2. Shaping Amplifier

The Shaping amplifier produces a Guassian-shaped pulse with amplitude varying from 0 to 3.3 volts depending on the amount of energy deposited. The Gaussian pulse output of the shaping amplifier is available for monitoring via a BNC connector. The same buffered signal is fed into the built-in Multi Channel Analyzer's (MCA) input.

3. Multi Channel Analyzer (MCA)

The hardware performs a variety of tasks such as pulse detection, signal post-processing, and signal sorting into predefined bins based on peak height. The MCA performs sorting and histogram generation and has a resolution of 1024 channels (1K) and an input voltage range of 0-3.3V. It has a USB interface, and the software works with Linux-based systems as well as Windows 7/10.

Threshold Setting:
Input pulses are only accepted if their amplitude exceeds a threshold value of 65 channels (to reject low energy peaks that may not be due to gamma rays). This can be changed using a 12-bit software-controlled DAC[5]. A sharp peak to the extreme left of the spectrum indicates high electrical noise that must be rejected. Open the bottom-right menu and set the threshold value to a channel that is greater than the noise peak.

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[a] The whole process is discussed later in the Theory section
[b] Discussed later in the Discussions section

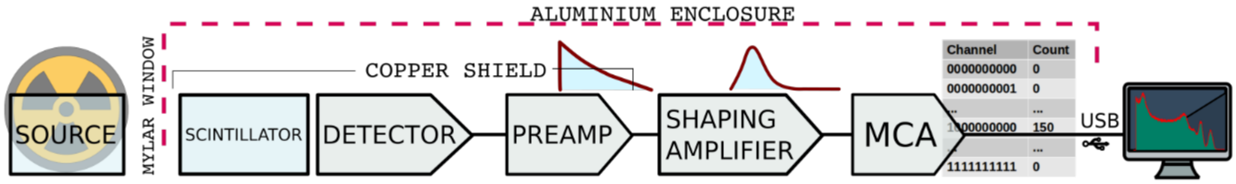

FIG. 1. Flow diagram for the entire process

C. The undergoing process

^{22}Na decays radioactively to an excited state of ^{22}Ne via positron emission (90% probability) or electron capture (10% probability). The excited ^{22}Ne nucleus decays to the ground state with a mean lifetime of 3×10^{-12} s, emitting a 1.274 MeV gamma.

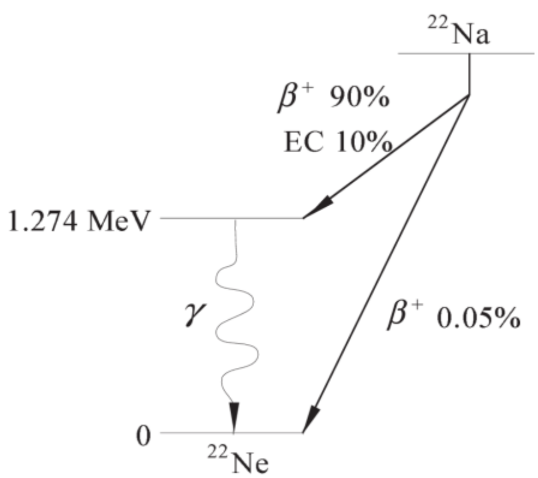

FIG. 2. The decay of ^{22}Na proceeds by positron β^+ emission (90%) or electron capture (10%) to produce an excited state of ^{22}Ne which decays by emission of a 1.274 MeV γ.

In this process, positrons with kinetic energies up to about 0.5 MeV are emitted. When they reach atomic (eV) energies by losing this energy due to the surrounding material of the source, they capture an electron to form positronium—a hydrogen-like atom.
The positronium then decays (with a lifetime on the order of 10^{-10} s) by the annihilation of the e^+ and e^- into two γ.
By energy conservation,

$$E_\gamma = E_{positronium}$$

and, by momentum conservation,

$$p_\gamma = p_{positronium}$$

Positronium has no initial momentum in the rest frame, and so the two annihilations γs must oppose each other wrt momentum in that frame. So the energies of the two photons must be equal and travel in opposite directions. Since the initial energy of the positronium (neglecting a few eV of the binding energy) is simply the rest mass energy of the electron and positron (both 0.511 MeV), the energy of each γ is $E_\gamma = 0.511$ MeV.
In the lab frame, the kinetic energy of positronium varies up to a few eV (the typical energy of the electrons formed with it). Then, depending on the direction of the original positron pulse with respect to the direction of the gamma-ray, the transformation of the laboratory frame gives gamma energies that can deviate from 0.511 MeV and/or produce gammas that are not emitted accurately 180° apart.

D. Coincidence Measurements

Coincidence measurements with multiple spectrometers allow better identification of events simultaneously with multiple gamma rays. This requires precise digitization and time-stamped data from multi-detector signals.

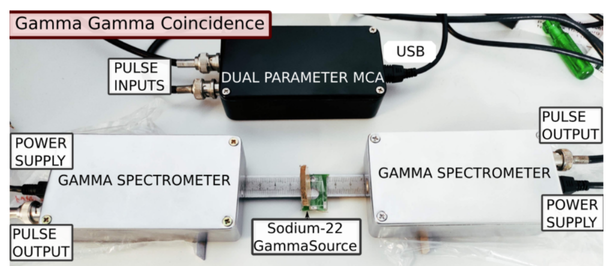

FIG. 3. Two gamma spectrometers placed with a Na-22 positron source in the middle. The dual MCA carries out the data acquisition

The data acquisition includes the following steps:

- Calibration using ^{22}Na:
  It includes saving the data in a .csv file in some directory and starting the data acquisition process for 1.5 hours at each angle between the two detectors.
  After the data acquisition is over, Gaussian fit is done over the histogram by fixing the photopeak at 511 keV. This is the calibration process, i.e. chang-

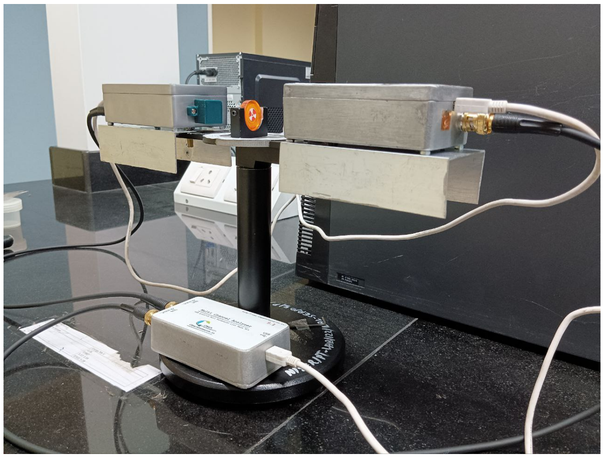

FIG. 4. Experimental Setup

ing the channel number to energy values. Then the corresponding heat map is generated and saved.

- Applying Energy gates:
  In this, one can isolate the counts obtained through input 1 where the corresponding Input 2 signal is between channels A and B. After applying the energy gate, one observes that spectrum 1(black trace) is automatically updated to represent the events that satisfy the criteria and the coincidence counts are displayed on the screen.

This process is repeated for various angles between the detectors. We have done it for 4 different angles: 90°, 175°, 180°, and 185°.

III. EXPERIMENTAL SETUP

The experimental setup of the experiment is shown below in Fig.4. This setup is connected to a desktop using the USB connector from MCA.
The source is approximately 2 mm in size and is located near the center of the disk, and the annihilation events occur within a few millimeters of the source. One detector is fixed and the other is rotated around the source to adjust the angle. In front of each detector, there is a lead shield with a small aperture drilled in the center. Apertures, scintillators, and their relationship to the source and to each other are the important factors in determining the rate of gamma detection.

IV. OBSERVATIONS AND DATA

The histograms corresponding to the different angles between the detectors are attached on the next page in Fig.6. Please refer to page 4. We see that there is a large peak during the initial point of the energy spectra. This is generally due to the electrical noise unrelated to gamma rays, which can be controlled by controlling the threshold settings efficiently. There is also a short peak which is supposed to represent Compton scattering.

The heat maps thus generated for the different angles are shown in Fig.7 on page 5. We see the 3-D data or heat maps corresponding to different angles between the detectors.

- For 90°, there is a dispersed pattern which implies no sufficient scattering is seen.

- For larger angles, we generally see four peaks, the highest one corresponding to the (photopeak+photopeak) absorption, the two intermediate ones corresponding to the (photopeak+compton) and the shorter one corresponding to the (Compton+Compton).

The corresponding coincidence counts found for the different angles between the detectors are as follows:

- For 90°: Coincidence counts=36

- For 175°: Coincidence counts=247

- For 180°: Coincidence counts=3684

- For 185°: Coincidence counts=1527

Comparing the coincidence counts, we see that, it is maximum when the angle between the detectors is 180° and minimum when the angle between the detectors is 90°. Also, there is a significant decrease in the coincidence events when we just shift by ±5° from 180°.

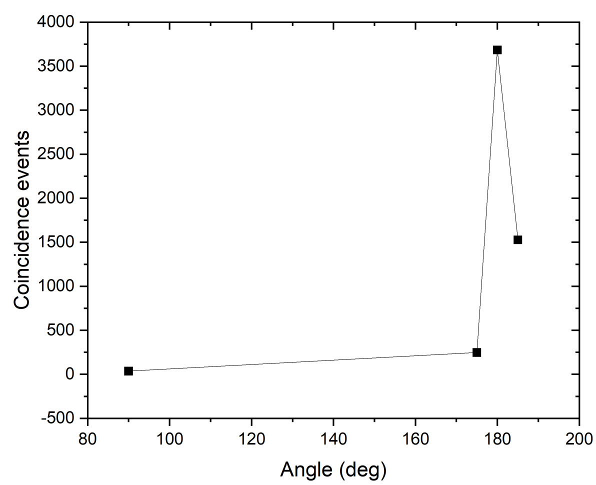

FIG. 5. Coincidence events vs angle between the detectors.
Maximum coincidence events at 180° and
Minimum coincidence events at 90°

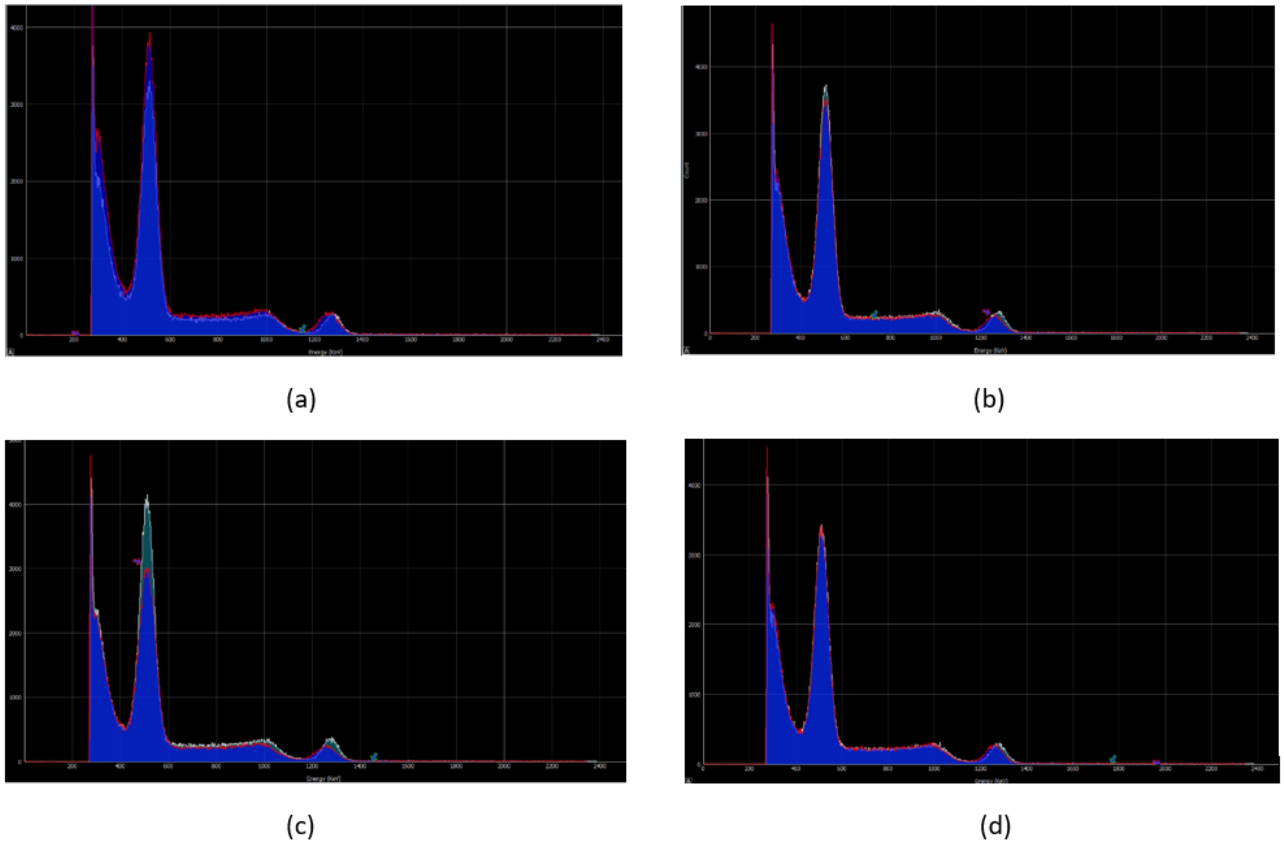

FIG. 6. Count vs energy spectrum for different angles between the detectors is obtained for 1.5 hours each keeping the threshold constant to 120 channel number. The photopeak is calibrated to 511 keV for ^{22}Na source.
(a) Energy spectrum when the angle between the detectors is 90°.
(b) Energy spectrum when the angle between the detectors is 175°.
(c) Energy spectrum when the angle between the detectors is 180°.
(d) Energy spectrum when the angle between the detectors is 185°.

V. CONCLUSIONS AND DISCUSSIONS

- In the histograms above, we observed that there is a huge peak at the starting point of the energy spectra and a short peak at the last point of the spectra. The huge peak is generally due to the high electrical noise unrelated to gamma rays, which can be controlled by controlling the threshold settings efficiently, and the short peak is due to Compton scattering.

- For 90°, there is a dispersed pattern in the heat map which implies no sufficient coincidence events is observed. For larger angles, we observed four peaks, the highest one corresponding to the (photopeak+photopeak) absorption, the two intermediate ones corresponding to the (photopeak+compton), and the shorter one corresponding to the (Compton+Compton).

- We observed that the coincidence counts are maximum when the angle between the detectors is 180° and minimum when the angle between the detectors is 90°. Also, there is a significant decrease in the coincidence events when we just shift by ±5° from 180°.

1. Sources of errors in the experiment

- Since in this experiment, every measurement is done inside the CNSPEC software and we didn't have any hands-on experience, we can just think of the sources of errors to be systematic errors, which include the errors due to some external noises present in the room, such as electromagnetic noise, thermal noise, etc.

- The other significant source of error is the goniometer, which had some zero error of about 3', so the angle shown by it is not so accurate. Establishing the detectors at the required angle was also a chal-

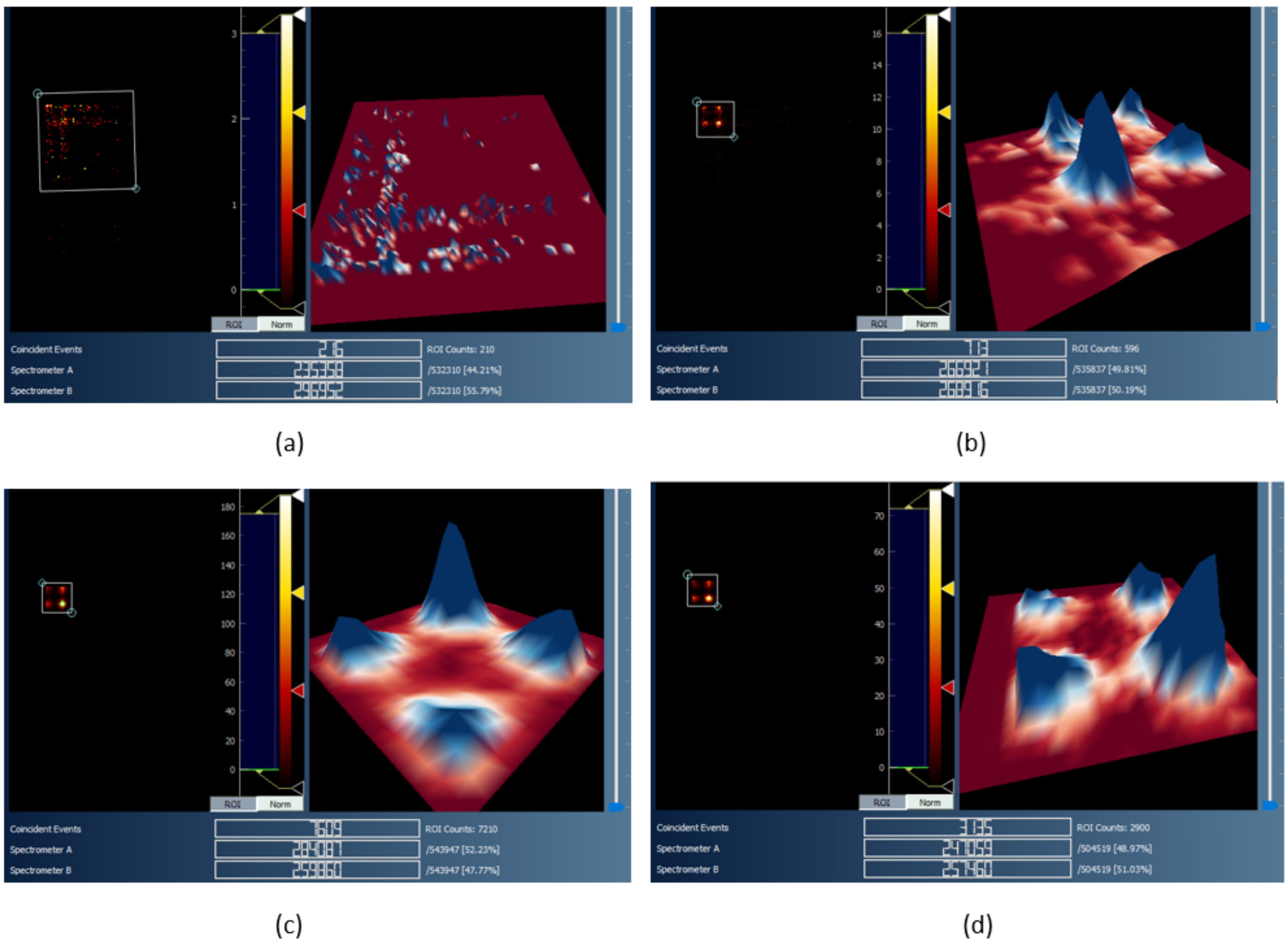

FIG. 7. 3-D data or heat maps for different angles between the detectors is obtained for 1.5 hours each keeping the threshold constant to 120 channel number. The photopeak is calibrated to 511 keV for ^{22}Na source.
(a) Heat map when the angle between the detectors is 90°.
(b) Heat map when the angle between the detectors is 175°.
(c) Heat map when the angle between the detectors is 180°.
(d) Heat map when the angle between the detectors is 185°.

lenging task. This needs to be improved to get a better result for a preferred angle.

VI. REFERENCES

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[1] A scintillator is a material that exhibits scintillation, the property of luminescence when excited by ionizing radiation.
[2] The region of the pulse height spectrum caused by the complete photoelectric absorption of γ rays.
[3] The scattering of a high-frequency photon after the interaction with a charged particle.
[4] Signal-to-noise Ratio.
[5] Digital to Analog converter circuit.