Demonstrating Momentum Conservation in Electron-Positron Annihilation in Na-22 using Gamma-Ray Coincidence

Laboratory Experiment Report

Course No.: PHY315

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Momentum Conservation in Beta-positive Decay of Na22

Abstract

This experiment was conducted to demonstrate the conservation of momentum in Beta-positive (β^+) decay using Sodium-22 (Na-22) source. Two photons were detected simultaneously by two scintillation detectors that were placed anti-parallel to each other and connected to a Digital Storage Oscilloscope (DSO) to measure the coincidence rate. The Na-22 source exhibited a significantly larger frequency ($\sim$ 400 Hz), than the frequency observed for a Cesium-137 (Cs-137) source, which served as a control. The high coincidence rate confirms the anti-parallel emission of the annihilation photons, thereby validating the conservation of linear momentum in the decay and annihilation process.

1 Introduction

Na-22 is a proton-rich radionuclide with a half-life of 2.6 years, and to increase stability Na-22 undergoes radioactive decay. The vast majority of Na-22 decays ($\sim$ 90%) proceed through β^+ emission, where one of the protons in the nucleus converts into a neutron via the weak nuclear force and produces an excited Ne-22 nucleus.

$$^{22}_{11}\mathrm{Na} \rightarrow {}^{22}_{10}\mathrm{Ne}^* + e^+ + \nu_e, \tag{1}$$

The excited Ne-22 nucleus quickly transitions to its stable ground state by emitting a single gamma ray photon of 1275 keV energy, which results in the photopeak of Na-22 in its energy spectrum.

The emitted positron (e^+) is antimatter and travels a short distance before slowing down and encountering an electron (e^-). When the electron and positron annihilate, their entire mass is converted into energy according to $E = mc^2$.

$$e^+ + e^- \rightarrow \gamma + \gamma \tag{2}$$

The rest mass of an electron (positron) is 511 keV, therefore the total energy released is 2×511 keV = 1022 keV. This energy is released as two gamma photons that have the same energy.

To conserve linear momentum, the two 511 keV photons must be emitted 180° anti-parallel to each other. The experimental setup facilitates the demonstration of conservation of momentum in the β^+ decay of Na-22 by measuring the frequency of its coincidence signal when the two detectors are kept 180° to each other.

2 Experimental Procedure

2.1 Apparatus Used

Two NaI scintillation detectors, Two Single Channel Analysers (SCA), Multi-Channel Analyser (MCA), Coincidence Analyser, Digital Storage Oscilloscope (DSO), Radioactive Sources (Cs-137, Co-60 and Na-22)

2.2 Procedure

1. The two NaI scintillator detectors were positioned at a 180° angle to each other, as detailed in the schematic (Figure 1). Cesium-137 (Cs-137) and Sodium-22 (Na-22) were used as the radioactive sources, with Cs-137 serving as the control source.

2. The Coincidence Analyser was tested for functionality by applying a test signal. This was a 1000 Hz pulse waveform with a 5.0 V amplitude, simulating the output signal generated by the SCA.

3. The output signal, specifically the SCA amp-out, was channeled directly to the DSO (Digital Storage Oscilloscope). This allowed for a preliminary, qualitative observation of the pulse shapes and amplitudes generated by both the Cs-137 and Na-22 sources. The signals were examined using both the Normal mode and the X-Y display mode.

4. The output from the first SCA was connected to Channel A, and the output from the second SCA was connected to Channel B of the Coincidence Analyser. The analyser's output was monitored on the DSO, and the resulting coincidence signals from Na-22 were compared against those from the Cs-137 control source.

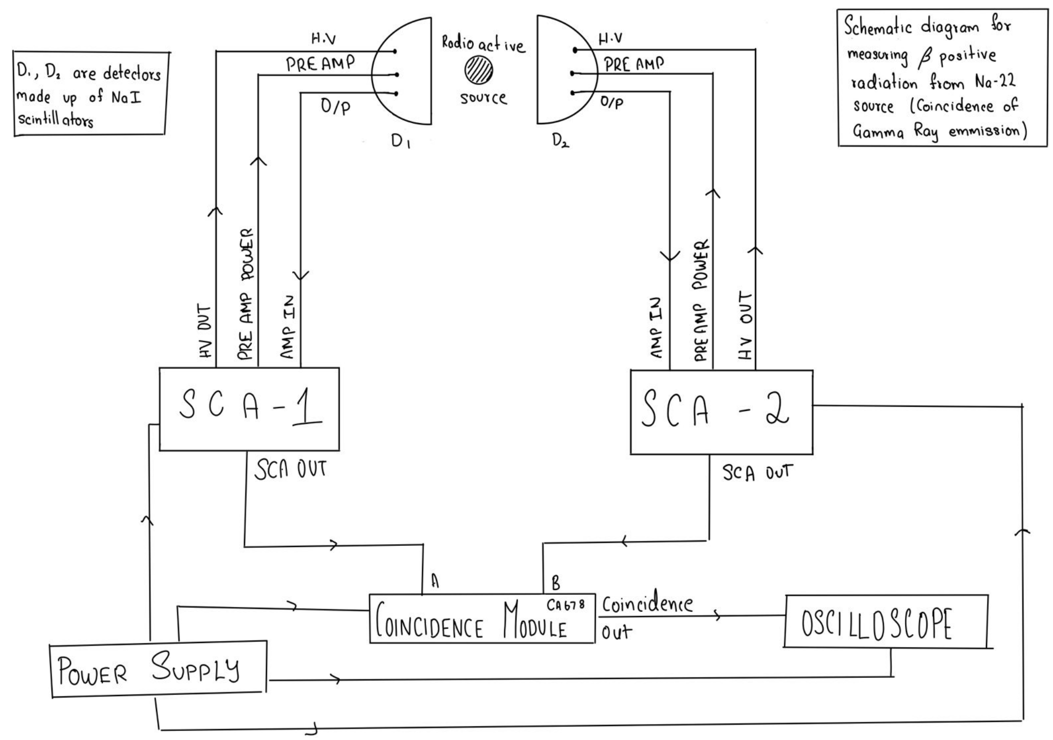

Figure 1: Schematic for Coincidence Experiment

3 Observations

The SCAs were connected to the Coincidence Analyser and the signals from both the radioactive sources were observed. It was seen that the frequency of the coincidence signals from Na-22 was significantly larger than the frequency of the coincidence signals from Cs-137.

The observed frequencies were:

Source	**Coincidence Freq. Range**	**Characteristic**
Cs-137	20 to 60 Hz	Low and erratic, indicative of background noise
Na-22	350 to 400 Hz	High and relatively stable, indicative of a highly correlated emission process.

Table 1: Coincidence Signal Frequencies and Characteristics

This can also be seen qualitatively by connecting the outputs of the SCAs directly to the DSO and observing how frequently the outputs coincide for the two radioactive sources.

Furthermore, upon decreasing the angle between the scintillation detectors from 180° to 90° for Na-22, we observed that the frequency of the coincidence signal decreased. The frequency values of the two sources are shown in Figure 2 and Figure 3.

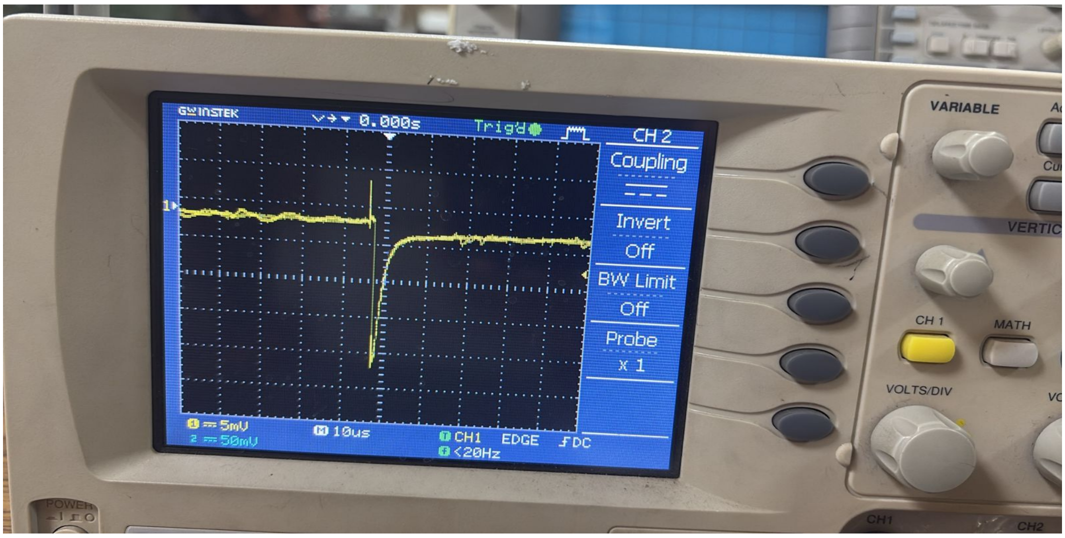

Figure 2: Coincidence Signal from Cs-137

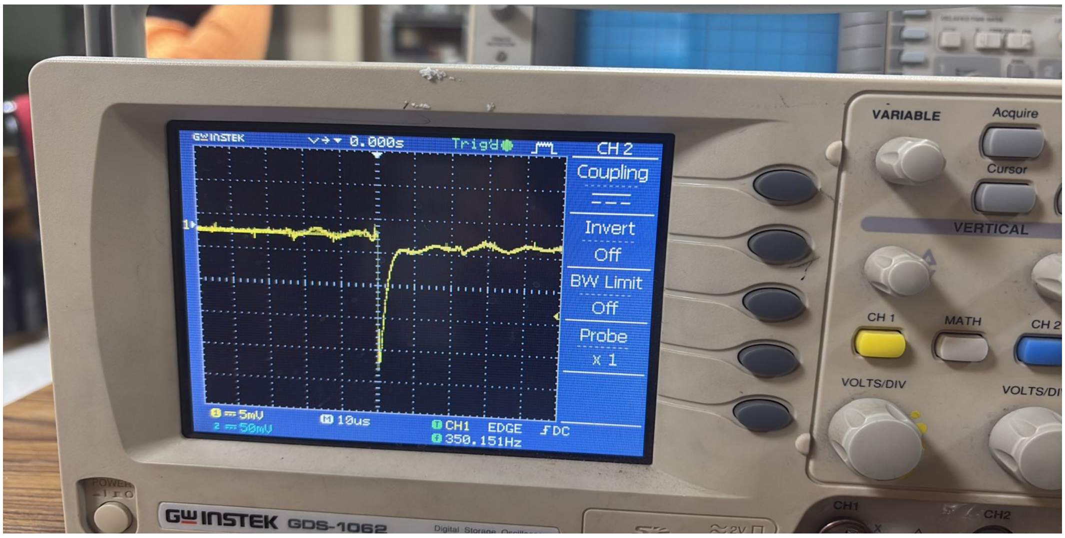

Figure 3: Coincidence signal from Na-22

4 Conclusion

The significantly larger frequency of the coincidence signal from Na-22 source and, the decrease in this frequency upon changing the angle between the scintillation detectors from $180°$ to $90°$, implies that the decay of Na-22 results in the simultaneous emission of two anti-parallel gamma rays, thus demonstrating the conservation of momentum.

Appendix

Working of SCA and MCA

In NaI(Tl) scintillators, incident radiation excites electrons, which de-excite through thallium activator sites to produce flashes of light. A sensitive photomultiplier tube (PMT) then detects this weak light and converts it into a corresponding electrical signal.

The detector pulse from the preamplifier output is first amplified by an amplifier and then processed by the SCA. The SCA basically acts as a discriminator which provides a threshold level to the signal amplitude so that the signals above the threshold are only accepted.

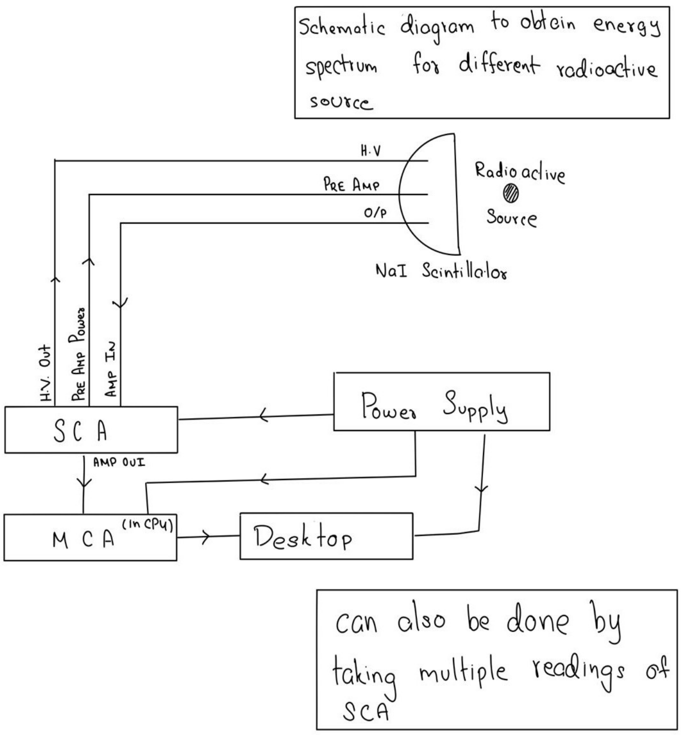

Figure 4: Schematic for SCA and MCA

A Single-Channel Analyzer (SCA) has two modes: WIN (window mode) and THR (threshold mode). The SCA is set in window mode and the window knob is used to change the window (the difference between the upper and lower level thresholds). We use the baseline knob to set the lower level threshold. This sets the SCA to count only the pulses that fall within that specific amplitude range, which is shown on the display as count rate.

However, a Multichannel Analyzer (MCA) performs this function automatically by sorting all incoming pulses into thousands of individual channels simultaneously, building the entire pulse height spectrum at once without manual scanning.

The schematic for SCA and MCA is given in Figure 4. This setup was used for obtaining the energy spectra of the radioactive sources.

Understanding the Characteristic Curve

The characteristic curve is an important tool used to determine the correct operating voltage for the scintillation detector system.

This curve shows how the detector's Count Rate (the number of radiation particles detected) changes as the High Voltage (HV) adjust supplied to the Photomultiplier Tube (PMT) is increased.

The HV adjust is a gain control mechanism. By varying the voltage, it exponentially scales the PMT's gain, therefore adjusting the output amplitude in proportion to the energy deposited by the incident radiation.

The operating point was set to the HV adjust of 4.70 (approximately 705 V). This voltage provides the optimal gain needed for accurate measurement. Operating at any voltage higher than this would result in signal clipping.

The characteristic curve obtained in given in Figure 5.

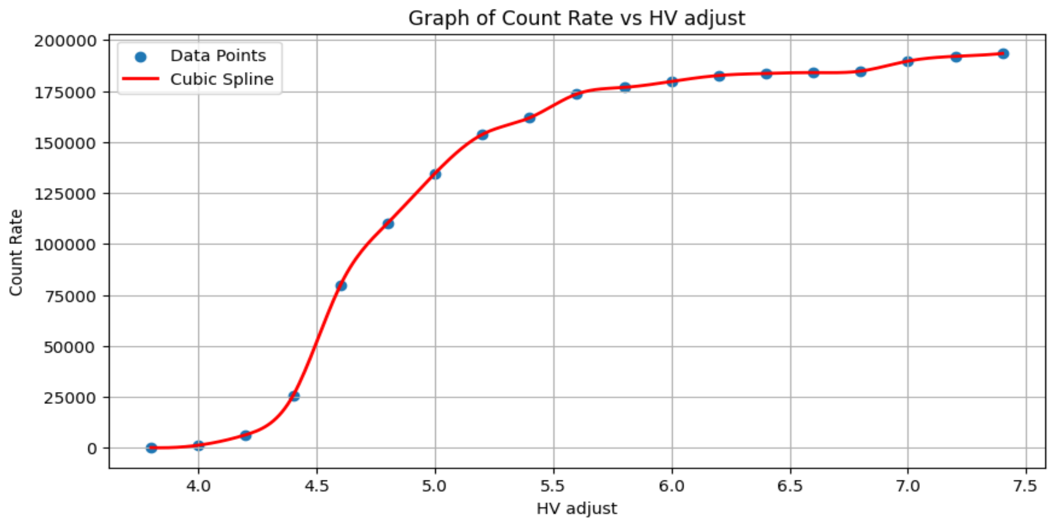

Figure 5: Graph of Count Rate Vs HV Adjust

Energy Spectra of Cs-137 and Co-60 using SCA and MCA

The energy spectrum of Cs-137 obtained using SCA and MCA are given in Figure 6 and Figure 7 respectively.

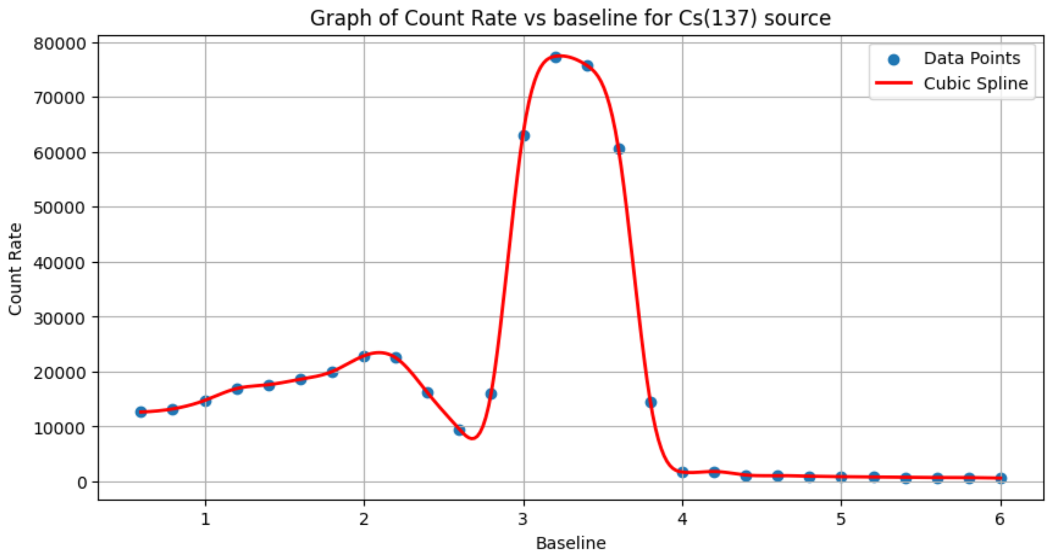

Figure 6: Energy Spectrum of Cs-137 using SCA

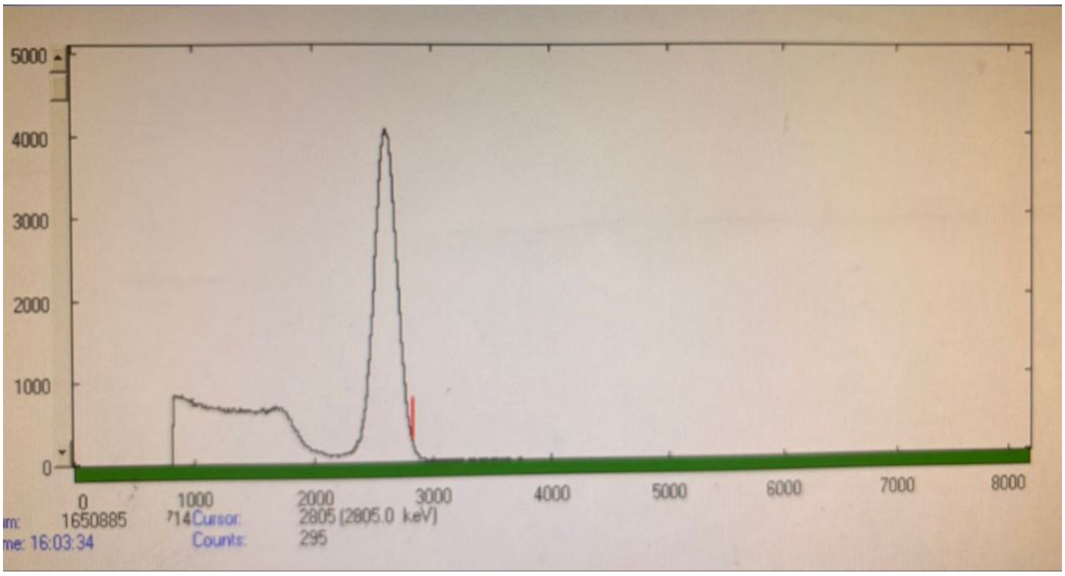

Figure 7: Energy Spectrum of Cs-137 using MCA

The energy spectrum of Cs-137 obtained using SCA and MCA are given in Figure 8 and Figure 9 respectively.

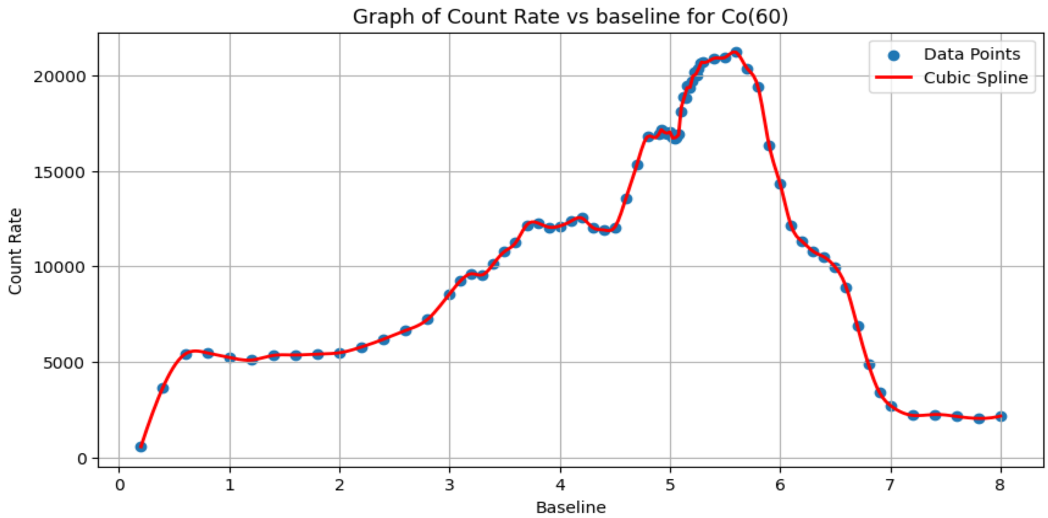

Figure 8: Energy Spectrum of Co-60 using SCA

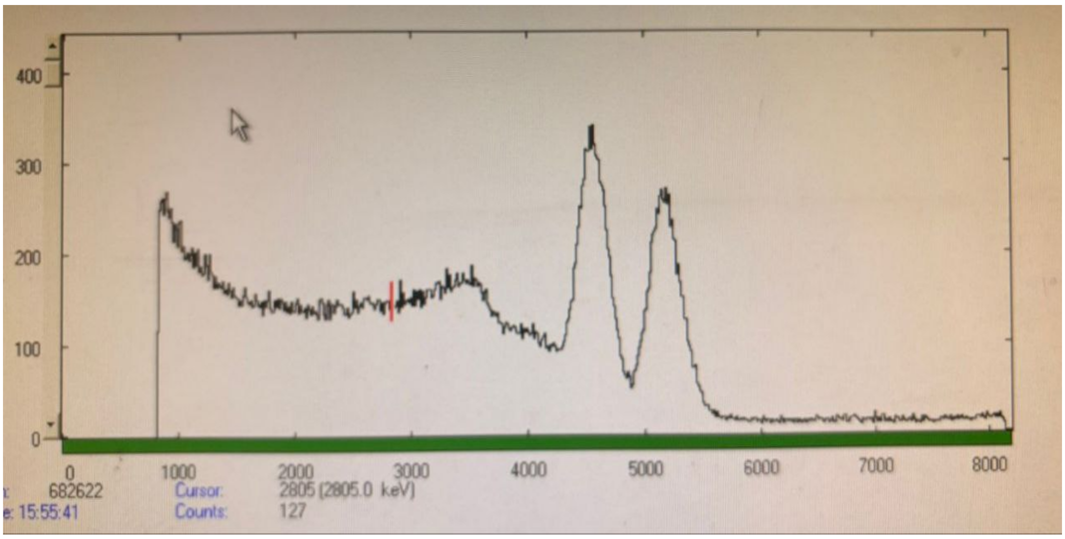

Figure 9: Energy Spectrum of Co-60 using MCA

Notice how the energy spectra obtained using the MCA are more precise. This is because a Multichannel Analyzer (MCA) automatically sorts all incoming pulses into thousands of individual channels simultaneously and thus has better resolution.