Gamma Ray Spectroscopy

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Introduction

- Gamma rays are emitted by excited nuclei
- Very high energy
  - Can be as much as 10^7 times greater than photons released from electron transitions.
- Effectively "invisible" to detector
  - We have to rely on various interactions within absorbing material to gain any insight.

- Alpha decay
  - ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}X' + {}^{4}_{2}\alpha$
- Beta decay
  - Positive ${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}X' + {}^{0}_{1}\beta + \nu_e$
  - Negative ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}X' + {}^{0}_{-1}\beta + \bar{\nu}_e$
- Gamma emission
  - ${}^{A}_{Z}X \xrightarrow{\text{relaxation}} {}^{A}_{Z}X' + \gamma$

- Photo-electric effect
    - Lower energies
- Compton scattering
    - Most common interaction within the energy spectrum of this experiment.
- Pair production
    - At higher energies; i.e., $\sim$ 1022 keV, or twice the rest energy of an electron.

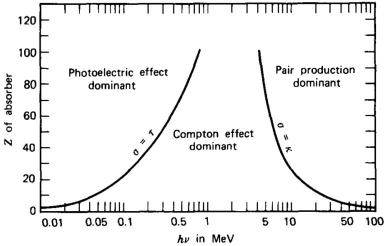


Figure: The relative importance of the three major gamma ray interactions. [Knoll, 2010]

Detector

- Made of sodium iodide (NaI)
- Gamma rays enter and interact with atoms in the crystal lattice
- Gamma energy is transferred to the electrons orbiting each atom, causing them to jump to excited states.
- Electrons de-excite and release visible light photons.
- Visible light photons are captured by photocathode at the entrance to a photomultiplier tube (PMT).

- Initial visible light photon knocks a primary electron from the photocathode into the PMT.
- Primary electron is pulled into an electric field emitted from an anode towards a dynode.
- Electron knocks several additional electrons (roughly 6) out of place upon contact with the dynode.
- The loose electrons are pulled into another, stronger electric field towards another dynode where the process repeats.
- This process occurs ten times in the PMT, which results in $\sim 6^{10}$ electrons being released.

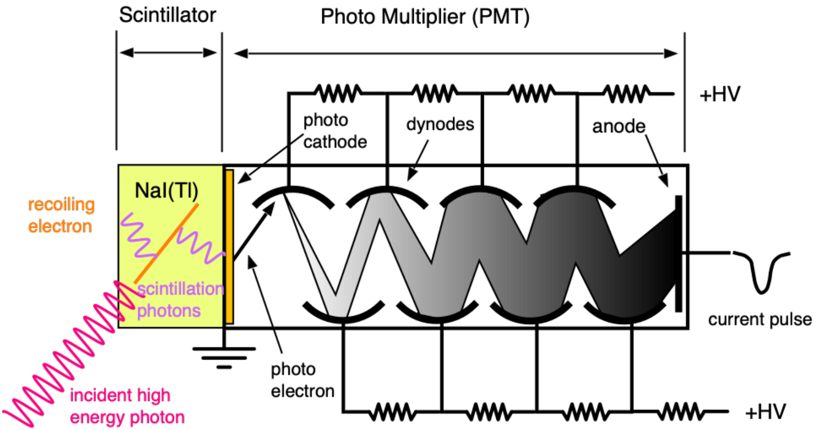


Figure: Diagram of sodium iodide scintillation detector with PMT. [Boeglin, 2023]

- Compton backscatter
  - Compton scatters into detector.
- Compton edge
  - Compton scatters inside detector.
- Full energy peak
  - Full gamma energy absorbed

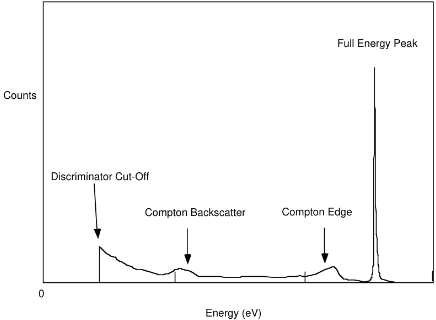


Figure: Typical spectrum for single gamma ray. [Bailey, 2002]

- Analytically identified the most likely locations of the full energy peaks by attempting to identify smaller, ancillary peaks in the data for known substances.
- Used matplotlib.pyplot, numpy, scipy.optimize and scipy.stats python libraries to write code to return specific values associated with each peak.
- For peaks that were more difficult to identify, we took the ratio of a known channel number and corresponding energy to algebraically solve for a likely channel number and used that estimate to focus our code to specific ranges.
- We took the calculated channel numbers and corresponding energies and used linregress() function from scipy to make a line of best fit.

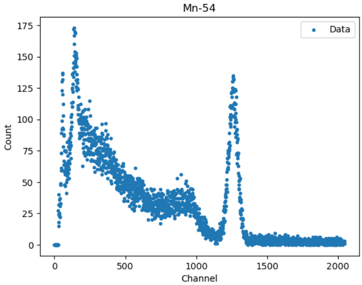


Figure: Spectrum for Mn-54.

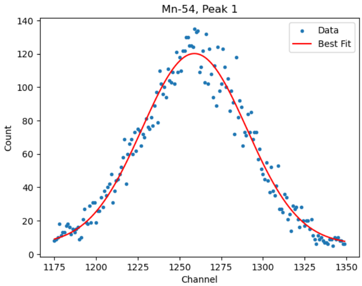
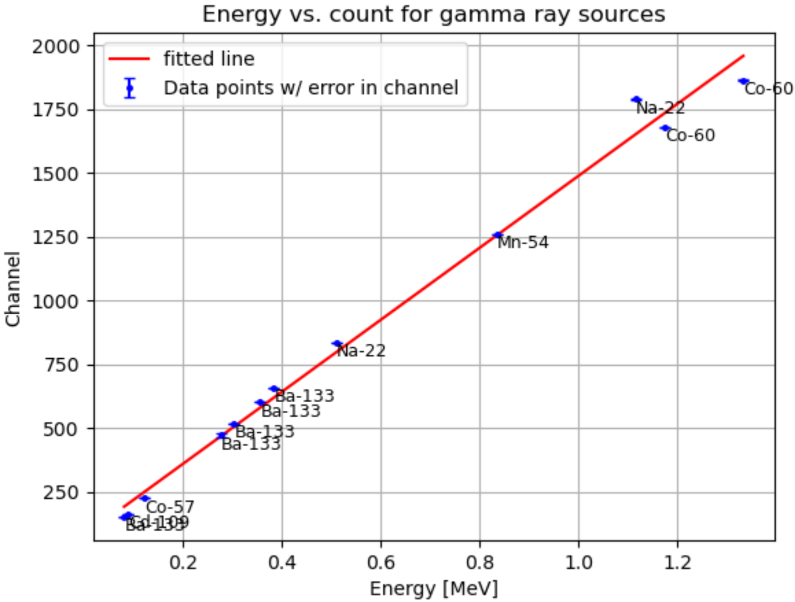


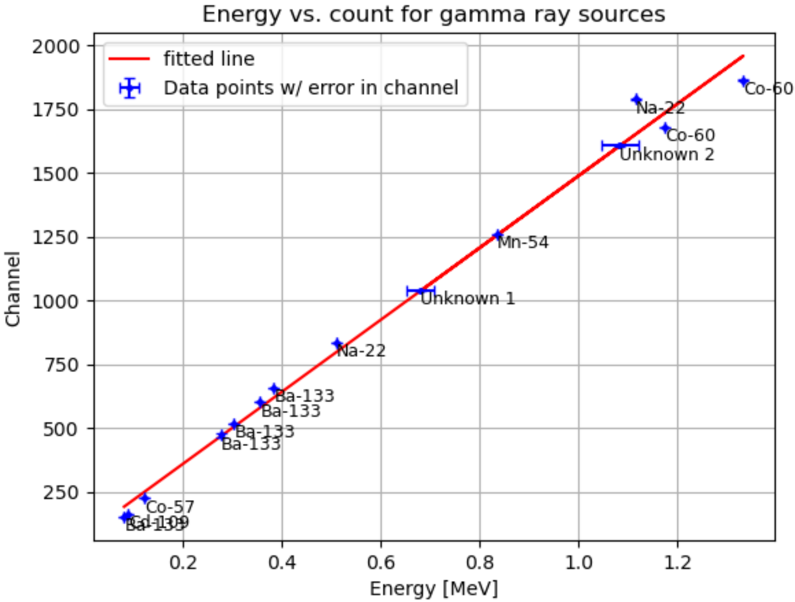
Figure: Peak for single 835 keV gamma ray.


Energy vs. count for gamma ray sources
fitted line
Data points w/ error in channel
Co-60
Na-22
Co-60
Mn-54
Na-22
Ba-133
Ba-133
Ba-133
Ba-133
Co-57
Cd-109
Ba-133
Channel
Energy [MeV]
2000
1750
1500
1250
1000
750
500
250
0.2
0.4
0.6
0.8
1.0
1.2

Finding Unknowns and Error Propagation

- Used similar methods to find the peaks for the unknown compound.
- Error for each channel was calculated using the curve_fit function from the scipy library.
- Used the equation for line-of-best-fit to solve for the unknown gamma peak energies.
  - $C = mE + b$
  - $E = \frac{C - b}{m}$
- Found error in the calculated energies using the below equation for the propagation of error.
  - $\sigma_E = \sum_{i=1}^{n=3} \left(\sigma_i \frac{\partial E}{\partial x_i} \right)^{1/2}$
  - Where x_1, x_2, and x_3 correspond to m, C, and b respectively.

Finding Unknowns and Error Propagation



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Peak 1 is at (E1, C1) = (0.680288864768523 ± 0.028591785162186863, 1037.26734817 ± 0.12423879)
Peak 2 is at (E2, C2) = (1.0835812776221945 ± 0.03783534499638608, 1606.17412676 ± 1.43986508)
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Figure: Energies and Channel Number of the two unknown gamma rays.

- https://atom.kaeri.re.kr/old/gamrays.html

Compton Edge Energy

- Being able to find the energy of the Compton edge could help to more accurately find peaks.
- The energy of the recoiled electron due to Compton scattering can be found using the below equation.
    - $E_{e^-} = h\nu - h\nu' = h\nu \left[\frac{\frac{h\nu}{m_0 c^2}(1 - \cos\theta)}{1 + \frac{h\nu}{m_0 c^2}(1 - \cos\theta} \right]$ [Knoll, 2010]
- There are two extreme cases we can see from this equation:
    1. $\theta \cong 0$, in which $h\nu \cong h\nu'$ and the Compton electron has very little energy while the scattered gamma ray retains nearly full energy.
    2. $\theta = \pi$, in which the gamma ray backscatters towards its direction of origin and the electron recoils in the direction of incidence with the maximum amount of energy that can be transferred in a single Compton interaction.
- In the case where $\theta = \pi$, this gives us the energy of the Compton edge.

References

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