Radiation Spectroscopy with Scintillators
General Considerations in Gamma-Ray Spectroscopy

- γ-Photons are in general, invisible to the absorber material, and only through ionization of fast electron show the character the primary γ particle.
- Thus, energy losses through ionization of electrons and Bremsstrahlung.
- For a detector to serve as a γ-ray spectrometer it must retain two properties:
    1) Acts as a conversion medium in which incident γ-rays have a reasonable probability of interacting to yield one or more fast electrons
    2) Function as a conventional detector for secondary electrons
- In general, this promotes the use of not just scintillators, but other solid and liquid detection media and rules out gas detectors (unless under high pressure). We will focus on the scintillator NaI(Tl), but the discussions can be applied to other materials, accounting for differences and efficiency, etc.

Gamma Ray Interactions

Photoelectric Absorption:

- Dominates the low energy gamma ray interactions and has a cross sectional interaction variation that goes as $Z^{4.5}$.
- The photoelectron generally comes from the K- shell and process is illustrated in the figure on pg. 309.
- Produces characteristic x-rays and Auger electrons
- Low energy x-rays will most likely be absorbed into the detector producing low energy electrons. The sum of the kinetic energies of the electrons is then the energy of the original gamma ray.
- The figure at the bottom of page 309 shows a differential distribution showing the narrow distribution corresponding to the gamma ray photon energy.

Compton Scattering:

- The process is illustrated in the figure on top of pg. 310.
- The energy of the scattered gamma, in terms of the scattering angle θ:

$$h\nu' = \frac{h\nu}{\left[1 + \frac{h\nu}{m_0 c^2}(1 - \cos\theta)\right]}$$

  $m_o c^2$ is the rest mass of the electron.
- The kinetic energy of the scattered electron is:

$$E_{e^-} = h\nu - h\nu' = h\nu\left[\frac{\frac{h\nu}{m_0c^2}(1-\cos\theta)}{1+\frac{h\nu}{m_0c^2}(1-\cos\theta)}\right]$$

- Look at the two extreme cases:
  1) Grazing angle scattering, $\theta \cong 0$:
     $h\nu' \cong h\nu, \quad E_{e^-} \cong 0;$ so the recoil electron has almost no energy, and the incident γ-ray has about the same amount of energy as the scattered γ-ray.
  2) Head on collision, $\theta = \pi$; gamma ray is backscattered and electron scatters along angle of incidence. This is the maximum transfer of energy to the electron:

$$h\nu'\big|_{\theta=\pi} = \frac{h\nu}{1+2h\nu/m_0c^2}; \quad E_{e^-}\big|_{\theta=\pi} = h\nu\left[\frac{2h\nu/m_0c^2}{\left(1+2h\nu/m_0c^2\right)}\right]$$

- At the bottom of pg. 310, the Compton edge is illustrated. The gap between the Compton edge and the photopeak (hν):

$$E_e = h\nu - E_e\big|_{\theta=\pi} = \frac{h\nu}{\left(1+2h\nu/m_0c^2\right)} = \left(\frac{1}{h\nu}+\frac{2}{m_0c^2}\right)^{-1}$$

- In the limit of large x-ray energy ($h\nu >> \frac{m_0c^2}{2}$) then $\frac{1}{h\nu} << \frac{2}{m_0c^2}$:

$$E_C = \frac{m_0c^2}{2} = 256 \quad keV$$

- The sharp features of the Compton plot are rounded by:

  1) Compton scattering involves electrons which are bound, not just free electrons
  2) Energy resolution of the detector
  3) Finite momentum of orbital electrons (as opposed to single energy)

Pair Production

- Occurs in the intense electrical field surrounding the protons in the nuclei of the absorbing material
- The energy threshold of production is twice the electron mass (rest).
- The gamma ray is converted into an electron-positron (e^+) pair, where the sum of the kinetic energies is:

$$E_{e^-} + E_{e^+} = h\nu - 2m_0c^2$$

- When all the energies of the electron-positron contribute to the scintillation, the energy shows up as a line below the photopeak by twice the rest mass of the electron.
- The positron is unstable and will likely annihilate with an electron, where the resulting two gamma photons (1.02 MeV) are not absorbed by the detector, thus only the combined kinetic energy of the electron-positron pair is registered at the double escape peak. ($h\upsilon - 2m_0c^2$)

Predicted Response Functions

Small Detectors:

- Figure 10.2 illustrates the possible interactions and resulting spectrum of a small detector, note the Compton spectrum, photopeak, and double escape peak (at higher energies)

Very Large Detectors:

- Figure 10.3 illustrates the interactions and spectrum of a very large detector (where the entire energy of the gamma photon is absorbed including all secondary photons and electrons; the result is the photopeak (full energy peak)

Intermediate Sized Detectors:

- Figure 10.4 illustrates the interactions and response of "real" sized detectors where one or both annihilation gammas can escape the detector; the spectrum shows the full energy peak, double and single escape peaks, and the Compton continuum and several Compton scattering events between the Compton edge and the full energy peak.

Complications in the Response Function:

- Secondary electron escape: When the detector is small compared to the range of the secondary electrons, these electrons can escape
- Bremsstrahlung Escape: electrons can lose energy by Bremsstrahlung process (probability approximately z^2) and the generated x-rays escape.
- Characteristic x-ray escape: Shown in the figure on top of pg. 318, the photoelectric absorption forms a characteristic x-ray which escapes.
- Occurs below the full energy peak by the energy of the characteristic x-ray, and is likely for detectors with large surface to volume ratios.
- Secondary radiations created near the source: (figure 10.6) processes happen within surrounding materials which give rise to characteristic x-ray peak, backscatter peak, and annihilation peak.
    a) Annihilation Radiation – may see 511 keV photon from precursor interaction or 1.022MeV (if detector geometry is favorable).
    b) Bremsstrahlung - β^- particles from primary radiation may interact with surrounding materials, producing detectable x-rays.
- Effects of surrounding materials
    1) Backscattered gamma rays – the energy of backscattered gamma rays have the energy $h\nu'|_{\theta=\pi}$ and appear as a backscatter peak.

$$h\nu'\big|_{\theta=\pi} = \frac{h\nu}{\left(1 + 2h\nu / m_0c^2\right)}$$

and for the limit $h\nu \gg m_0c^2$, then $\frac{1}{h\nu} \ll \frac{2}{m_0 c^2}$

$$h\nu'\big|_{\theta=\pi} = \frac{m_0 c^2}{2} = 256 \quad keV$$

- Thus the back scatter peak occurs at 256 keV or less.
  2) Other secondary radiations – can also detect a characteristic x-ray from gamma ray interactions with neighboring materials, or a positron which escapes from the detector and annihilates in the neighboring material. If one photon registers it will be at 511 keV, and if both at 1.022MeV.

Summation Effects:

- Two gamma rays may be detected simultaneously with the sum of their energies registered as one event. (figure 10.8 shows a decay scheme which might lead to such an event).
- True coincidence is when the two gammas emitted simultaneously are detected.
- The full energy peaks for the two gammas without summing are:

$$N_1 = \varepsilon_1 \Omega S y_1; \quad N_2 = \varepsilon_2 \Omega S y_2$$

  Where ε_1 and ε_2 are the intrinsic peak efficiencies of the detector, Ω is the fractional solid angle subtended by the detector (steradians/4π), S is the number of source decays and y_1 and y_2 are the yields (Intensities or branching ratios) of gammas per decay.
- The probability of detecting both gammas in the same detection is the product of the above probabilities and a modified angular correlation between the two γ's:

$$N_{12} = S(\varepsilon_1 \Omega y_1)(\varepsilon_2 \Omega y_2) W(0^\circ) = S \varepsilon_1 \varepsilon_2 y_1 y_2 \Omega^2 W(0^\circ)$$

  Where W (0^o) is the relative yield of γ_2 per unit solid angle about the direction (0^o) defined by the detector position, e.g. W(0^o) = 1 for no correlation.

- The remaining number of full energy events for γ_1 becomes:

$$N_1\big|_{with\ \ summation} = N_1 - N_{12} = \varepsilon_1 \Omega S y_1 \left[1 - \varepsilon_2 \Omega S y_2 W(0^\circ)\right]$$

  Similar for the full peak energy of γ_2.
- This is for a ***true*** coincidence counting.
- A chance coincidence occurs if a second pulse arrives within a resolving time, t_r, following a typical signal pulse
- For random pulse rate, r_s, and $r_s t_r \ll 1$, the total amount of resolving time associated with r_s is approximately $r_s t_r$.
- The expected pulses arriving within this interval are:

$$r_{ch} = r_s (r_s t) = r_s^2 t$$

- Therefore accidental sum peaks will $\propto r_s^2$ where true sum peaks and photopeaks will $\propto r_s$.

Coincidence Methods in Gamma Ray Spectrometers:

- Continuum reduction: use of surrounding detectors to reject (anti-coincidence) Compton scattered events.
- The Compton spectrometer: (Fig 10.9 shows a schematic of a Compton spectrometer, where a second detector at an angle to detect the scattered photon)
- Selecting an angle (coincidence of scattered photon with absorbed energy) means selecting only Compton scattered photons of a certain energy.