Lecture 22
Properties of Scintillation Gamma Ray Spectrometers

Response function:

- Fig 10.12 shows two sources ^{86}Rb (1.08 MeV) and ^{60}Co where there is coincidence peaks for two energies (1.17 MeV and 1.33 MeV) with a sum peak at 2.5 MeV
- Fig 10.13 shows a spectrum with many standard features apparent in the spectrum (^{24}Na source)
- Fig 10.14 compares a NaI(Tl) and BGO detectors for both efficiency and resolution (higher resolution NaI(Tl), better efficiency BGO)

Energy resolution (R)
- Defined as R = FWHM/H_0, FWHM is the full width at half maximum of the pulse and H_0 is the mean pulse height corresponding to the same peak.

Origin of resolution loss: charge collection statistics, electronic noise, variations in the detector response over its active volume, drifts in operating parameters over the course of measurement
- Fluctuations in PM tube gain from event to event
- Departure from exact proportionality between absorbed particle energy and light yield (non linearity of the scintillation material)

Photoelectron statistics: note the diagram on page 330, where 20K photons are produced but only 3K photoelectrons are generated.

Noise characteristics ($\sqrt{N}$) is limited by the number of photoelectrons

Poisson statistics: $R \equiv FWHM/H_0 = K\sqrt{E}/E = K/\sqrt{E}$, K is a constant of proportionality

$\ln R = \ln K - \frac{1}{2}\ln E$, therefore *lnR* vs *lnE* should produce *m* = -1/2

Note Fig 10.17, where data show a relation of a straight line but not as steep as m = -1/2, better approximation:

$R = (\alpha + \beta E)^{1/2} / E$, where α and β are constants particular to any scintillator / PMT combination.

Other factors in Energy Resolution:

- Intrinsic crystal resolution, uniformity of crystal and non linearity response to electron energy
- Effects of the PM tube, statistical fluctuation of the electron multiplication
- Transfer variance – uniformity of photoelectron collection from the cathode

Prevention of resolution loss caused by long term drift:

- Use electronic monitoring for a single isolated peak to derive an error signal
- Provide a reference light source (for scintillators) to generate false peak feedback and monitor and modify gain over time to prevent drift

Linearity:

- Ideal scintillators would have a constant scintillations efficiency (dL/dE) giving a perfectly linear response (a given amount of light produces from a given energy of a particle)
- Reality produces Fig 10.19 where there is some dependence of an energy normalized pulse height with energy. This leads to 10.20 which produces a non constant light output (energy normalized) per particle energy. Note the dip in 10.20 is from K shell absorption

Detection efficiency:

- Crystal shapes – how much of the detector intersects the trajectory of the radiation
- Efficiency data – plots of detector efficiency accounting for all general components of loss, plots 10.22 and 10.23 shows the calculated efficiency for a right cylindrical and well detector 9 absolute total efficiency) while 10.24 shows the intrinsic total efficiency vs detector thickness.

Peak area determination:

- Fig 10.29 shows a peak on top of a continuum, where the continuum is negligible.
- The simplest method is a linear interpolation between the continuum values on either side of the peak :

$$Peak\ Area = \left(\sum_{i=A}^{B} C_i \right) - (B - A)^{(C_A + C_B)/2},$$

  for a peak that lies between energy bin A to energy bin B (channel A toB) and C_i is the number of counts in bin *i*

Can also use mathematical models (e.g Gaussian or Lorentzian) distribution

Response of Scintillation detectors to Neutrons

In NaI(Tl) and BGO, prompt pulses are principally caused by the detection of γ-rays produced in inelastic scattering interactions of the neutron with the scintillator.

Delayed pulses can be triggered by two categories of events

1. Neutron is moderated (requiring ~ 100 μs) and then captured. γ-rays can be emitted in capture

2. Neutron capture produces a radiative species that subsequently decays. Examples in NaI : ^{24}Na ($T_{1/2}$ = 15 hr) and ^{128}I ($T_{1/2}$ = 25 min). examples in BGO : ^{75}Ge ($T_{1/2}$ = 83 min) and ^{77}Ge ($T_{1/2}$ = 11.3 hr)

Electron Spectroscopy with Scintillators

- For scintillator with a thickness greater than the range of the electron, the response functions generally show a full energy peak with a tail in the lower energy
- Fig 10.31 shows a response curve (pulse height spectra) for a 1.0 MeV electrons on a plastic scintillator
- The major cause of the lower energy events are from backscattering, where the electron re emerges from the surface through which it entered after having undergone only partial energy loss. Another possibility is where the electron losses some energy to the scintillator and some to bremsstrahlung
- Both the probability of back scattering and the fraction of energy loss due to bremsstrahlung increase markedly with the atomic number of the scintillator
- Note table 10.1 with the listing of the fractionally backscattered electrons from various detector surfaces

Specialized Detector Configuration Based Scintillation

Phoswich detector (Phosphor sandwich):

- Combination of two dissimilar (different decay time) scintillators optically coupled to the PMT
- The shape of the output pulse is dependent on the relative contribution of scintillation light
- An example is lightly penetrating radiation is stopped in the first material while more penetrating goes through both. Signal processing can then sort out the types (e.g. NaI & CsI, BGO & CsI, different plastic scintillators, CsI(Na) and GSO, BGO & GSO, YSO & CSO)
- Can use a tin fast scintillator in front of a thick slow scintillator to measure dE/dx and E
- α- β particle probe thin ZnS(Ag) screen mounted behind the entrance window to detect and stop α particles, then a plastic scintillator to detect β particles

Moxon Ral Detector:

- a combination of a converter (converting γ-rays to secondary electrons) and scintillation detector
- example is a thick low Z converter and a thin plastic scintillator
- the detection efficiency could be made nearly proportional to the incident γ-ray energy, allowing for a simplified analysis of some classes of experimental neutron detection

Liquid Scintillator Counter:

- also called an internal source counting (a sample dissolved in a scintillation fluid)
- color quenching- sample alters the optical properties of the solution
- other types of quenching – sample interferes with energy transfer process within the scintillator
- noise in the system stem from long lived phosphorescence in the scintillator, chemiluminescence (light generated from chemical reactions within the sample-scintillator solution)

Position sensitive scintillator:

One dimensional position sensing:

- diagram on top of pg 347 shows a scintillator of length L with two PMT's on either end
- light is observed to drop off exponentially with distance from where the light is generated
- the number of photons created by a γ particle is E_γ / E_0 where E_γ is the energy of the γ and E_0 is the average energy deposited in the scintillator to create one photon
- suppose the γ creates scintillation at point *x*, and light is attenuated as it propagates to the PMT in the positive or negative direction
- the signal to PMT (1) (negative *x* direction) is:

$$E_1 = \frac{E_\gamma P}{E_0} \exp[-\alpha(L/2 + x)],$$

where P is the probability that a light quantum incident on a PMT will produce a photoelectron and α is the light attenuation coefficient
Similarly for PMT (2)

$$E_2 = \frac{E_\gamma P}{E_0} \exp[-\alpha(L/2 - x)]$$

Taking the ratio of the information from the PMT's we can get the position information

$$\frac{E_2}{E_1} = \frac{\exp[-\alpha(L/2 - x)]}{\exp[-\alpha(L/2 + x)]} = e^{+2\alpha x}$$

$$\Rightarrow \ln\frac{E_2}{E_1} = 2\alpha x \Rightarrow x = \frac{1}{2\alpha}\ln\left(E_2/E_1\right)$$

By multiplying the two PMT signals

$$E_1E_2 = \frac{E_\gamma P}{E_0}\exp\left[-\alpha\left(L/2 - x\right)\right]\frac{E_\gamma P}{E_0}\exp\left[-\alpha\left(L/2 + x\right)\right] = \left(\frac{E_\gamma P}{E_0}\right)^2 e^{-\alpha L}$$

Solve for the energy of the γ (E_γ)

$$E_\gamma = \sqrt{E_1E_2}\left(E_0/P\right)e^{\alpha L/2}$$

Note that this is a quantity proportional to the energy of the γ and independent of position

Two Dimensional Position sensing:

These are the basis of image detectors (gamma camera)
Fig 10.32 shows the elements of two dimensional position sensitive scintillation detectors (gamma camera, scintillation camera or Anger camera)