Radiological Sciences @ OUHSC

Radiation Detection and Measurement

Lecture 22

Chapter 10: Radiation Spectroscopy with Scintillators

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)

Response function

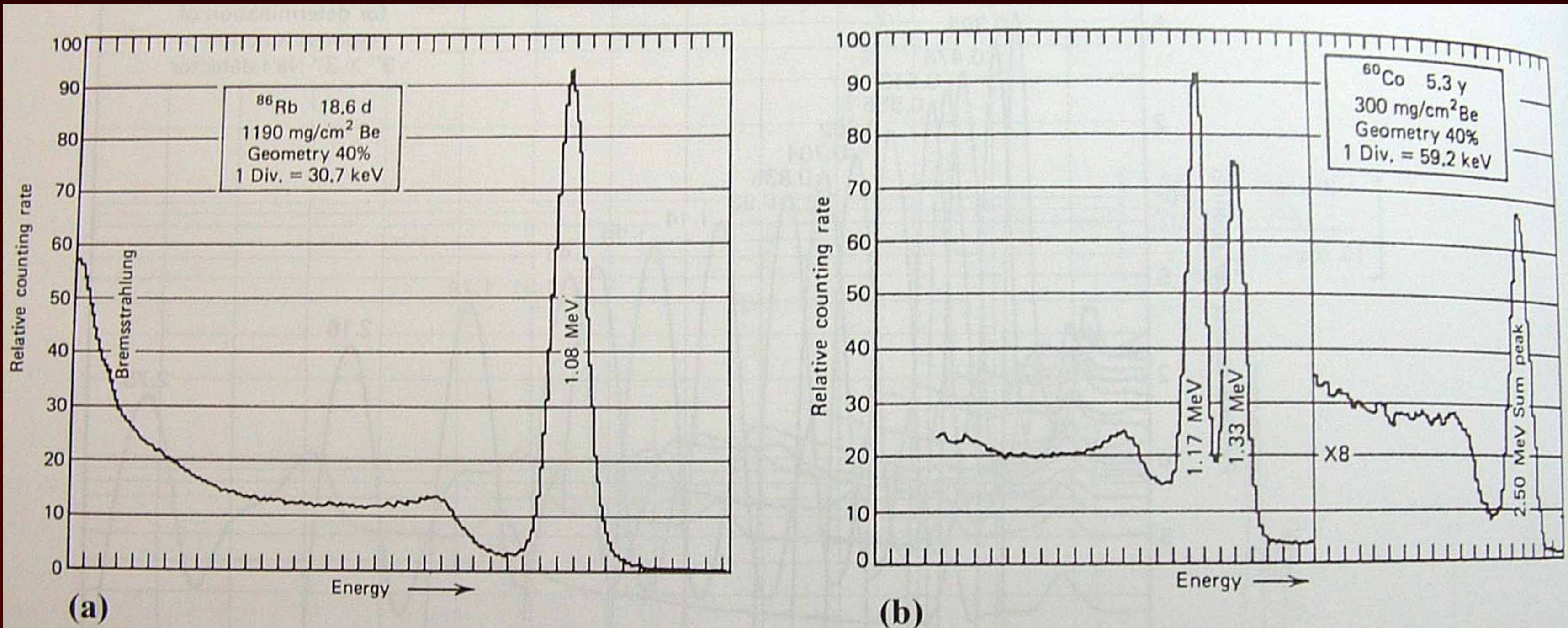

Figure 10.12 Pulse height spectra recorded from NaI(Tl) scintillation detectors. (*a*) A spectrum for a ^{86}Rb source (1.08 MeV gamma rays) showing the contribution at the lower end of the scale from bremsstrahlung generated in stopping the beta particles emitted by the source. (*b*) Spectrum from a ^{60}Co source (1.17 and 1.33 MeV gamma rays emitted in coincidence) taken under conditions in which the solid angle subtended by the detector is relatively large, enhancing the intensity of the sum peak at 2.50 MeV. (From F. Adams and R. Dams, *Applied Gamma-Ray Spectrometry*, 2nd ed. Copyright 1970 by Pergamon Press, Ltd. Used with permission.)

Response function

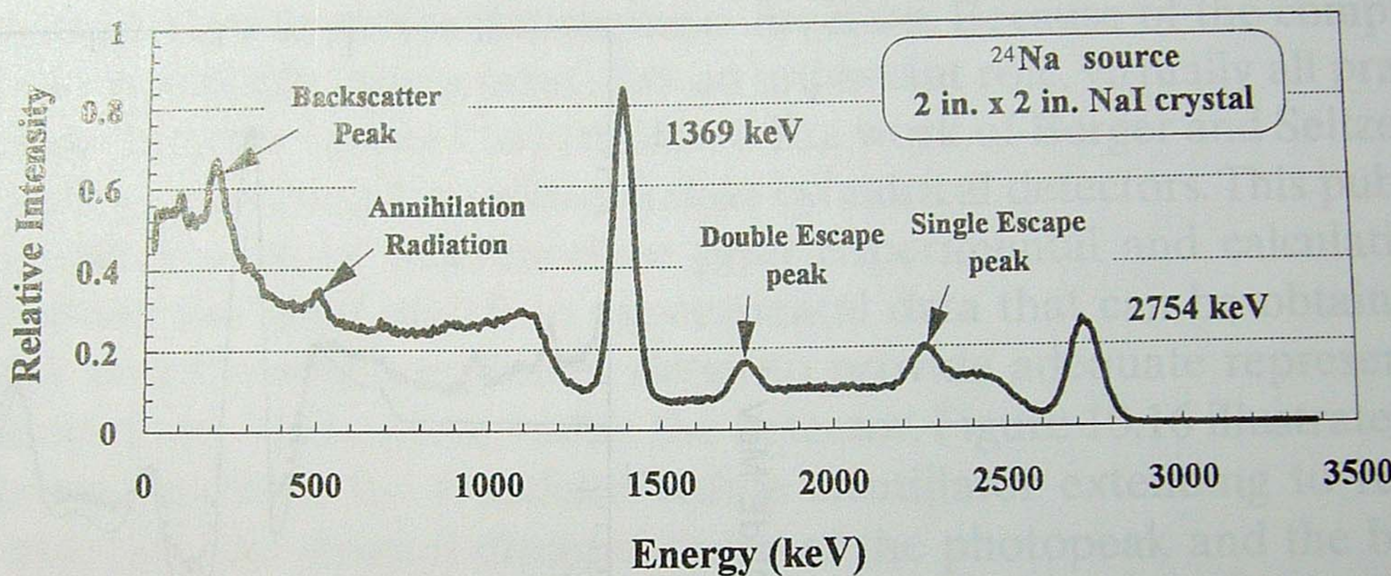

Figure 10.13 Pulse height spectrum from a NaI(Tl) scintillator for gamma rays emitted
^{24}Na at 1369 and 2754 keV. The single and double escape peaks corresponding to pair p
duction interactions of the higher energy gamma rays are very apparent, as is the annihilat
radiation peak at 511 keV due to pair production interactions in surrounding materials.

Response function

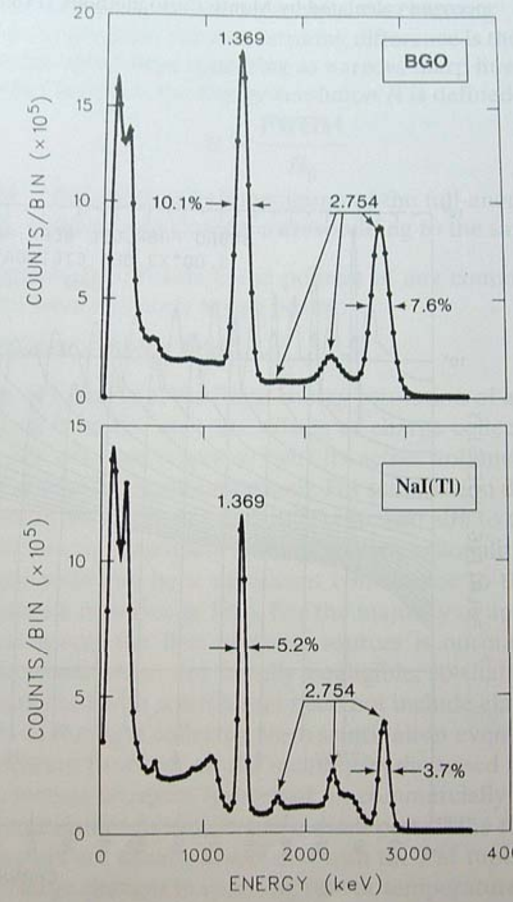

Figure 10.14 Comparative pulse height spectra measured for BGO (top) and NaI(Tl) (bo scintillators of equal 7.62 cm × 7.62 cm size for gamma rays from ^{24}Na. (From Moss et al.[1]

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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.

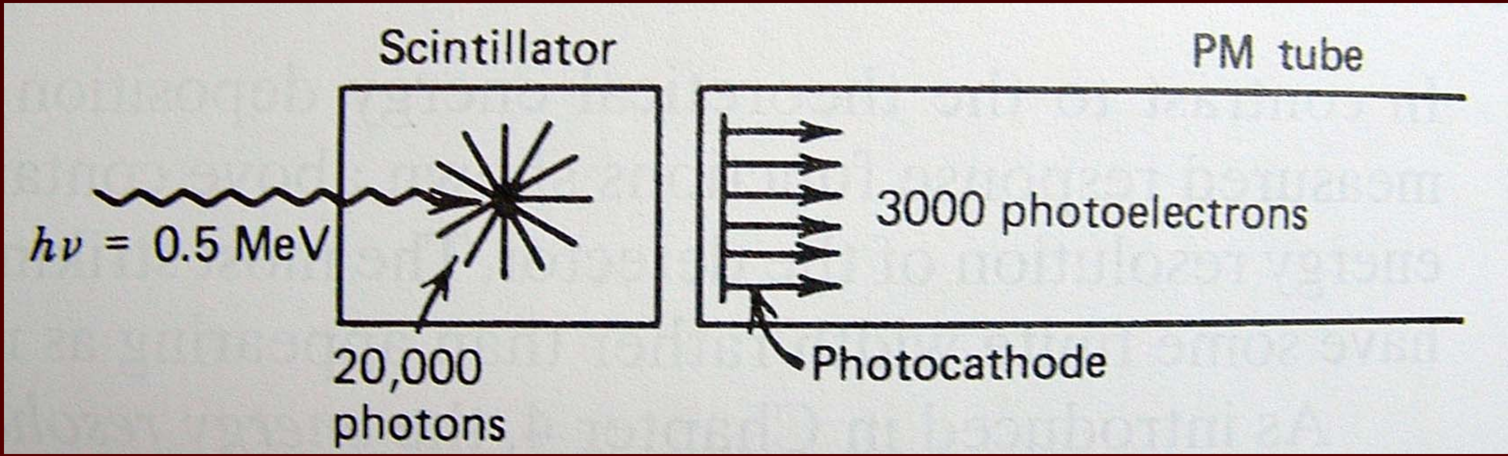
Energy resolution (R)

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)

Energy resolution (R)

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



Energy resolution (R)

- 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

Energy resolution (R)

$$\ln R = \ln K - \tfrac{1}{2} \ln E$$

- therefore *ln R* vs *ln E* 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:

$$R = \left(\alpha + \beta E\right)^{1/2} / E$$

  - where α and β are constants particular to any scintillator / PMT combination.

Energy resolution (R)

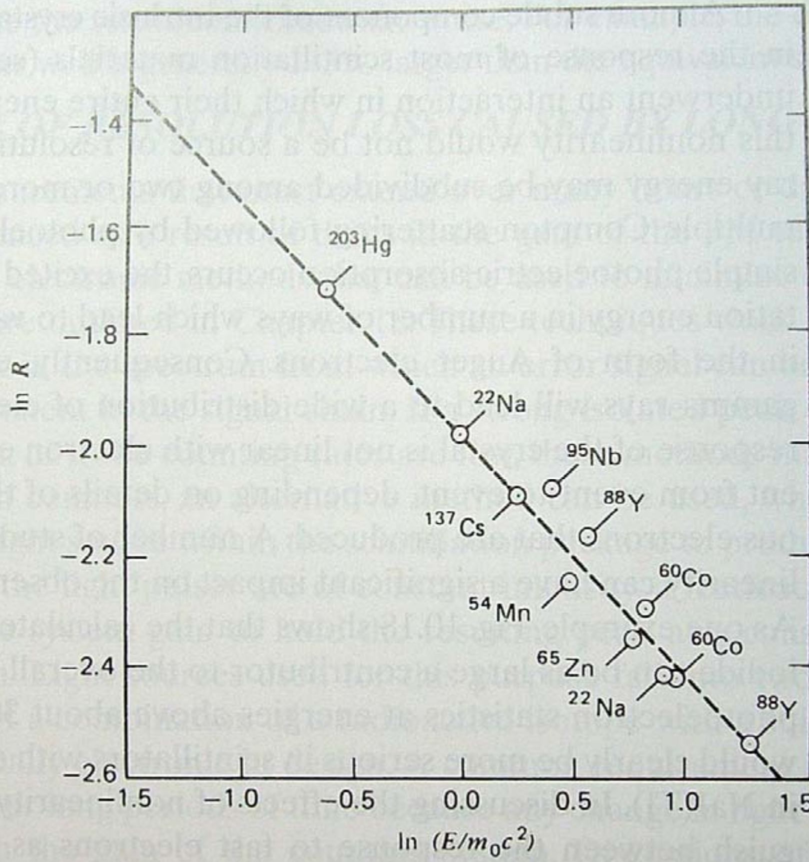


Figure 10.17 Experimentally measured resolution R from a NaI(Tl) scintillation detector for various gamma-ray energies E. (From Beattie and Byrne.[16])

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Energy resolution (R)

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

Energy resolution (R)

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

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)

Linearity

- 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

Linearity

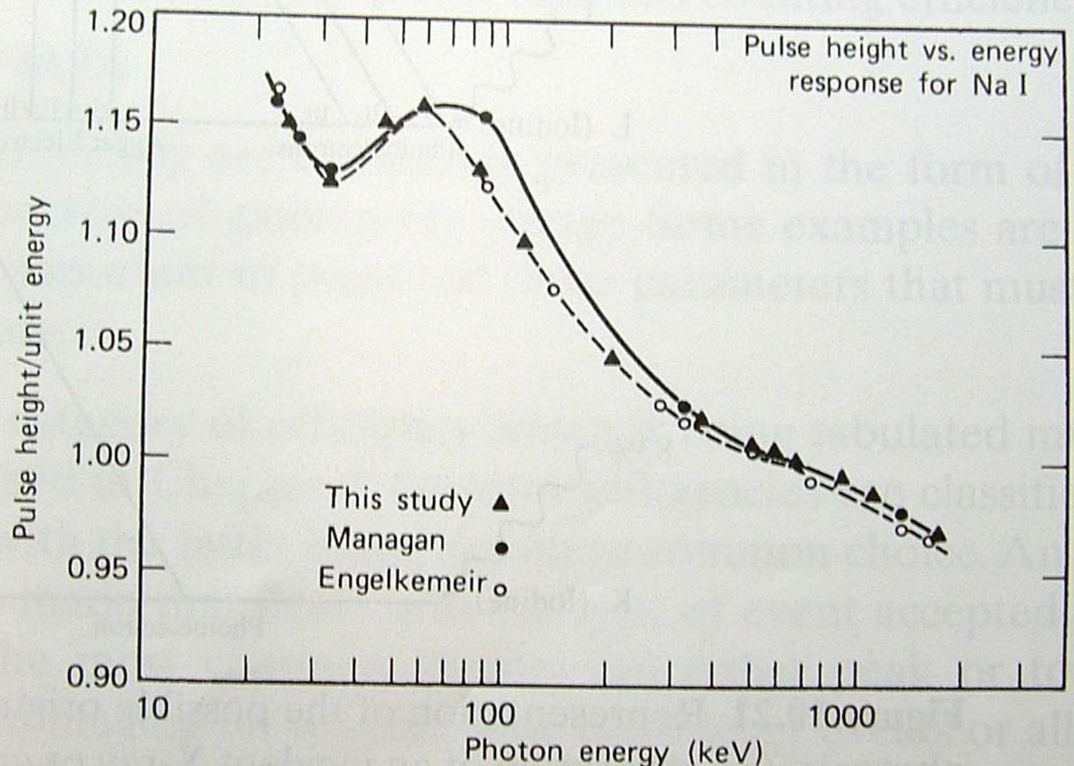

Figure 10.19 The differential linearity measured for a NaI(Tl) scintillator. (From Heath.[5])

Linearity

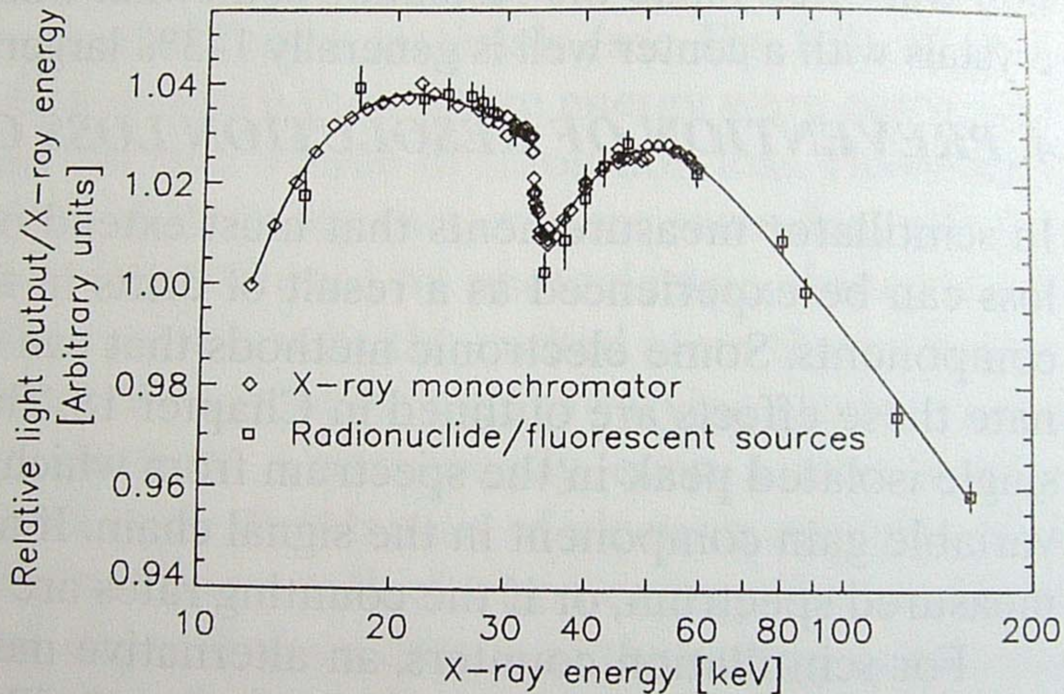

Figure 10.20 Measured light output per unit deposited energy for NaI(Tl), normalized to unity at 88 keV. (From Wayne et al.[26])

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.

Detection efficiency

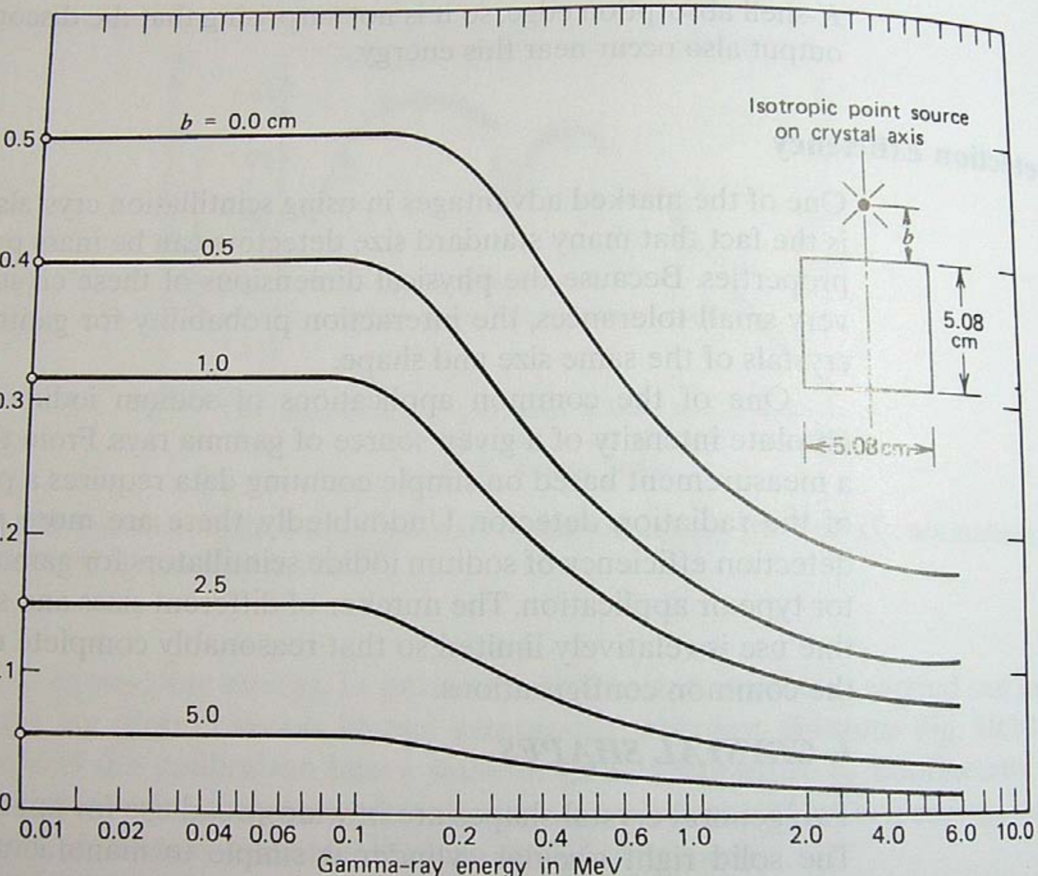

Figure 10.22 The absolute total efficiency calculated for a 5.08 cm × 5.08 cm solid cylindrical NaI(Tl) scintillator. Different values of the source location are shown. (From Snyder.[28])

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Detection efficiency

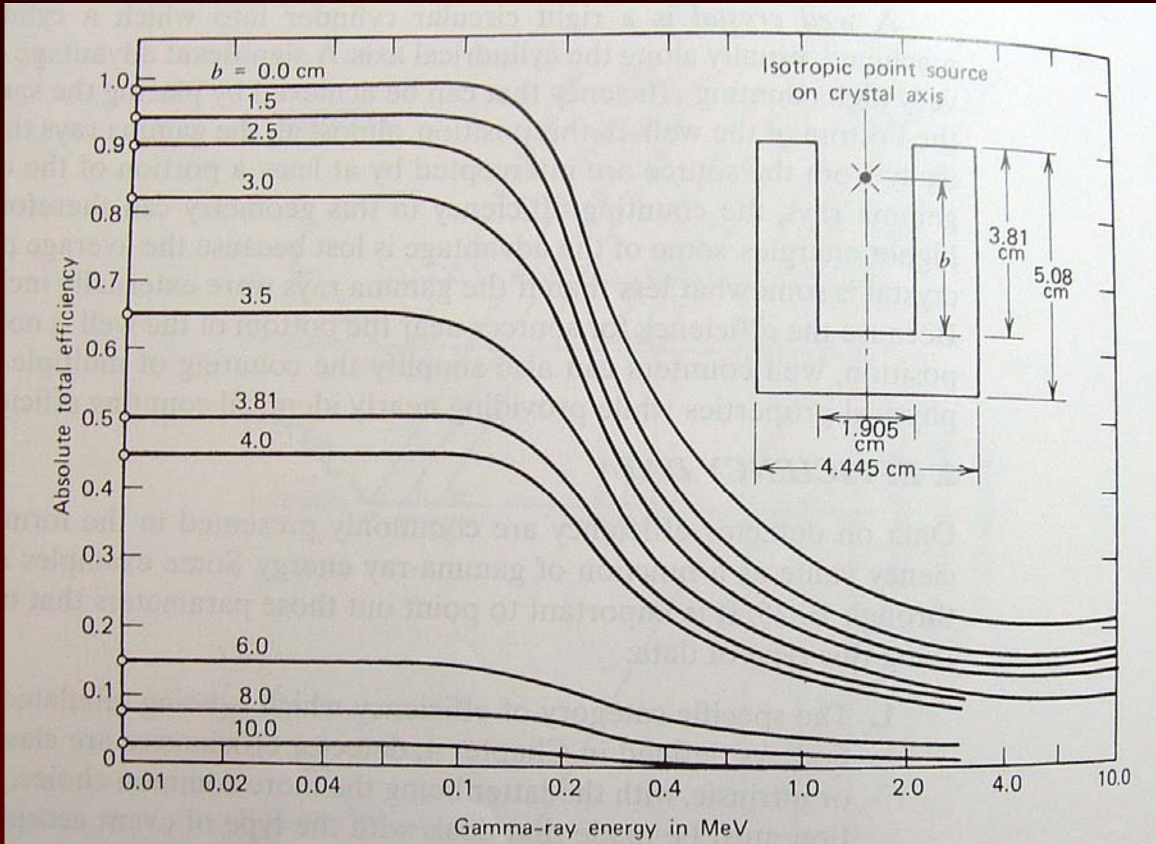

Figure 10.23 The absolute total efficiency calculated for a point gamma-ray source and a NaI(Tl) well-type scintillator with the dimensions shown. The parameter b is the source height above the well bottom. (From Snyder.[28])

Detection efficiency

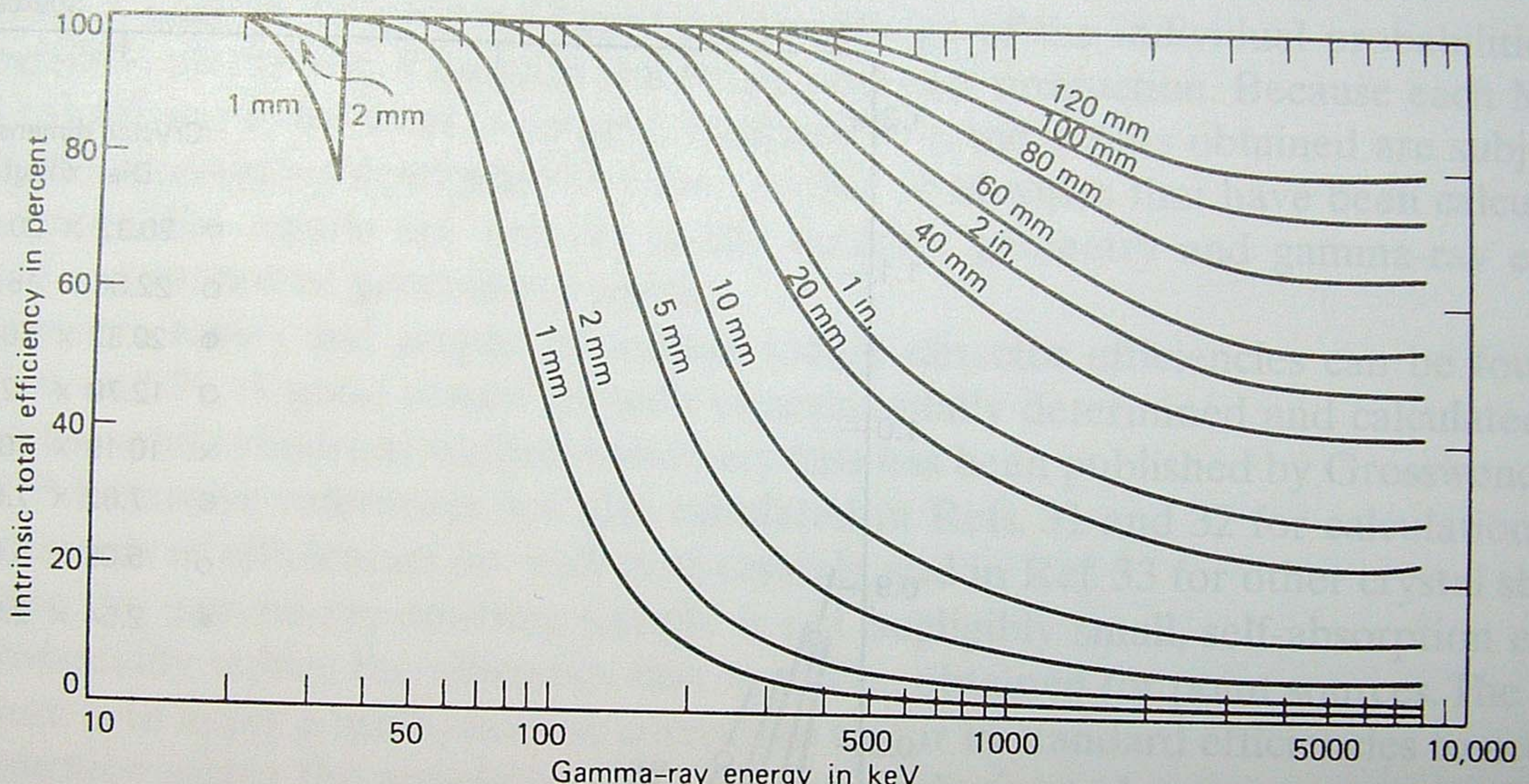

Figure 10.24 The intrinsic total efficiency of various thicknesses of NaI(Tl) for gamma rays perpendicular to its surface.

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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 Ci is the number of counts in bin *i*
- Can also use mathematical models (e.g Gaussian or Lorentzian) distribution

Peak area determination

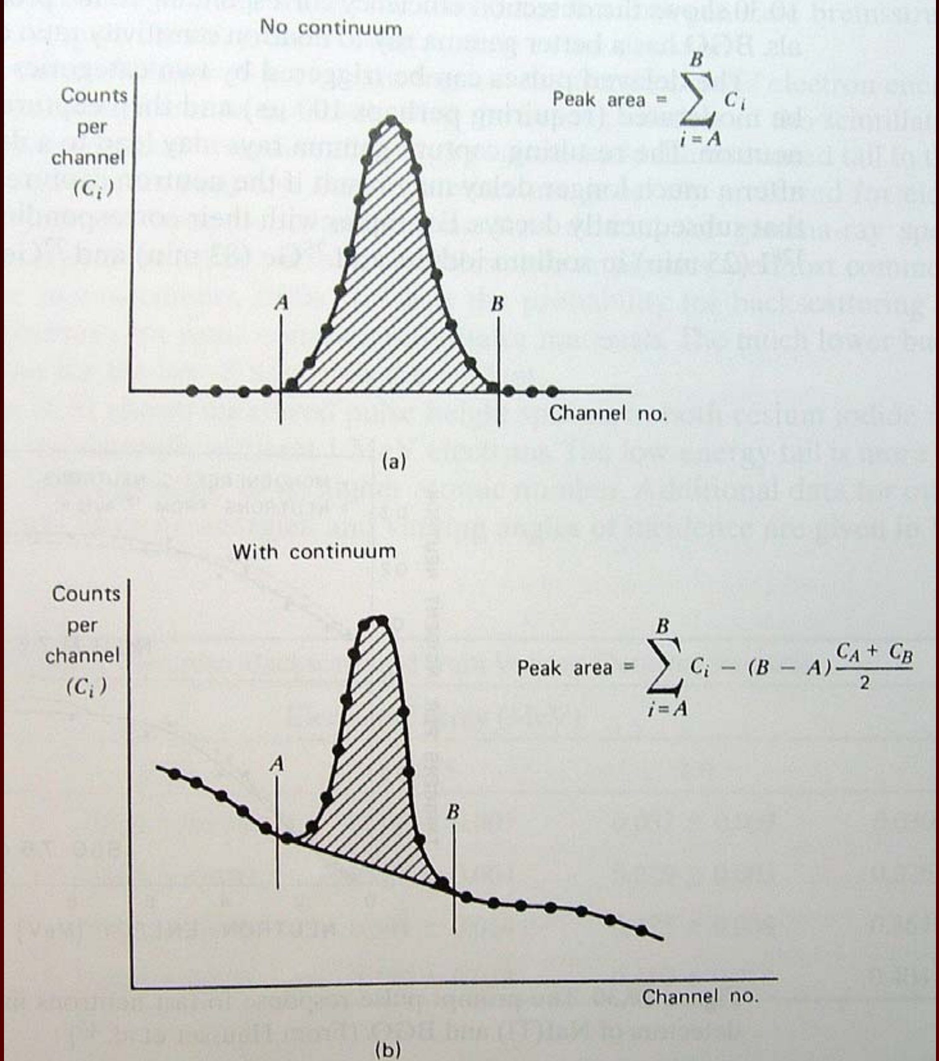

Figure 10.29 Methods of obtaining peak areas from multichannel spectra. In part (*a*) the continuum under the peak present in part (*b*) is negligible.

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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.

Response of scintillation detectors to neutrons

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

Electron spectroscopy with scintillators

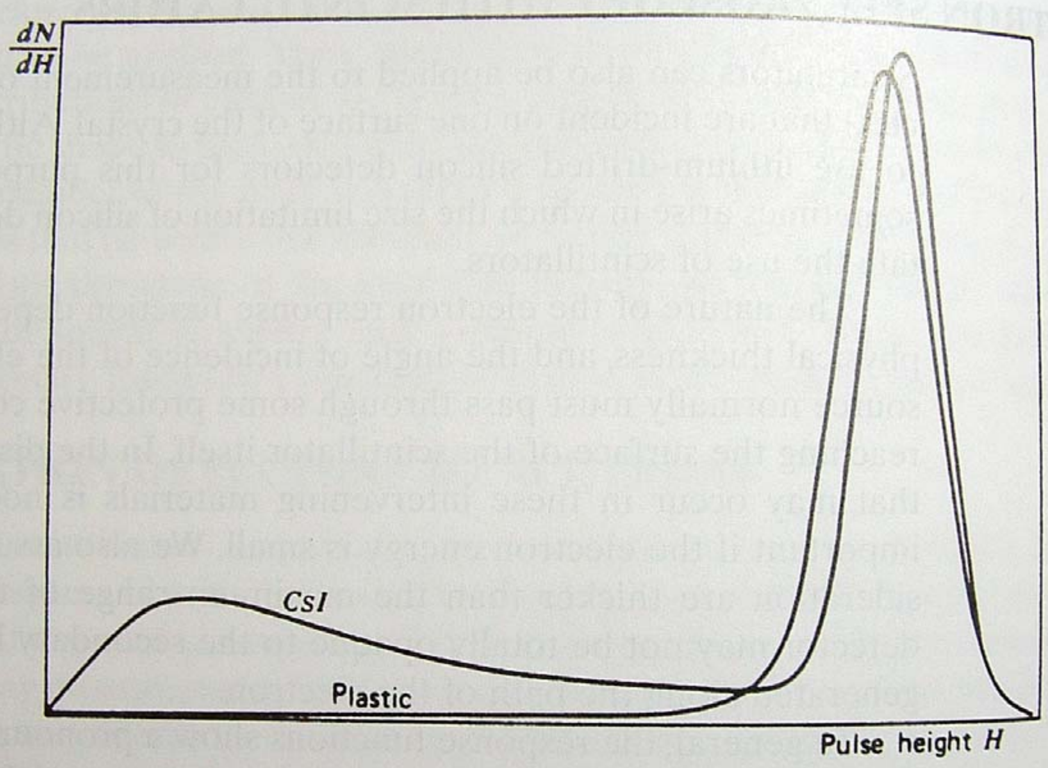

Figure 10.31 Experimental pulse height spectra from CsI(Tl) and plastic scintillators for 1.0 MeV electrons at normal incidence. The spectra are normalized to the same maximum pulse height. (From Titus. 47)

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Electron spectroscopy with scintillators

- 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

Electron spectroscopy with scintillators

- 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

Electron spectroscopy with scintillators

Table 10.1 Fraction of Normally Incident Electrons Backscattered from Various Detector Surfaces

Scintillator	Electron Energy (MeV) 0.25	0.50	0.75	1.0	1.25
Plastic	0.08 ± 0.02	0.053 ± 0.010	0.040 ± 0.007	0.032 ± 0.003	0.030 ± 0.005
Anthracene	0.09 ± 0.02	0.051 ± 0.010	0.038 ± 0.004	0.029 ± 0.003	0.026 ± 0.004
NaI(Tl)	0.450 ± 0.045	0.410 ± 0.010	0.391 ± 0.014	0.375 ± 0.008	0.364 ± 0.007
CsI(Tl)	0.49 ± 0.06	0.455 ± 0.023	0.430 ± 0.013	0.419 ± 0.018	0.404 ± 0.016

Source: Titus.[47]

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

Specialized detector configuration based scintillation

- 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)

Specialized detector configuration based scintillation

- 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

Specialized detector configuration based scintillation

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

Specialized detector configuration based scintillation

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

Specialized detector configuration based scintillation

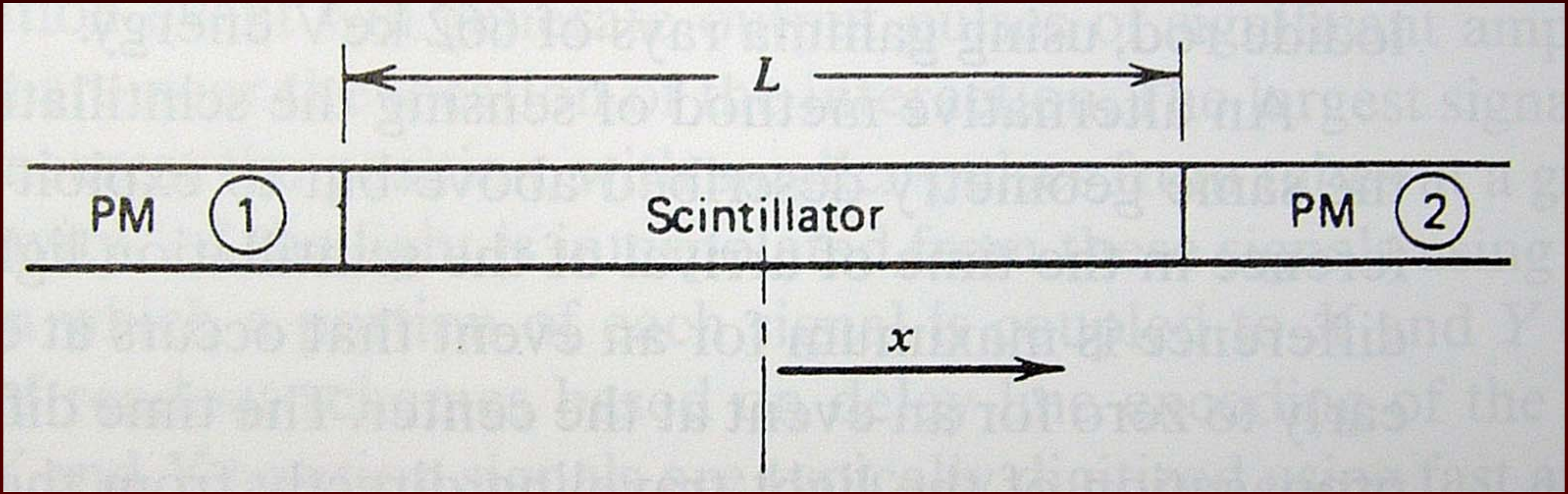
- other types of quenching – sample interferes with energy transfer process within the scintillator
- noise in the system stem from long lived phosphorescence in the scintillator, chemiluminescence (light generated from chemical reactions within the sample-scintillator solution)

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

Position sensitive scintillator



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Position sensitive scintillator

- 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

Position sensitive scintillator

- the signal to PMT (1) (negative *x* direction) is:

$$E_1 = \frac{E_\gamma P}{E_0} \exp[-\alpha\left(L/_2 + x\right)]$$

  - where P is the probability that a light quantum incident on a PMT will produce a photoelectron and α is the light attenuation coefficient

Position sensitive scintillator

- Similarly for PMT (2) :

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

Position sensitive scintillator

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

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

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

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Position sensitive scintillator

- By multiplying the two PMT signals:

$$E_1 E_2 = \frac{E_\gamma P}{E_0} \exp\left[-\alpha\left(L/2 - x\right)\right] \frac{E_\gamma P}{E_0} \exp\left[-\alpha\left(L/2 + x\right)\right]$$

$$= \left(\frac{E_\gamma P}{E_0}\right)^2 e^{-\alpha L}$$

Position sensitive scintillator

- Solve for the energy of the γ (E_γ)

$$E_\gamma = \sqrt{E_1 E_2}\left(E_0 / P\right) e^{\alpha L / 2}$$

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

Position sensitive scintillator

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)

Position sensitive scintillator

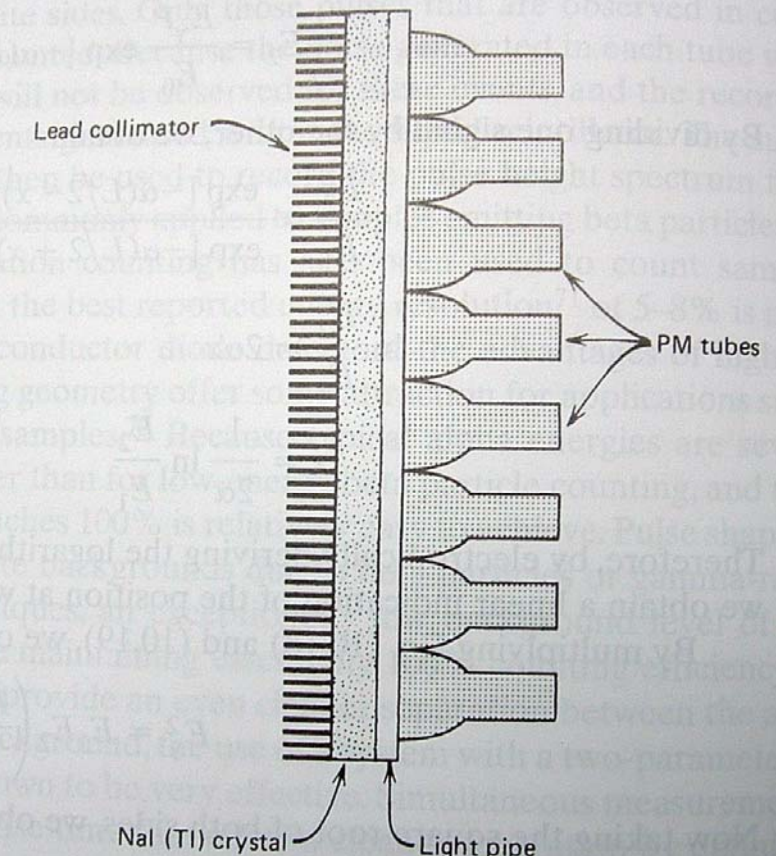

Figure 10.32 Elements of a two-dimensional position-sensitive scintillation detector, commonly called a *gamma camera*.

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