Spectroscopy refers to the measurement of the *energy* of the radiation.

Charged particles: the light output was shown to be proportional to the range of the particles and so each measurement of each particle at each energy requires a calibration – limiting the applicability.

$$\frac{dL}{dx} = \frac{S}{kB} \quad when \quad \frac{dE}{dx} \text{ is large}$$

Neutrons: primarily detected with organic scintillators and interact by scattering from hydrogen or capturing on seed materials. The scattering leaves varying amounts of energy in the material (depending on kinematics). Neutron spectroscopy with scintillators relies on Time-of-flight techniques that can essentially ignore the energy.

Gamma-rays: are very penetrating and high density materials are needed to have significant absorption – inorganic scintillators.

There are three classes of interactions: PE, CS and PP, and the probability of each depends on the photon energy and on the Z of the absorber.

The workhorse scintillator for photons is NaI(Tl), the observed spectra have characteristic features that depend on the incident photon energy.

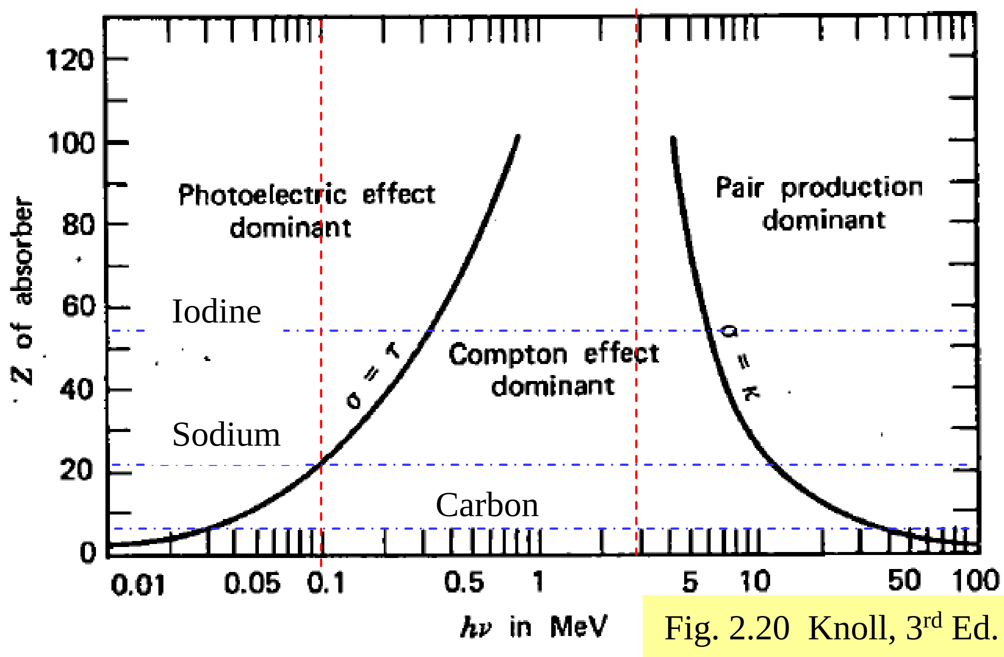

Fig. 2.20 Knoll, 3rd Ed.

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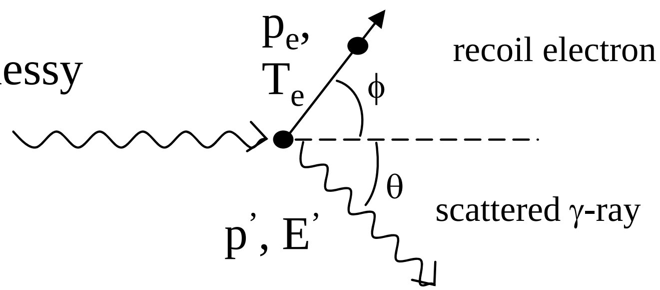
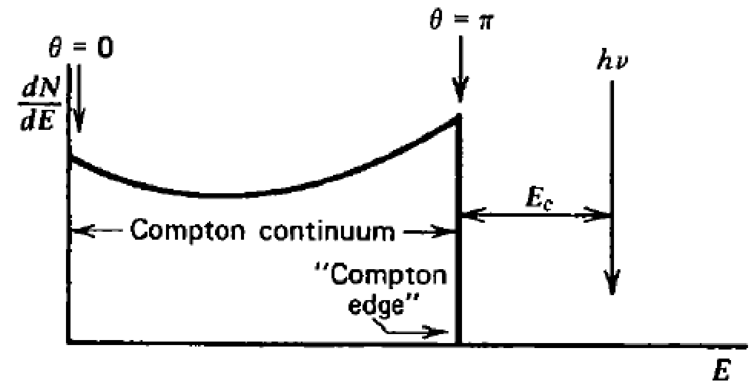
Spectroscopy w/ Scintillators – Line Shape

Photoelectric Absorption: low photon energy phenomenon, complete conversion of hν into KE of one e^- and on into visible photons, back into photoelectrons, then into a current.

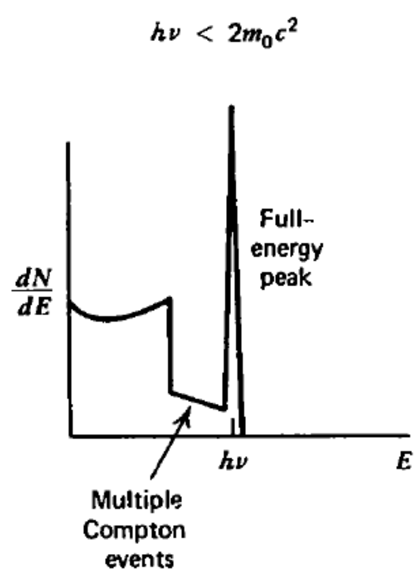
Compton Scattering: messy

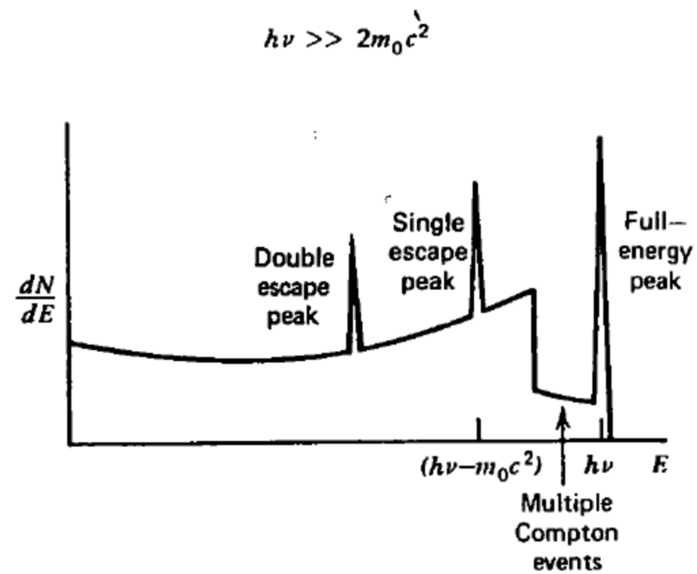
$$h\nu' = \frac{h\nu}{1 + \left(\frac{h\nu}{m_e c^2}\right)(1 - \cos\theta)}$$





Pair production: photons with more than twice the rest mass energy of an electron can convert (in an electric field) into a positron/electron pair. The positron annihilates at the end of its range creating two new photons (E=511 keV) each that may escape. The fraction of escapes depends on the crystal dimensions.





Two or three processes take place for each incident γ ray creating a complicated spectrum even from a monoenergetic source.

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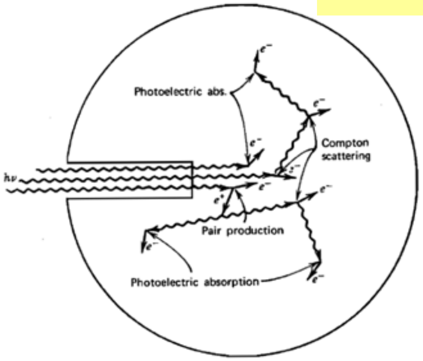
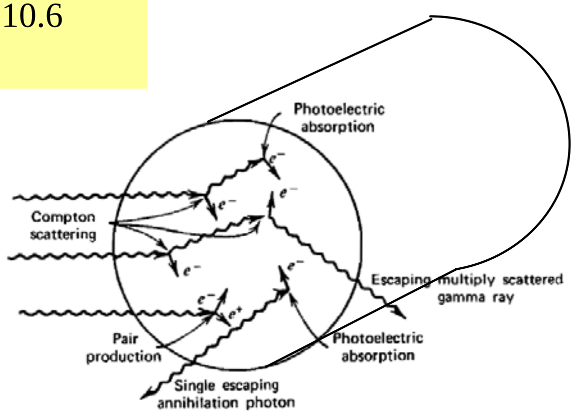
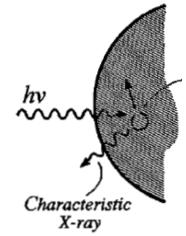
Spectroscopy w/ Scintillators – Incomplete Interactions

Figs. 10.2, 10.3, 10.4, 10.6 from Knoll, 3rd Ed.

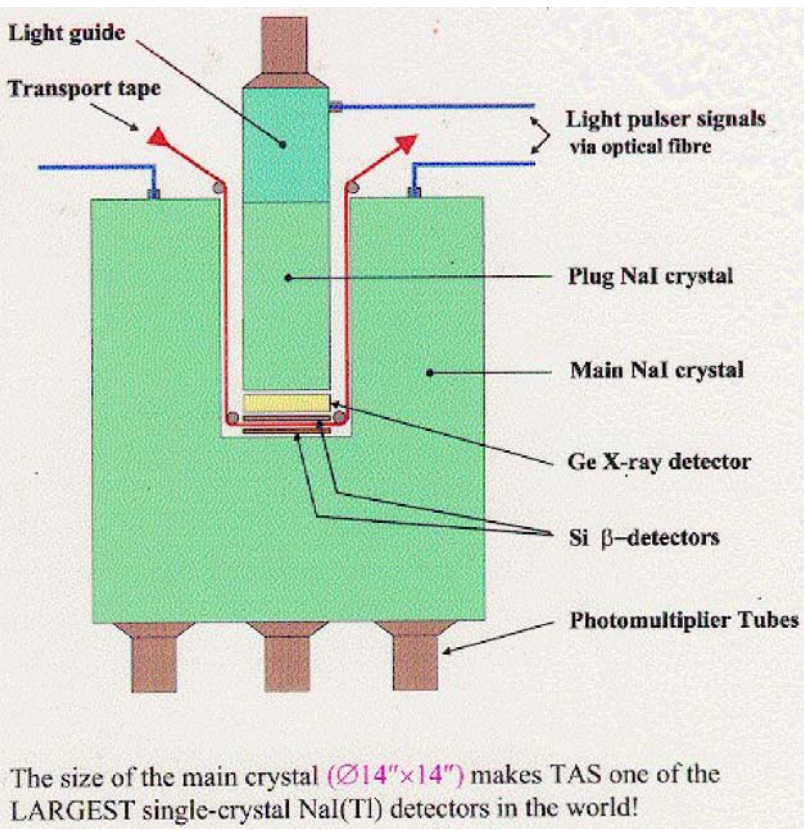


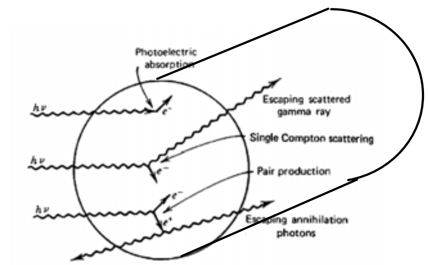




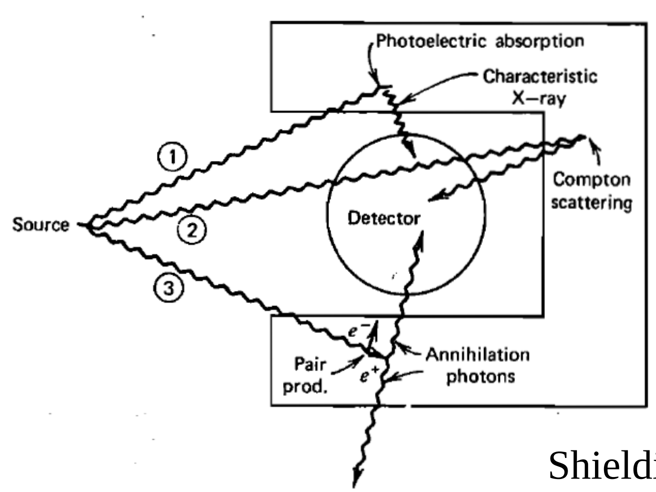
Surface interactions

Sum Spectrometer





Small Detector



Shielding events

Spectroscopy w/ Scintillators – Observed Spect.

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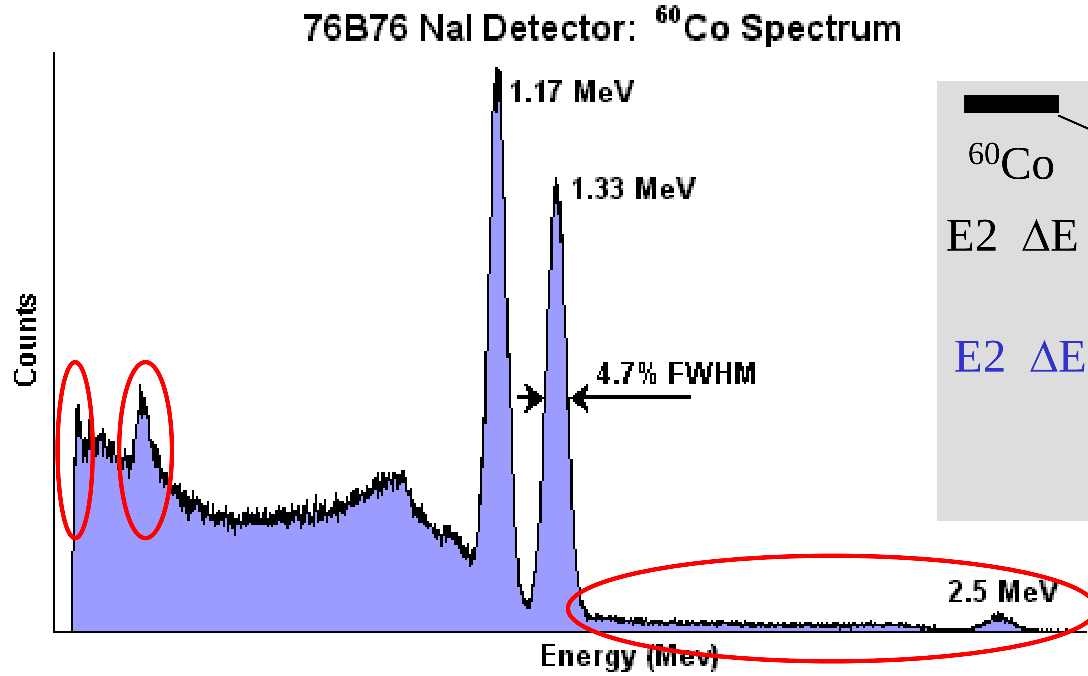
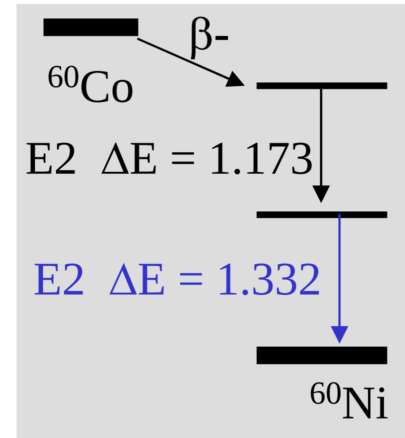
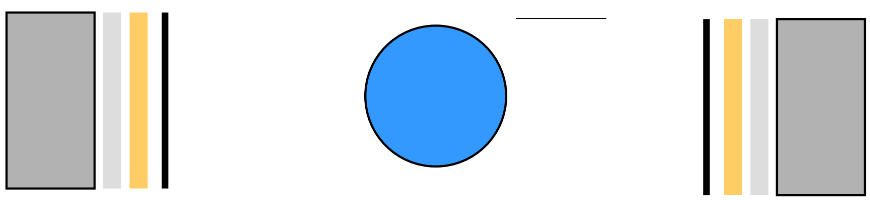
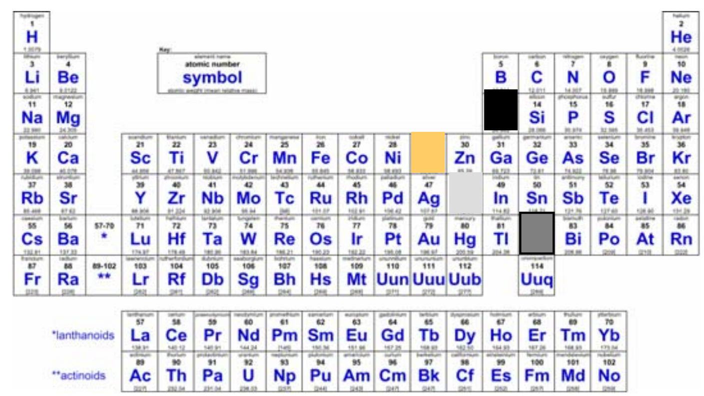
^{60}Co one expects:
two full-energy peaks,
two Compton edges ..





Compton backscatter, the photon scattered at θ ~180^o from the environment back into the detector. $E(h\nu, \theta \sim 180^o) \sim m_o c^2/2$
Solution: move shielding far from the detector.





X-rays generally from fluorescence of scintillator or often from shielding.
Solution: move shielding far from detector and use a “graded shield”

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Spectroscopy w/ Scintillators – Summing

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Summing is a loss mechanism that depends on the geometry (true coincident) and on the rate (random).

True Coincident Summing: two photons are emitted in cascade from the same nucleus (with the total resolving time) and both strike the detector…

$$N_1 = \varepsilon_1^{Photo} \varepsilon_{Geo} (A * \Delta t) BR_1 \qquad [= \varepsilon_1 \Omega S y_1 \quad in\ text]$$

$$N_2 = \varepsilon_2^{Photo} \varepsilon_{Geo} (A * \Delta t) BR_2$$

The sum peak: $$N_{12}^{E-sum} = \left(\varepsilon_1^{Photo} \varepsilon_{Geo} BR_1\right)\left(\boxed{\varepsilon_2^{Photo}} \varepsilon_{Geo} BR_2\right)(A * \Delta t) W(\Theta = 0) \qquad \propto \varepsilon_{Geo}^2$$

Any loss from “1”: $$N_{12}^{Loss} = \left(\varepsilon_1^{Photo} \varepsilon_{Geo} BR_1\right)\left(\boxed{\varepsilon_2^{Total}} \varepsilon_{Geo} BR_2\right)(A * \Delta t) W(0) \qquad \propto \varepsilon_{Geo}^2$$

Observed “1”: $$N_1^{Net} = N_1 - N_{12}^{Loss} = N_1\left[1 - \left(\varepsilon_2^{Total} \varepsilon_{Geo} BR_2\right) W(0)\right]$$

Random Summing: two photons from different nuclei strike the detector within the total resolving time, τ, -- only depends on the total counting rate, r :

$$r_1 = \frac{N_1}{\Delta t} = A\left(\varepsilon_1^{Photo} \varepsilon_{Geo} BR_1\right) \qquad r_{12} = (r_1 \tau) r_{pu}$$

Where r_{pu} is the rate of all events that add signal onto “1” or pile up … $r_{pu} = r_2 + r_1 + r_{back} + \ldots$

N.B. random summing occurs with sources that only emit one gamma ray!

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Spectroscopy w/ Scintillators–Response Function

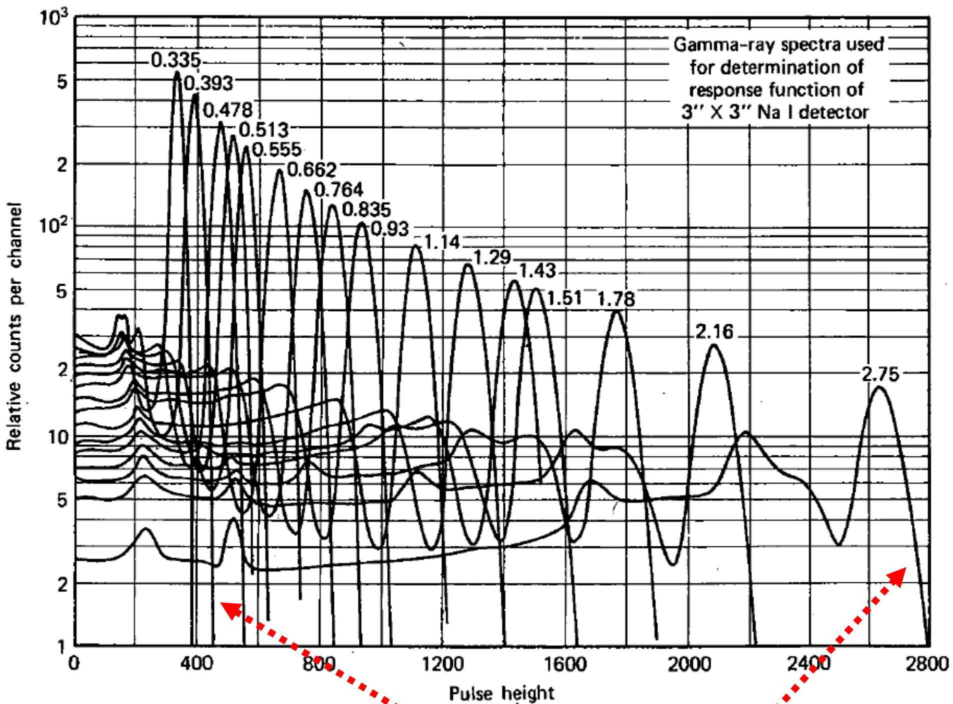
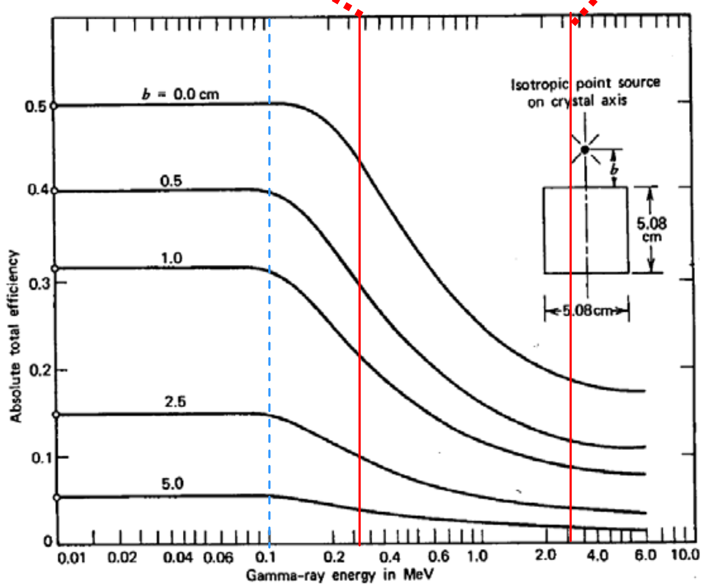


Fig. 10.11 & 22 Knoll, 3rd Ed.



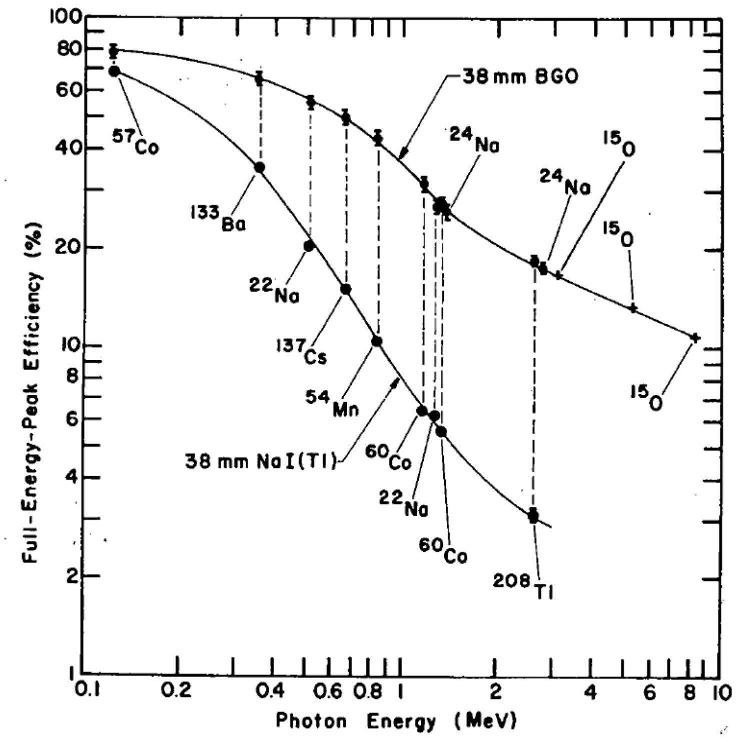


Fig. 10.28 Knoll, 3rd Ed.

Beware the crystal sizes are different in each of these figures!

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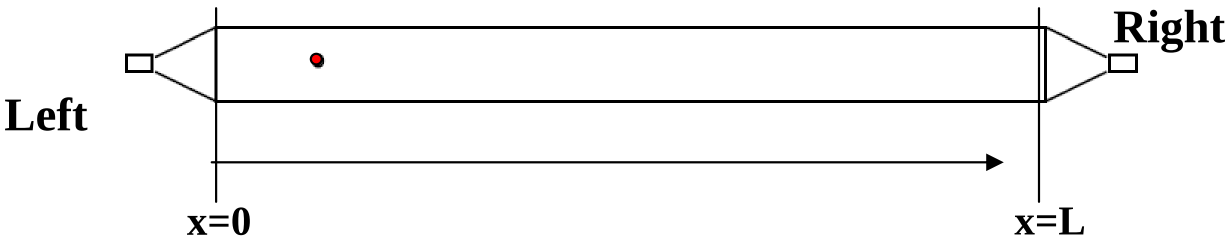
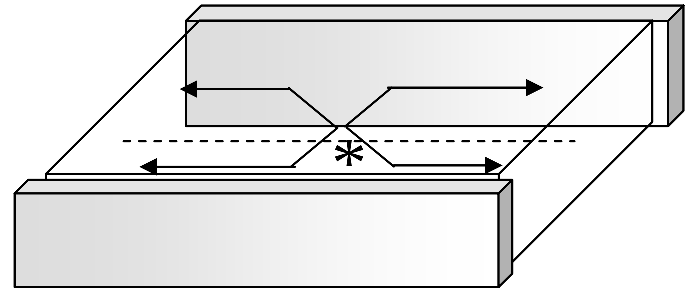
Spectroscopy w/ Scintillators – Position

Position measurements can use the light output reaching each end of a bar
or if the electronics are suitable, the time difference between signals at each end.





Assume that light is “piped” to the end with a Beer’s Law attenuation coefficient, α

$$I_L = \frac{I_0}{2} e^{-\alpha x} \qquad I_R = \frac{I_0}{2} e^{-\alpha (L-x)}$$

$$I_L * I_R = \left(\frac{I_0}{2} e^{-\alpha x}\right)\left(\frac{I_0}{2} e^{-\alpha (L-x)}\right) = \left(\frac{I_0}{2}\right)^2 e^{-\alpha L} \qquad \rightarrow \qquad I_0 \propto \sqrt{I_L * I_R}$$

$$R = \frac{I_L}{I_R} = \frac{e^{-\alpha x}}{e^{-\alpha (L-x)}} = e^{-\alpha (L-2x)} \qquad \rightarrow \qquad \ln R \propto \frac{x}{L}$$

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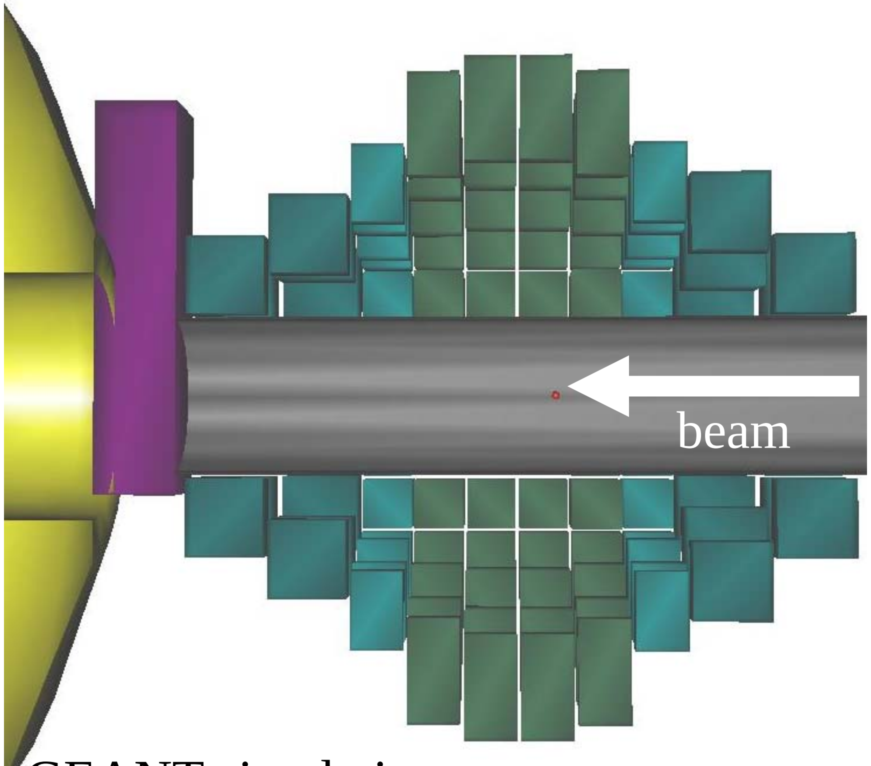
High-Efficiency Scintillator Array - CAESAR



GEANT simulations:

- Solid angle coverage 95%
- In-beam resolution (FWHM): 9.2% at 1 MeV
- Photopeak efficiency exceeding 40% at 1 MeV

Why CsI and not NaI?

- 25-30% higher stopping power
- Superior resolution achieved with CsI(Na)

Typical detector: 3”x 3” **CsI(Na)** crystal + digital electronics (eMorpho)

Energy resolution (^{137}Cs):

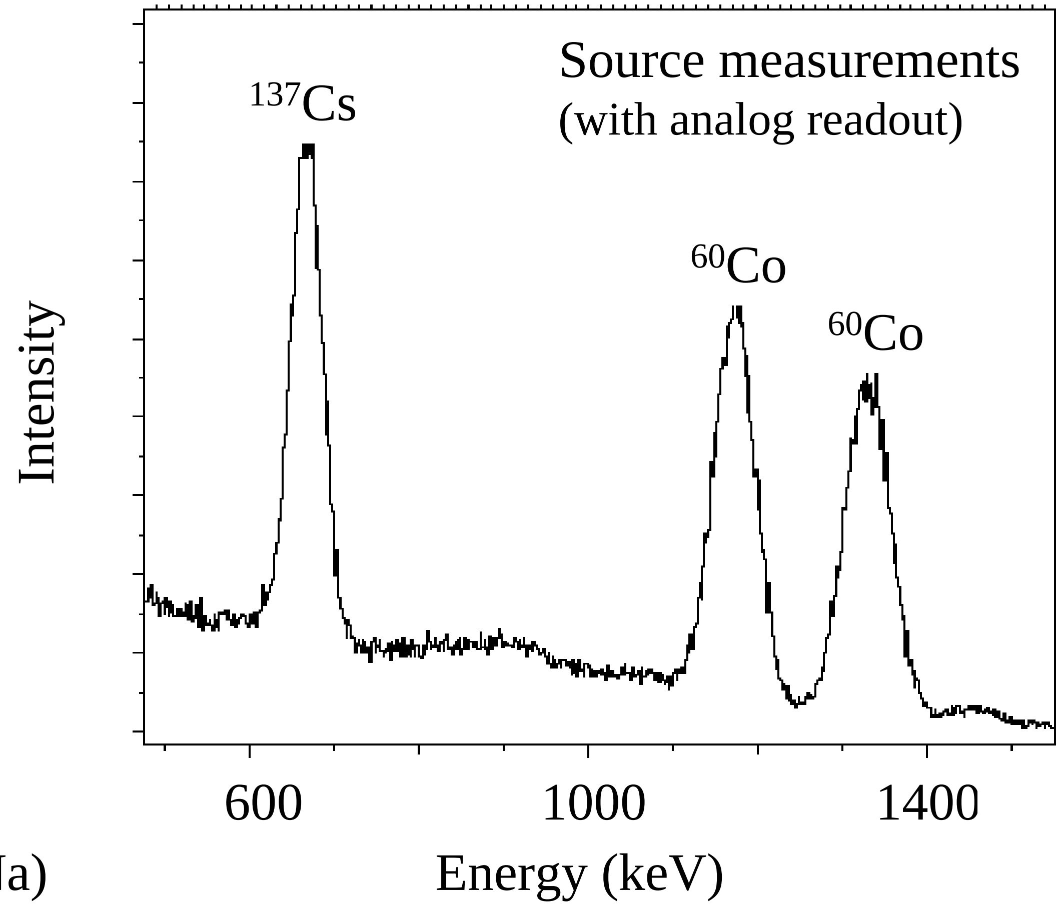
6.6% (analog)

5.6% (digital)

Timing resolution:

7.0 ns (^{22}Na)

4.5 ns (^{60}Co)



CAESAR facts

- 192 detectors in total, CsI(Na) crystals (PMT readout)
  - 48 crystals with nominal dimensions 3”x3”x3”
  - 144 crystals with dimensions 2”x2”x4”
  - All encapsulated in Al-housing since CsI(Na) is hygroscopic
  - PMTs: Hamamatsu R1306 and R1307 (spectroscopic quality)
  - resistive voltage dividers, passive bases.

- Possible future: ASIC-based readout
- First electronics: FERA-based readout of energies and times