Gamma Ray Spectroscopy with Scintillation Detector

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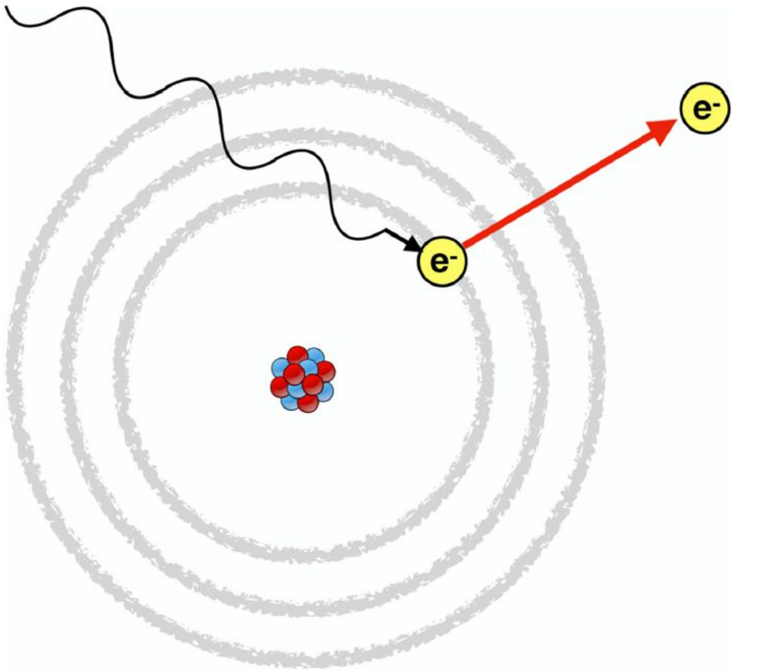
Three main processes relevant for γ-ray spectroscopy

- Photoelectric effect, dominant for γ-ray energy below a few 100 keV
- Compton scattering, dominant for γ-ray energy in the range about 100 keV up to about 10 MeV
- Pair production, dominant for γ-ray energy above 10 MeV

- **Cross-section of these process not only depends on the energy of the γ-ray, but also on the atomic number of the absorber material**

Photoelectric effect



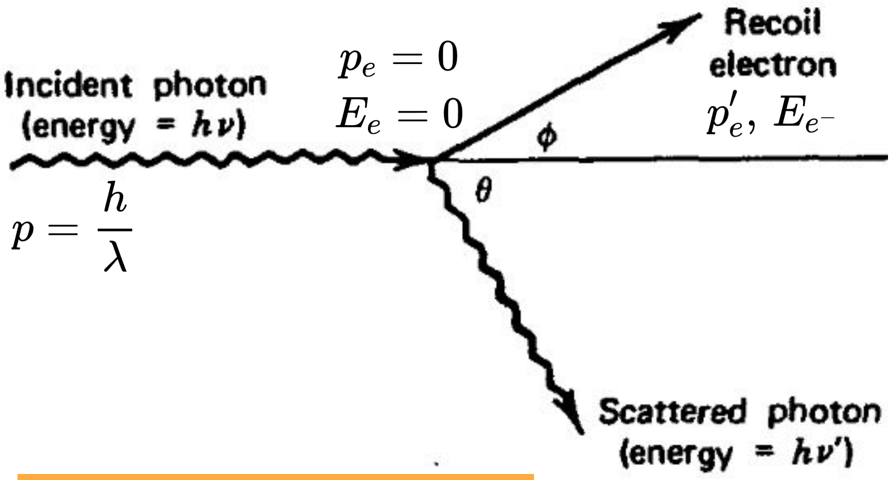
- An incident γ-ray photon transfers all its energy to a bound core electron if the γ-ray energy is larger than the binding energy of the electron
- The electron is ejected with a kinetic energy $E_e = E_\gamma - E_b$
- The cross-section of photoelectric effect shows resonances when γ-ray energy matches with K, L, M, … shell binding energy of electron
- Photoelectric effect cannot take place for a free electron in vacuum
- For momentum conservation, the atom recoils; recoil energy is negligibly small

Probability of photoelectric effect is given very approximately by $\tau \cong \text{constant} \times \dfrac{Z^n}{E_\gamma^{3.5}}$
n is in between 4 and 5, Z is atomic no., E_γ is γ-ray energy

Photoelectric effect - net result in the medium

- Net result of a photoelectric interaction is release of a photoelectron which carries most of the energy (photon energy - electron binding energy) from the γ-ray, together with one or more lower energy electrons corresponding to the binding energy of the photoelectron
- Electrons ejected from a number of photoelectric events have same energy with a narrow (delta-function-like) distribution.
- The liberated electrons lose energy quickly and the γ-ray is detected through the energy loss of these electrons in the material

Compton scattering



$$p' = \frac{h}{\lambda'}$$

- An incident γ-ray photon scatters of a free electron and transfers part of its energy to scattered electron
- Energy remaining within the scattered photon is

$$h\nu' = \frac{h\nu}{1 + (h\nu/m_0c^2)(1 - \cos\theta)}$$

- Kinetic energy of the scattered electron

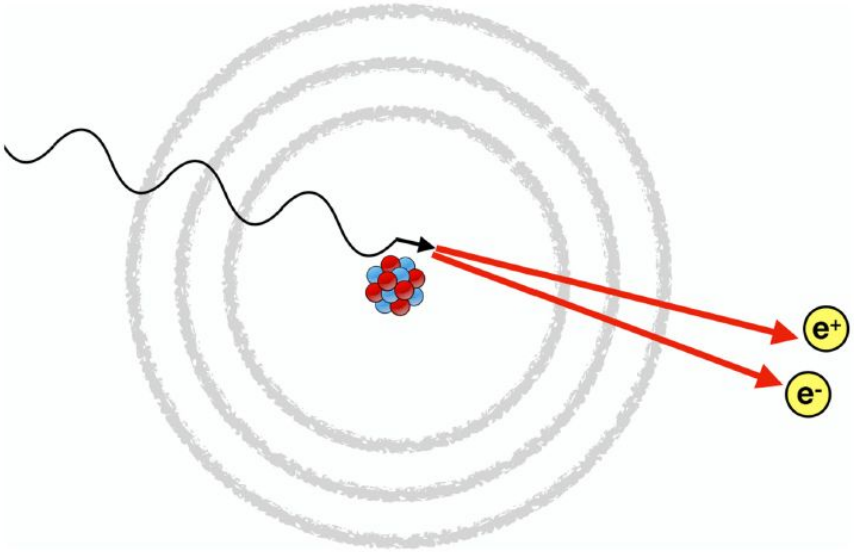
$$E_{e^-} = h\nu - h\nu' = h\nu\left(\frac{(h\nu/m_0c^2)(1 - \cos\theta)}{1 + (h\nu/m_0c^2)(1 - \cos\theta)}\right)$$

Compton scattering cross-section increases linearly with Z (atomic no.)

Compton effect - net result in the medium

- Net result of a Compton scattering is release of an electron which carries a part of the energy from the γ-ray, together with teh scattered photon with reduced energy
- Scattered electrons resulted from a number of Compton events have a continuous distribution of energy from 0 to a certain maximum energy below the incident photon energy
- The liberated electrons lose energy quickly and the γ-ray is detected through the energy loss of these electrons in the material

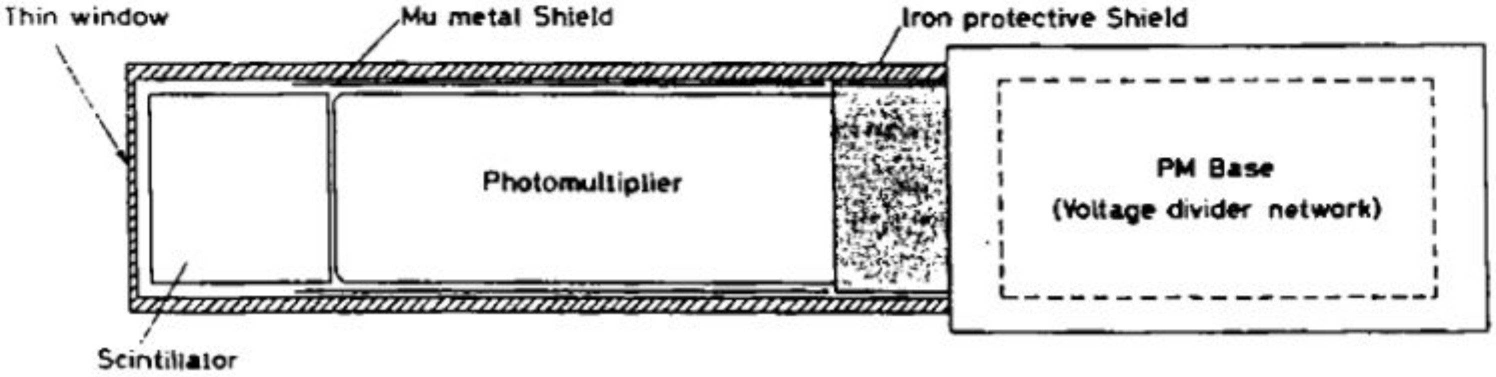
Pair production



Cross-section of pair-production increases quadratically with Z (atomic no.)

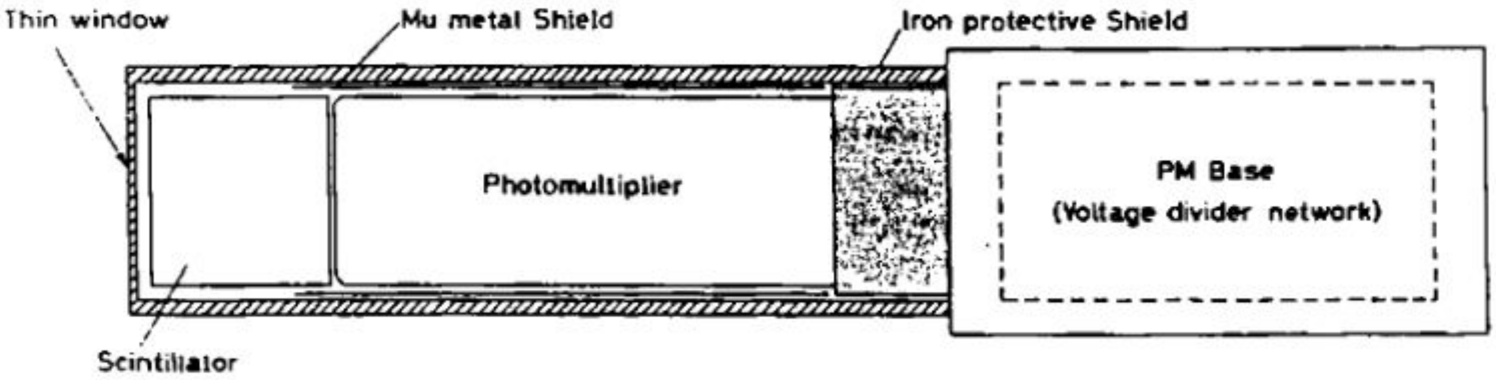
- A γ-ray photon transforms in to an electron-positron pair
- The process becomes energetically possible only if the photon energy exceeds $2m_0c^2 = 1.02$ MeV
- Practically, this process become significant only for photon energy exceeding ~10 MeV

Scintillation Detector



Schematic diagram of a scintillation counter detector

Scintillation Detector



Schematic diagram of a scintillation counter detector

- Scintillator converts energy deposited in it by the incoming radiation to a bunch of visible photons, No. of vis. photons $\propto$ deposited energy
- Photomultiplier tube (PMT) converts incident visible photons to a bunch of electrons giving electrical pulse, No. of electrons $\propto$ No. of vis. photons

What is scintillation?

- Scintillation meaning a flash of light
- It originates through a process known as Luminescence - emission of light from a material
- Electrons in a material goes to an excited state by absorbing energy from an external source → they relax to ground state in a characteristic time scale → energy relaxation through radiative process gives luminescence
- Depending on the time-scale luminescence is categorized to Fluorescence (time-scale ~ 10^{-8} s) and phosphorescence (time-scale in ms to hours)

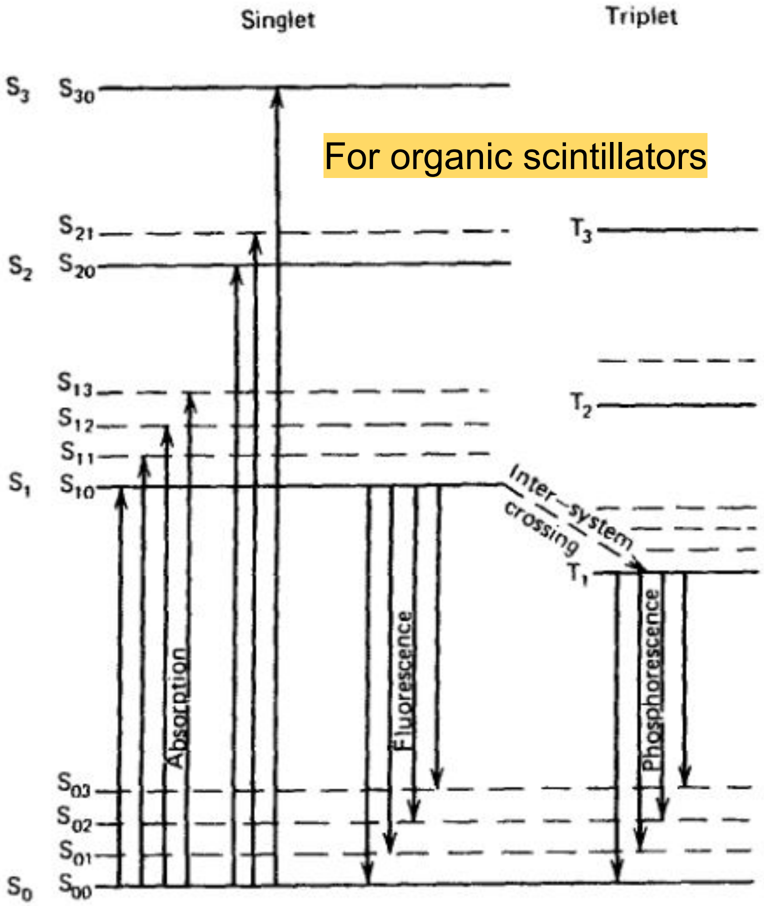
Desirable features of a good scintillator

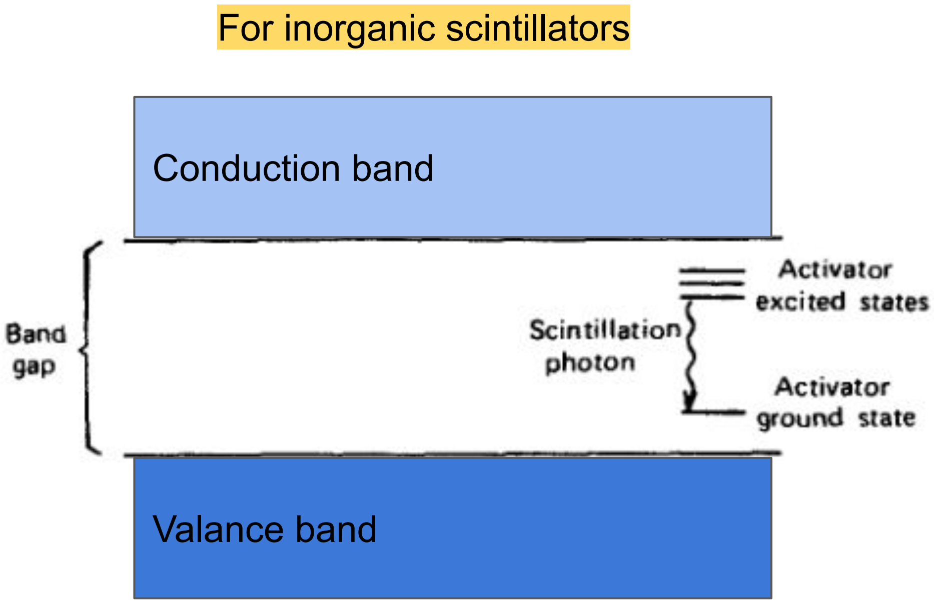
1. It should convert the kinetic energy of charged particles into detectable light with a high scintillation efficiency.
2. This conversion should be linear—the light yield should be proportional to deposited energy over as wide a range as possible.
3. The medium should be transparent to the wavelength of its own emission for good light collection.
4. The decay time of the induced luminescence should be short so that fast signal pulses can be generated.
5. The material should be of good optical quality and subject to manufacture in sizes large enough to be of interest as a practical detector.
6. Its index of refraction should be near that of glass (~1.5) to permit efficient coupling of the scintillation light to a photomultiplier tube or other light sensor.

Different types of scintillators

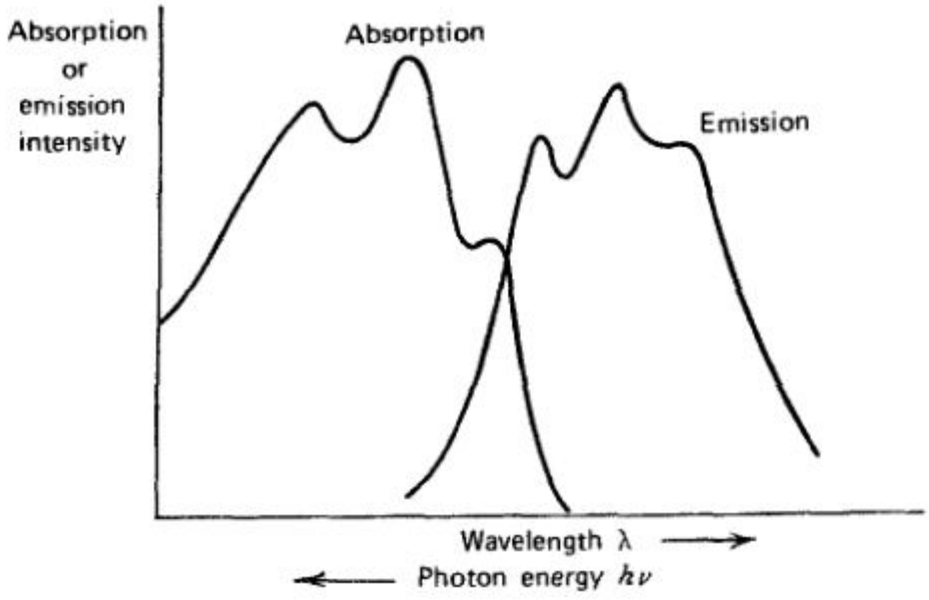
- Organic scintillators - optical transitions between molecular orbitals
  - Pure organic crystals (polycrystalline solid form) - anthracene having high scintillation efficiency
  - Liquid organic solutions - organic scintillator dissolved in a aromatic solvent (π electron rich)
  - Plastic scintillators - organic scintillator in a plastic polymer solid solution
- Inorganic crystalline solids - optical transitions between band states
  - Alkali halide crystalline solid doped with a suitable metal atoms, most popular is Thallium doped Sodium Iodide crystals NaI(Tl)
  - Other examples: CsI(Tl), CsI(Na), LiI(Eu), etc.
  - Non alkali halides: BaF_2, $Bi_4Ge_3O_{12}$, ZnS(Ag), etc.

Mechanisms of scintillation

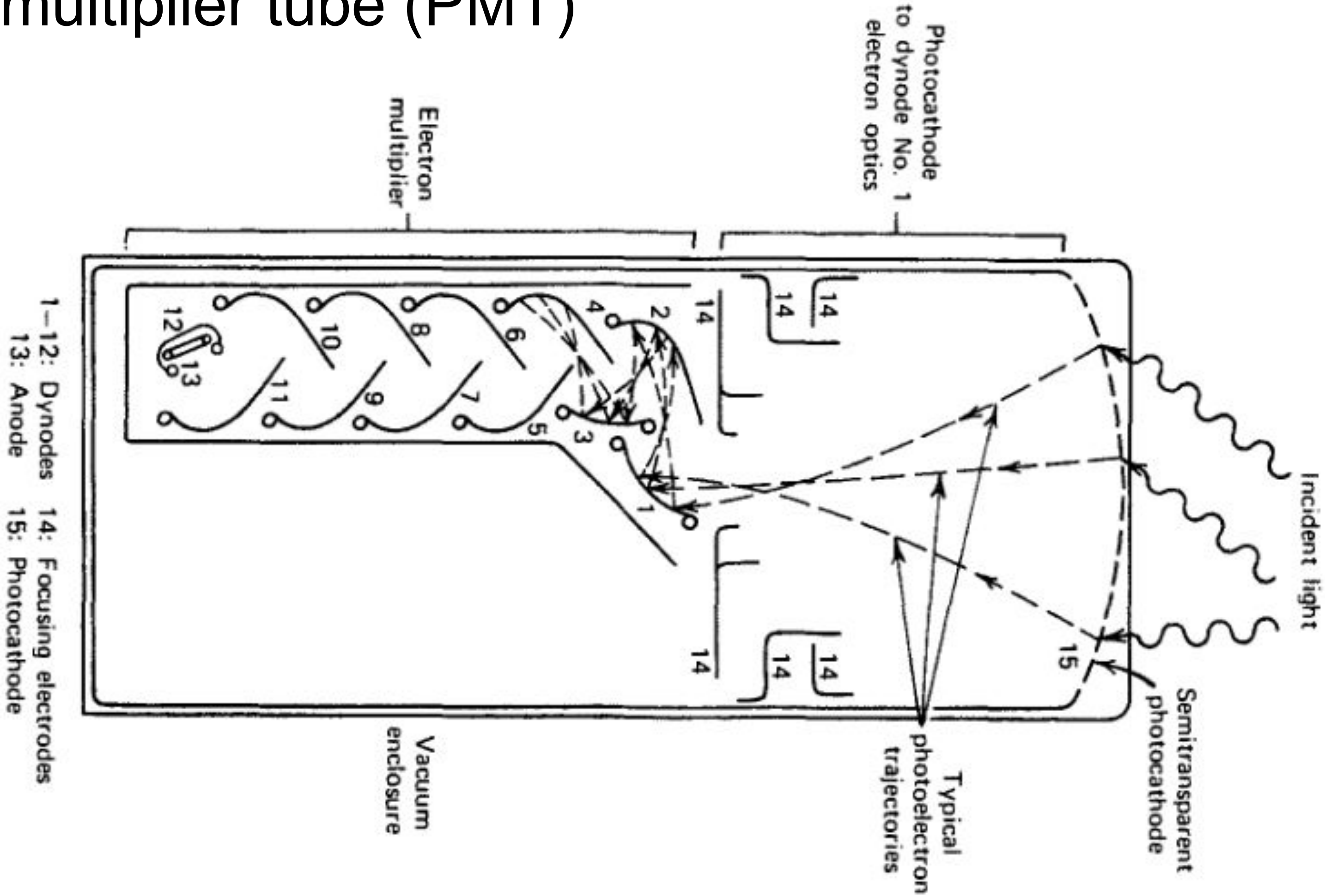




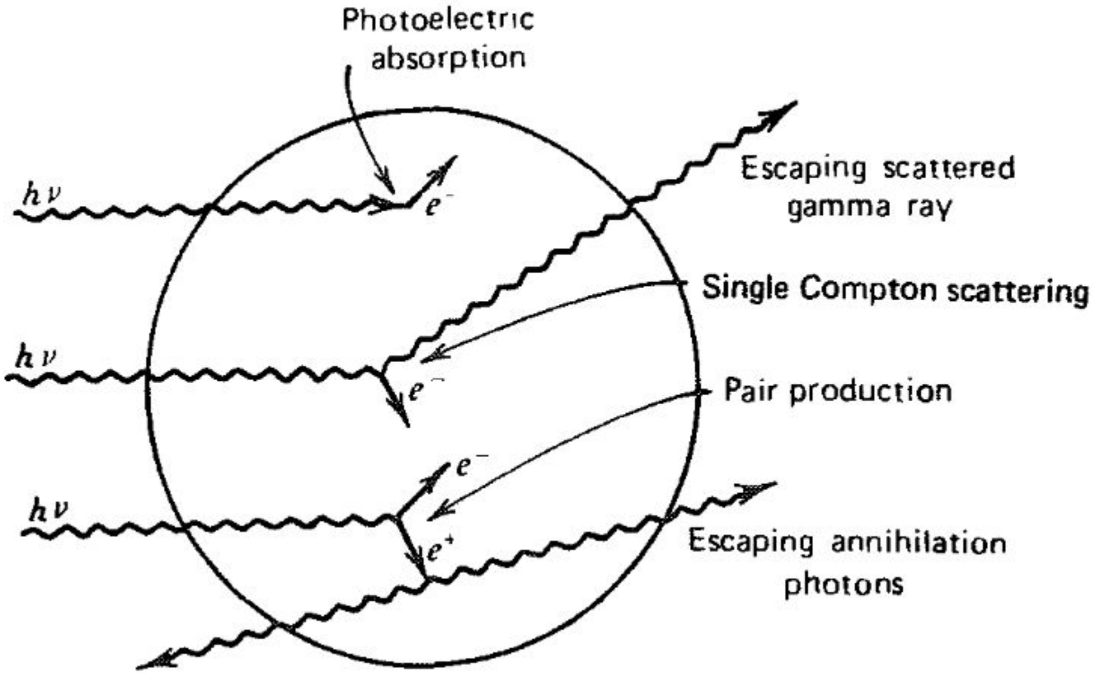
Optical absorption and emission spectra - organic scintillator



Photomultiplier tube (PMT)



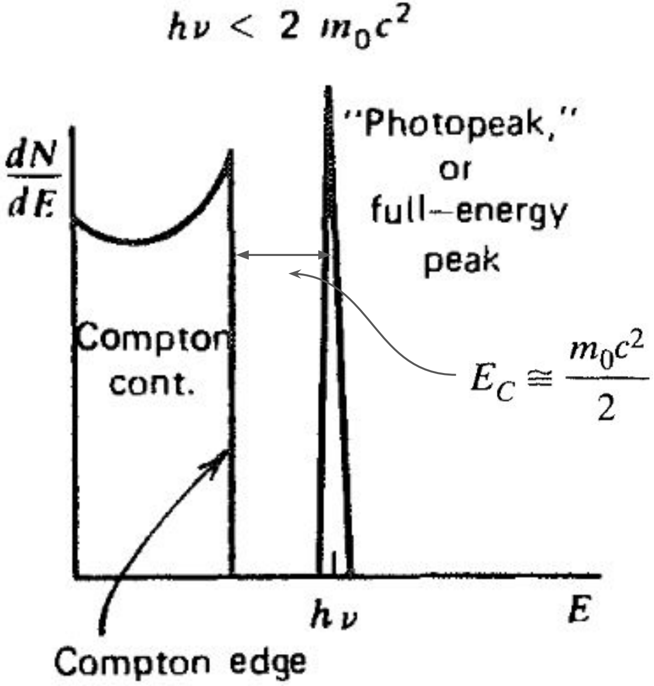
γ-ray escaping the detector after one interaction in a "small" size detector

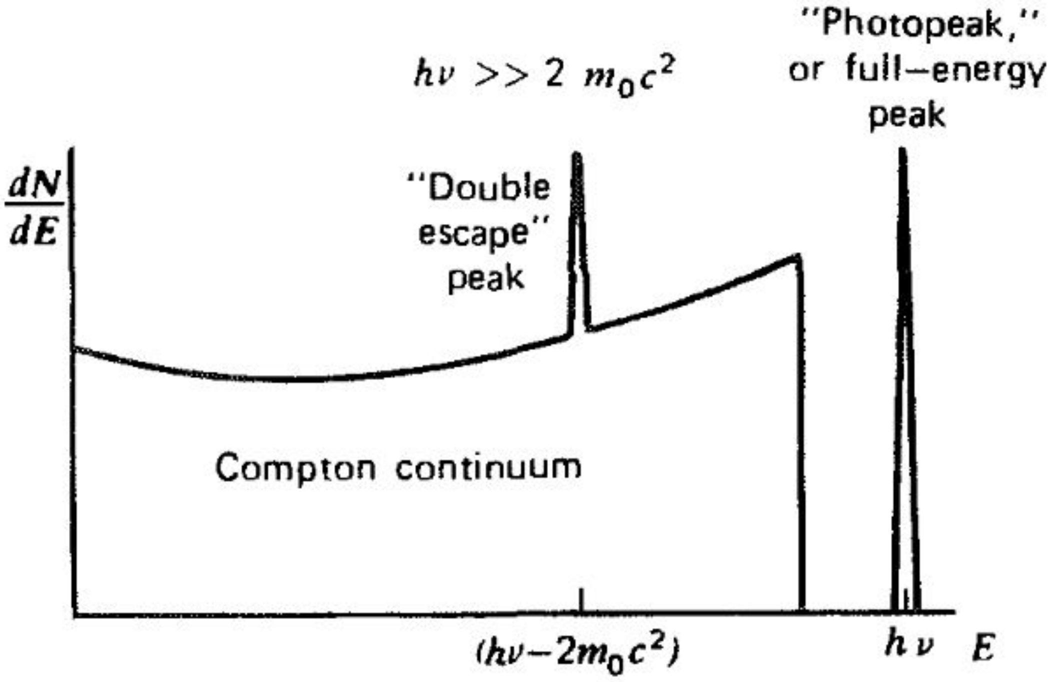


What is meant by "small" size detector:

- Detector size is ~ cm which larger than typical range of energetic electrons but smaller than typical range of energetic γ-rays
- Almost all secondary electrons generated from interactions of γ-rays are stopped in the detector
- Almost all secondary γ-rays generated from interactions of primary γ-rays can escape the detector

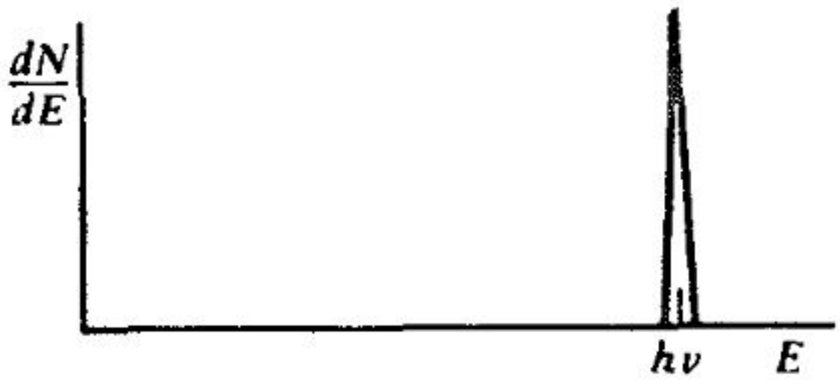
γ-ray spectrum for "small" size detector



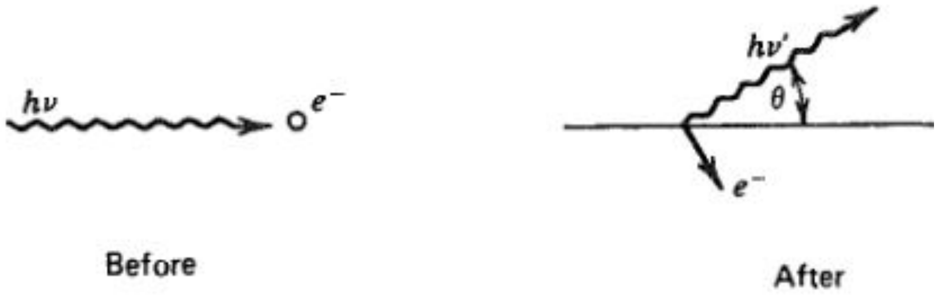


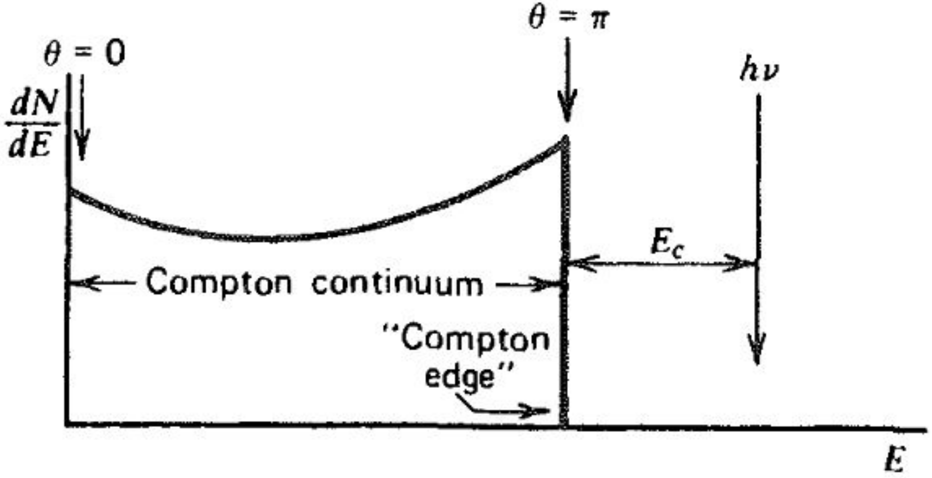
Spectrum expected for photoelectric effect

- One photoelectric event produces one or more electrons - sum of kinetic energy of these electrons is equal to the energy of the incident γ-ray
- These electrons lose all their energy in the detector materials (range of charged particle is small)
- Differential distribution of electron kinetic energy for a number of photoelectric events for monoenergetic γ-ray will be a delta function at the incident γ-ray energy



Energy distribution of the Compton recoil electrons





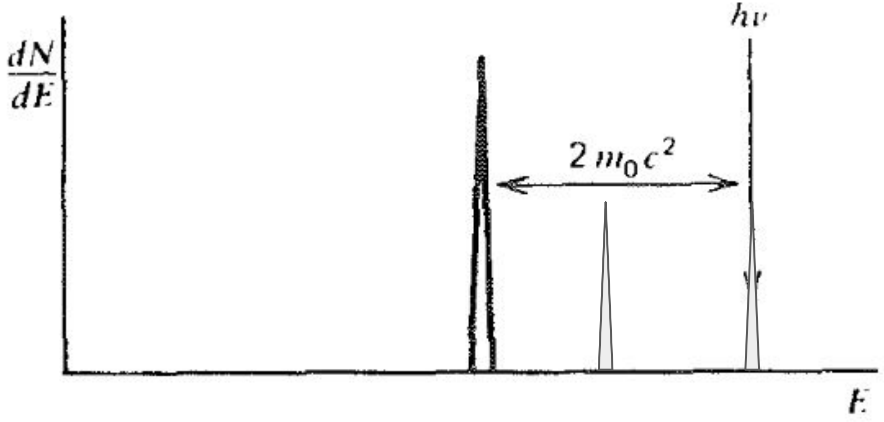
- The maximum energy of the recoil electron is known as Compton edge
- The gap between Compton edge and incident γ-ray energy is given as

$$E_C \equiv h\nu - E_{e^-}\Big|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu/m_0c^2}$$

- For $h\nu \gg m_0c^2/2$

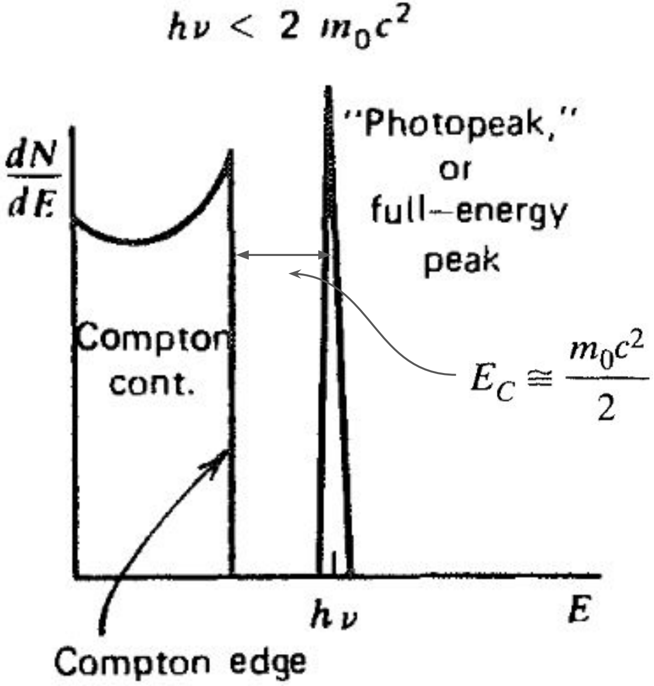
$$E_C \cong \frac{m_0c^2}{2} \; (= 0.256 \text{ MeV})$$

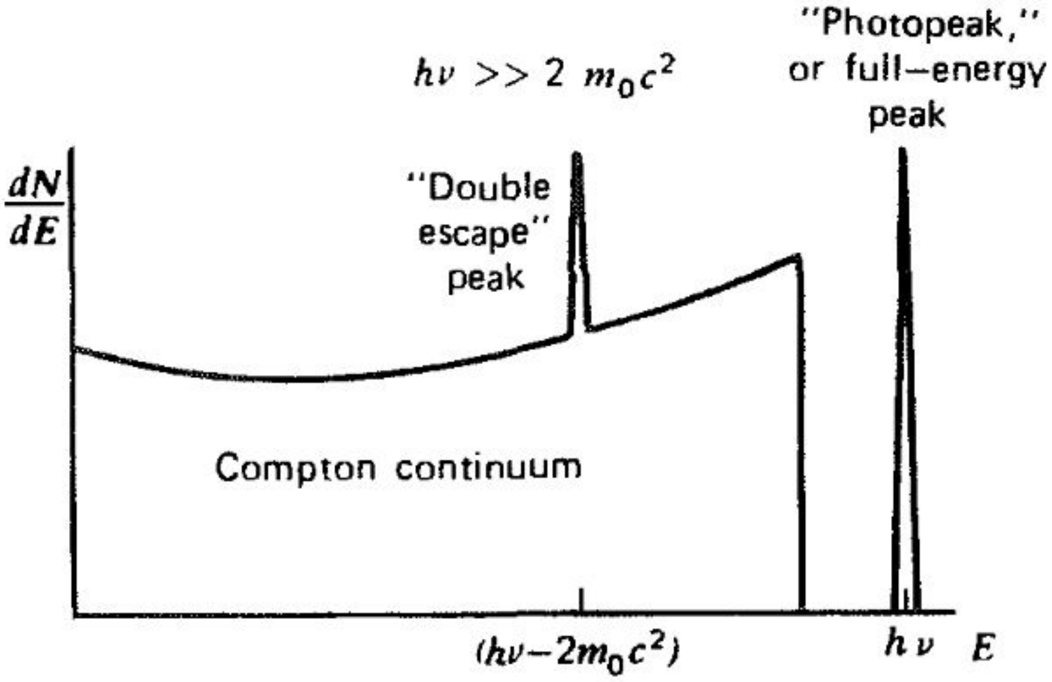
Pair production



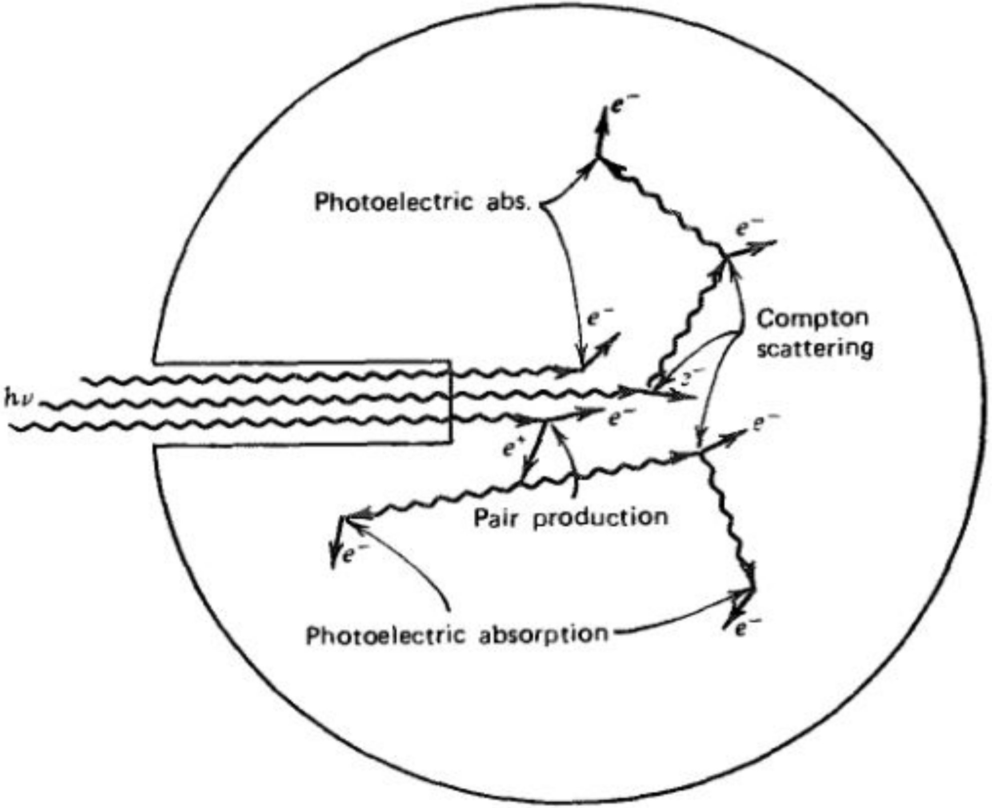
- Excess energy of photon beyond $2m_0c^2$ = 1.02 MeV is shared as the kinetic energy of the electron and positron: $E_{e-} + E_{e+} = h\nu - 2m_0c^2$
- The generated charge particles deposit their energy in the absorber material. The energy distribution of charge particle is a delta function at an energy $2m_0c^2$ = 1.02 MeV below the γ-ray energy
- The positron, after losing kinetic energy, annihilates with an electron, giving a pair of photons, each having energy m_0c^2 = 0.51 MeV

γ-ray spectrum for "small" size detector





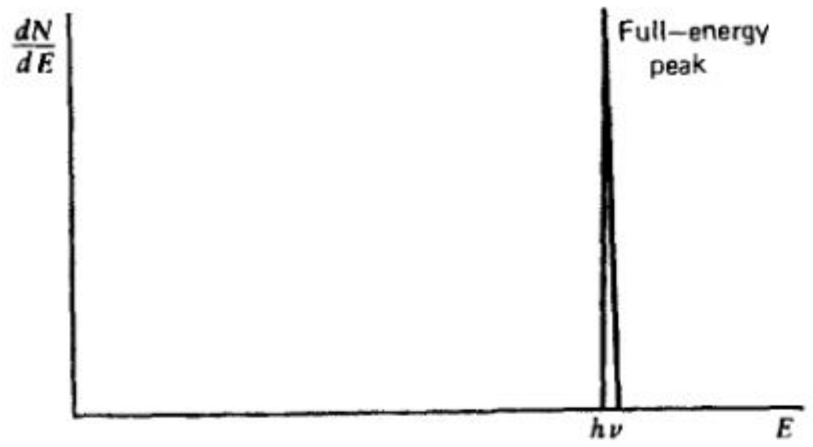
γ-ray interactions in a "very large" size detector



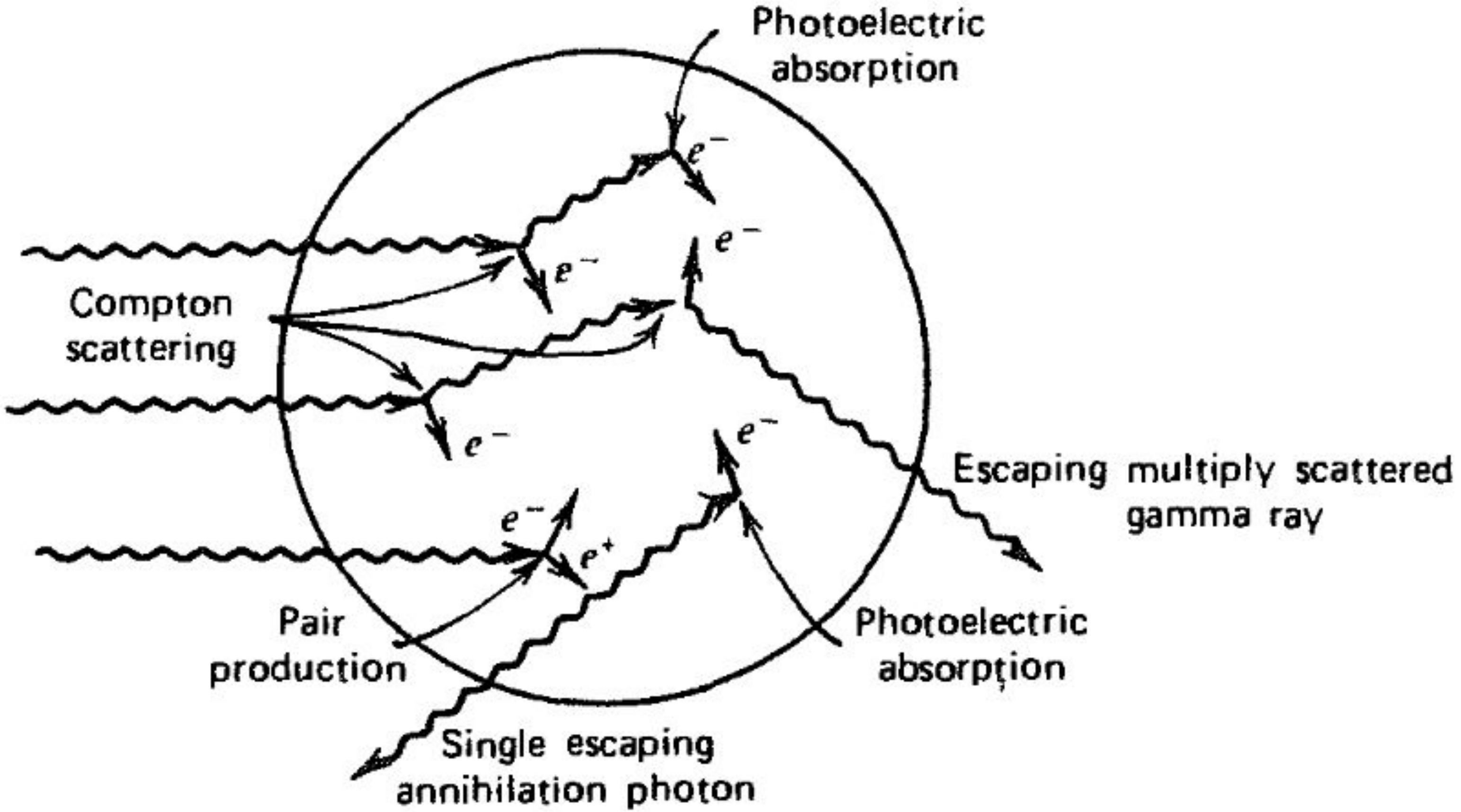
What is meant by "very large" size detector:

- Detector size is ~ m which larger than typical range of energetic γ-rays
- No secondary radiations including secondary γ-rays generated from interactions of primary γ-rays can escape the detector

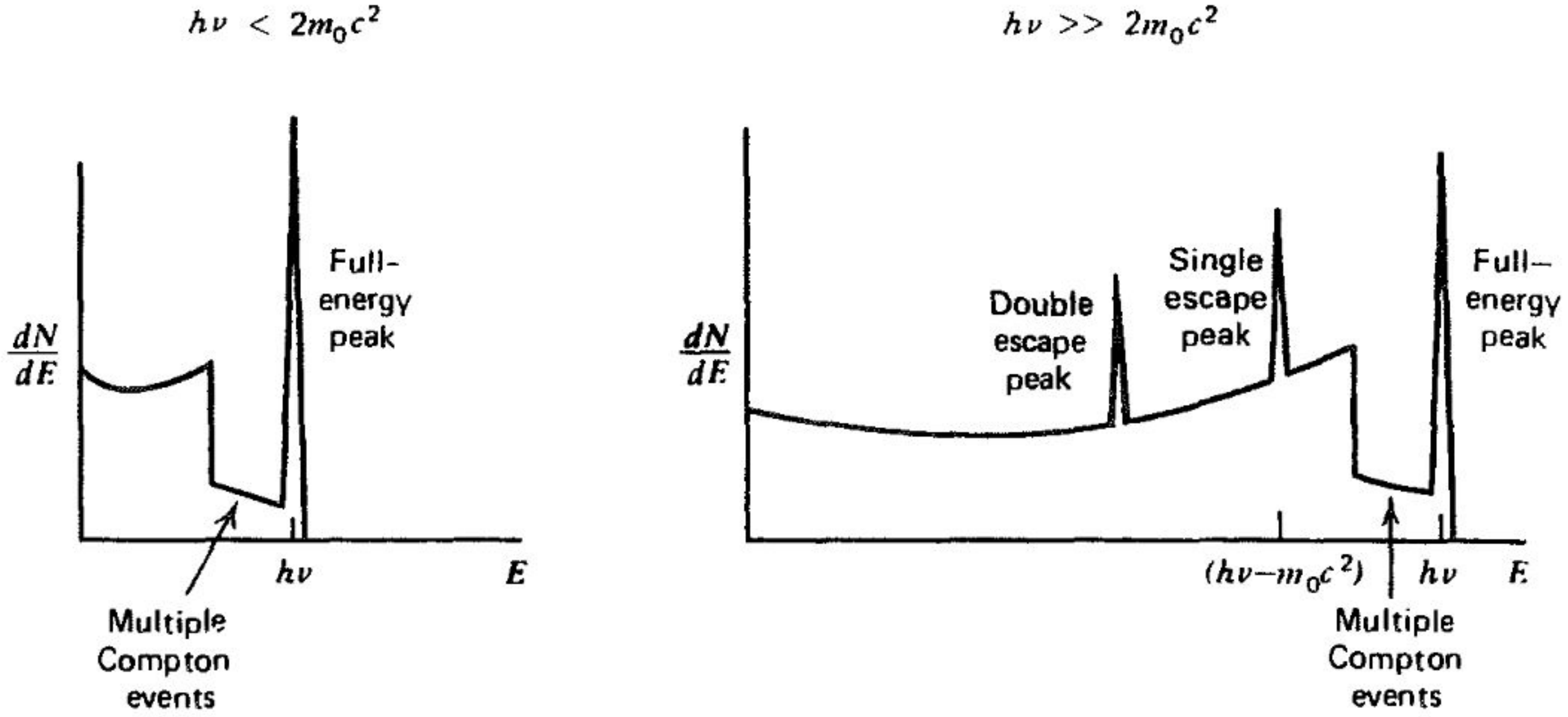
Typical γ-ray spectrum in a “very large” size detector



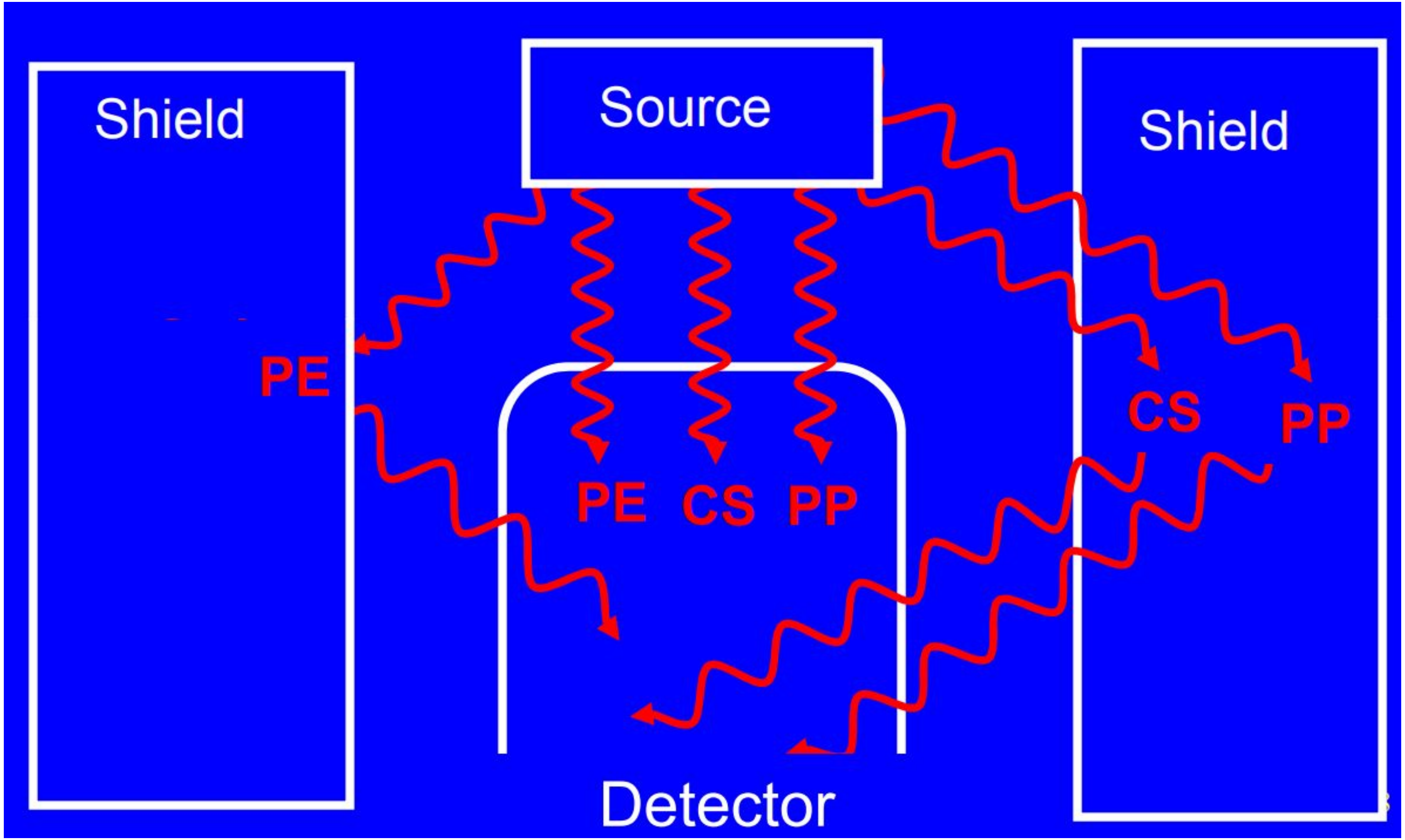
γ-ray spectrum for "practical" size detector



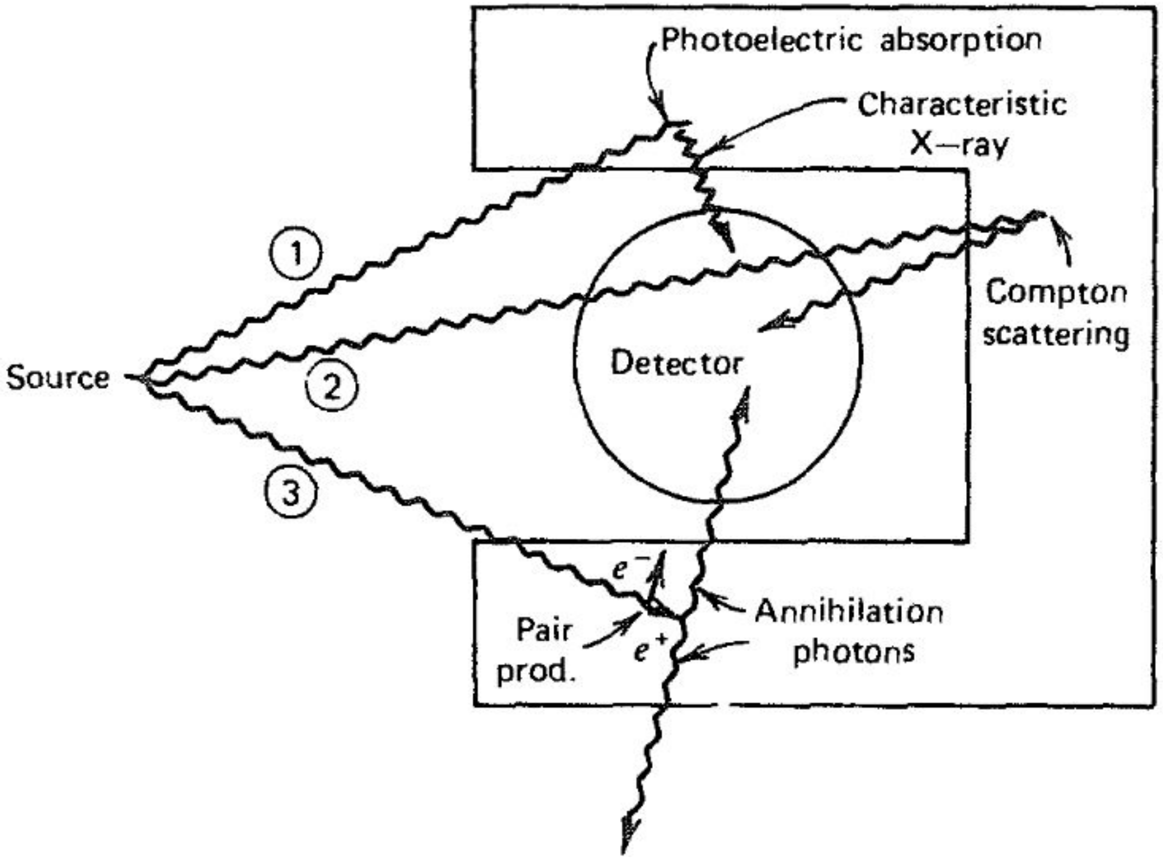
γ-ray spectrum for "practical" size detector



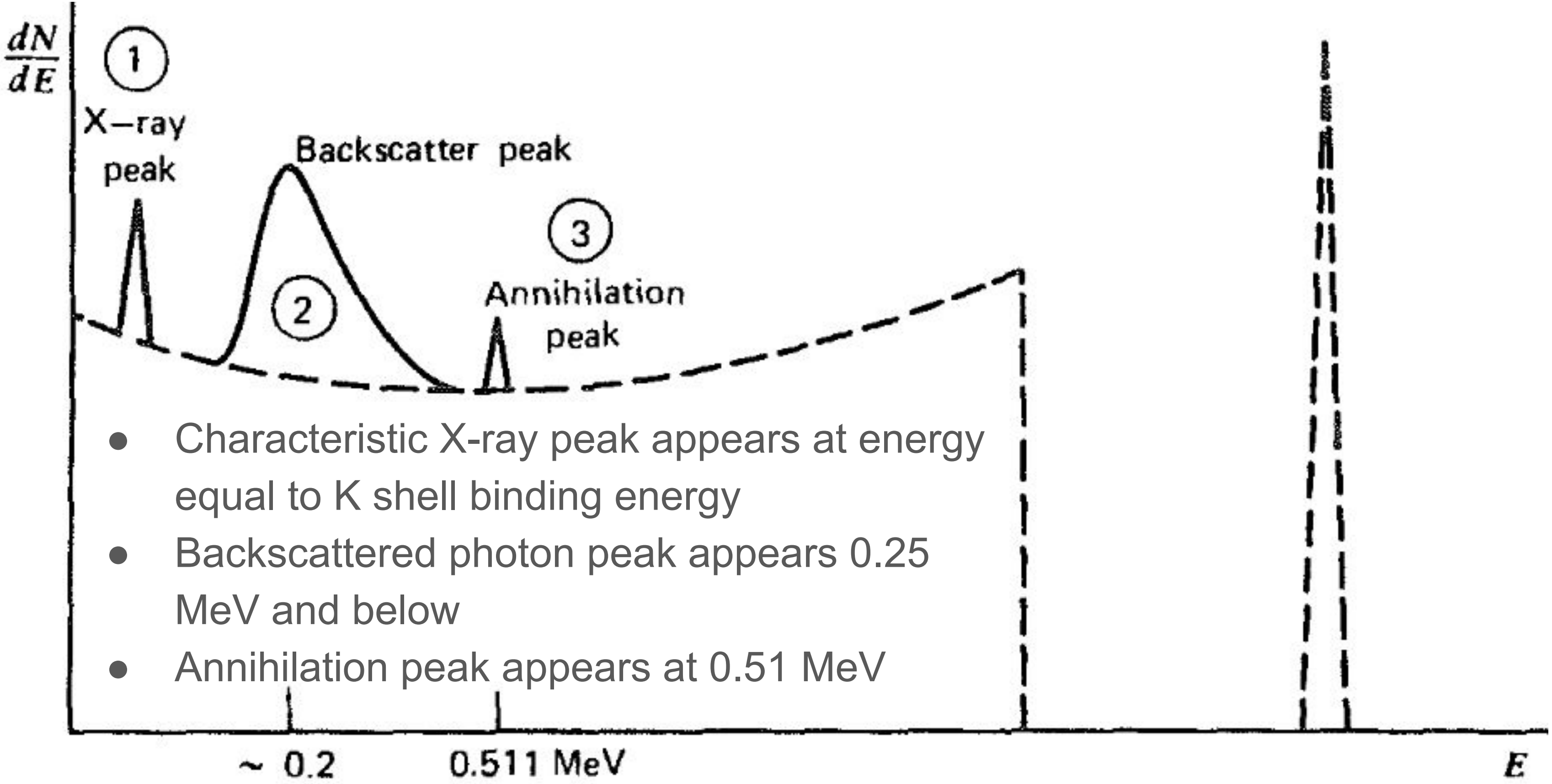
Primary and secondary gamma-ray entering the detector



Effect of surrounding (shielding) material

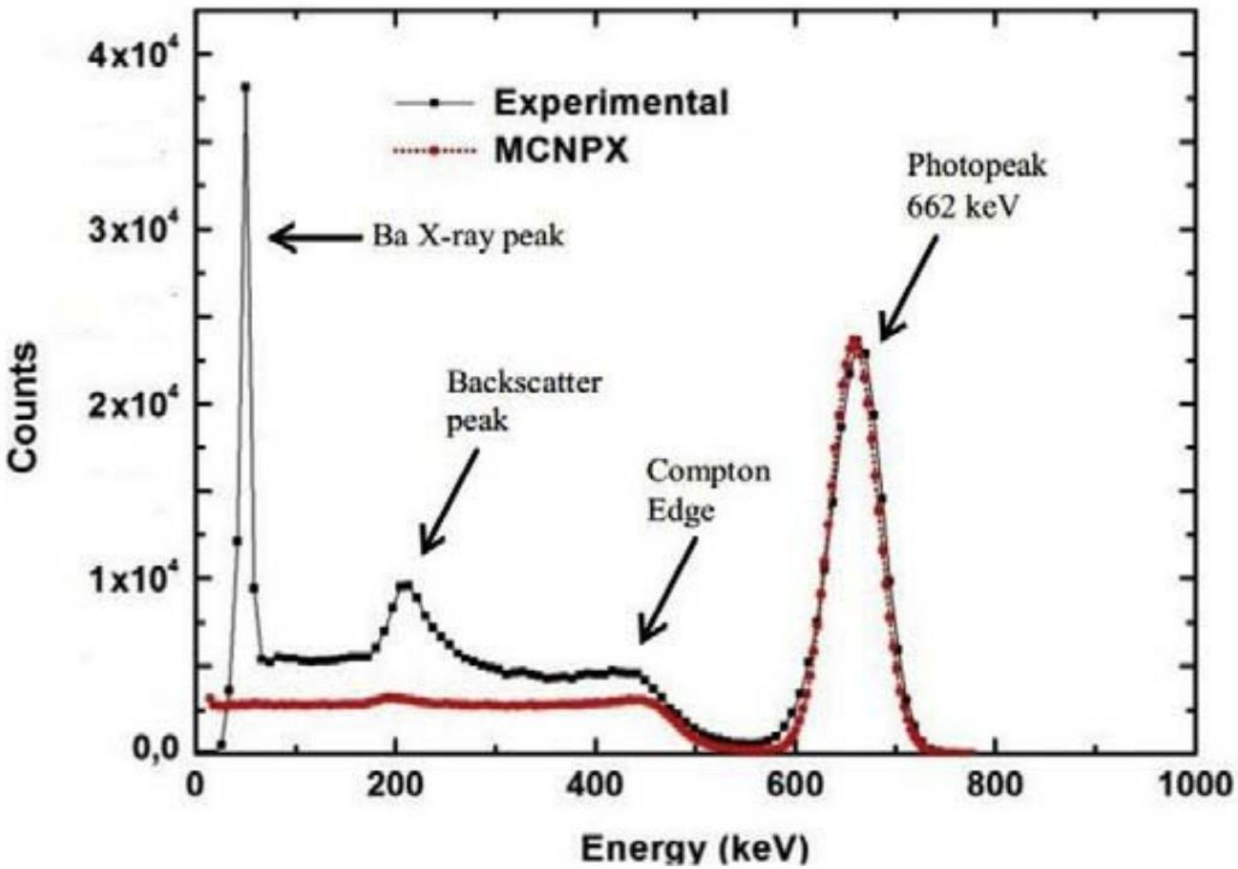


Effect of surrounding (shielding) material

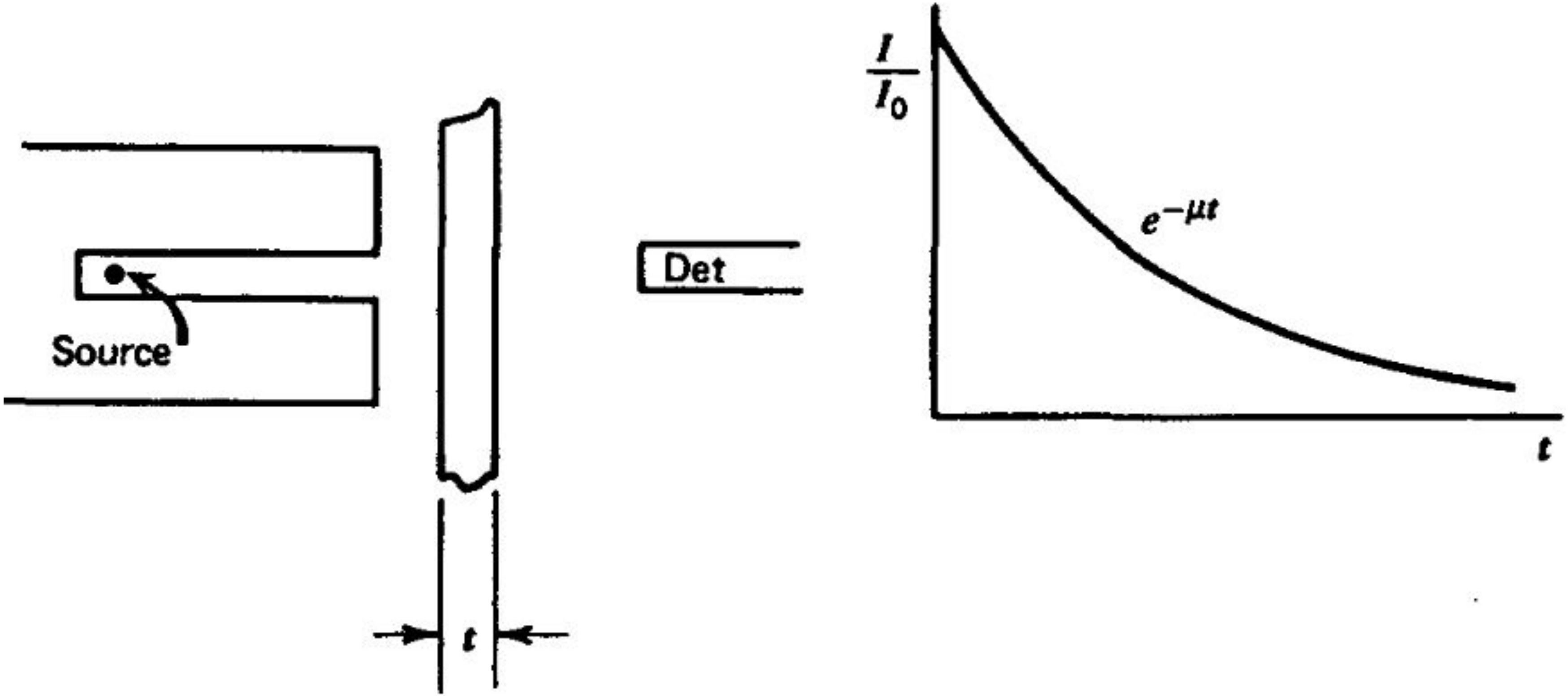


- Characteristic X-ray peak appears at energy equal to K shell binding energy
- Backscattered photon peak appears 0.25 MeV and below
- Annihilation peak appears at 0.51 MeV

γ-ray spectrum from Cs-137



γ-ray attenuation



γ-ray attenuation

- Exponential attenuation for monoenergetic, collimated beam of γ-ray
- Each interaction removes a gamma photon from the beam by absorption or scattering
- Each interaction has a fixed probability of occurrence per unit length of the absorber material

Detection of γ-ray by G M counter

- Gas medium has very less probability of interaction with γ-ray photons
- Interaction γ-ray photons with the wall of the G M counter gives charged particle, that can interact with gas medium and be detected