Interactions of Gamma Radiation with Matter

PH3105 - Autumn 2024

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Characteristic difference in energy loss processes for Gamma ray and high energy charged particle

High energy charged particle	Gamma ray
Slows down gradually through continuous, simultaneous interactions with many atoms of the absorber materials	Losses energy discontinuously through sudden and abrupt interaction
Small deviation from the original trajectory in each collision	Large deviation or complete removal from the original beam path
Range is quite small, typically in mm	Range is relatively large, typically in several cm

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**

Relative importance of three major interactions

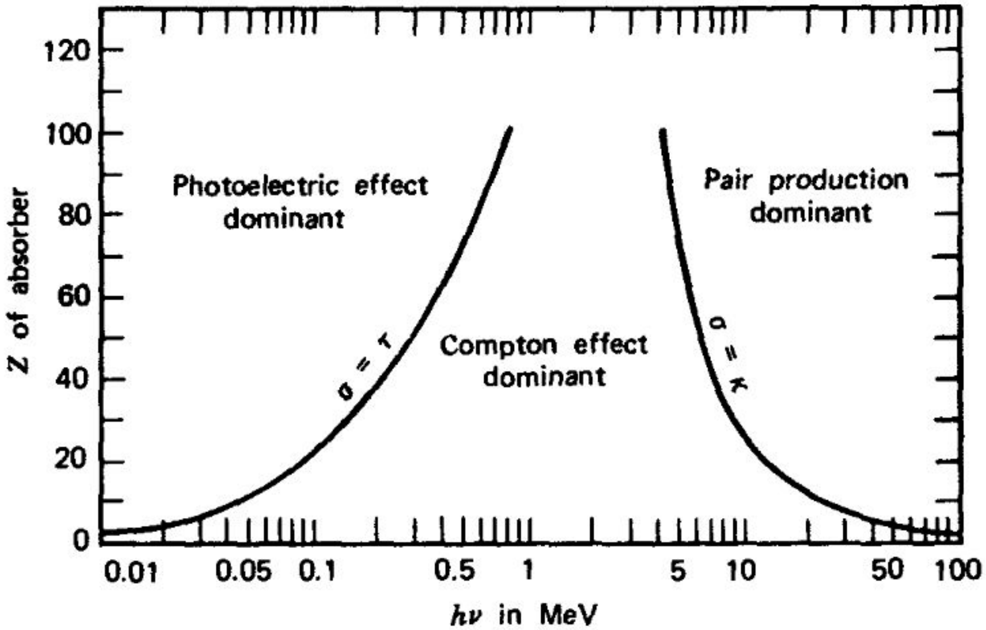
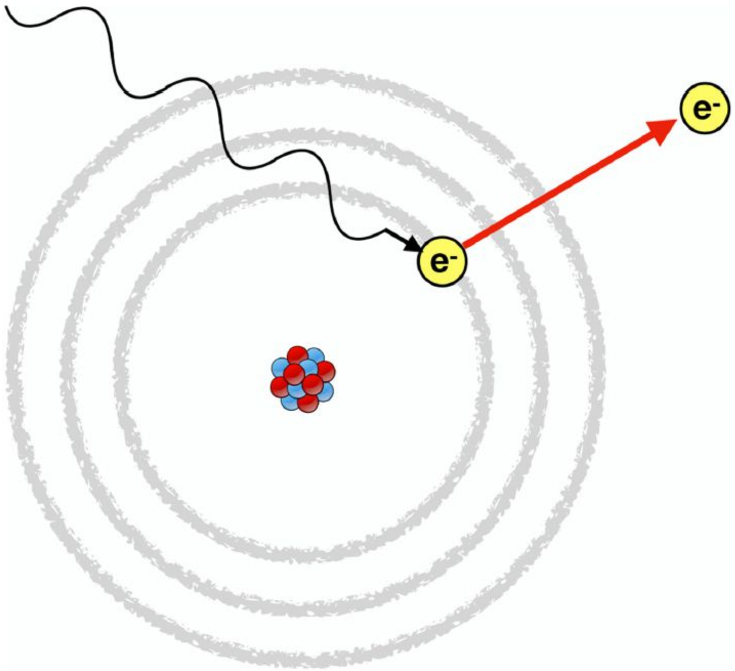


Figure 2.20 The relative importance of the three major types of gamma-ray interaction. The lines show the values of Z and $h\nu$ for which the two neighboring effects are just equal. (From *The Atomic Nucleus* by R. D. Evans. Copyright 1955 by the

Photoelectric effect

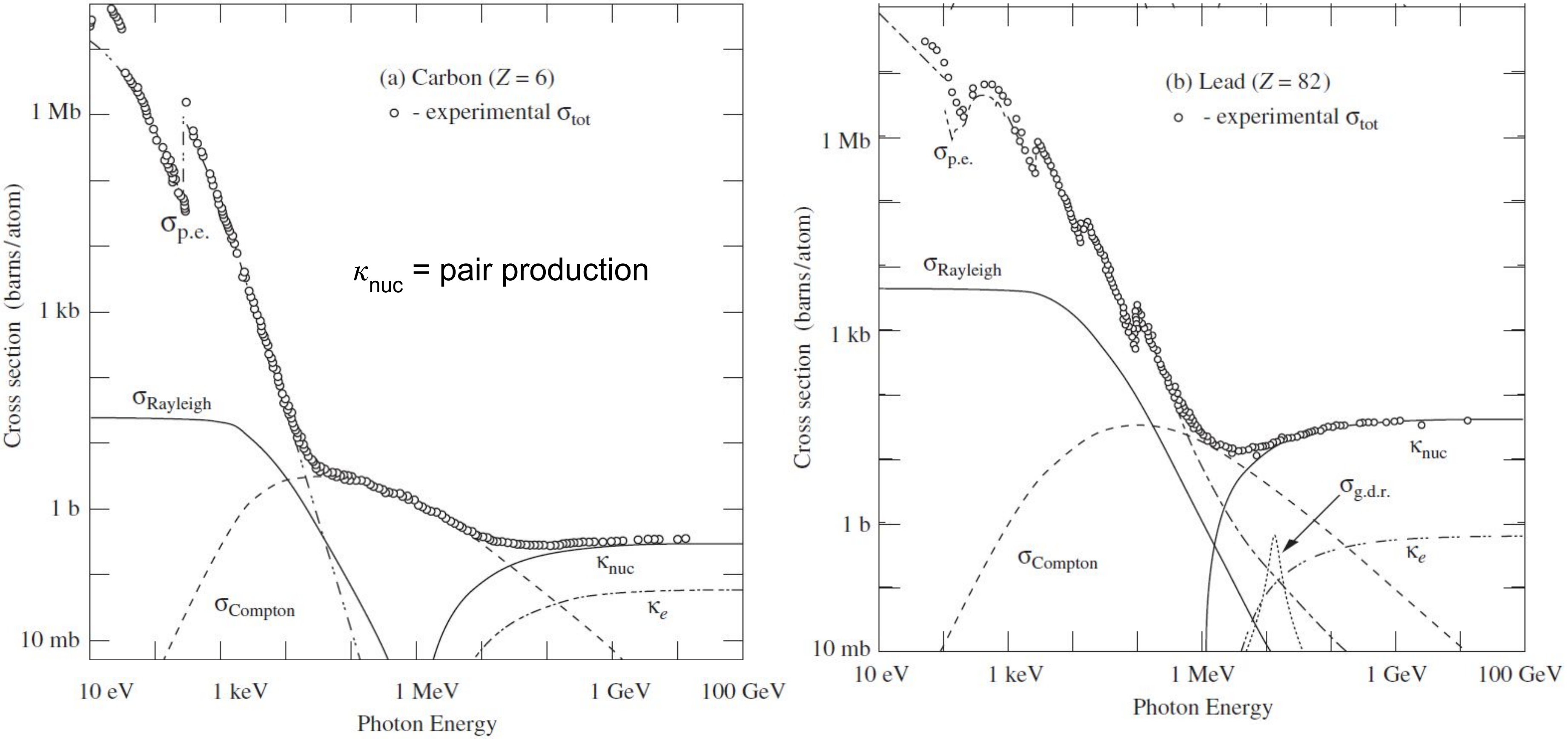


- An incident γ-ray photon transfers all its energy to a bound core electron if the γ-ray energy is larger than the binding energy of the electron
- The electron is ejected with a kinetic energy $E_e = E_\gamma - E_b$
- The cross-section of photoelectric effect shows sharp features when γ-ray energy 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 $\tau \cong \text{constant} \times \frac{Z^n}{E_\gamma^{3.5}}$

n is in between 4 and 5, Z is atomic no., E_γ is γ-ray energy

Cross-section of various process for different γ-ray energy



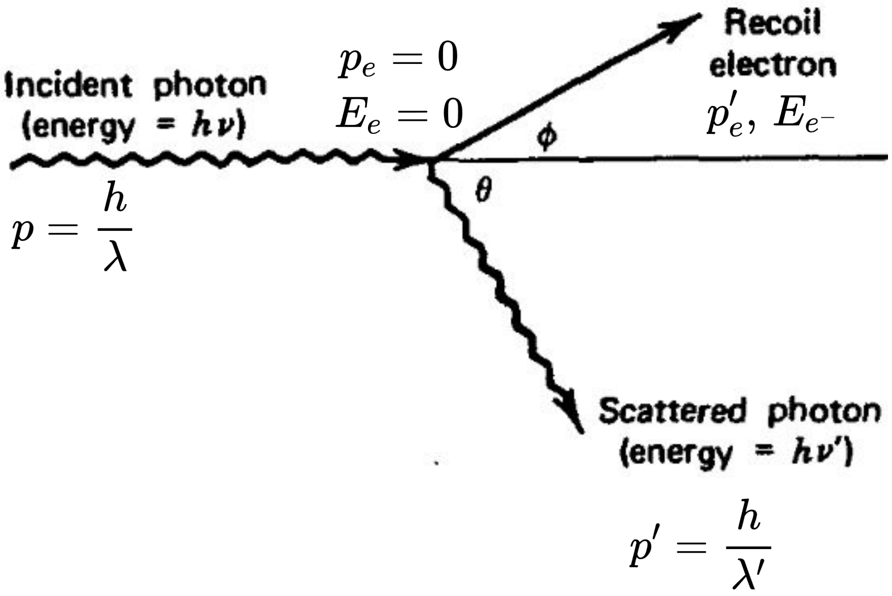
Photoelectric effect

- The vacancy created in inner core is filled by rearrangement of electrons
- The energy corresponding to the binding energy of the core electron is released as a characteristic X-ray or sometimes through a Auger electron
- The characteristic X-ray can cause further photoelectric effect involving less tightly bound electrons in the upper shells
- Net result of photoelectric interaction is release of a photoelectron which carries most of the energy from the γ-ray, together with one or more lower energy electrons corresponding to the binding energy of the photoelectron
- The liberated electrons lose energy quickly and the γ-ray is detected through the energy loss of these electrons in the material

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 (broadening comes e.g from the distribution of binding energy of the electrons)

Compton scattering



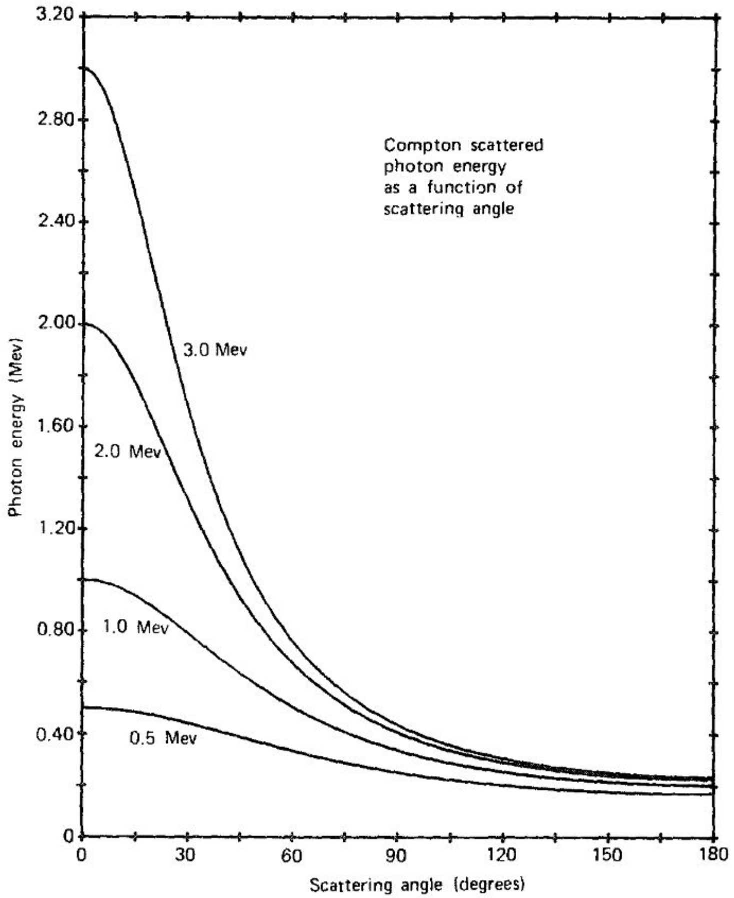
- An incident γ-ray photon scatters of a free electron and transfers part of its energy to scattered electron
- Energy remaining within the scattered photon is

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

- Kinetic energy of the scattered electron

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

Variation of scattered γ-ray energy with scattering angle



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

$$h\nu'\Big|_{\theta=\pi} = \frac{h\nu}{1 + 2h\nu/m_0c^2}$$

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

$$h\nu'\Big|_{\theta=\pi} \cong \frac{m_0c^2}{2} = 0.25\ \text{MeV}$$

Compton scattering

- Least energy is transferred to the scattered electron for grazing angle $\theta \approx 0$

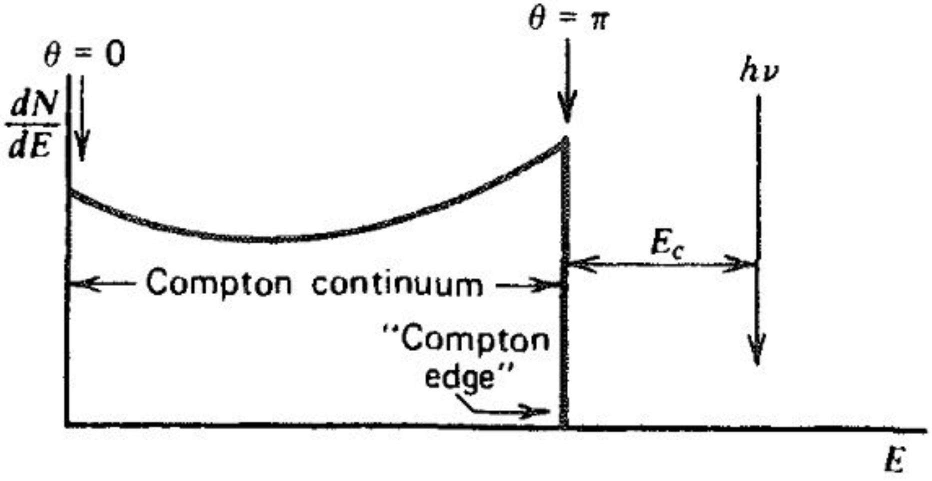
  Then $h\nu' \approx h\nu$ and $E_{e^-} \approx 0$

- Maximum energy is transferred for head-on collision, $\theta = \pi$

  Then $h\nu'\Big|_{\theta=\pi} = \dfrac{h\nu}{1 + 2h\nu/m_0c^2}$ $\quad E_{e^-}\Big|_{\theta=\pi} = h\nu\left(\dfrac{2h\nu/m_0c^2}{1 + 2h\nu/m_0c^2}\right)$

- Scattering may occur at all angle between 0 and π with certain probability
- There is a distribution of energy of the scattered electrons over many Compton scattering events

Energy distribution of the Compton recoil electrons



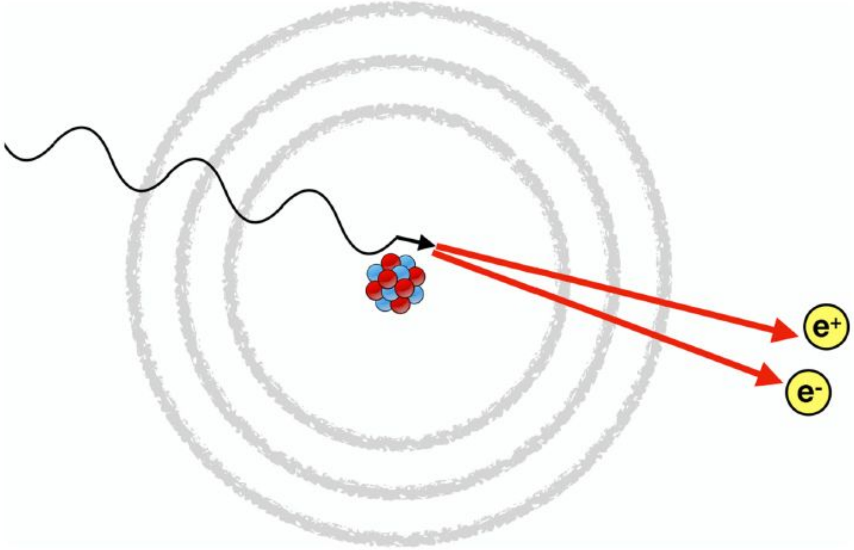
- The maximum energy of the recoil electron is known as Compton edge
- The gap between Compton edge and incident γ-ray energy is given as

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

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

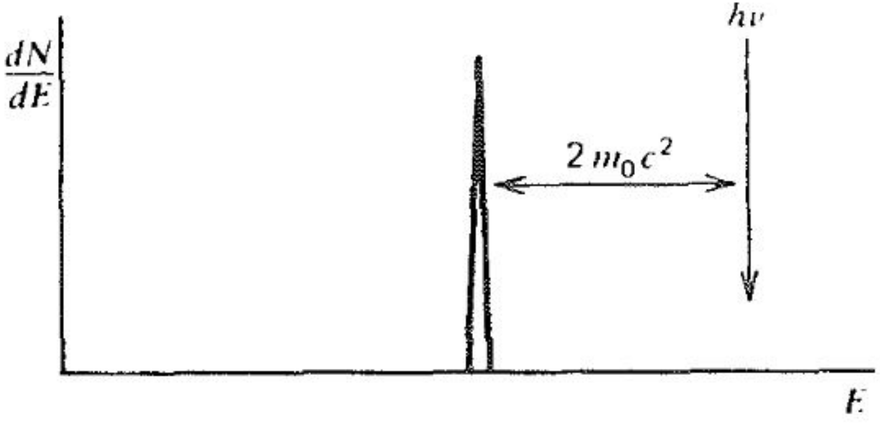
$$E_C \cong \frac{m_0c^2}{2} \; (= 0.256\ \mathrm{MeV})$$

Pair production



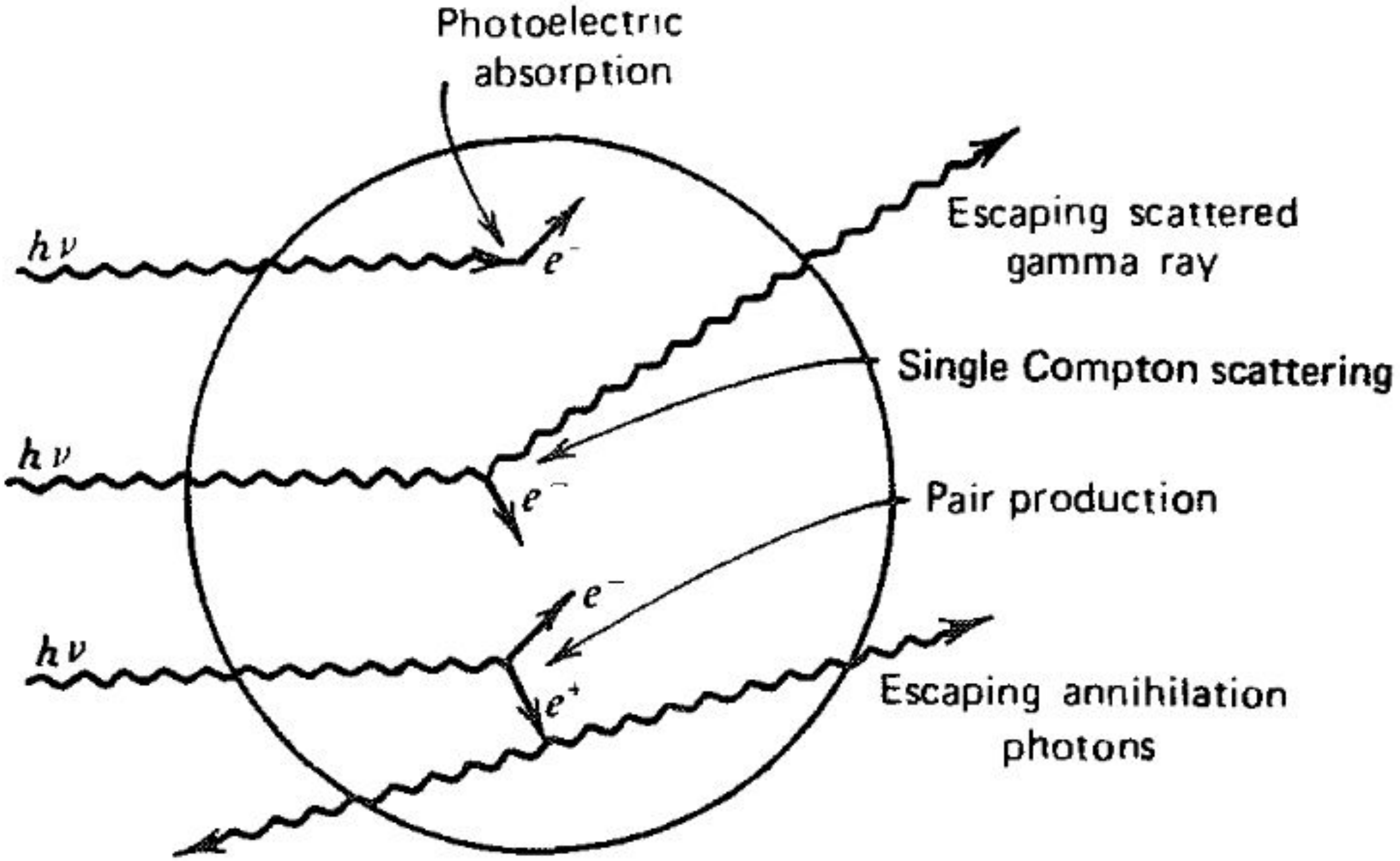
- A γ-ray photon transforms in to an electron-positron pair
- To conserve momentum, the process can take place only in presence of a third body, usually a nucleus
- The process becomes energetically possible only if the photon energy exceeds $2m_0c^2 = 1.02$ MeV
- Practically, this process become significant only for photon energy exceeding ~10 MeV
- The cross-section of this process scales as the square of the atomic no. of the absorber materials

Pair production

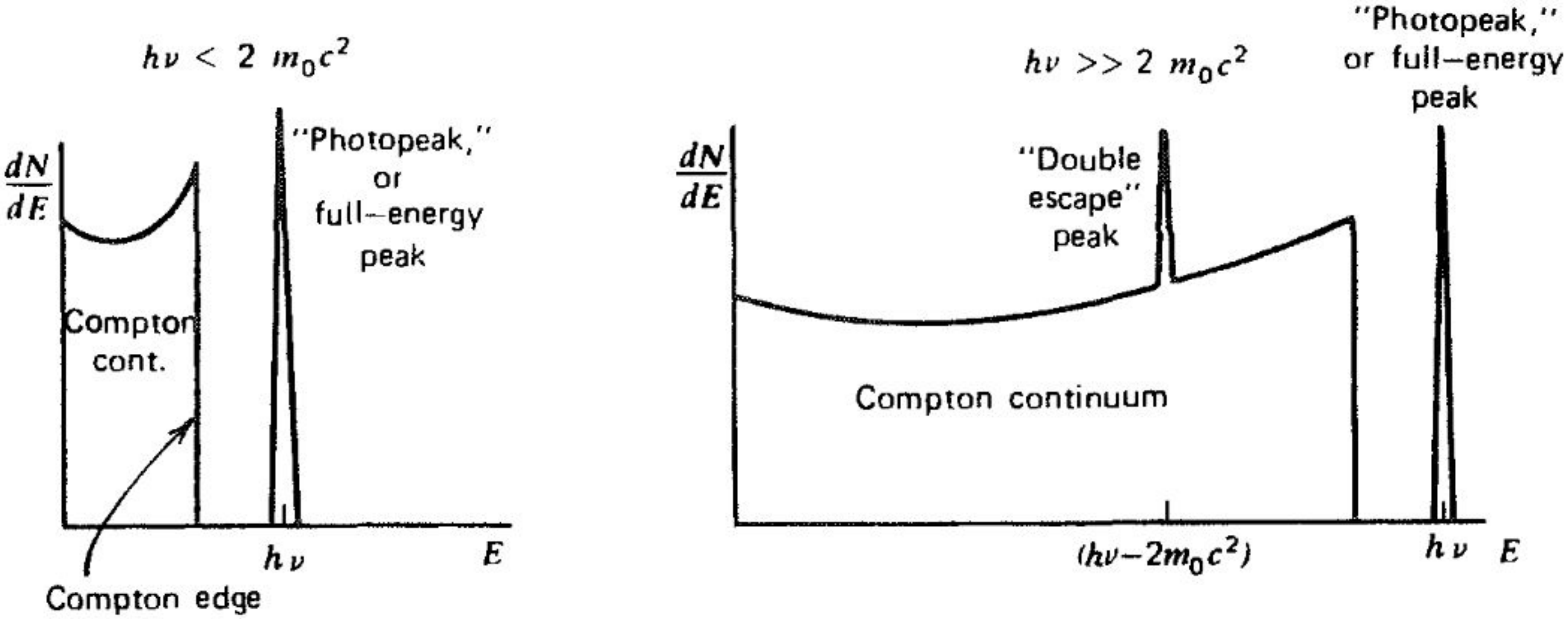


- Excess energy of photon beyond $2m_0c^2$ = 1.02 MeV is shared as the kinetic energy of the electron and positron: $E_{e^-} + E_{e^+} = h\nu - 2m_0c^2$
- The generated charge particles deposit their energy in the absorber material. The energy distribution of charge particle is a delta function at an 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

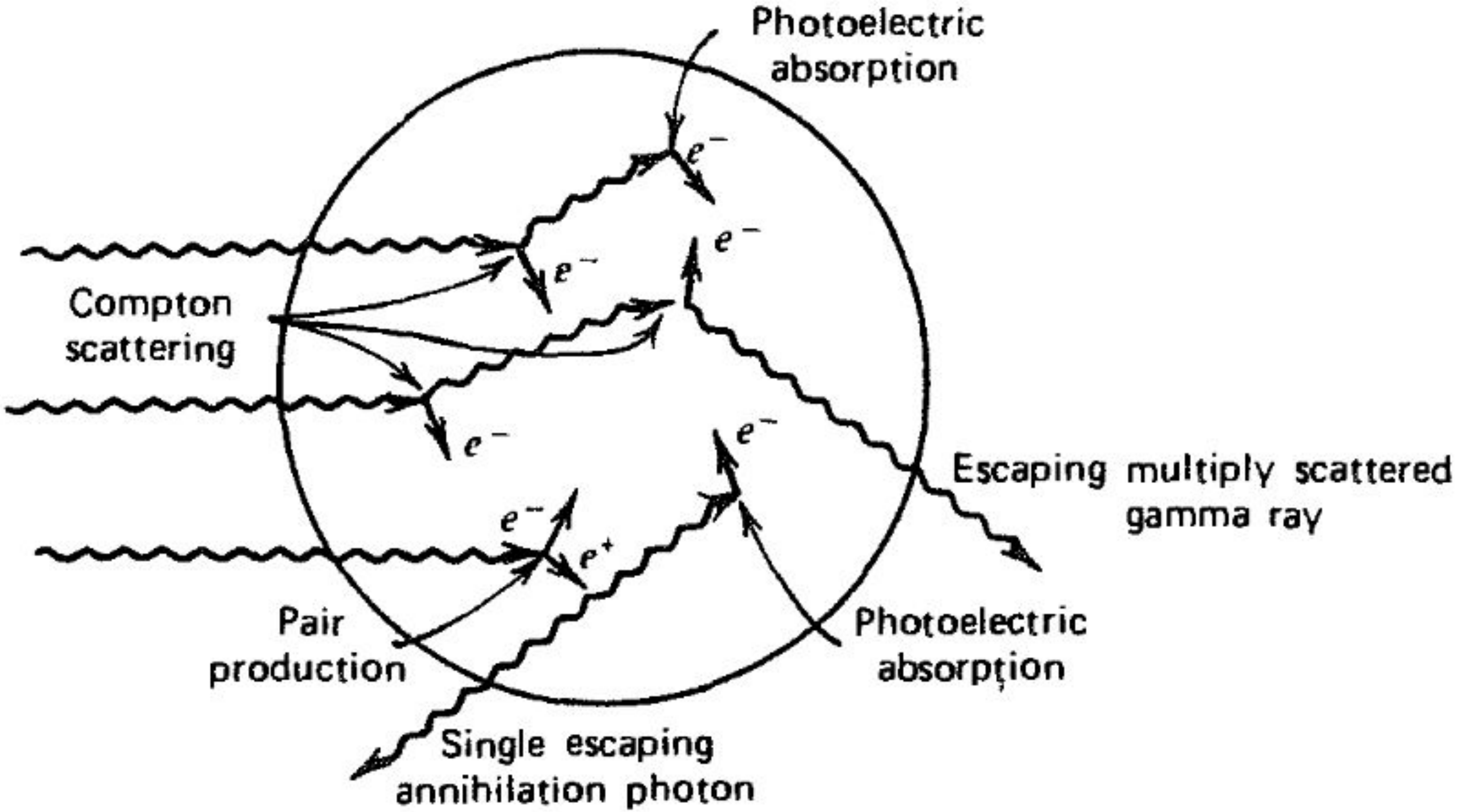
γ-ray spectrum for “small” size detector



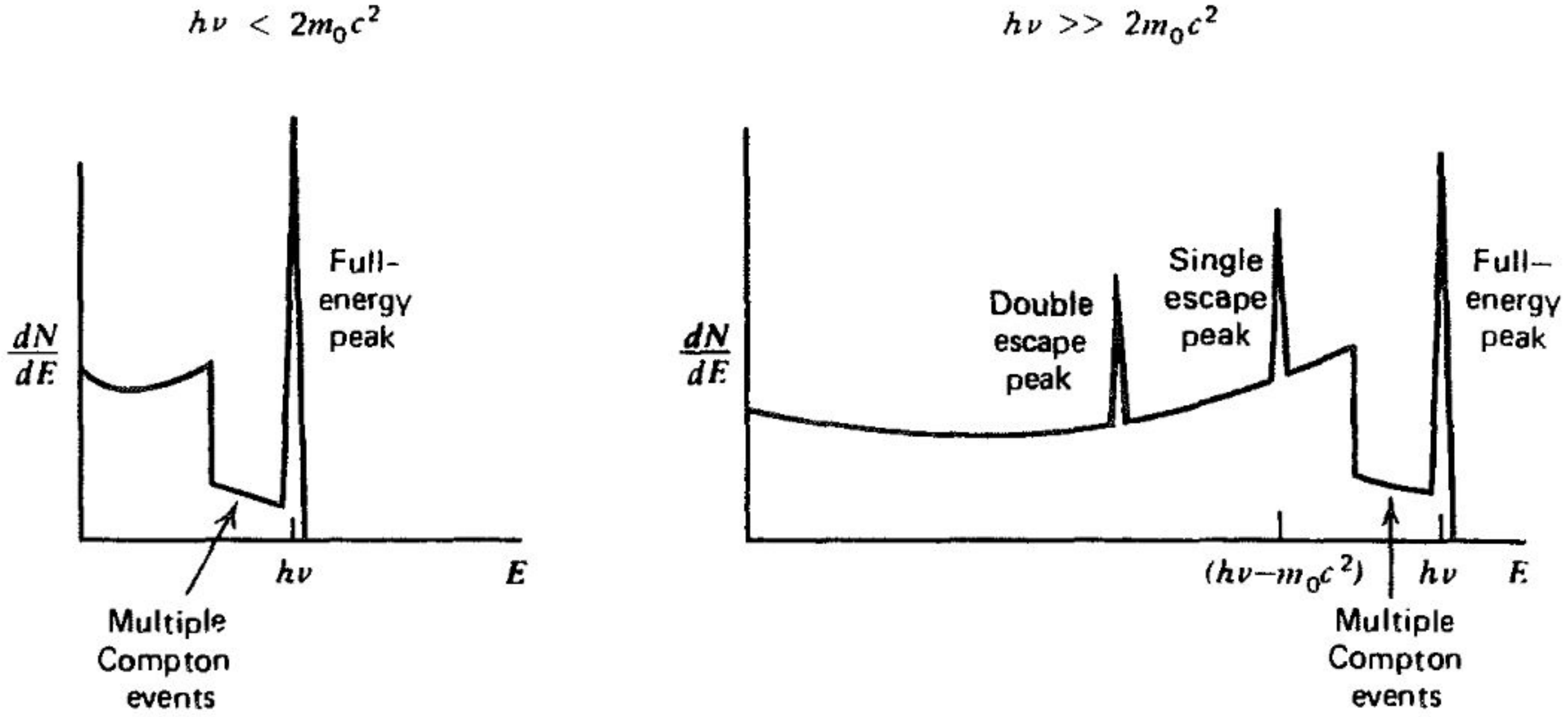
γ-ray spectrum for "small" size detector



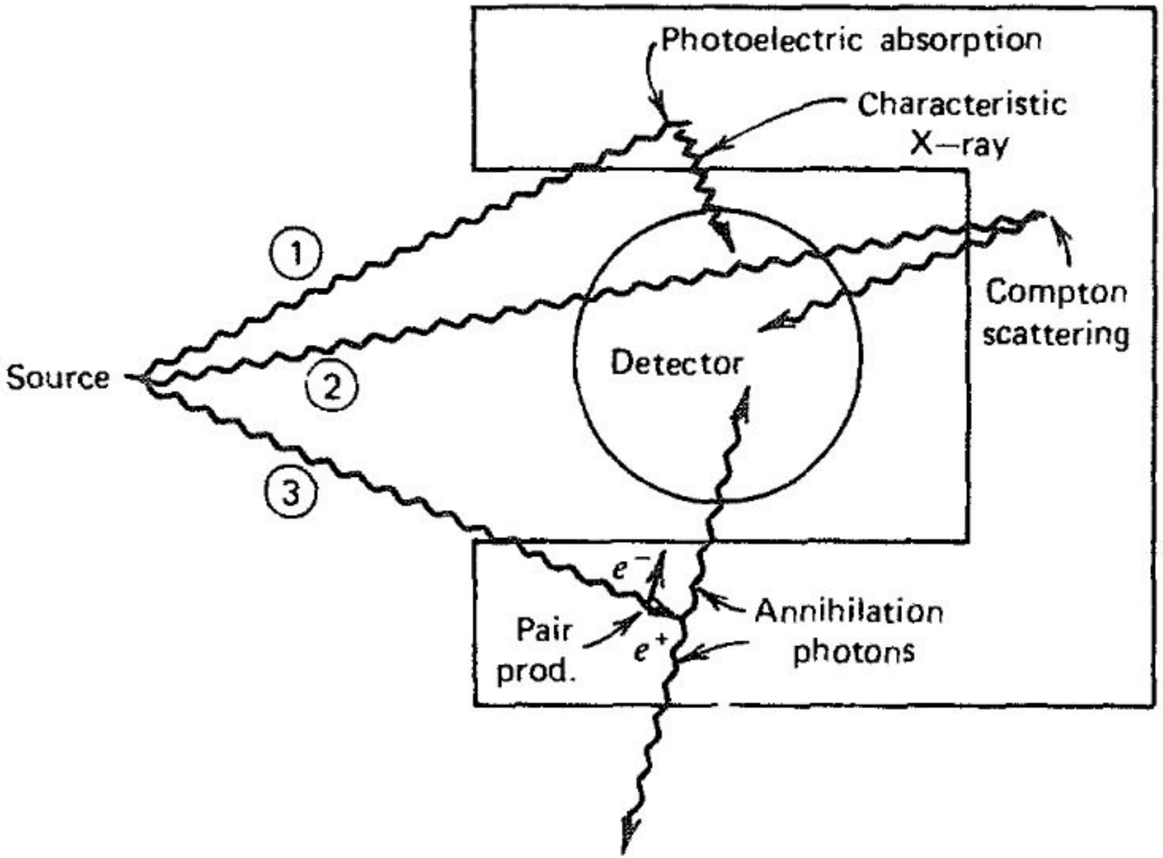
γ-ray spectrum for "practical" size detector



γ-ray spectrum for "practical" size detector



Effect of surrounding (shielding) material



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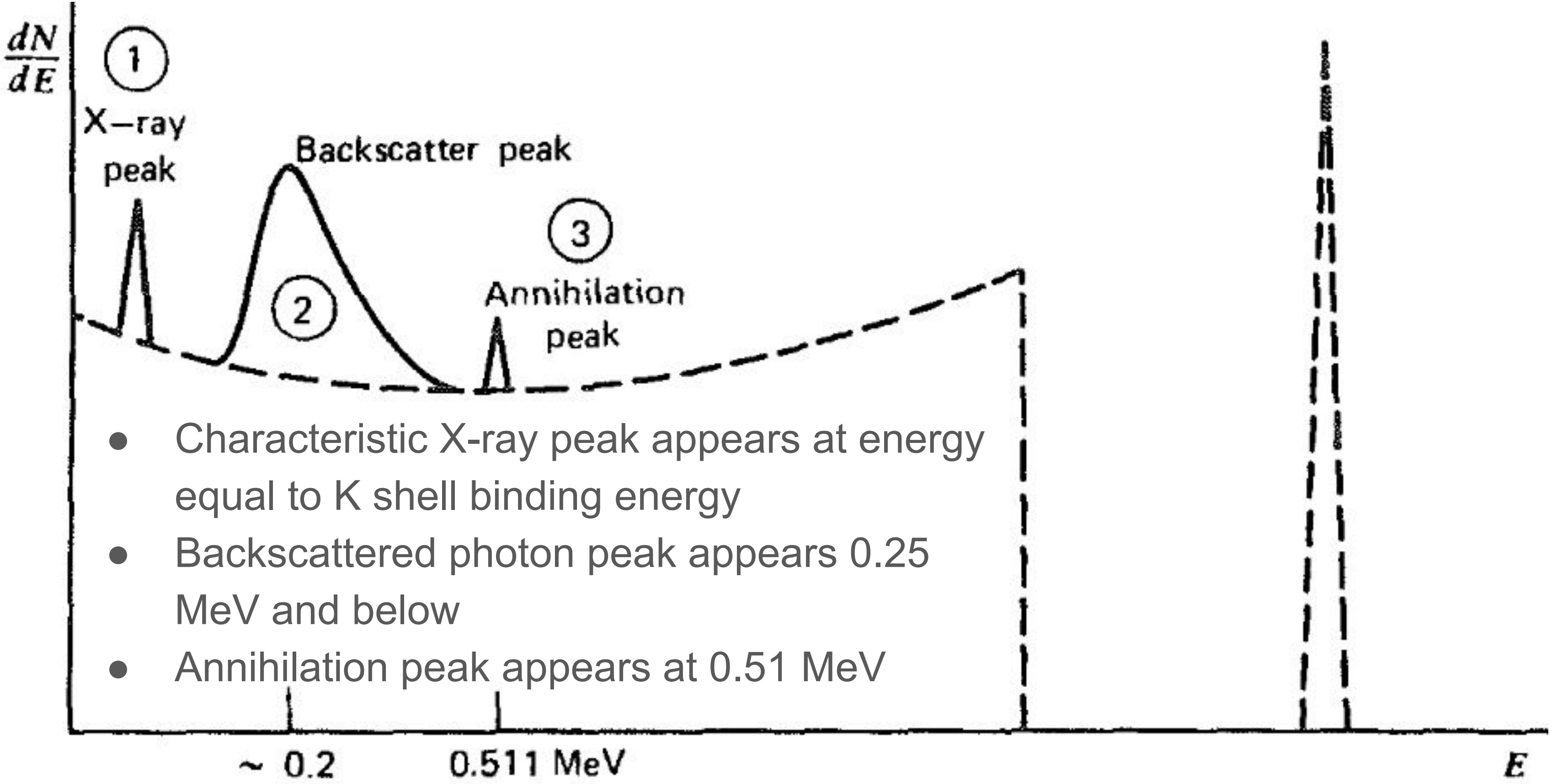
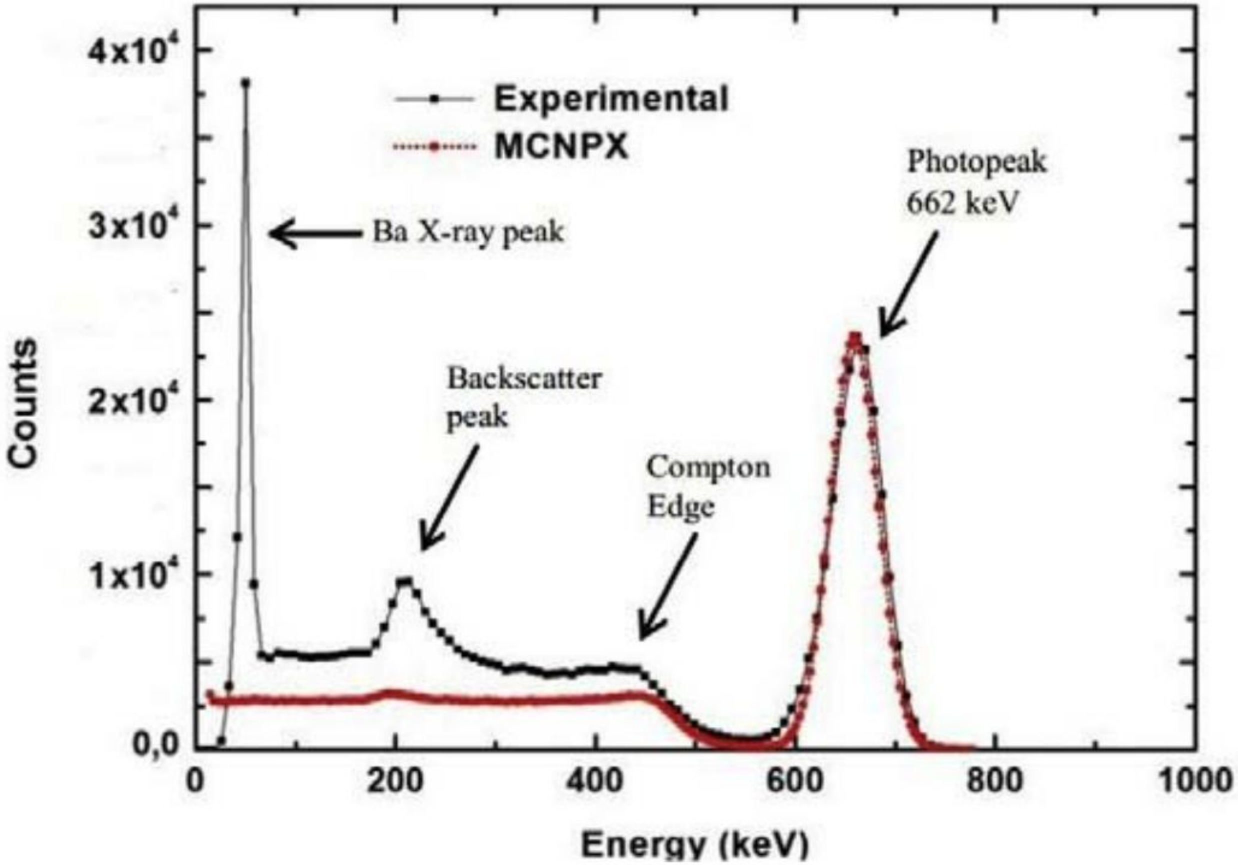
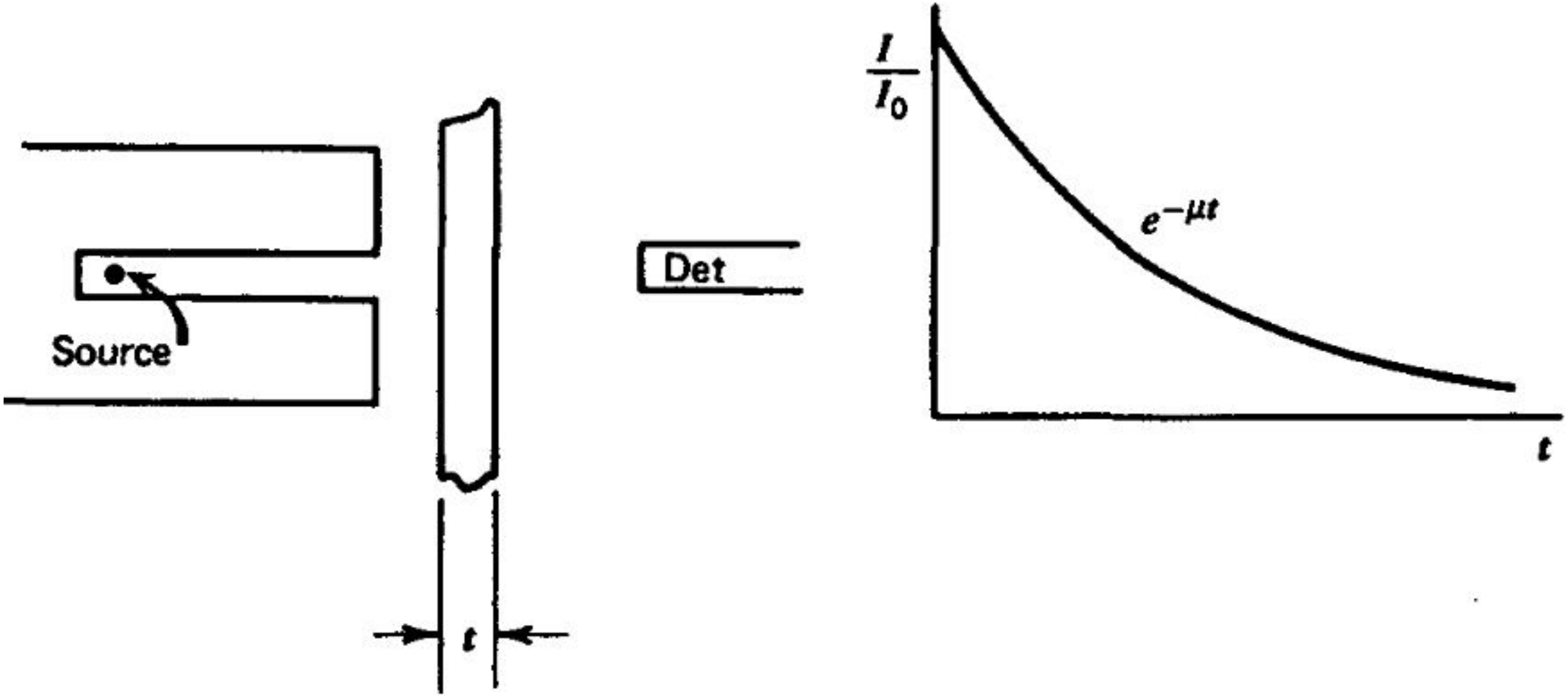


- Characteristic X-ray peak appears at energy equal to K shell binding energy
- Backscattered photon peak appears 0.25 MeV and below
- Annihilation peak appears at 0.51 MeV

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