Lecture 10 : Basic properties of radiation

- Types of radiation
- Interaction of charged particles with matter
- Interaction of gamma-ray photons with matter
- Neutrons

Types of Radiation

- The radiation of primary concern to us originates in atomic or nuclear processes and can be divided into four general types:
  - **Charged particle radiation**: (1) Fast electrons (2) Heavy charged particles.
  - **Uncharged radiation**: (3) Electromagnetic radiation (4) Neutrons.
- **Fast electrons**: beta particles emitted in nuclear decay.
- **Heavy charged particles**: encompasses all energetic ions with mass of >1amu. This will include alpha particles, protons and fission products.
- **Electromagnetic radiation**: X-rays from atomic electron rearrangement and gamma-rays from transitions in the nucleus itself.

Interaction of α particles with matter

- Charged particles interact via the Coulomb force between their positive charges and the negatively charged electrons of absorber atoms.
- The electrons of the absorber are either **excited** or completely removed - **ionised**.
- The α-particle loses energy on each interaction, but its large mass (relative to the electron) means it suffers a small deflection.
- In any one collision, the maximum energy transfer is:

$$\frac{\Delta T_{max}}{T} \approx 4\frac{m_e}{M_\alpha} \approx \frac{1}{2000}$$

- The incident α-particle loses its energy through many such interactions.
- The linear stopping power S is defined as the energy loss per unit path length in a material

$$S = -\frac{dT}{dx}$$

Bethe-Bloch Formula

- A classical expression that describes **collision** energy loss of a charged particle in an absorber material:

$$-\frac{dT}{dx} = \frac{4\pi z^2 \alpha^2 (\hbar c)^2}{m_e v^2} N_a B$$

$$B = Z_a \left[\ln\left(\frac{2 m_e v^2}{I(1 - v^2/c^2)} \right) - \frac{v^2}{c^2} \right]$$

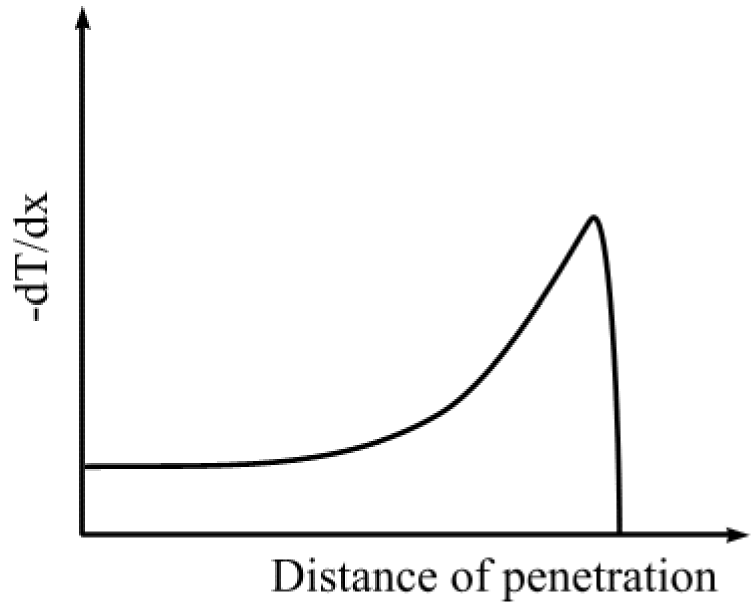
- Where (v,z) are the velocity and charge state of the incident particle, (N_a,Z_a) are the number density and atomic number of the absorber, m_e is the electron rest mass, α is the fine structure constant and I the average ionisation and excitation energy of the absorber.
- Higher density materials have greater stopping power.

$$\frac{dT}{dx} \propto \frac{1}{v^2} \propto \frac{1}{\text{energy}} \qquad \frac{dT}{dx} \propto z^2$$

Heavy particles lose energy faster

The Bragg Curve

- A plot of the specific energy lost along the track of a heavy charged particle is known as the Bragg curve.
- An example for an α particle is shown. The charge on the α is +2 and the energy loss increases roughly as 1/T.
- Near the end of the track, the charge on the α changes through electron pickup and the curve rapidly falls.



Particle Range

- The range of a particle is defined as the distance R traversed by a particle of initial kinetic energy T_0 before it comes to rest in the stopping material

$$R = \int_{T_0}^{0} \frac{dT}{dT/dx}$$

- For non-relativistic particles, losing energy by collision.

$$-\frac{dT}{dx} \approx a\frac{z^2}{v^2}$$

- Where a is a constant. Hence, with $T_0 = \frac{1}{2}Mv_0^2$

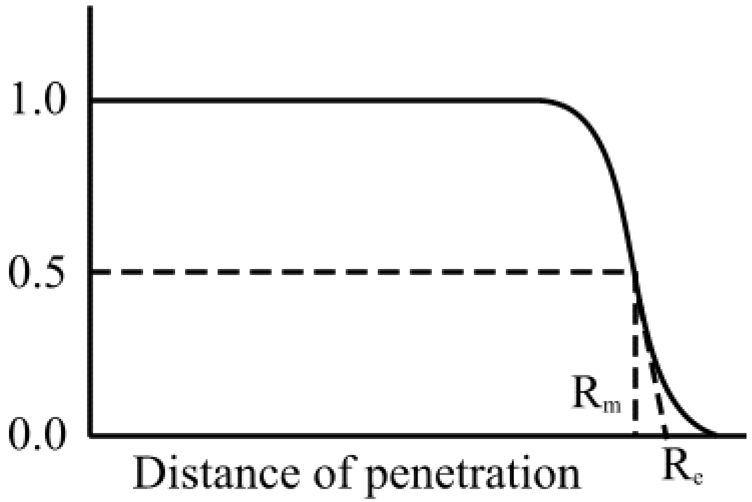
$$R = \frac{aT_0^2}{z^2 M} = \frac{aMv_0^4}{4z^2}$$

- The range is proportional to M/z^2 if the initial velocity is the same

Particle range

- The **mean range** R_m is the absorber thickness that reduces the incident intensity to half its initial value.
- The **extrapolated range** R_e is obtained by extrapolating the linear portion of the end of the transmission curve to zero.

Alpha-particle beam



Interaction of β particles with matter

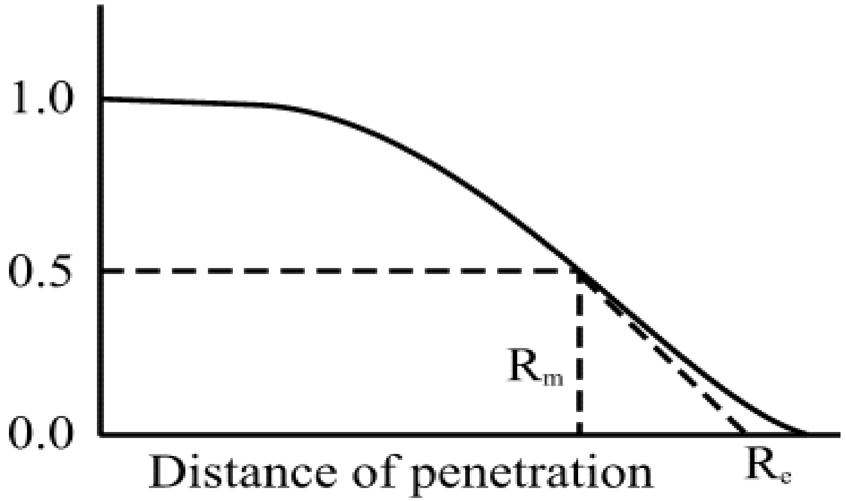
- As opposed to α particles, the low mass of incident β particles means relatively large amounts of energy can be transferred per collision.
- β particles are deflected significantly at each collision.
- β particles can also lose energy by **radiation** – bremsstrahlung –"braking radiation" in German.
- The total linear stopping power is then given by the sum of the collision and radiative losses.
- For energies below a few MeV, radiative losses are small and only collision losses are significant.

$$S = -\frac{dT}{dx} = -\left[\left(\frac{dT}{dx}\right)_{COLL} + \left(\frac{dT}{dx}\right)_{RAD}\right]$$

Beta-particle range

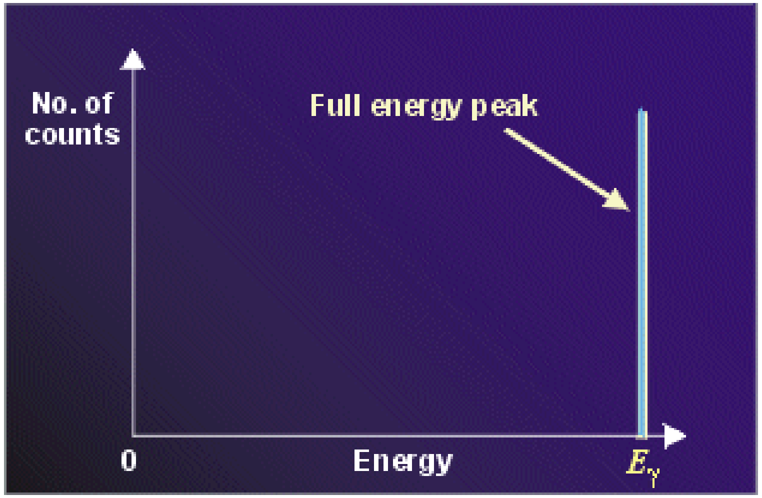
- The **mean range** R_m - is not a good measure of absorber thickness needed to stop beta particles.
- The **extrapolated range** R_e is a much better measure of required absorber thickness.

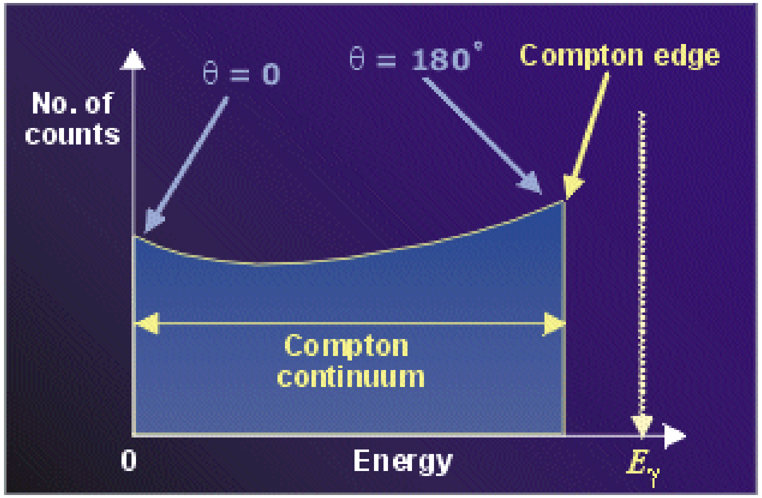
Beta-particle beam



How do γ-rays Interact with Matter?

- Gamma-ray photons can interact with matter through 3 primary processes:
  - Photo-electric absorption.
  - Compton Scattering
  - Pair Production.
- An electron with a finite energy will be left in the material.





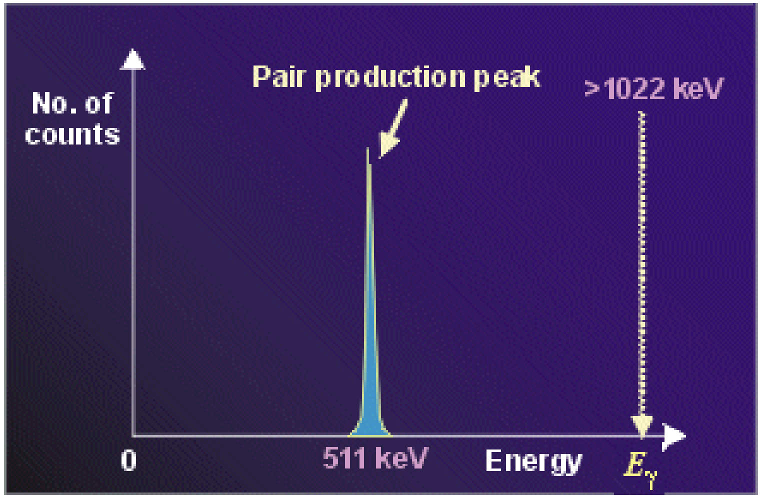


Photo-electric absorption

- Photo-electric absorption
- The gamma-ray interacts with a bound atomic electron.
- The photon completely disappears and is replaced by an energetic photoelectron.
- The energy of the photoelectron can be written:

$$E_e = E_\gamma - E_b$$

- The incident gamma-ray photon minus that of the binding energy of the electron (12eV in germanium).

Compton Scattering

- Compton Scattering
- The gamma-ray interacts with a loosely bound atomic electron.
- The incoming gamma-ray is scattered through an angle θ with respect to its original direction.
- The photon transfers a proportion of its energy to a recoil electron.
- The expression that relates the energy of the scattered photon to the energy of the incident photon is:

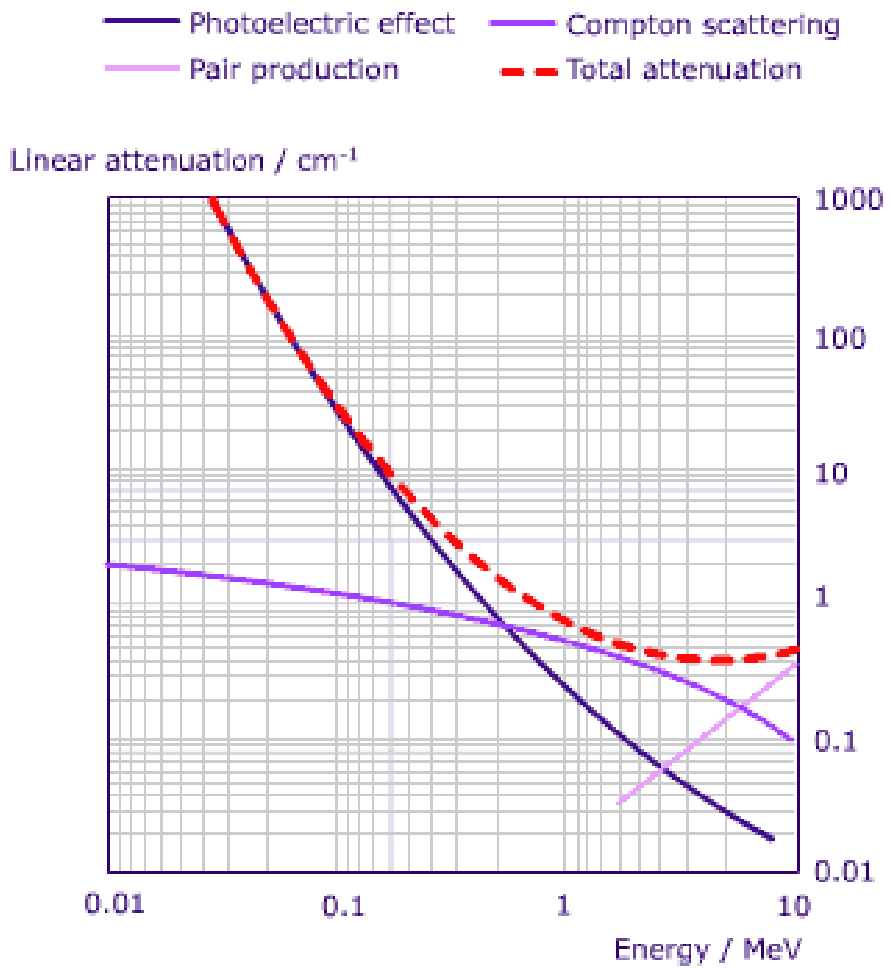
$$E_s = \frac{E_\gamma}{1 + \frac{E_\gamma}{m_0 c^2}(1 - \cos\theta)}$$

Pair Production

- Pair Production
- If the energy of a gamma-ray exceeds twice the rest mass energy of an electron (1.02MeV) the process of pair production is possible.
- A gamma-ray disappears in the Coulomb field of the nucleus and is replaced by an electron-positron pair.
- The excess energy above 1.02MeV goes to the kinetic energy of the electron and the positron.
- The positron will subsequently annihilate after slowing down in the absorbing medium, producing two annihilation photons (511keV) which may be subsequently detected.

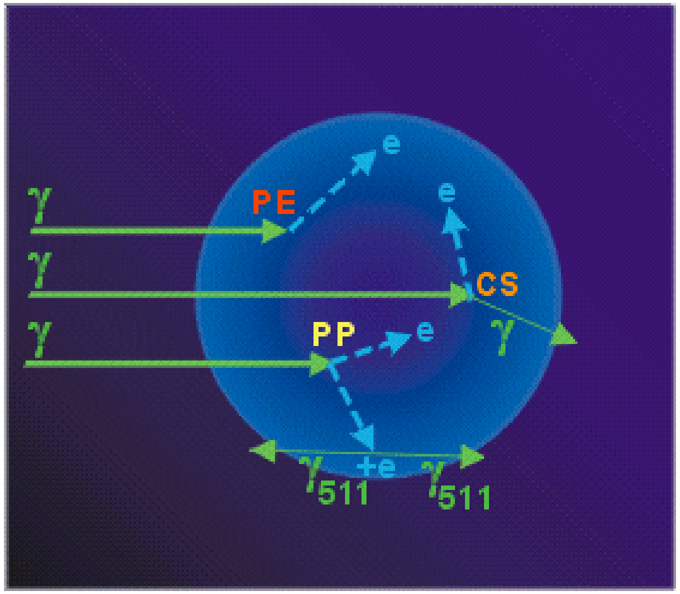
Energy dependence of γ-ray Interaction

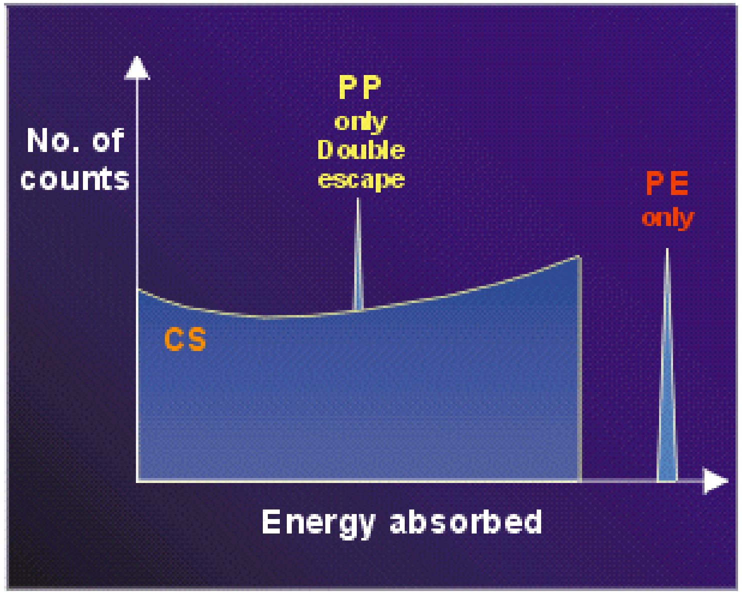
- Gamma-ray photons can have a large range of energies. Typical energies of interest to us range between 60keV and 10 MeV.



Interactions in a small detector

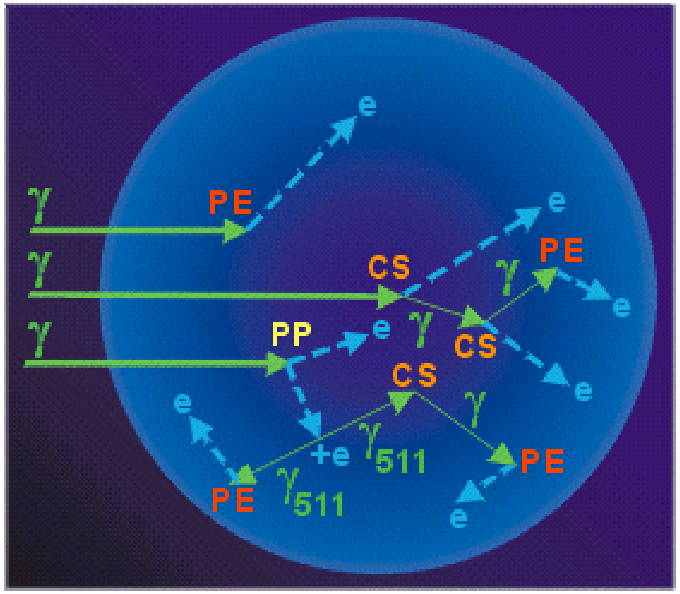
- A **small detector** is one so small that only one interaction can take place within it. Only the photoelectric effect will produce full energy absorption. Compton scattering events will produce the Compton continuum. Pair production will give rise to the double escape peak due to both gamma-rays escaping.

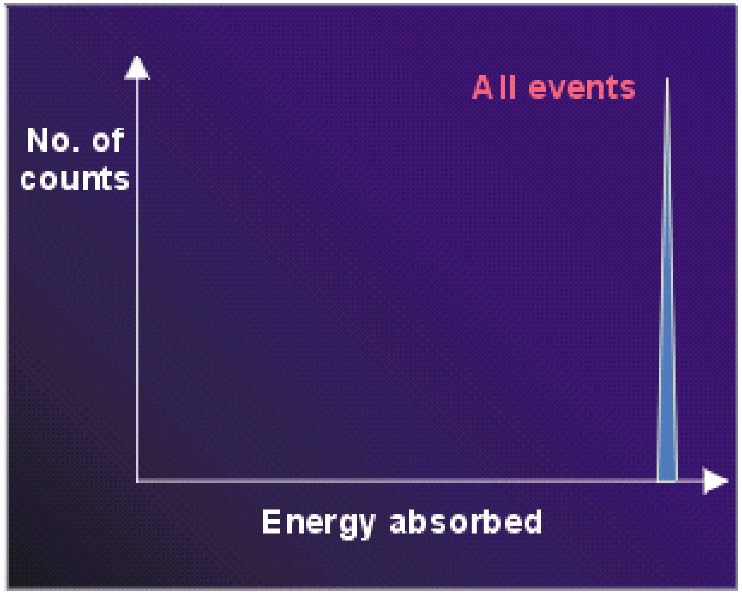




Interactions in a large detector

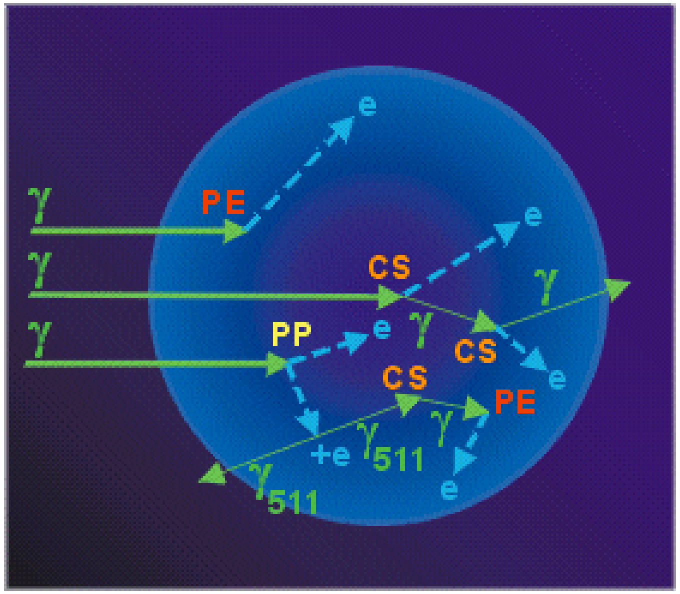
- A **large detector** is one in which we can ignore the surface of the detector. Various successive photoelectric absorption, Compton scattering and pair production interactions will occur. The result is complete absorption of the gamma-ray and a single gamma-ray peak, referred to as the full energy peak.

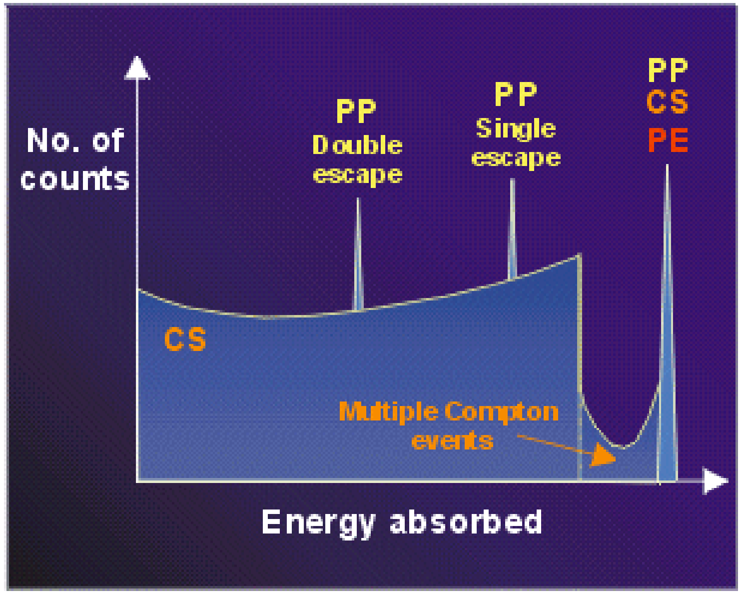




Interactions in a real detector

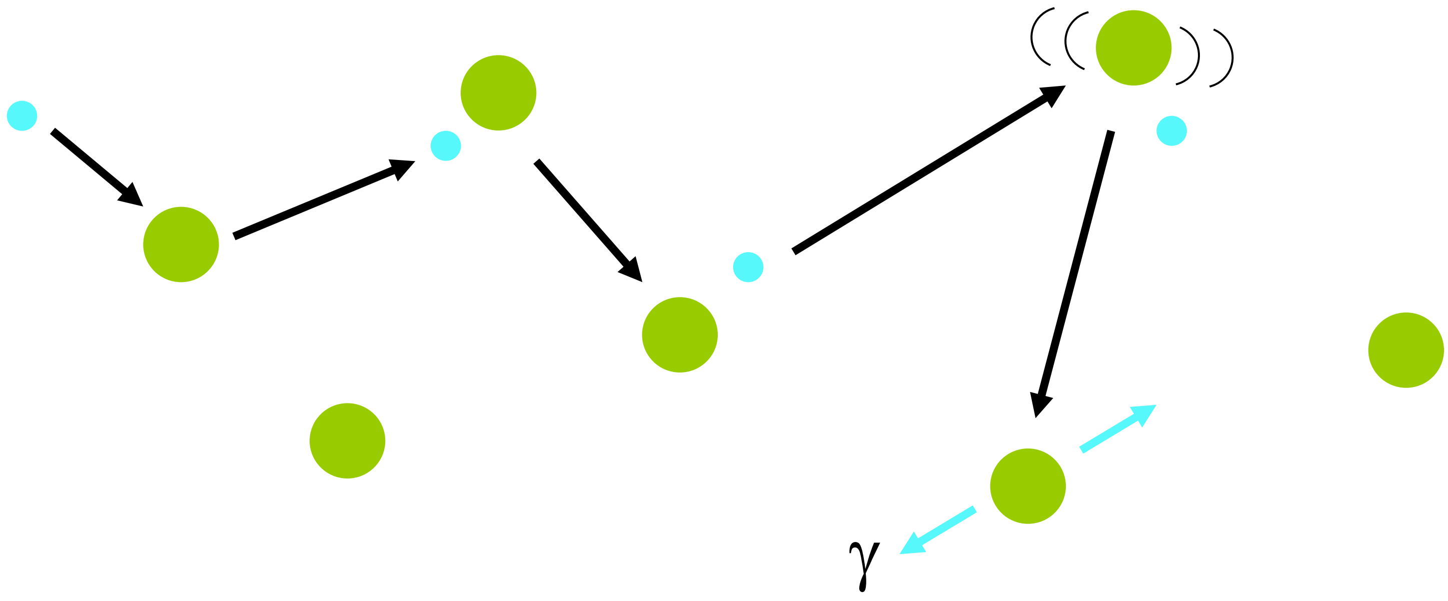
- Within a **real detector** the interaction outcome is not as simple to predict as the small or large detector case. Compton scattering may be followed by other Compton scatterings before the gamma-ray photon escapes from the detector. Also, pair production may be followed by the loss of only one annihilation gamma-ray, resulting in a single escape peak as well as a double escape peak.





Neutron scattering

- Neutrons carry no charge – undergo energy loss by **direct** interactions.
- Neutrons can undergo:
  - –Elastic scattering
  - –Inelastic scattering (n,n’)
  - –Radiative capture (n,γ)



Neutron moderation

- Neutrons are slowed down by successive elastic collisions $\rightarrow$ low A most effective
- $n \rightarrow {}^{1}H$ (equal masses)
- Average fractional energy loss per collision depends only on A (assuming scattering is isotropic in c-m system).
- After n collisions: $\left\langle \frac{E_0}{E_n} \right\rangle = \left\langle \frac{E_0}{E_1} \right\rangle \times \left\langle \frac{E_1}{E_2} \right\rangle \times \ldots \times \left\langle \frac{E_{n-1}}{E_n} \right\rangle$
- Define log. Energy decrement $\xi = \left\langle \ln \frac{E_0}{E_1} \right\rangle$
- Then: $\left\langle \ln \frac{E_0}{E_n} \right\rangle = n\xi$

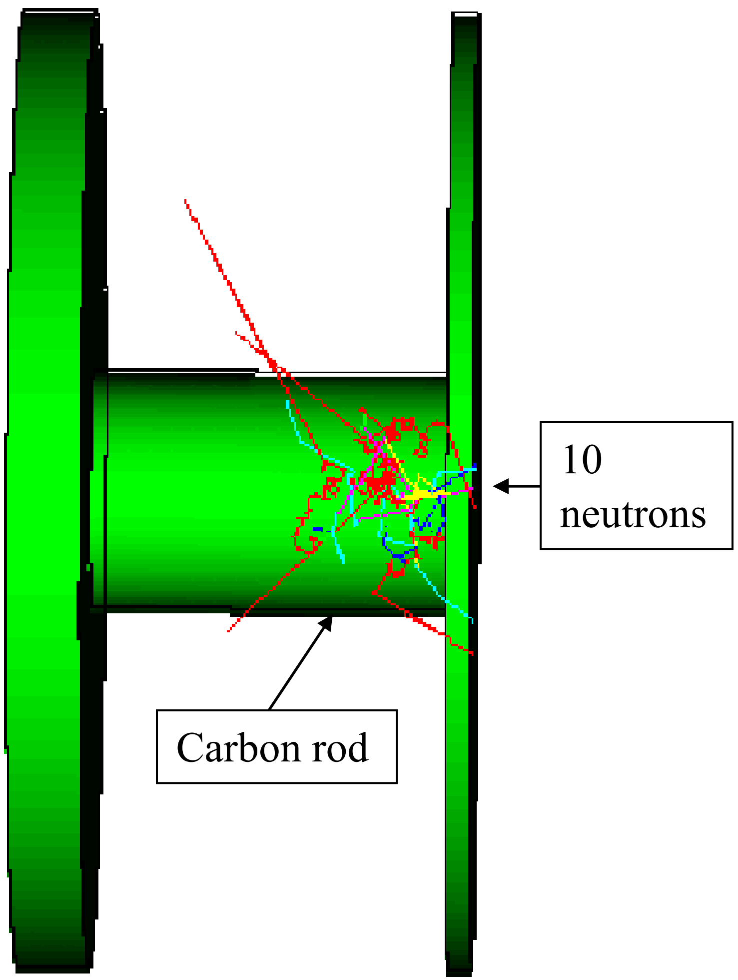
Neutron moderation

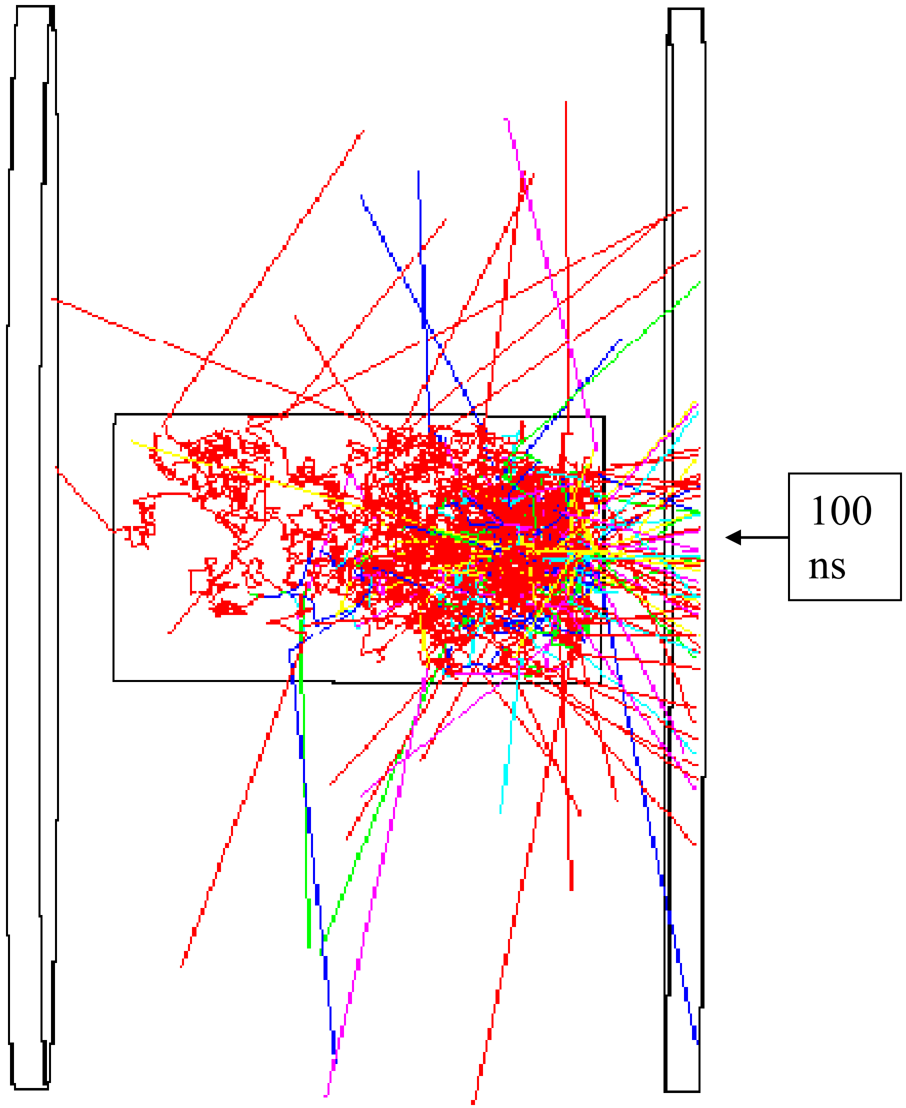
Nuclide	ξ - En. decrem.	N (to thermalise)
H	1	18
D	0.725	25
C	0.158	110
A	$\frac{2}{(A+2/3)}$;	$A \geq 10$

Ideal properties of moderators

Property	High σ(scatt)	Low σ(abs)	High ξ	Cost
$H_2 0$	v.good	Poor	v.good	v.good
$D_2 0$	Good	v.good	Good	Poor
Graphite	Good	Good	Poor	Good

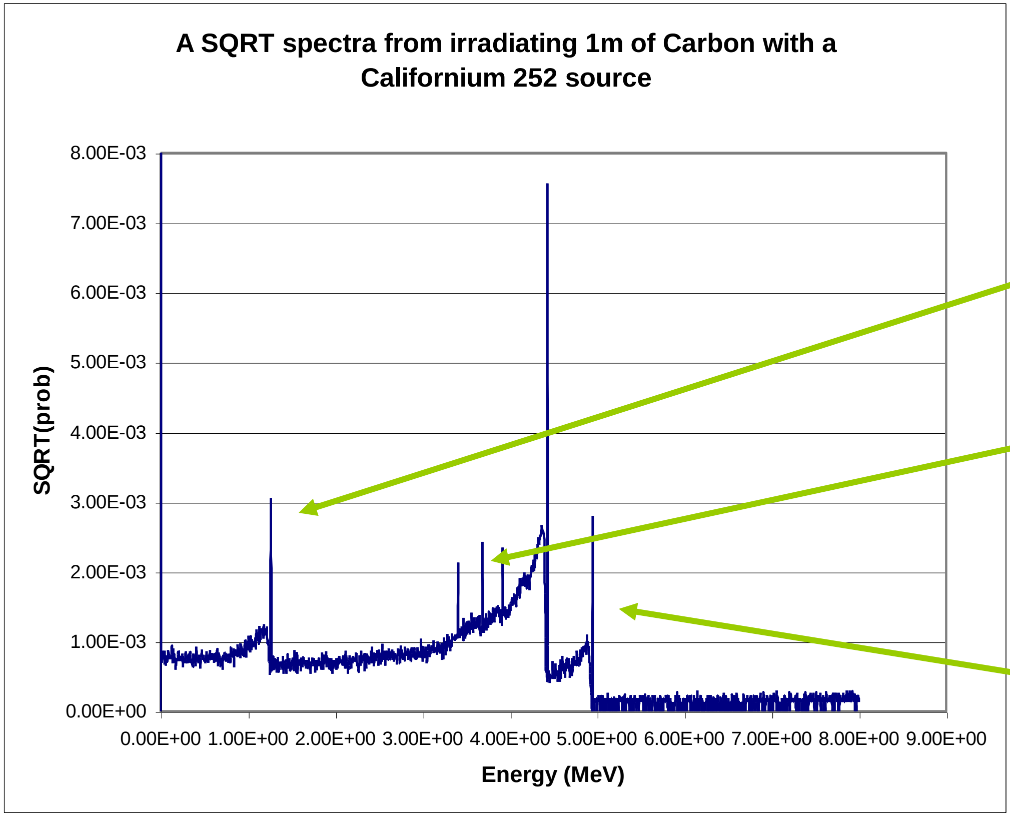
Complexity of neutron scattering





Neutron-induced γ-rays by Monte Carlo

- Irradiation of carbon with neutrons from ^{252}Cf fission
- Arrows indicate (n,γ)



Energy[MeV]	Probability
1.26	9.34×10^{-6}
3.41	4.55×10^{-6}
3.69	5.87×10^{-6}
3.92	5.48×10^{-6}
4.43	5.72×10^{-5}
4.95	7.84×10^{-6}

Radiation Detection and Measurement

- Types of radiation
- Interaction of charged particles with matter
- Interaction of gamma-ray photons with matter
- Neutrons