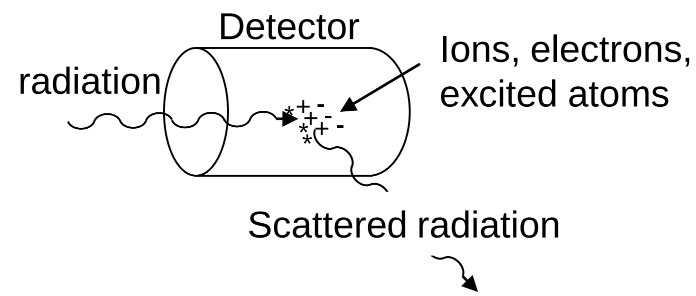
Fundamentals – Radiation Interactions

- Types of radiation and means of energy conversion
- Interaction/ detection processes
  - Charged particles
  - Electrons
  - Photons
  - Neutrons

General Principles of Radiation Detection

- Radiation detection
  - Interaction of radiation with matter produces ionization and electronic excitation or heat that can be measured:
  - Either primary charges are collected:
    - Gas detectors — **Ionization chamber**, **Proportional counter**, **Geiger-Müller counter**
    - Solid state detectors — **Si, Ge, CdZnTe, HgI_2,…**
  - Or photons resulting from de-excitation of molecules of the detector are converted to secondary charges which are collected:
    - Scintillators — **Inorganic: NaI(Tl), CsI(Tl), LaBr, BGO,…** **Organic: anthracence, stilbene, plastic,…**



Types of "Ionizing" Radiation

- Charged particulate radiation
  - Fast electrons and positrons (e^-/e^+ or β particles)
  - Heavy charged particles ($A \geq 1$, protons, α particles, fission fragments)
- Uncharged radiation
  - Electromagnetic radiation (photons/ X rays, γ rays)
  - Neutrons (slow/fast, (ultra-)cold/hot)
  - Neutrinos
  - Cold Dark Matter (?)

Directly Ionizing (or other means…)

Indirectly Ionizing (or other means…)

Some Properties of Ionizing Radiation

Heavy charged particles	Energy when Generated
• α-decay	Discrete
• Spontaneous fission	Continuous
Electromagnetic radiation	
• Gamma rays following beta decay or other means of nuclear excitation	Discrete
• Annihilation radiation (511 keV)	Discrete
• Bremsstrahlung	Continuous
• Characteristic X rays	Discrete
Neutrons	
• Spontaneous and induced fission	Continuous
• Radioisotope (α,n) sources	Continuous
• Photo-neutron (γ,n) sources	~ Discrete
• Accelerated-based neutron generators [(D,D); (D,T); (p/d,n) reactions]	~ Discrete

Radiation Interactions – General Remarks

- To understand radiation detection, it is necessary to understand underlying physics processes how radiation interacts with matter, e.g. detectors…

<u>Classes of radiation and their relationship</u>

<u>Uncharged Radiation</u>		*<u>Charged Radiation</u>*	
Discrete energy loss		Continuous energy loss	
Neutrons	Nuclear reactions [(n,α),(n,p),…], scattering $\longrightarrow$	Heavy charged particles (nuclei)	EM interactions: •Ionization •Excitation
$\downarrow$ (n,γ)			
Photons	$\longrightarrow$ EM interactions, photoelectric absorption, Compton effect,…	Electrons	

Means of and materials for converting energy to signal

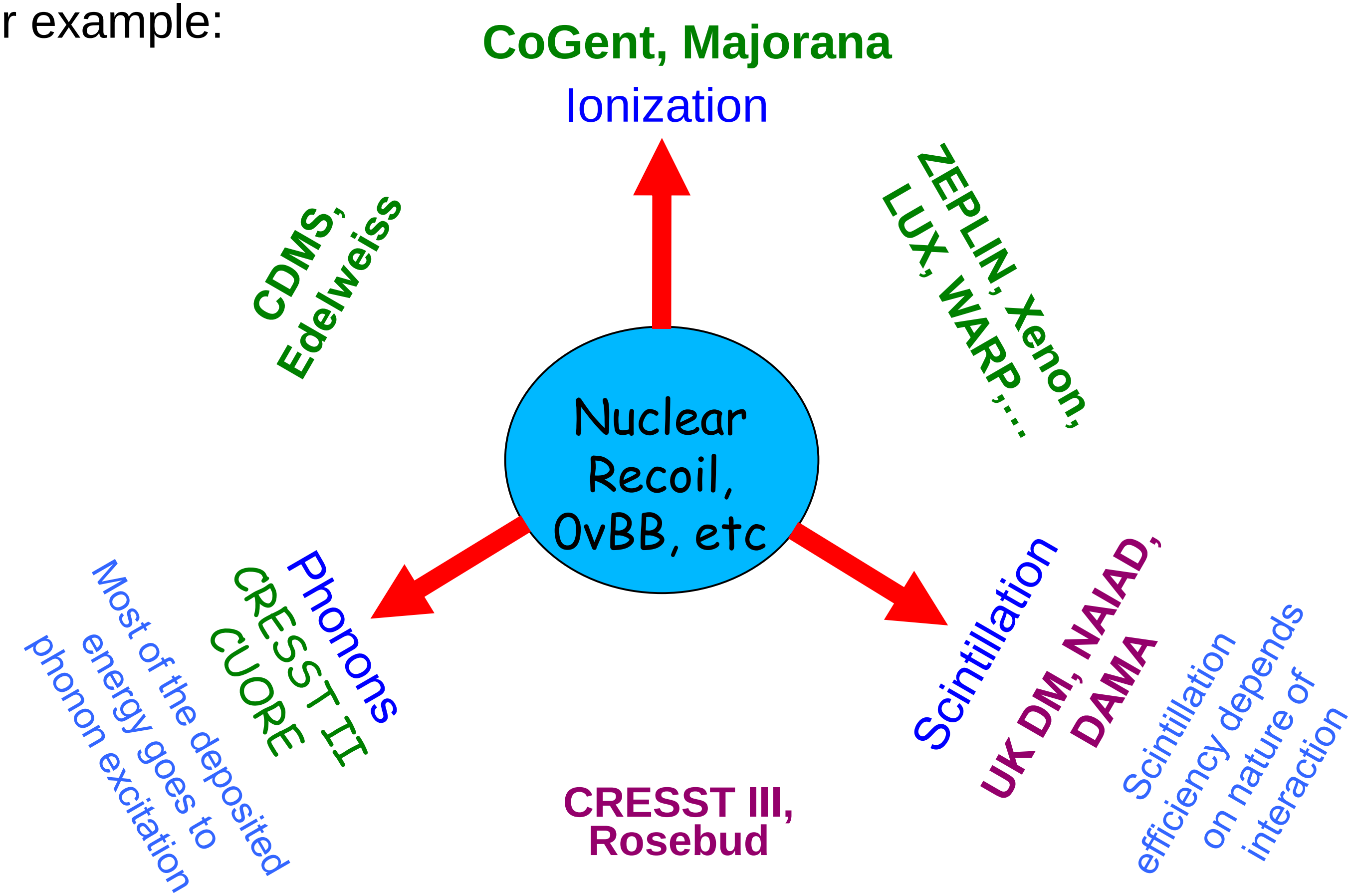
- Ionization, Scintillation, Heat vs. Gases, Liquids, Solids

Material State	Detector implementation	Signal	Excitation energy
Gas	Scintillation Ionization	Light - Photons Electron-ion pairs	10-200 eV ~ 30 eV
Liquid	Scintillation Ionization	Light - Photons Electron-ion pairs	10-200 eV ~ 30 eV
Solid	Scintillation Ionization Bolometer	Light - Photons Electron-hole pairs Heat - Phonons	10-200 eV 1-5 eV ~ 0.001 eV

- And combinations of implementations, e.g.
  - Gas & liquid: Scintillation (prompt) + ionization (delayed): Particle discrimination (nuclear vs. electronic) , energy resolution improvements, 3D position determination (Time-Projection Chamber)
  - Solid: Ionization + Bolometer: Particle discrimination (nuclear vs. electronic)

Other means of detection …
… Even non-EM radiation

- Detect by different interaction process as a way to distinguish particle types to increase sensitivity by recognizing background … important in the detection of rare particles and processes such as CDM or ν's …
- For example:

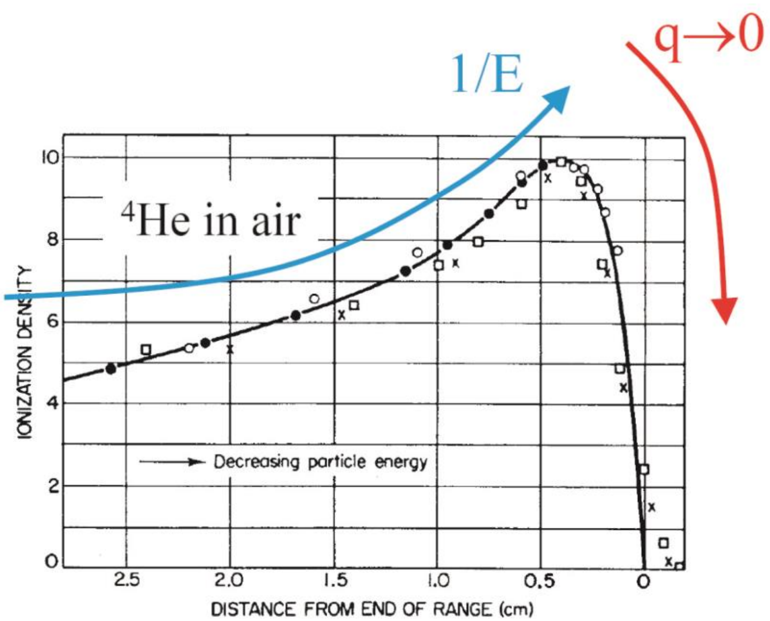


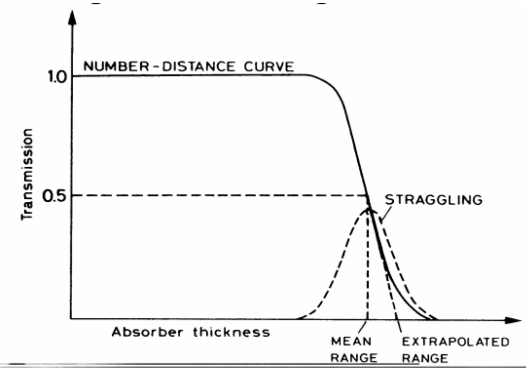
Review of Interactions

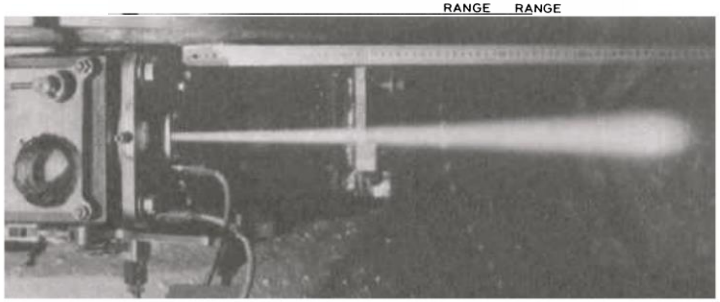
Interaction of Massive Charged Particles

- Charged particles experience energy loss and deflection due to interaction with:
  - Inelastic collisions with atomic electrons
  - Elastic scattering on nuclei
  - Bremsstrahlung

$$-\frac{dE}{dx} \propto K \frac{Mz^2}{E}$$

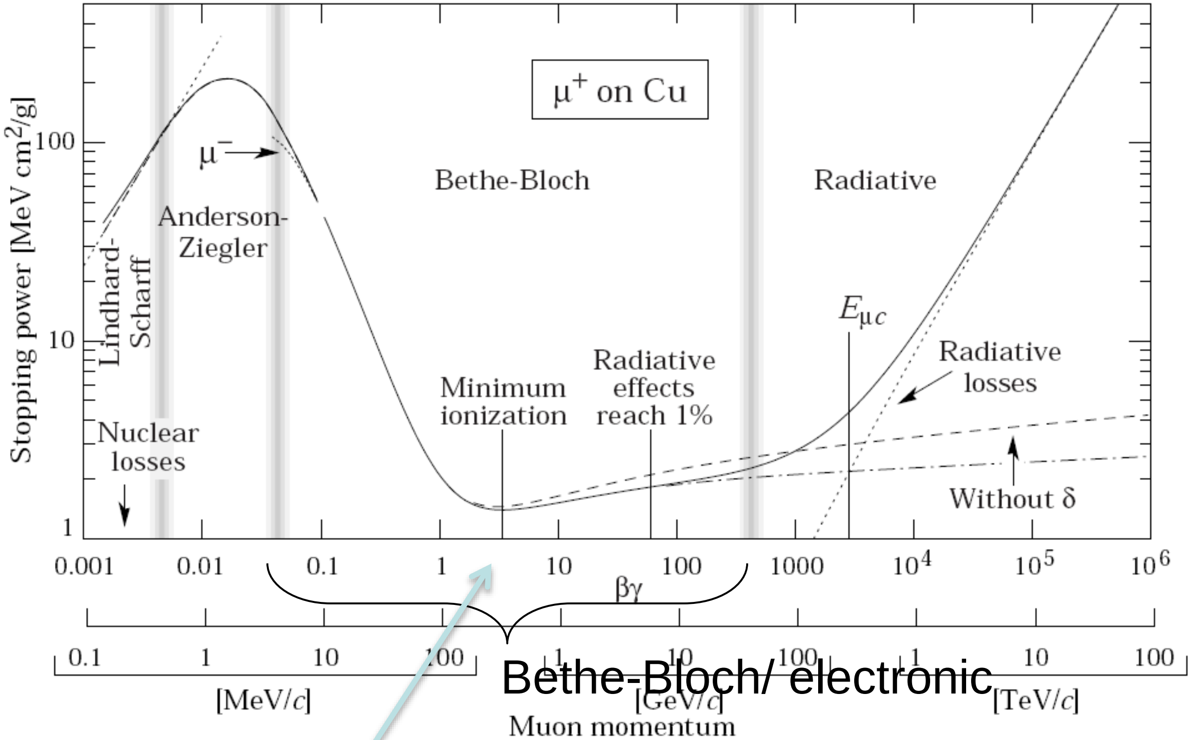




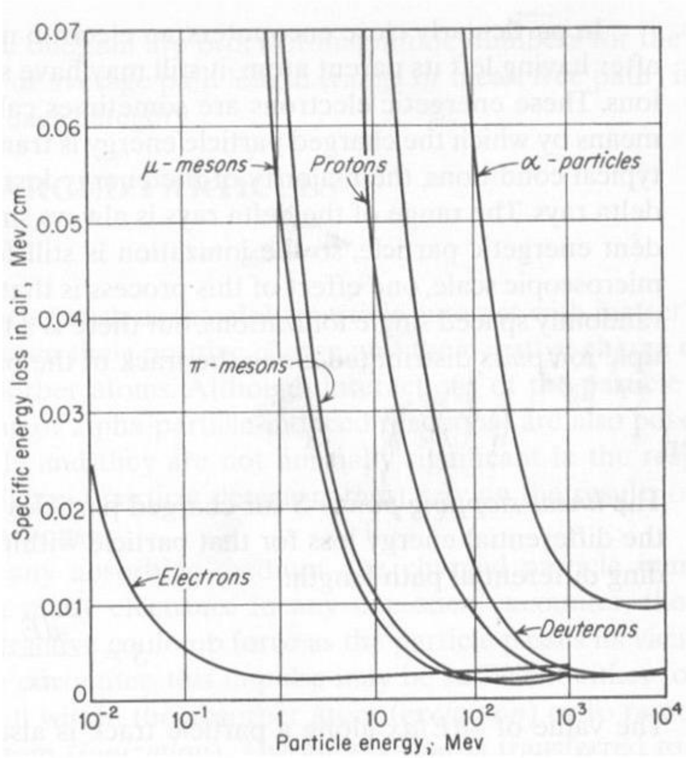


Deuterons in air from:
A.K. Solomon, "Why Smash Atoms?" (1959)

Stopping Power



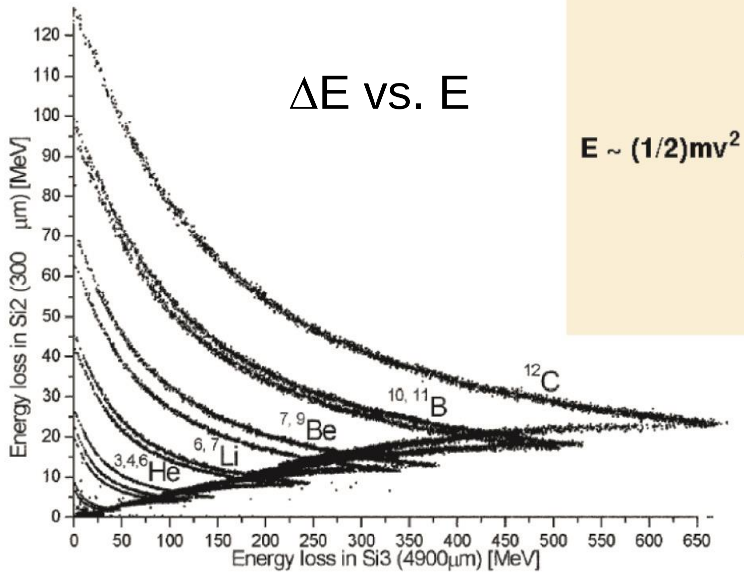
Bethe-Bloch/ electronic

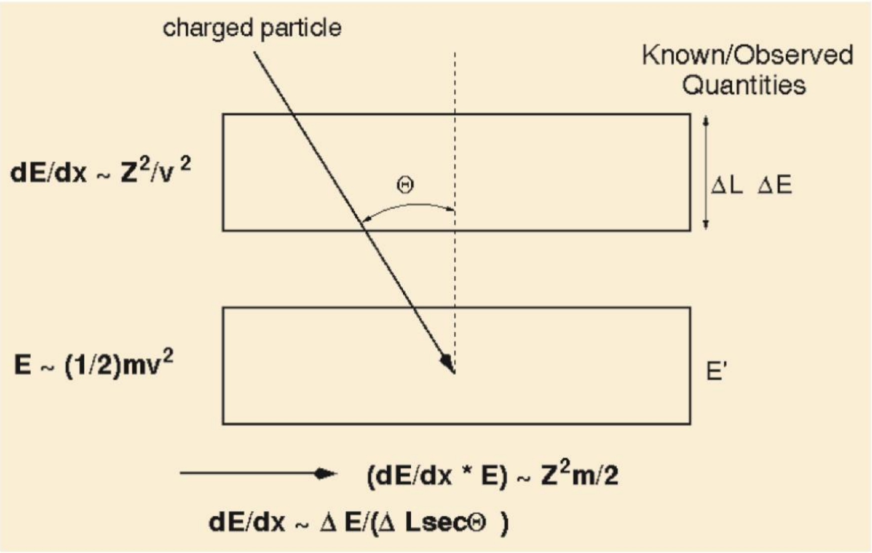


v/c~0.96, almost
independent on mass

Particle Identification

- E.g. $^{48}Ca + ^{208}Pb$ @ 200 MeV (P. Reiter, T.K. Khoo, Argonne National Laboratory):
  - Reaction products identification with ΔE-E telescope:

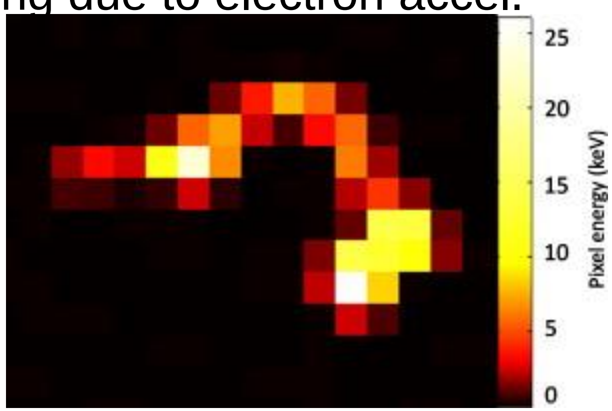




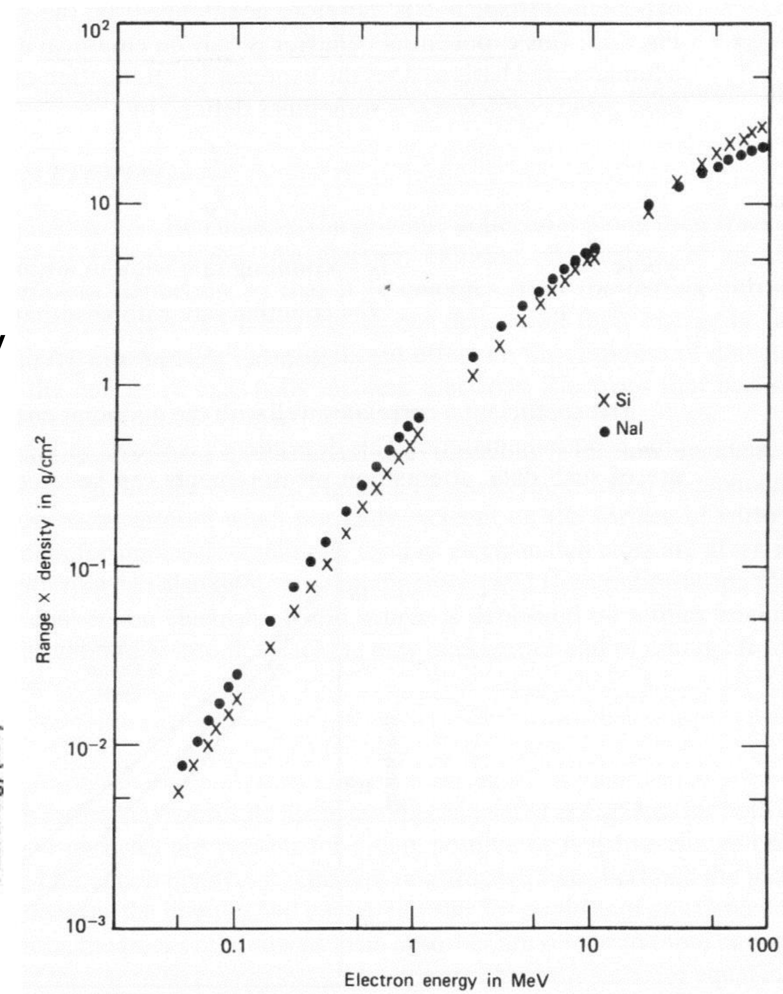
Interaction of Fast Electrons

- Fast electron sources: beta decay, high-energy gamma-ray interactions
  - Electronic losses with electrons from absorber material
    - Mass parity = can lose much more energy per interaction
  - Radiative losses
    - Bremsstrahlung due to electron accel.

$$\frac{\left.\frac{dE}{dx}\right|_r}{\left.\frac{dE}{dx}\right|_c} \approx \frac{EZ}{700}$$



227 keV electron track in Si CCD



Interactions of Photons/ Gamma Rays

- A beam of photons passes through material until each undergoes a collision at random and is removed from beam
  - Intensity continuously drops, but energy remains constant (in contrast to heavy charged particles which slow down continuously without losing intensity)

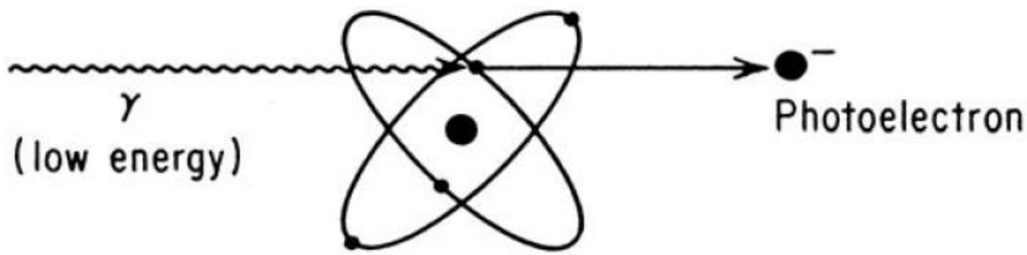
$$I = I_0 e^{-\mu x}, \qquad \mu = 1/\lambda$$

μ: attenuation coefficient
λ: mean free path

- Four interaction processes:
  - Photoelectric absorption
  - Compton scattering
  - Pair production
  - Coherent or Rayleigh scattering (elastic)

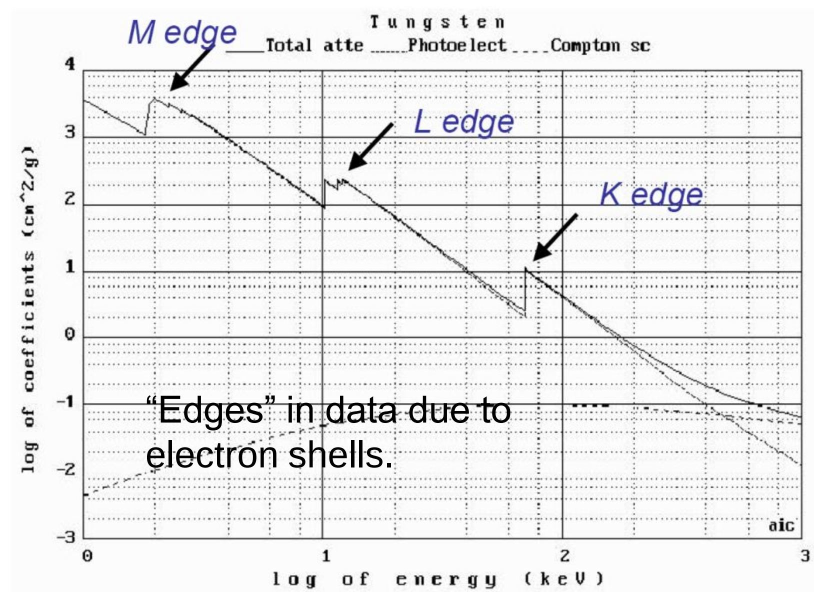
Photoelectric Absorption

- Entire photon energy is transferred to a bound (most likely K-) electron:



$$E_{e^-} = h\nu - E_b, \quad E_\gamma = h\nu$$

$$\sigma_{PE} \propto \frac{Z^{4-5}}{E_\gamma^{3.5}}$$

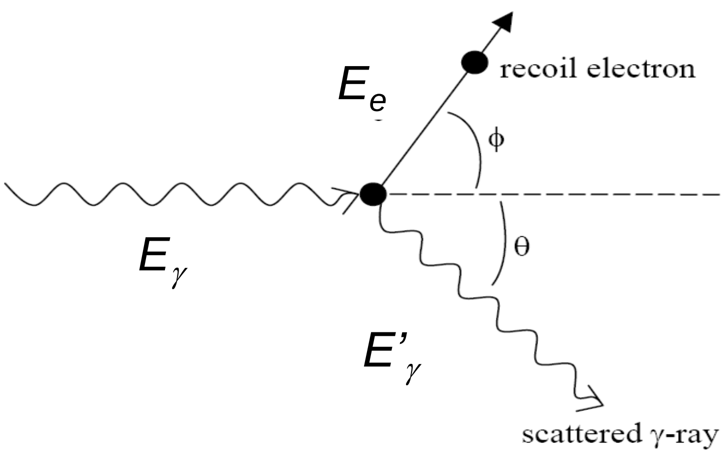


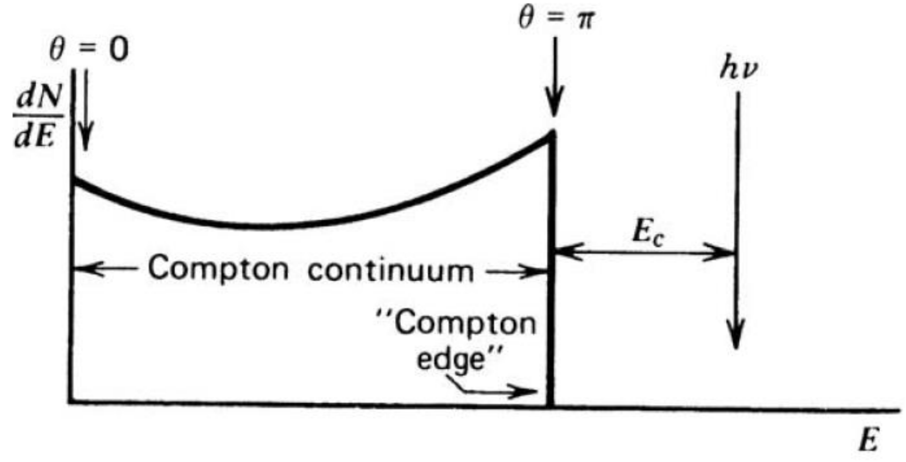
Compton Scattering

- Scattering of a photon by a (free) electron that leads to a moving electron and a lower energy photon:

$$E_{\gamma}' = \frac{E_{\gamma}}{1 + \frac{E_{\gamma}}{E_0}(1 - \cos\theta)}$$

$$\sigma_{CS} \propto Z/E$$



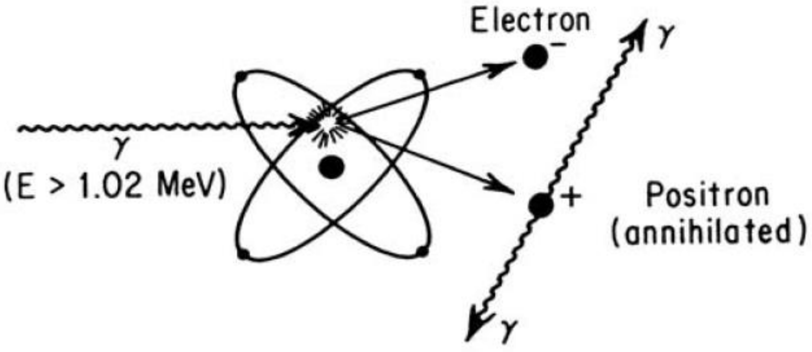


Pair Production

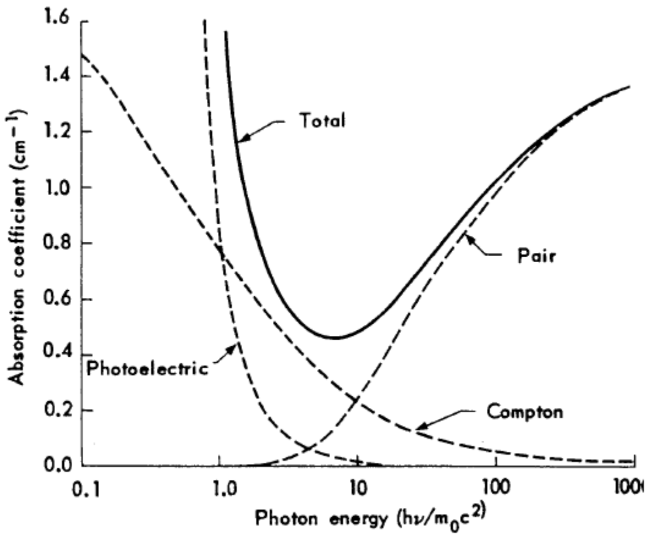
- For E_g>1.022 MeV, the photon can be converted into an electron-positron pair in the presence of a nucleus.
- After slowing down, the positron eventually annihilates into two 511 keV photons.

$$E_{e^-} + E_{e^+} = E_\gamma - 2m_e c^2$$

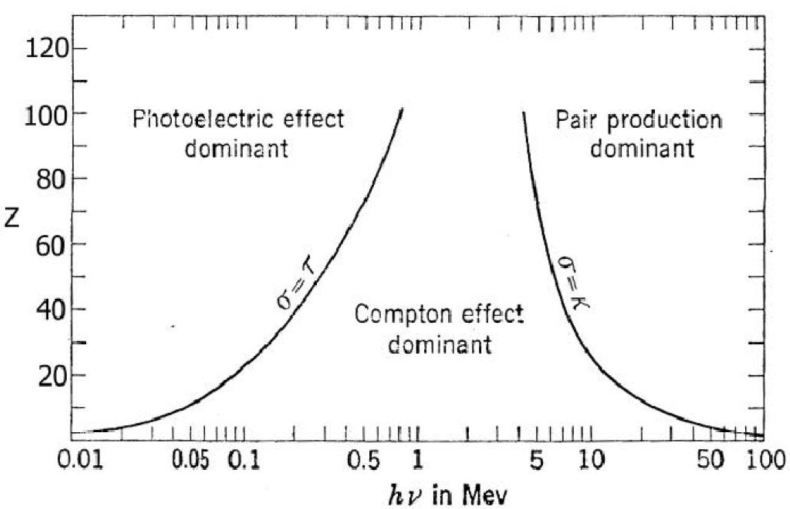
$$\sigma_{PP} \propto Z^2 \ln(E_\gamma - 2m_e c^2)$$



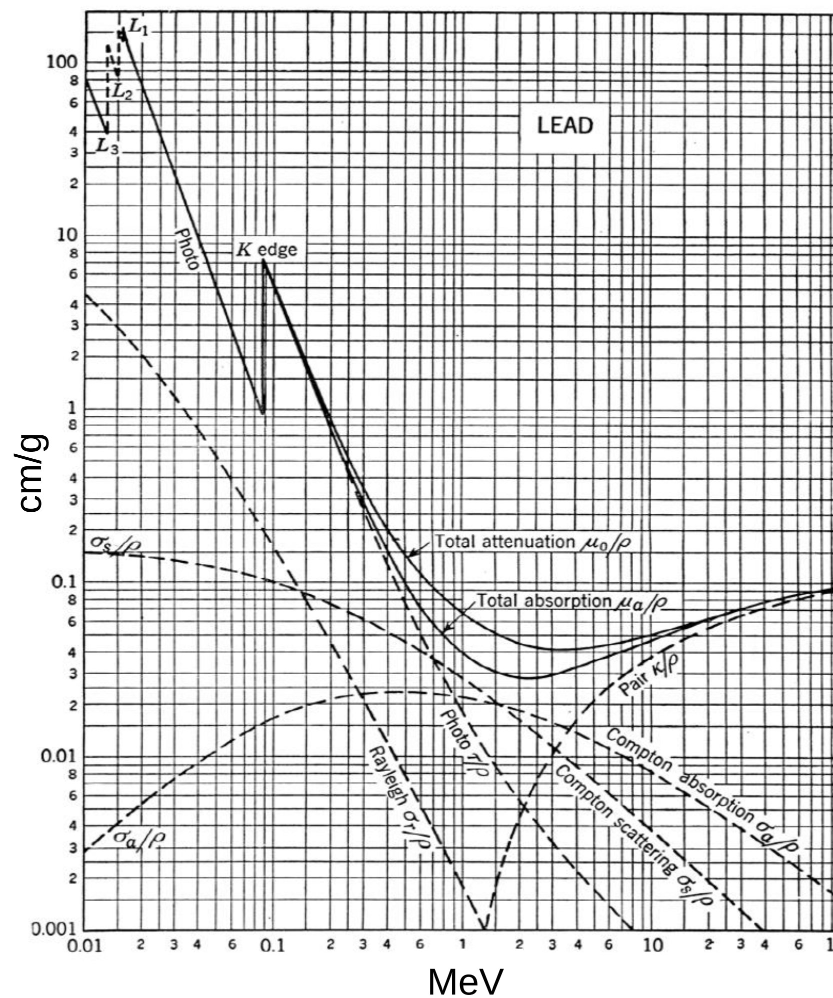
Absorption of Gamma Rays



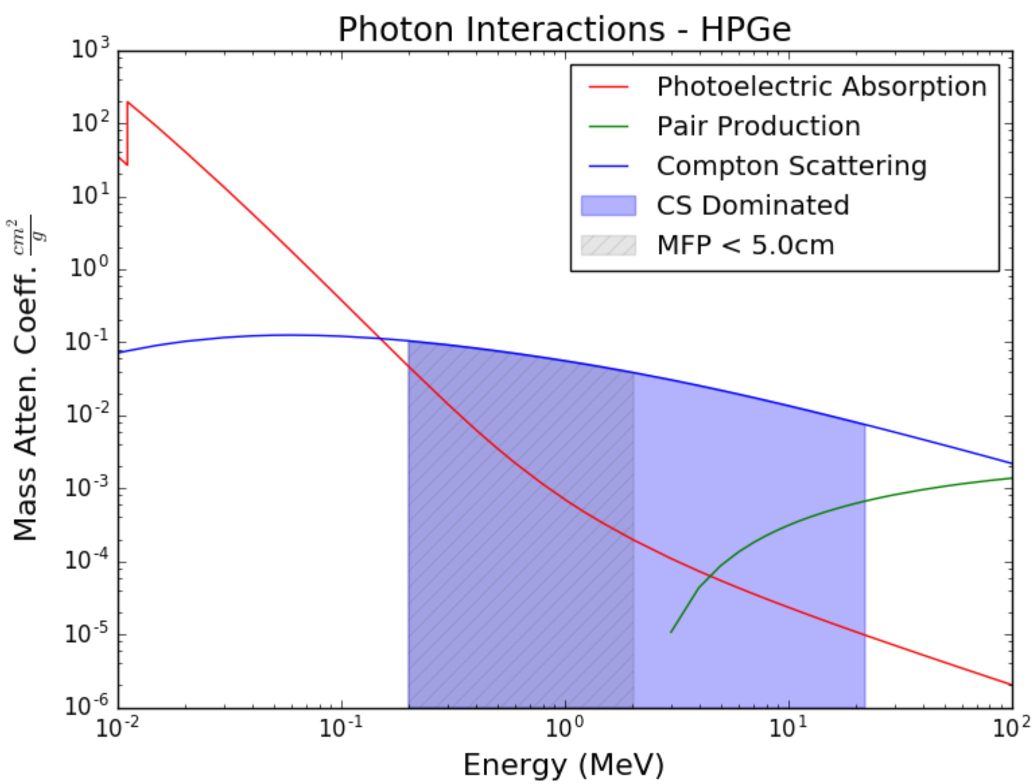
- $\mu_{PE} \propto Z^4/E^3$
- $\mu_{CS} \propto Z/E$
- $\mu_{PP} \propto Z^2$



μ/ρ mass attenuation from "The Atomic Nucleus" by R. Evans



Interaction of Photons in Germanium



Mean free path determines size of detectors:

l(10 keV)	~ 55 mm
l(100 keV)	~ 0.3 cm
l(200 keV)	~ 1.1 cm
l(500 keV)	~ 2.3 cm
l(1 MeV)	~ 3.3 cm
l(2 MeV)	~ 4.5 cm
l(5 MeV)	~ 5.9 cm
l(10 MeV)	~ 5.9 cm

Interactions of Neutrons

- A beam of neutrons passes through material until each undergoes a collision at random and is removed from beam (strong interaction…)
  - In contrast to photons, the neutrons are "scattered" by nuclei and usually leave only a portion of their energy in the medium until they are very slow and can get absorbed.
  - Intensity drops as well as the neutron energy continuously.
  - The degradation of the beam intensity follows Beer-Lampert exponential attenuation law:

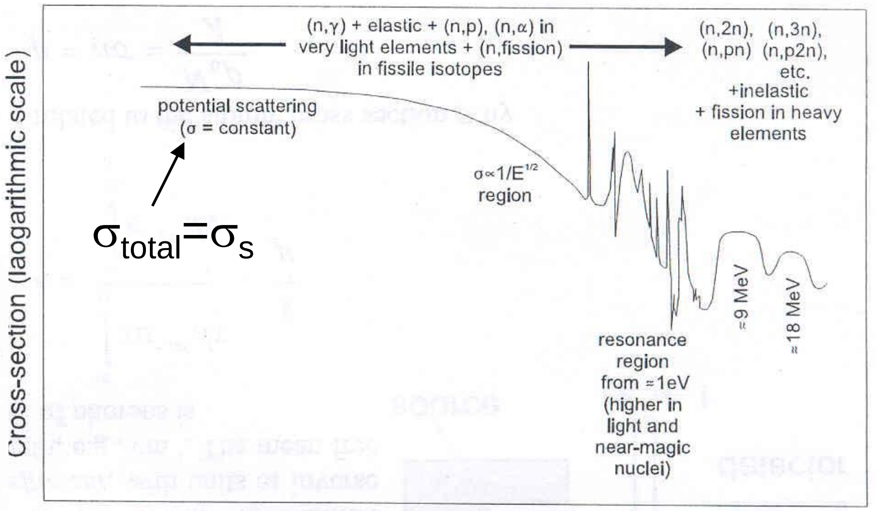
$$I = I_0 e^{-\mu x}, \qquad \mu = \mu_{scattering} + \mu_{(n,\gamma)} + \ldots$$

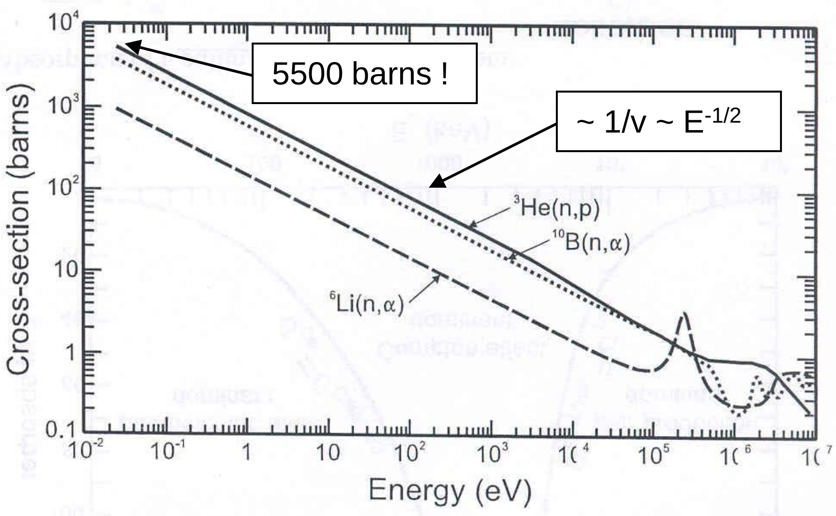
- We have to distinguish several classes of interactions:
  - Elastic scattering (n,n)
  - Inelastic scattering (n,n')
  - Radiative capture (n,γ)
  - Charged-particle production reaction (n,p), (n,α),…
  - Fission ^{235}U, ^{239}Pu,…(n,f)

Nuclear Reactions for Neutron Detection

- $\sigma_{total}=\sigma_s+\sigma_a$ (cross section σ expressed in barns [10^{-24} cm^2])
  - $\sigma_s=\sigma_e+\sigma_i$
  - $\sigma_a=\sigma_\gamma+\sigma_f+\sigma_p+\sigma_\alpha+\ldots$

General behavior of neutron cross-sections





Absorption and Dose Characteristics