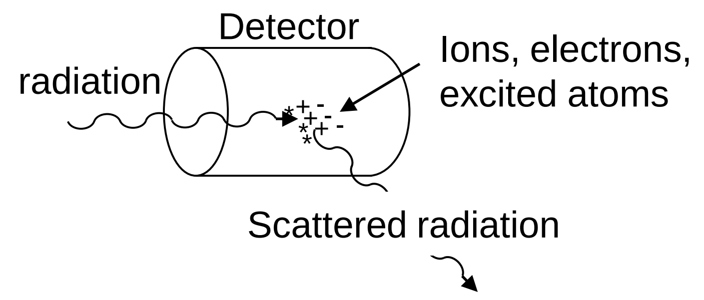
Fundamentals – Radiation Interactions

- 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≥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…)

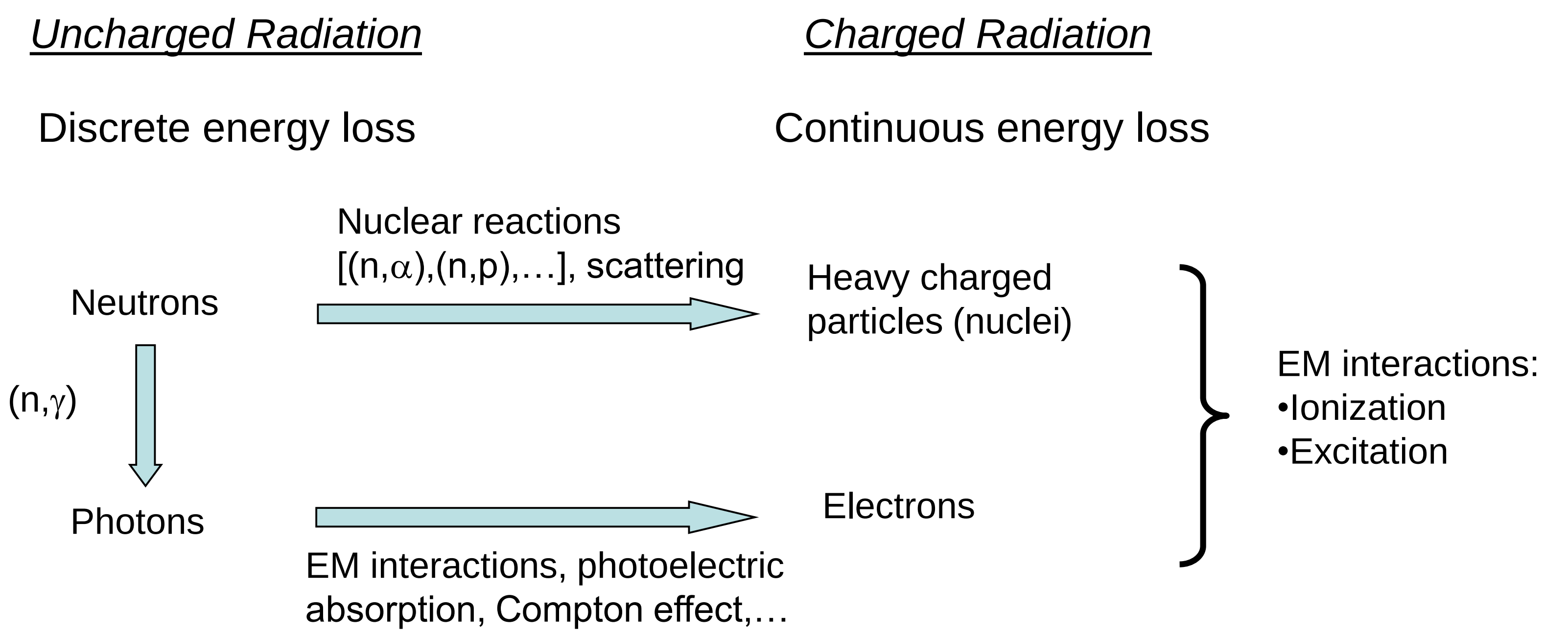
Some Properties of Ionizing Radiation

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…

Classes of radiation and their relationship



Means of and materials for converting energy to signal

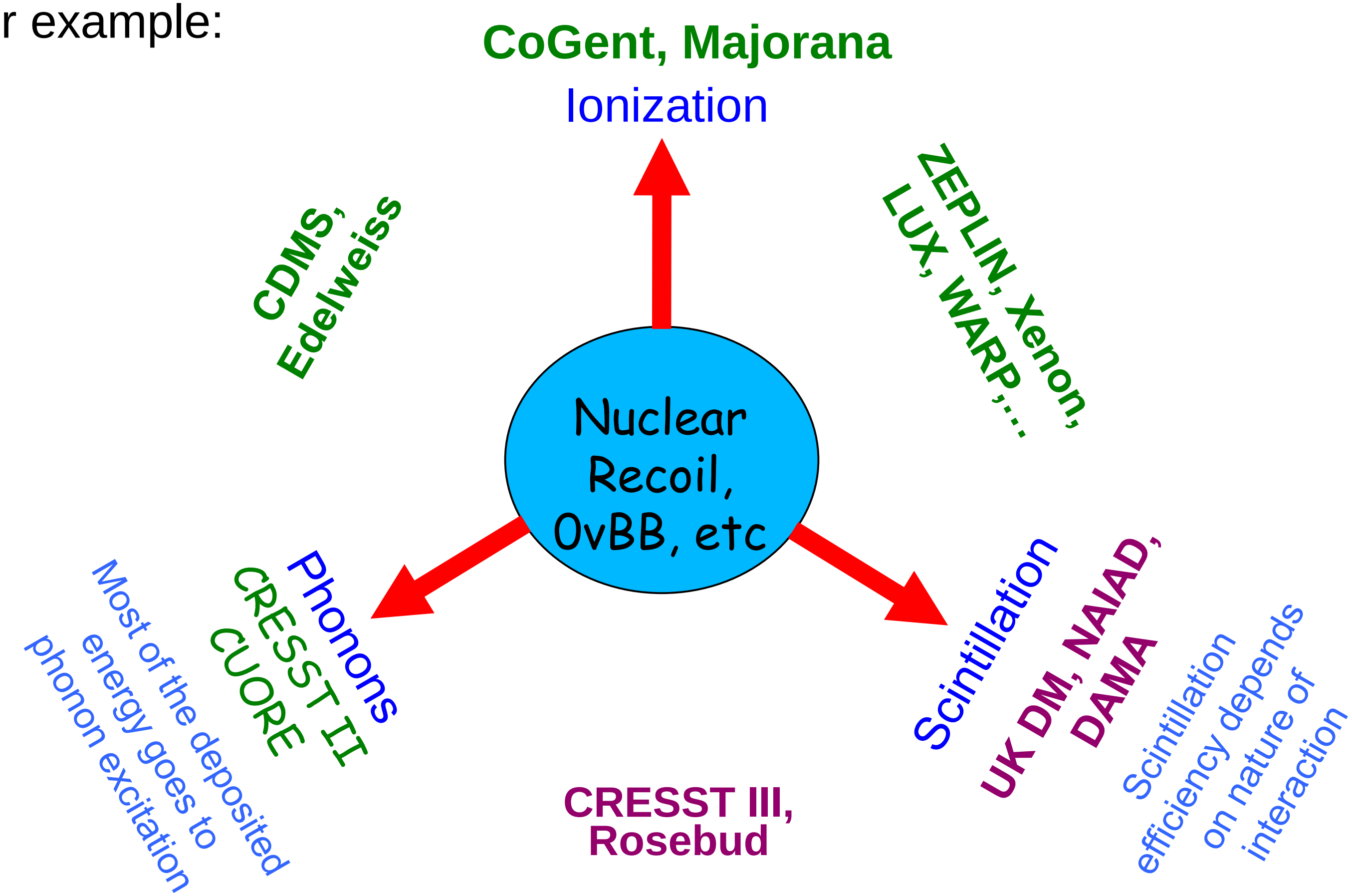
- Ionization, Scintillation, Heat vs. Gases, Liquids, Solids

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:

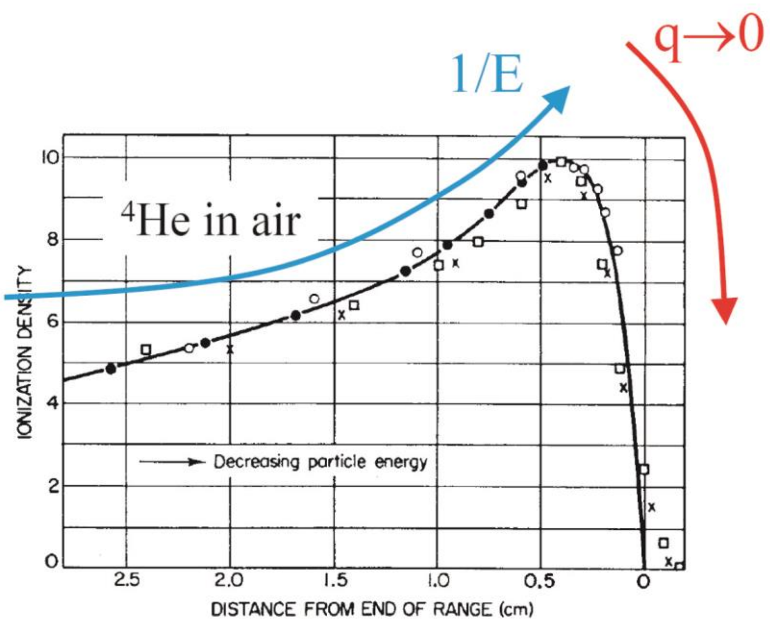


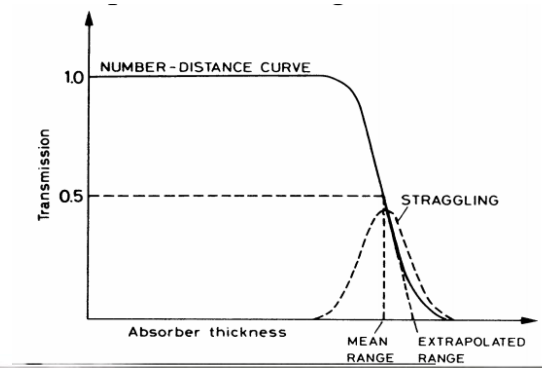
Review of Interactions

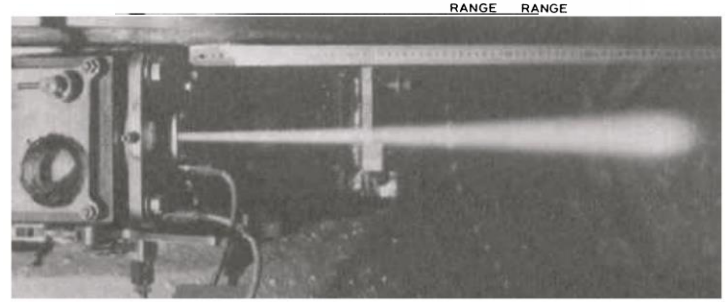
Interaction of Massive Charged Particles

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

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

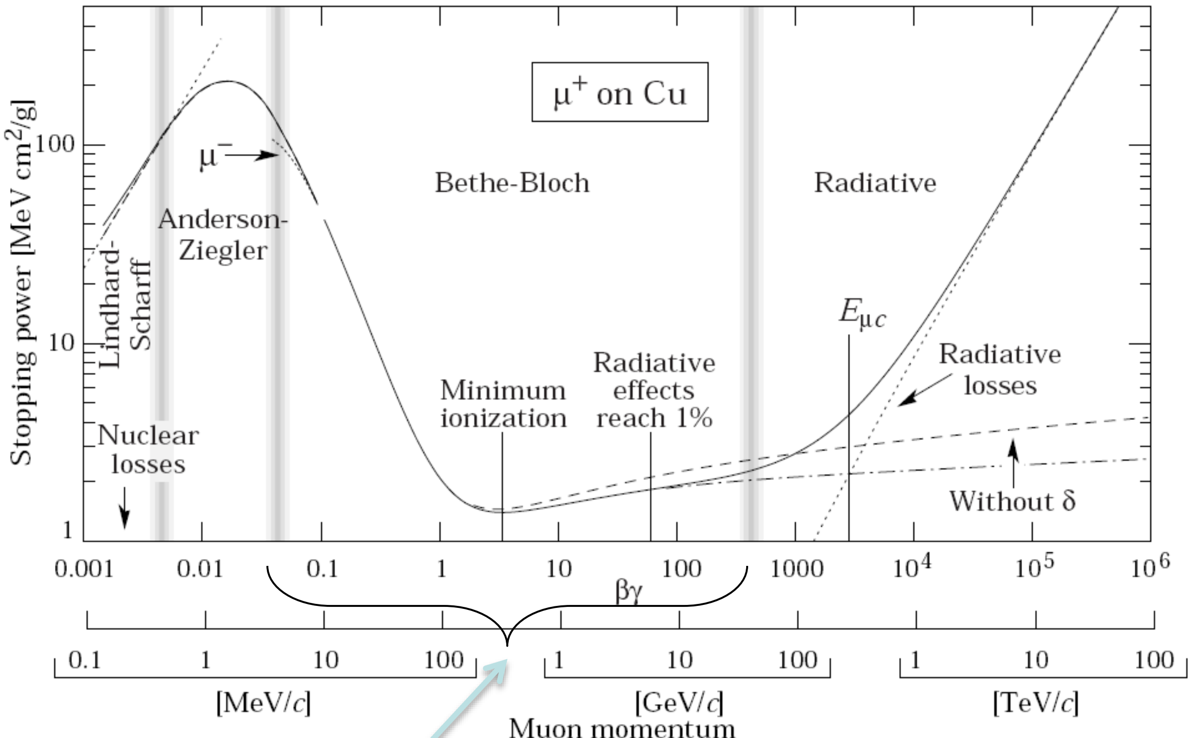






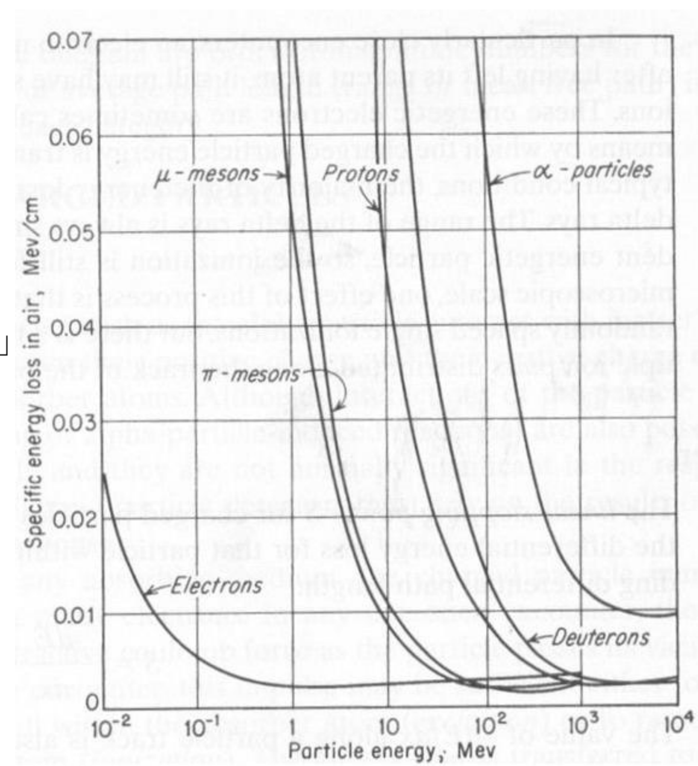
Deuterons in air from:
A.K. Solomon, "Why Smash Atoms?" (1959)

Stopping Power



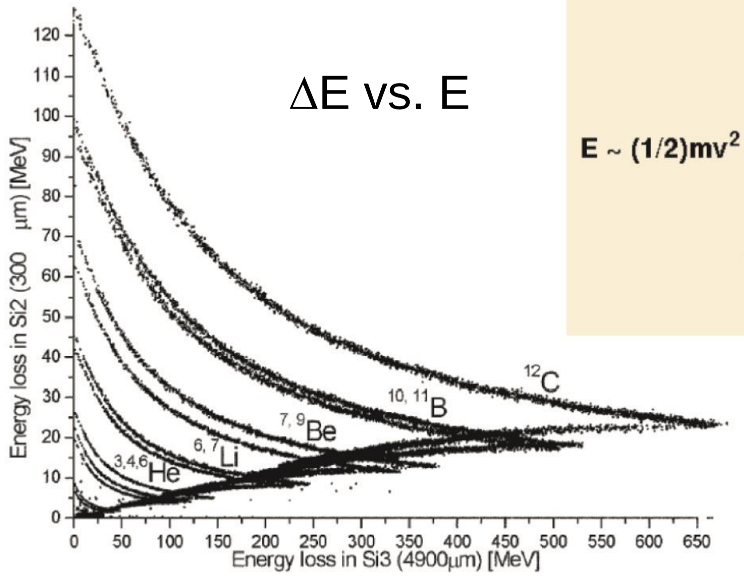
Bethe-Bloch/ electronic

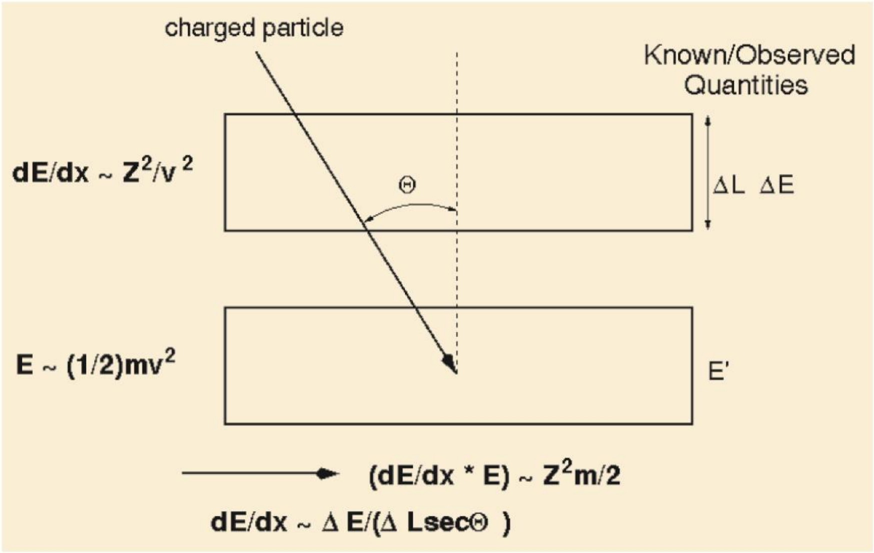
v/c~0.96, almost independent on mass



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:

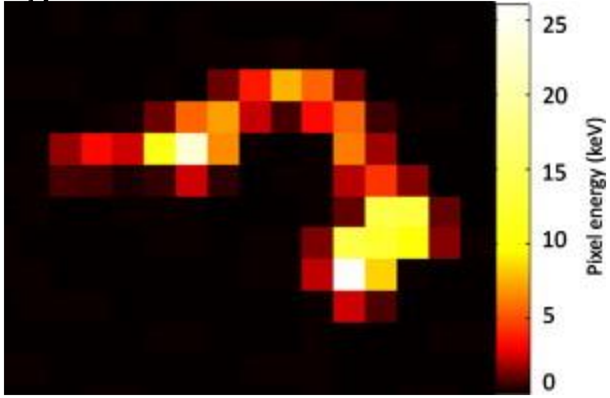




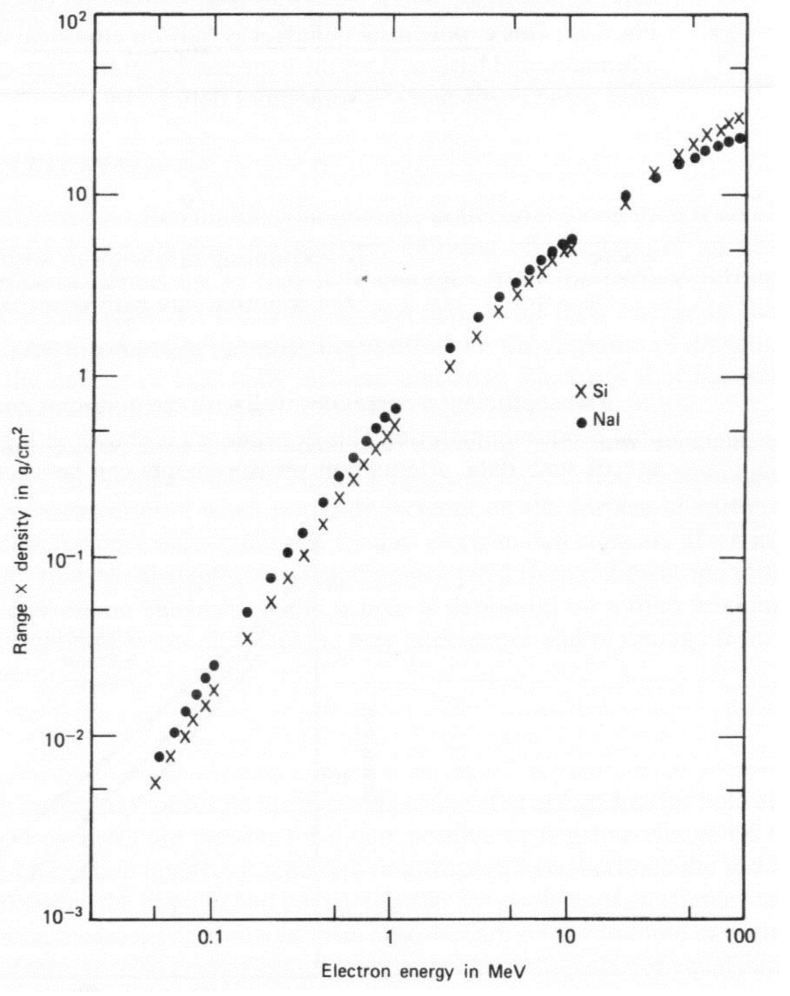
Interaction of Fast Electrons

- 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)

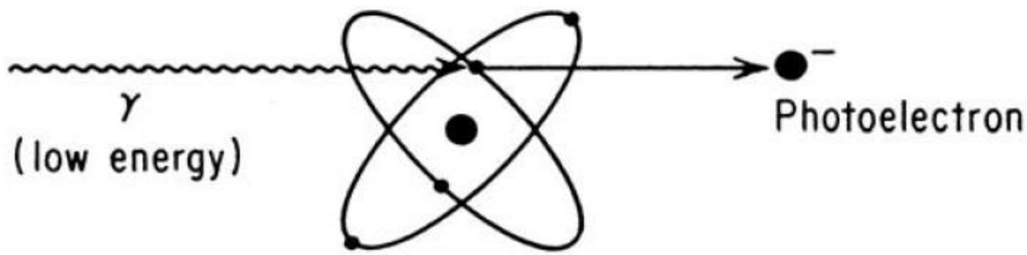
$$I = I_0 e^{-\mu x}, \qquad \mu = 1/\lambda$$

μ: attenuation coefficient
λ: mean free path

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

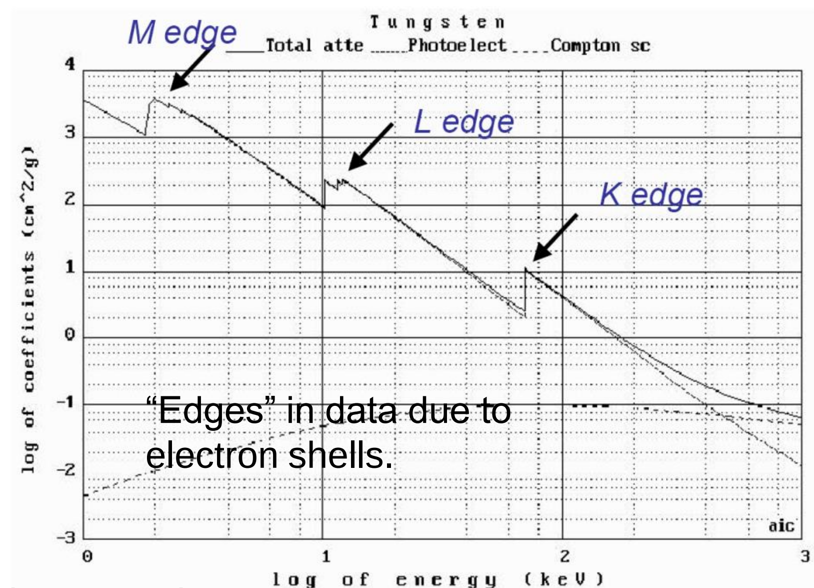
Photoelectric Absorption

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



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

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

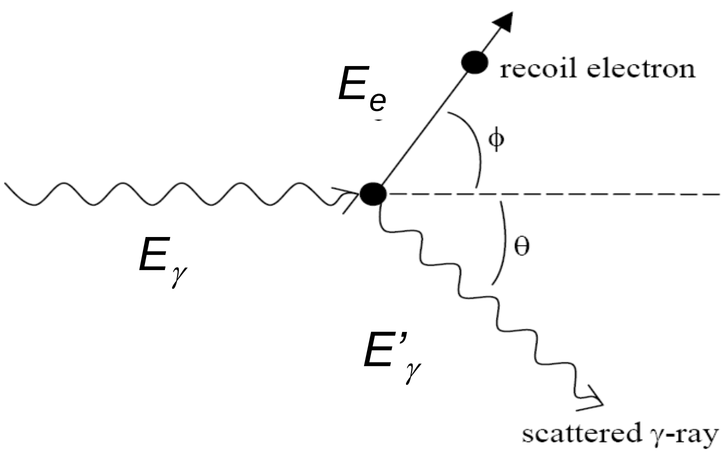


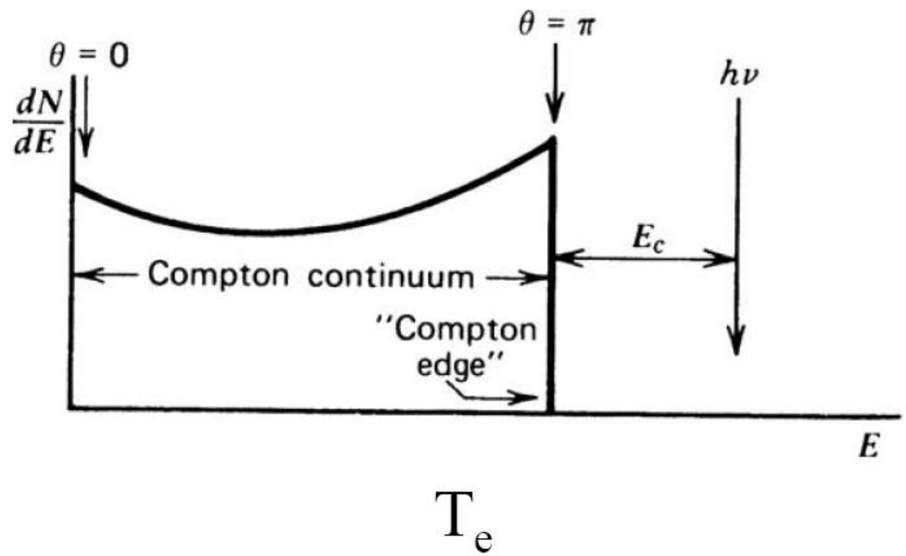
Compton Scattering

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

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

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



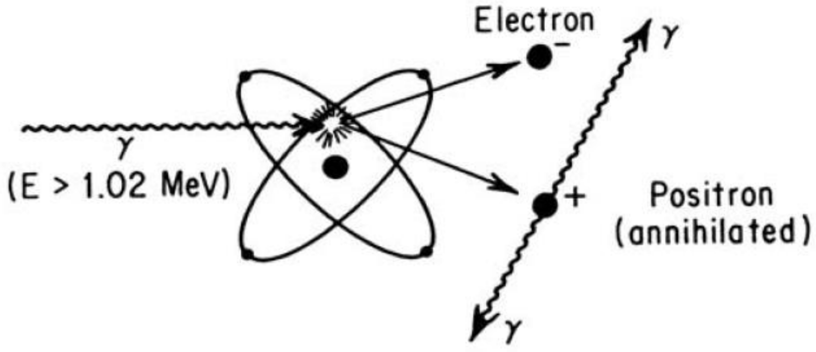


Pair Production

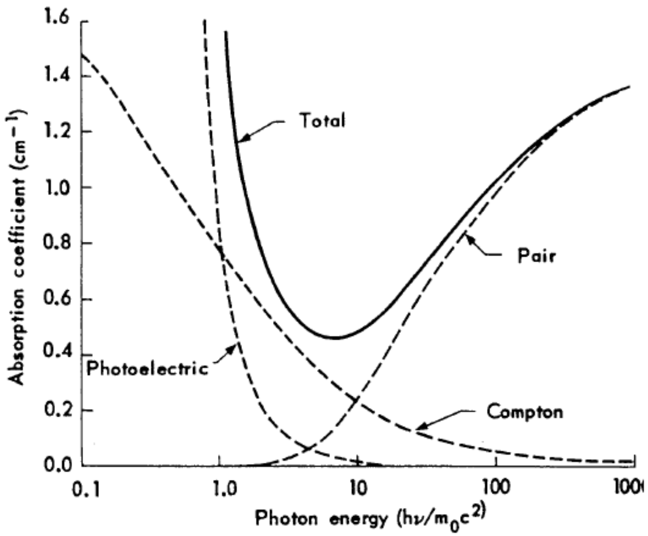
- For E_g>1.022 MeV, the photon can be converted into an electron-positron pair in the presence of a nucleus.
- After slowing down, the positron eventually annihilates into two 511 keV photons.

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

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

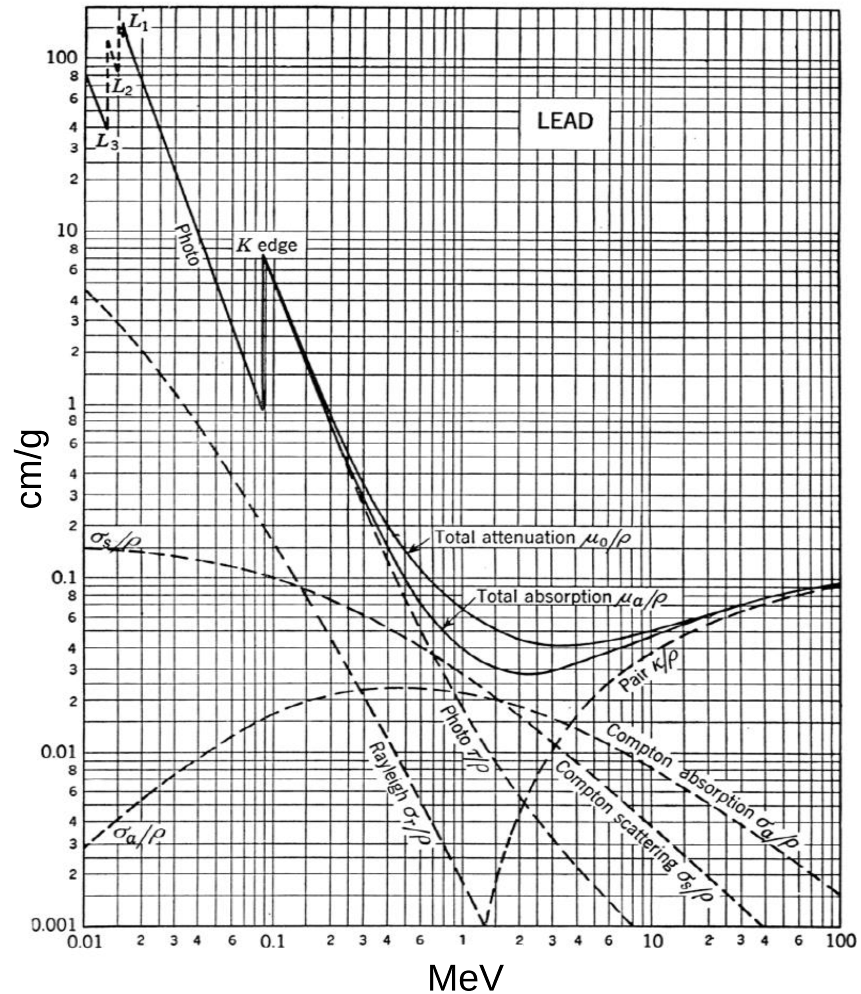


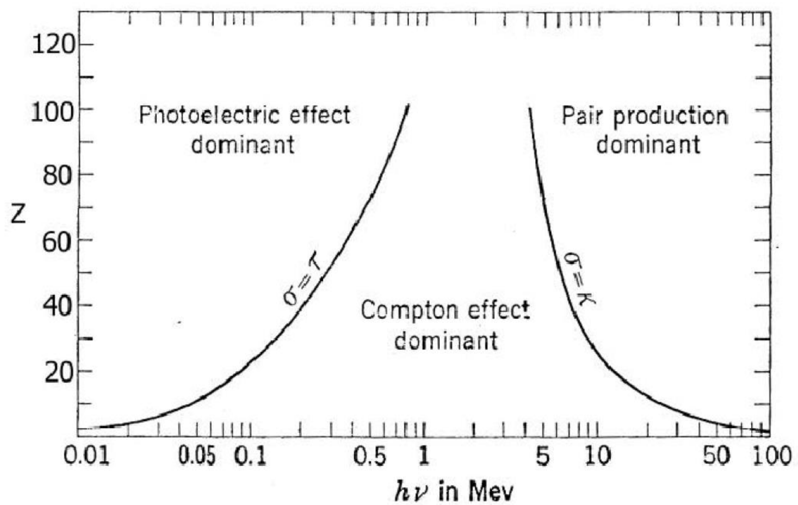
Absorption of Gamma Rays



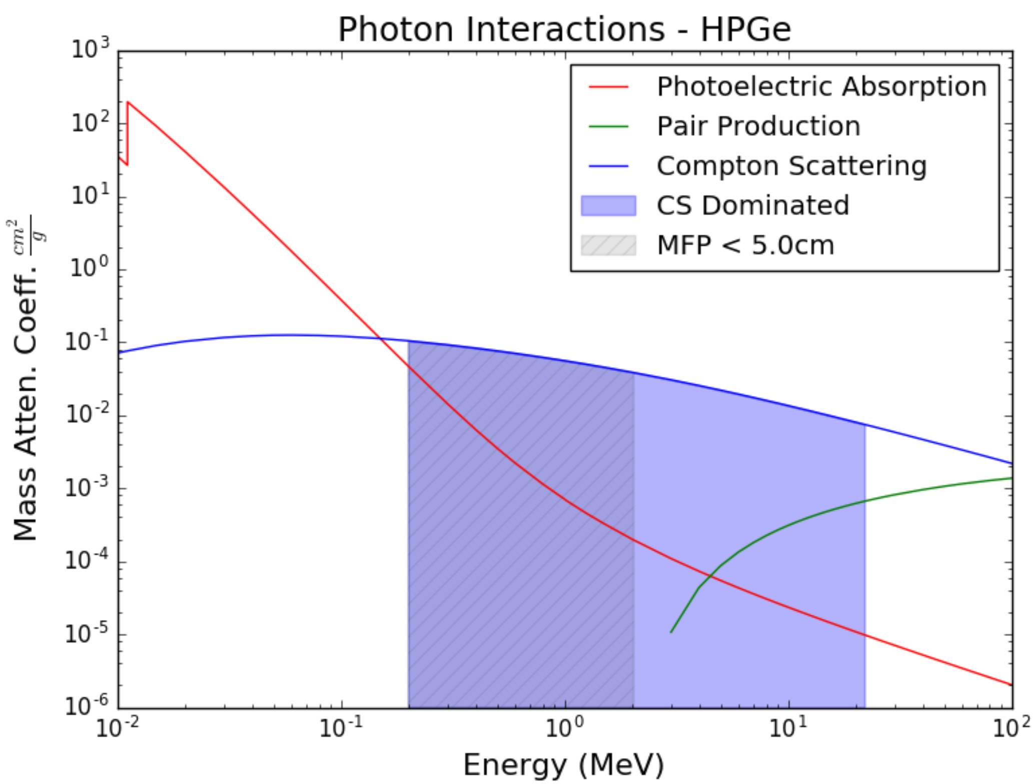
- $\mu_{PE} \propto Z^4/E^3$
- $\mu_{CS} \propto Z/E$
- $\mu_{PP} \propto Z^2$

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

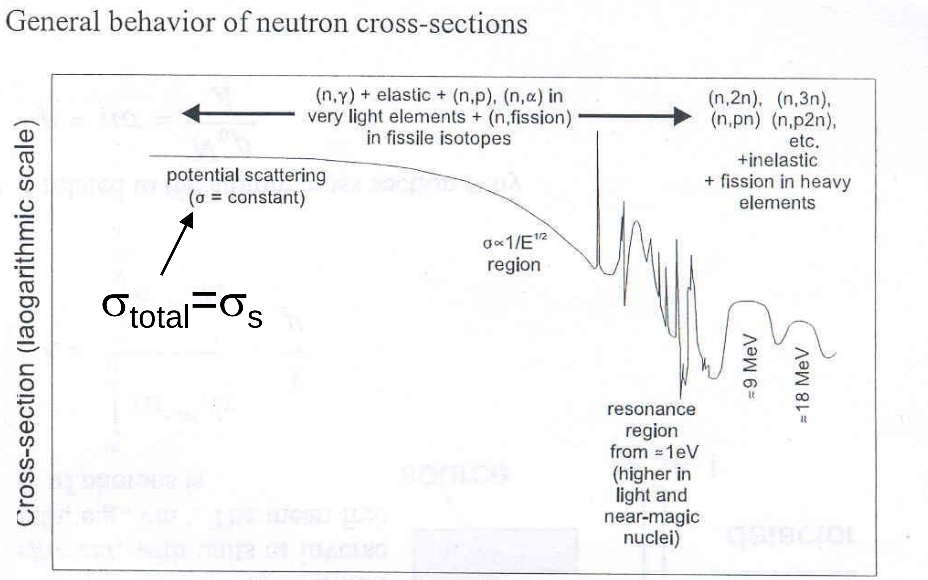
- A beam of neutrons passes through material until each undergoes a collision at random and is removed from beam (strong interaction…)
  - In contrast to photons, the neutrons are “scattered” by nuclei and usually leave only a portion of their energy in the medium until they are very slow and can get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

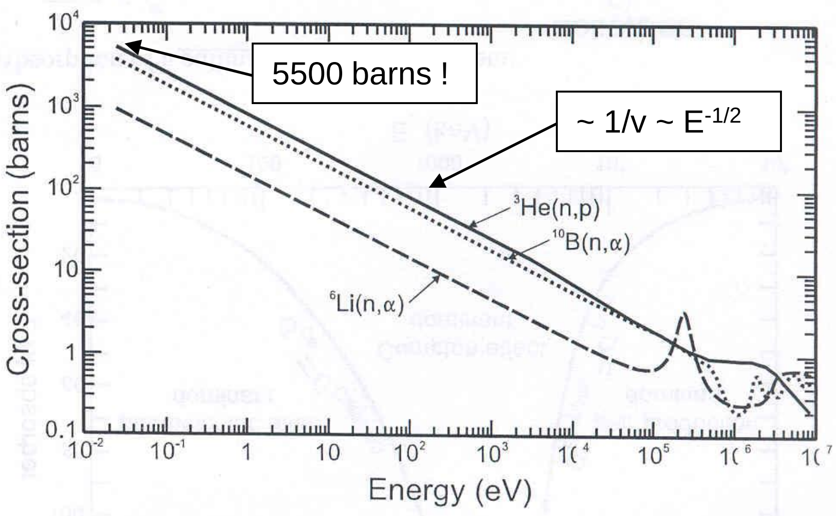
$$I = I_0 e^{-\mu x}, \qquad \mu = \mu_{scattering} + \mu_{(n,\gamma)} + ...$$

- 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])
  - $\sigma_s=\sigma_e+\sigma_i$
  - $\sigma_a=\sigma_\gamma+\sigma_f+\sigma_p+\sigma_\alpha+\ldots$





Absorption and Dose Characteristics