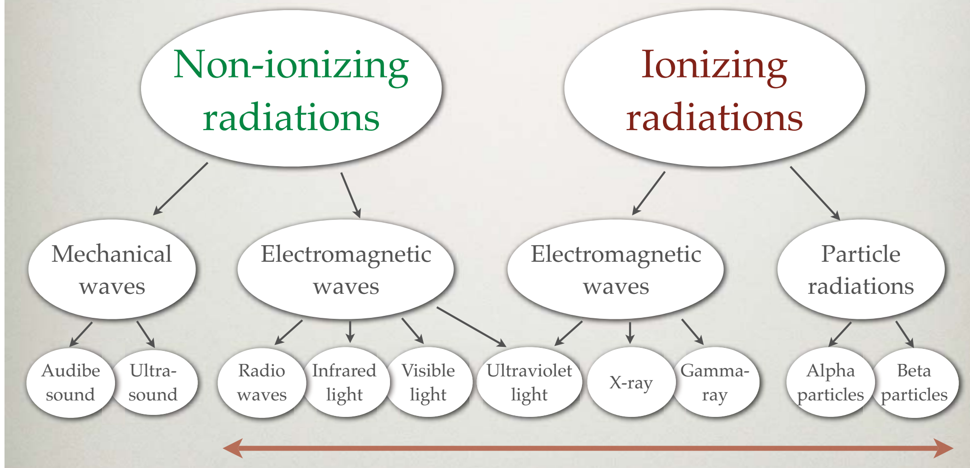
Interaction of radiations with matter

Miklós Kellermayer

Types of radiations



How do radiations interact with matter?

General outline

- Light
  reflection, refraction, scatter, absorption
- Ionizing electromagnetic radiation
  X-ray, γ-radiation
- Particle radiations
  alpha, beta, proton, neutron, heavy ions
- Mechanisms
  scatter, ionization, photoelectric effect, Compton scatter, pair production, nuclear reaction
- Quantitative description
  units, parameters, attenuation, coefficients, Bragg curve
- Biomedical applications

General scheme of discussion

- Definition
  e.g., ***α*-particles**=He nuclei / **X-ray**=high-energy photons from electron shell
- Interaction mechanisms
  e.g., ionization, scatter, nuclear reaction / photoelectric effect, Compton scatter, pair production
- Energy spectrum
  e.g., linear / linear or continuous
- Penetration path
  e.g., linear, but winding towards the end / linear
- Energy/intensity loss description
  e.g., Bragg curve / exponential attenuation function

Energy of radiation I. Photonic energy

Energy increases with frequency - wavelength decreases

Convenient energy unit: **electronvolt (eV)**

Energy of a single unbound electron accelerated by an electrostatic potential difference of one volt

$$1\ \text{eV} = q \cdot V = 1.6 \cdot 10^{-19}\ \text{CV} = 1.6 \cdot 10^{-19}\ \text{J}$$

• 1 TeV:	about the energy of motion of a flying mosquito.
• 210 MeV:	average energy released in fission of one ^{239}Pu atom.
• 200 MeV:	total energy released in nuclear fission of one ^{235}U atom.
• 17.6 MeV:	total energy released in fusion of deuterium and tritium to form ^{4}He.
• 13.6 eV:	energy required to ionize atomic hydrogen. Molecular bond energies: ~ eV per molecule.
• 2.5 eV:	energy of blue-green photon (500 nm).
• 1/40 eV:	the thermal energy at room temperature.

Energy of radiation II.

Physical parameters describing radiated energy

ENERGY

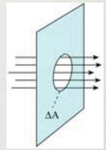
$E\ [\text{J}]$

POWER

$$P = \frac{\Delta E}{\Delta t}\ \left[\frac{\text{J}}{\text{s}} = \text{W}\right]$$

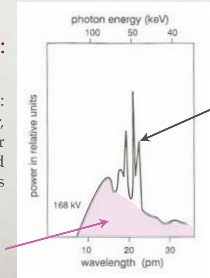
INTENSITY

$$J = \frac{\Delta P}{\Delta A}\ \left[\frac{\text{W}}{\text{m}^2}\right]$$



What *photonic emergies contribute* to radiated energy?

Spectrum of radiation:



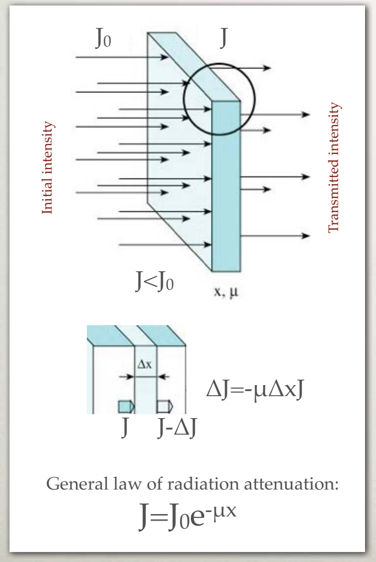
Y-axis: power, intensity or derived parameters

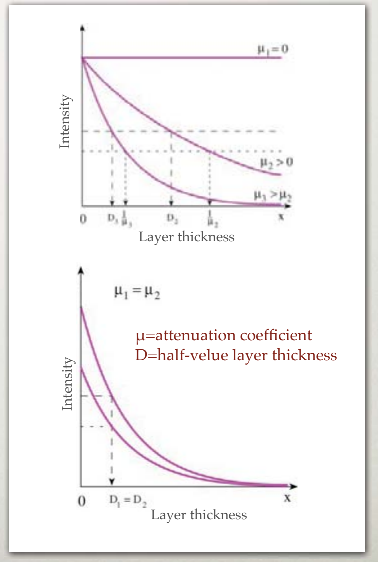
"Linear": narrow distribution of energy

"Continous": wide distribution of energy

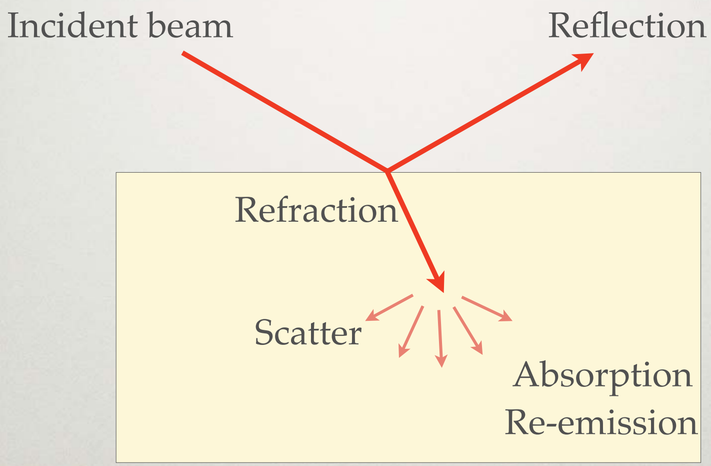
X-axis: Energy or derived parameters (frequency, wavelength, wavenumber)

General attenuation mechanism

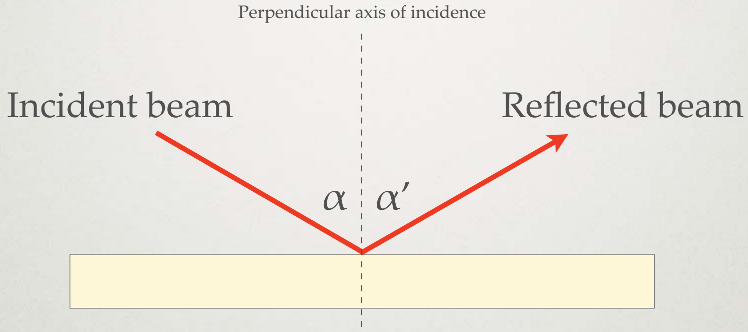




Interaction of light with matter

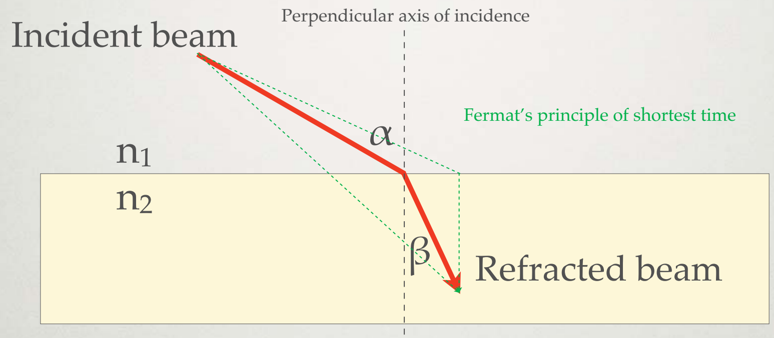


Reflection

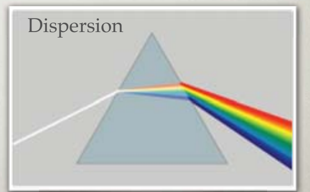


- Incident and reflected beams and axis of incidence are in the same plane.
- Incident and reflected angles are identical ($\alpha = \alpha'$)

Refraction



- Incident and refracted beams and axis of incidence are in the same plane.
- Snell's law: $\dfrac{\sin\alpha}{\sin\beta} = \dfrac{c_1}{c_2} = \dfrac{n_2}{n_1}$

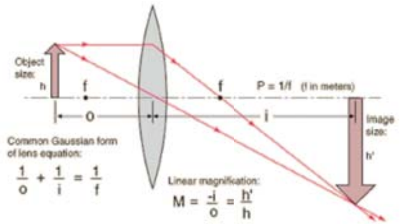


Refraction is the basis for optical image formation

Geometric optics

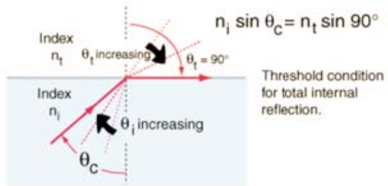
- Radiation:
  optical ray or beam
- Ray optic diagram:
  direction of energy propagation indicated as vectors
- Principle of reversibility:
  energy propagation is assumed to be reversible along the beam

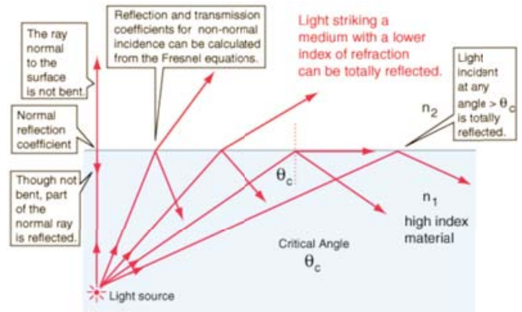
Image formation
(ray optics diagram)



Refractive power (diopter, m^{-1}): $D = \dfrac{1}{f}$

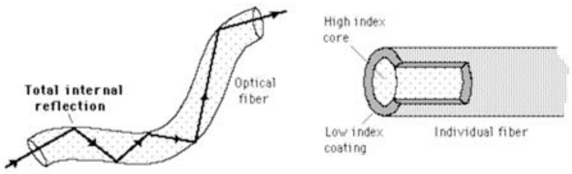
Total internal reflection



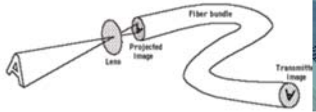


Biomedical Application of TIR: optical fibers

Single-mode fiber



Multi-mode fiber



If the arrangement of fibers is maintained within the bundle, then the image is faithfully transmitted.

Medical fiber optics: endoscopes

TYPES

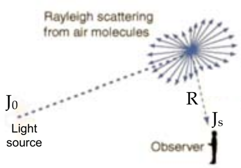
- **Arthroscopy:** diagnostic and therapeutic examination of joints (arthroscopic surgery)
- **Bronchoscopy:** examination of the trachea and bronchi
- **Colonoscopy:** examination of the colon
- **Colposcopy:** examination of the vagina and cervix
- **Cystoscopy:** examination of urinary bladder, urethra uterus, prostate. Through urethra.
- **ERCP (endoscopic retrograde cholangio-pancreatography):** delivery of X-ray contrast agent, via endoscope, into biliary tract and pancreatic duct.
- **EGD (Esophago-gastroduodenoscopy):** examination of upper GI tract (gastroscopy).
- **Laparoscopy:** examination of abdominal organs (stomach, liver, female gonads) through abdominal wall.
- **Laryngoscopy:** examination of the larynx.
- **Proctoscopy:** examination of the rectum sigmoidal colon (sigmoidoscopy, proctosigmoidoscopy)
- **Thoracoscopy:** examination of pleura, mediastinum and pericardium via chest wall.

OBJECTIVES

- **Diagnostics:** visual inspection, biopsy, contrast agent delivery
- **Therapy:** surgery, cauterization, removal of foreign objects

Arthroscopic surgery

Light scattering



- Elastic collision: photon energy (wavelength) does not change
- Emission by resonating dipoles

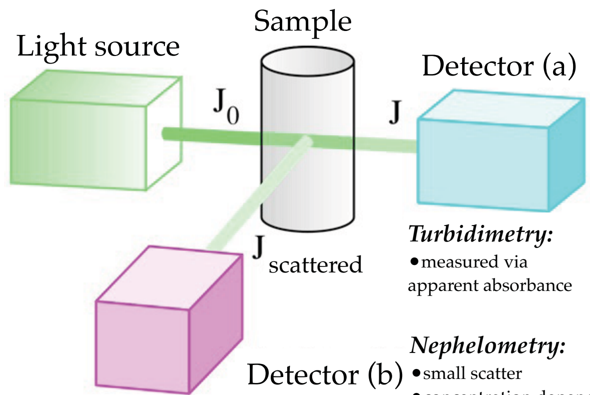
$$J_s = J_0 \frac{8\pi^4 N\alpha^2}{\lambda^4 R^2}\left(1+\cos^2\Theta\right)$$

J_s=intensity of scattered light
J_0=intensity of incident light
N=number of scattering particles
α=polarizability (dipole moment per electric field)
λ=wavelength of light
R=distance between scatterer and observer
Θ=angle of scattered light

Strong wavelength dependence -> enhancement of short wavelengths -> blue sky

Particle size greater than wavelength -> even reduction at all visible wavelengths -> gray clouds

Biomedical applications of light scattering



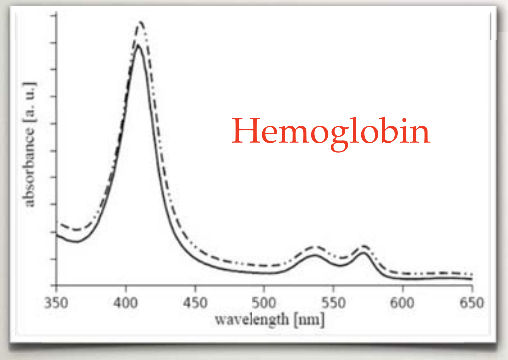
Turbidimetry:

- measured via apparent absorbance

Nephelometry:

- small scatter
- concentration dependence
- concentration measurement of immune complexes

Light absorption



From the general law of radiation attenuation:

$$J = J_0 e^{-\mu x}$$

$$\lg \frac{J_0}{J} = \mu x \lg e$$

$$\lg \frac{J_0}{J} \approx \mu$$

absorbance, optical density

Lambert-Beer's Law

$$\lg \frac{J_0}{J} = \varepsilon_\lambda c x$$

ε_λ = molar extinction coefficient

c = concentration

Interaction of ionizing radiations with matter

Classification possibilities

Nuclear radiation
Energy from atomic nucleus.
e.g, α, β, γ, p, n, …

X-ray
Energy from the electron shell.
e.g., X-ray

Particle radiation
Rest mass positive.
e.g., α, β, p, n, …

Electromagnetic radiation
No rest mass.
e.g., X-ray, γ

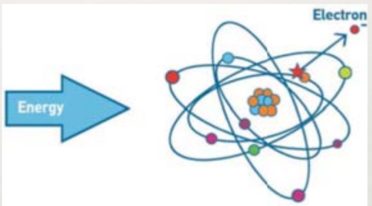
Direct ionizing radiation
Charged particles.
e.g., α, β, p, …

Indirect ionizing radiation
No charge.
e.g., X-ray, γ, n

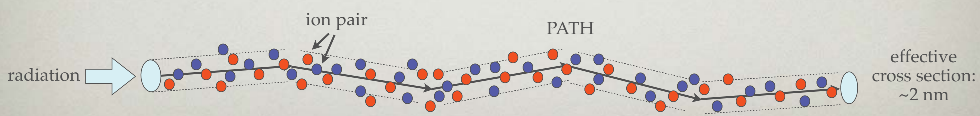
Ionization

- Conversion of an atom or molecule into an ion by the addition or removal of charged particles (i.e., electrons or ions).
- During ionization usually (e.g. in case of a gas) ion pairs are created which consist of a free electron and a positive ion.

In air, an average 34 eV (5.44×10^{-18} J = 5.44 aJ) energy is required to generate one ion pair.



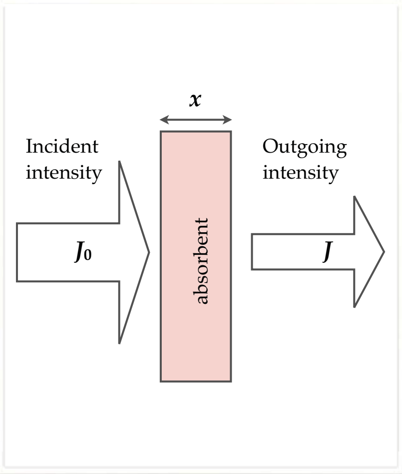
Ionizing radiations exert their effect on the interacting matter via generation of ion pairs:



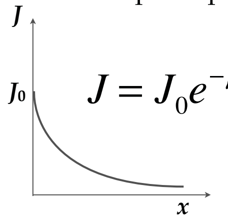
Ionizing electromagnetic radiations

- Types:
  - X-ray
  - γ-radiation
- Source:
  - electron shell (X-ray)
  - nuclear decay (γ-radiation)
- Energy spectrum:
  - continuous
  - linear (*For further info: see chapter on X-ray)*
- Mechanisms of interaction with matter:
  - photoelectric effect
  - Compton scatter
  - pair production
  - elastic scatter

General absorption mechanism



Exponential attenuation principle



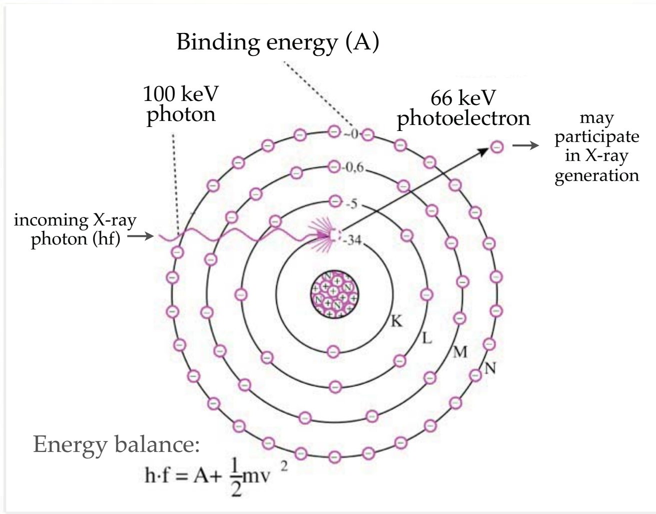
$$J = J_0 e^{-\mu x}$$

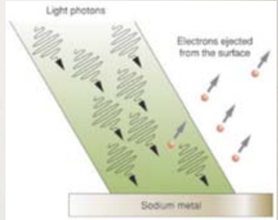
$$\mu = \mu_m \rho$$

μ=attenuation coefficient
μ_m=mass attenuation coefficient (cm^2/g)
ρ=density (g/cm^3)

Mass attenuation coefficient: measurement of how strongly a chemical species or substance absorbs or scatters EM waves at a given wavelength, per unit mass

X-ray photoeffect



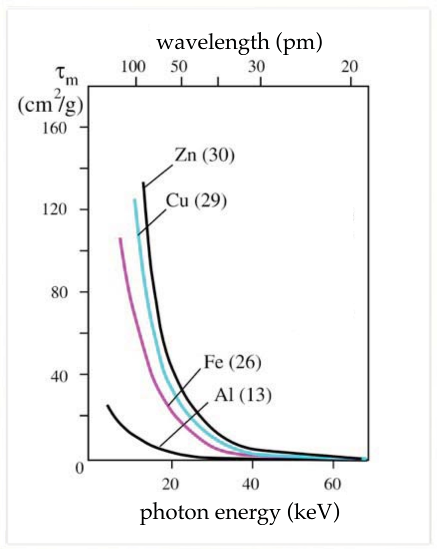


Photoeffect attenuation coefficient:

$$\tau = \tau_m \rho$$

τ_m=photoeffect mass attenuation coefficient

Photoeffect attenuation depends strongly on atomic number



$$\tau_m = const \cdot \frac{Z^3}{\varepsilon^3} = C \cdot \lambda^3 \cdot Z^3$$

For multi-component system:
"effective atomic number" (Z_{eff})

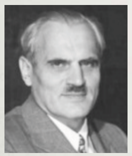
$$Z_{eff} = \sqrt[3]{\sum_{i=1}^{n} w_i Z_i^3}$$

ε=photon energy
Z=atomic number
w=mole fraction
n=number of components

Material	Z_{eff}
Air	7.3
Water	7.7
Soft tissue	7.4
Bone	13.8

For further info: see chapter on X-ray

Compton scatter



Arthur Holly Compton
(1892-1962)

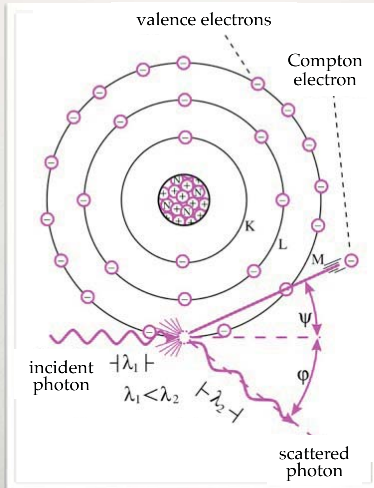
Energy balance:

$$hf = A + hf_{scatt} + E_{kin}$$

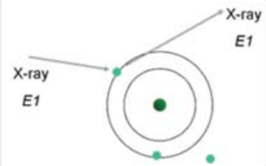
Compton scatter attenuation coefficient:

$$\sigma = \sigma_m \rho$$

σ_m=Compton scatter mass attenuation coefficient

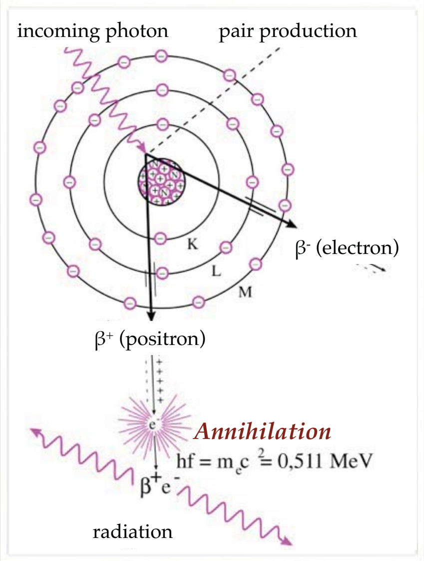


Note:
Elastic scatter



Incident photon energy = Scattered photon energy

Pair production



Energy balance:

$$hf = 2m_e c^2 + 2E_{kin}$$

m_e=mass of electron
c=speed of light

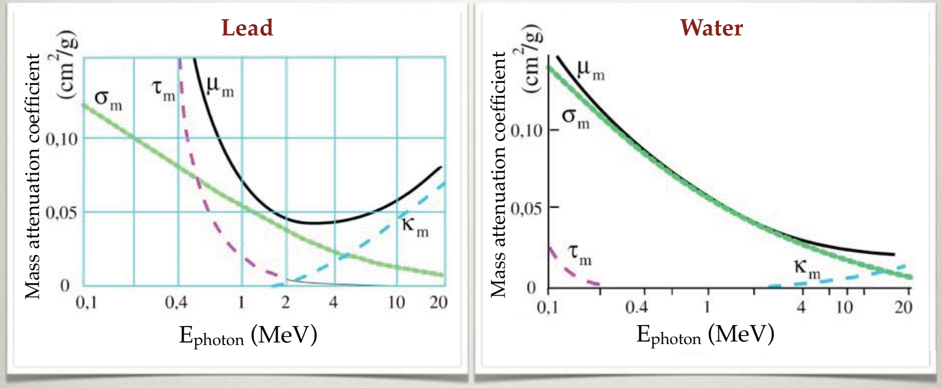
Pair production attenuation coefficient:

$$\kappa = \kappa_m \rho$$

κ_m=pair production mass attenuation coefficient

Attenuation mechanisms

Dependence on photon energy and material



$$\mu = \tau + \sigma + \kappa$$

μ_m=mass attenuation coefficient
σ_m=Compton effect mass attenuation coefficient
τ_m=photoeffect mass attenuation coefficient
κ_m=pair production mass attenuation coefficient

Summary of attenuation mechanisms

Mechanism	Variation of μ_m with E	Variation of μ_m with Z	Energy range in tissue
Rayleigh (elastic scatter)	~ 1 / E	$\sim Z^2$	1 - 30 keV
Photoelectric	$\sim 1/E^3$	$\sim Z^3$	10 - 100 keV
Compton scatter	falls gradually with E	independent ~Z	0.5 - 5 MeV
Pair production	rises slowly with E	$\sim Z^2$	> 5 MeV

Given the usual photon energy range, the mainain contrast mechanism in diagnostic X-ray: photoelectric effect ($\sim Z^3$)

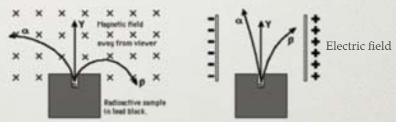
For further info: see chapter on X-ray

Alpha radiation

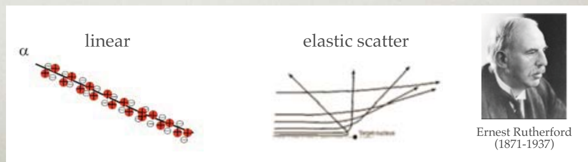
Alpha particles: two protons and two neutrons bound together into a particle identical to a helium nucleus

Generation: alpha decay

Properties:
Electric charge: $2e^+$
Initial velocity:> 1000 km/s
Kinetic energy: few MeV
Spectrum: linear



Propagation path:

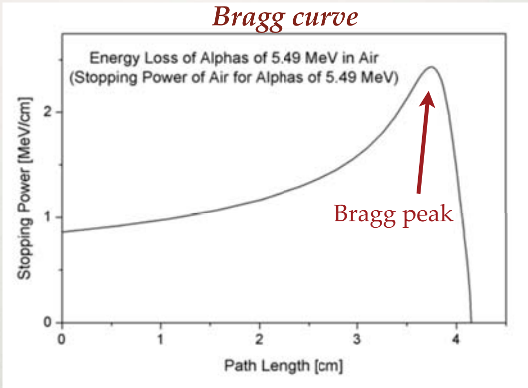


Effects of alpha radiation: Ionization

Energy loss of ionizing radiation as it travels through matter

Linear ion density: number of ion pairs per unit distance (m^{-1})

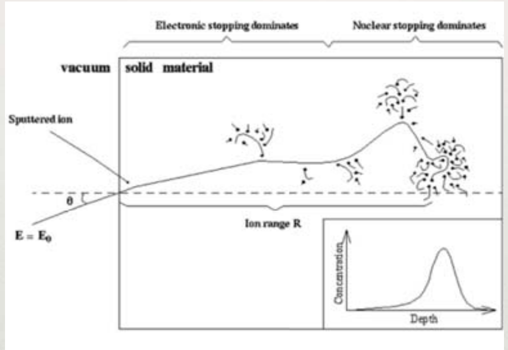
Stopping power: average energy loss per unit path length ($\Delta E/\Delta x$) (eV/cm) = ***Linear energy transfer:*** ratio of energy lost and path length



Range: average distance of travelled by the particle prior to energy loss to thermal levels.

Mechanisms of charged particle deceleration in matter

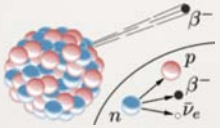
Particle energy gradually decreases - ineraction cross section increases.



Other effects of alpha radiation: Characteristic X-ray, scintillation, thermal effects, nuclear reaction (low probability)

Beta radiation

Beta particles: high-energy, high-speed electrons or positrons



Generation: beta decay

beta- decay: $n \rightarrow p + e^- + \bar{\nu}_e$ antineutrino: $\bar{\nu}_e$

beta+ decay: $p \rightarrow n + e^+ + \nu_e$ neutrino: ν_e

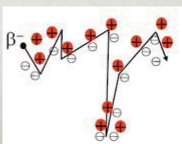
Properties:

Electric charge: $1e^-$ (or $1e^+$)

Linear ion density: 1000 times smaller than that of alpha

Spectrum: continuous (because of neutrino), therefore range varies widely

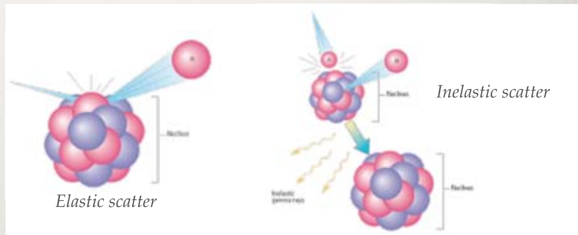
Propagation path: contortuous, winding (electrostatic effects)



Neutron radiation

Neutron: subatomic particle with no net electric charge and a mass slightly greater than that of the proton

Generation: in certain nuclear reactions; bombarded atomic nuclei are excited and relax by neutron emission



Effects:

Ionization by indirect effect

Elastic scatter

Inelastic scatter (above 5 MeV) - gamma or alpha emission follows relaxation from nuclear excited state

Neutron capture: thermal neutron is incorporated in the atomic nucleus (radioactive isotope is formed)

Nuclear fission (>100 MeV): nuclear fragments, neutrons, γ-radiation are genarated

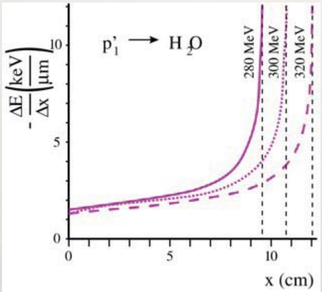
Proton radiation

The **proton** is a subatomic particle (symbol p or p^+) with a positive electric charge of 1 elementary charge.

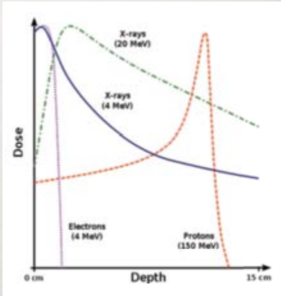
One or more protons are present in the nucleus of each atom.

Propagation in mater is very similar to that of alpha radiation

Bragg curve and Bragg peaks

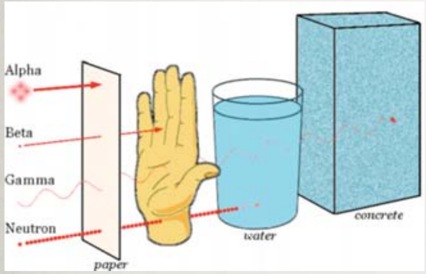


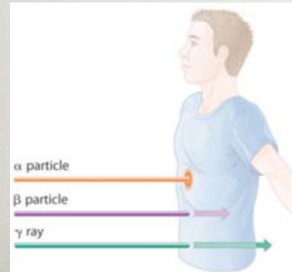
Comparison of radiations



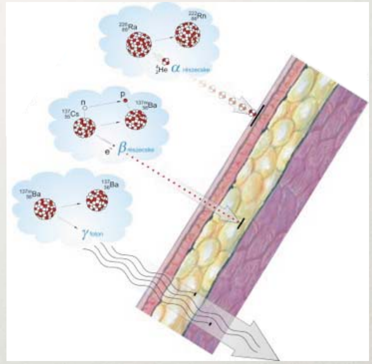
Therapeutic significance: proton radiation therapy of cancer

Biomedical importance and applications



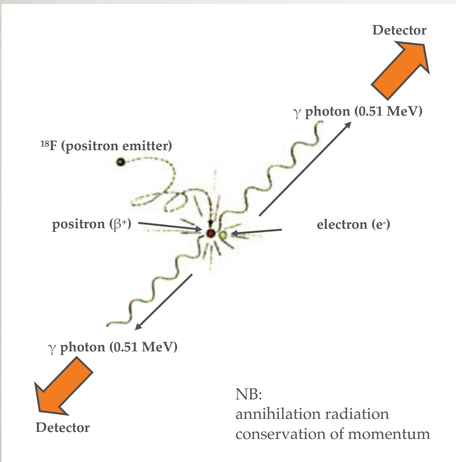


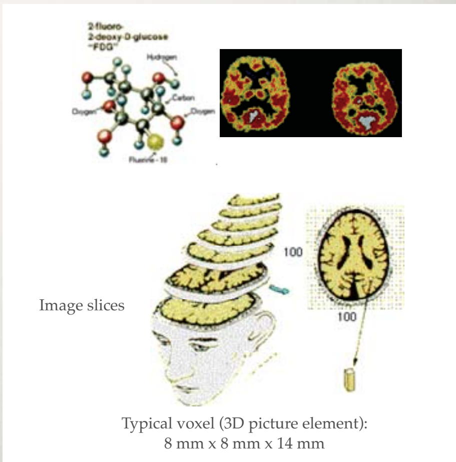
Penetration depth: depends on radiation energy and mass attenuation coefficient



Note: protection against the effect of ionizing radiations!

Positron emission tomography





Superposed MRI and PET sequence

PET activity: during eye movement
Volume rendering