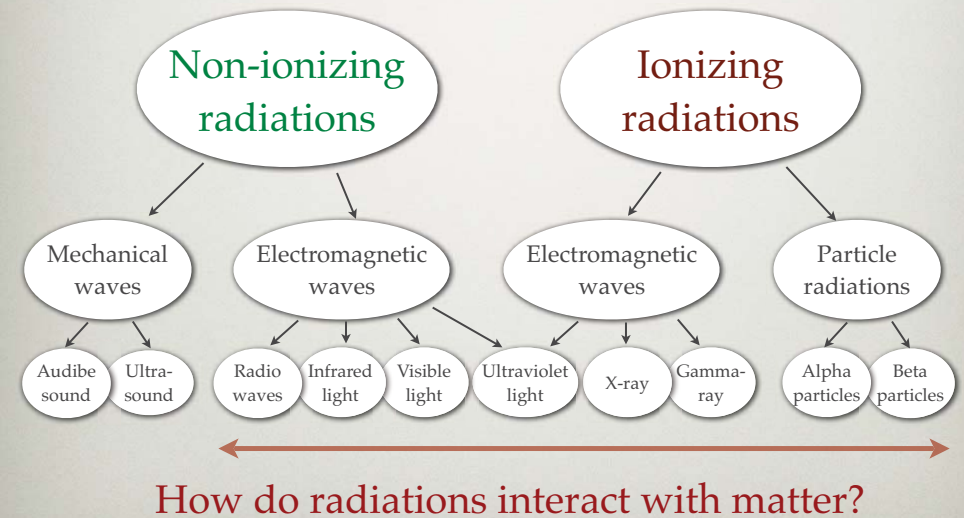


# INTERACTION OF RADIATIONS WITH MATTER

MIKLÓS KELLERMAYER

## TYPES OF RADIATIONS



## GENERAL OUTLINE

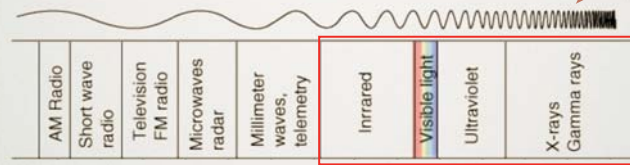
- Light  
reflection, refraction, scatter, absorption
- Ionizing electromagnetic radiation  
X-ray,  $\gamma$ -radiation
- Particle radiations  
alpha, beta, proton, neutron, heavy ions
- Mechanisms  
scatter, ionization, photoelectric effect, Compton scatter, pair production, nuclear reaction
- Quantitative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

## GENERAL SCHEME OF DISCUSSION

- Definition  
e.g.,  $\alpha$ -particles=He nuclei /  $\gamma$ -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  $^{239}\text{Pu}$  atom.
- 200 MeV: total energy released in nuclear fission of one  $^{235}\text{U}$  atom.
- 17.6 MeV: total energy released in fusion of deuterium and tritium to form  $^4\text{He}$ .
- 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.

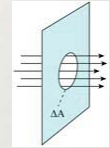
# ENERGY OF RADIATION II.

*Physical parameters describing radiated energy*

ENERGY  
 $E \text{ [J]}$

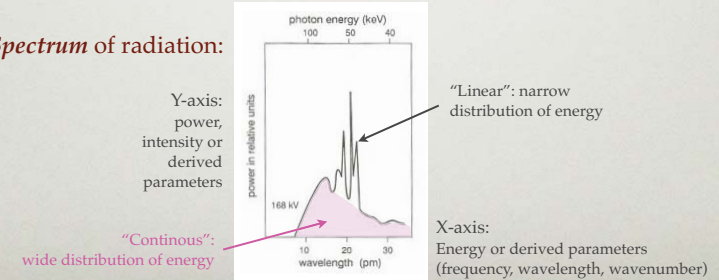
POWER  
 $P = \frac{\Delta E}{\Delta t} \left[ \frac{\text{J}}{\text{s}} = \text{W} \right]$

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

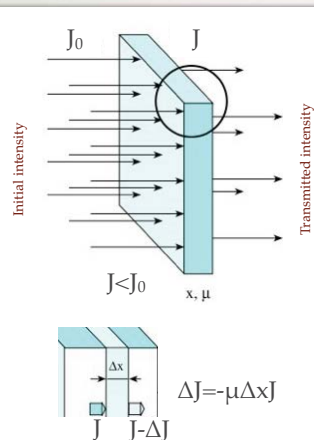


What *photonic energies contribute* to radiated energy?

*Spectrum of radiation:*

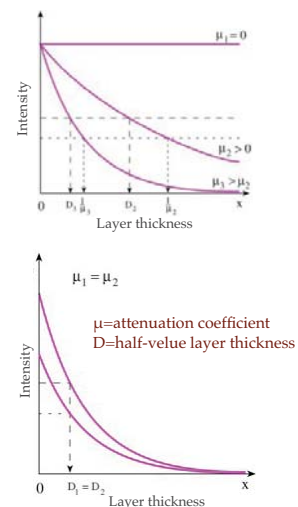


# GENERAL ATTENUATION MECHANISM

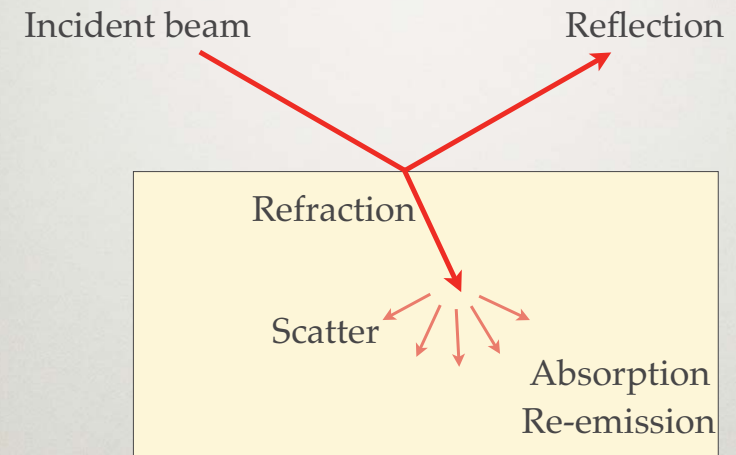


General law of radiation attenuation:

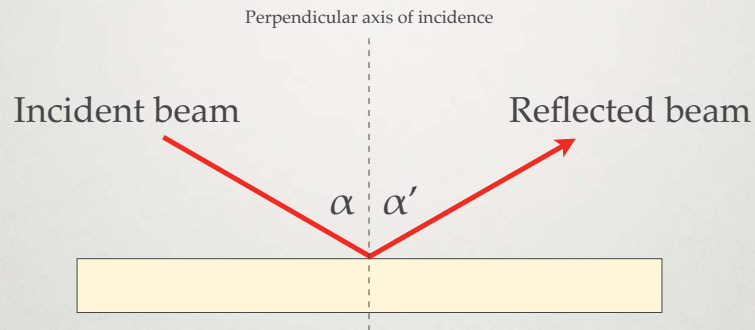
$$J = J_0 e^{-\mu x}$$



# INTERACTION OF LIGHT WITH MATTER

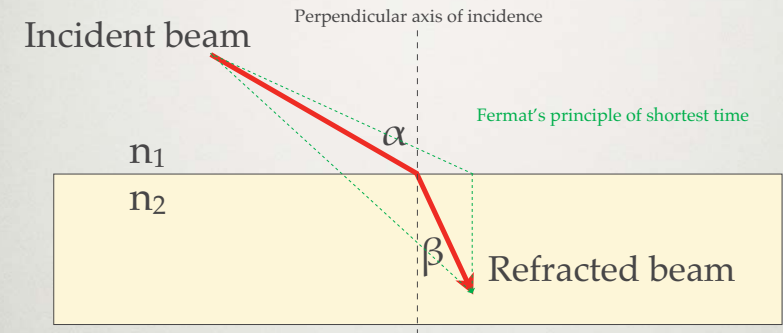


# REFLECTION

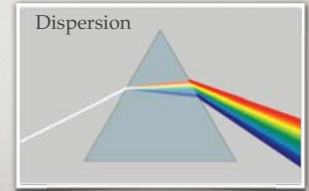


- Incident and reflected beams and axis of incidence are in the same plane.
- Incident and reflected angles are identical ( $\alpha = \alpha'$ )

# REFRACTION



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

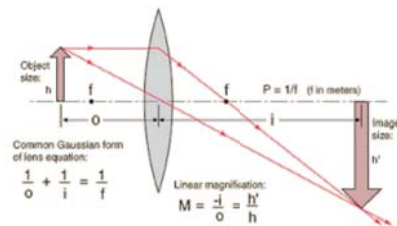


# REFRACTION IS THE BASIS FOR OPTICAL IMAGE FORMATION

## Geometric optics

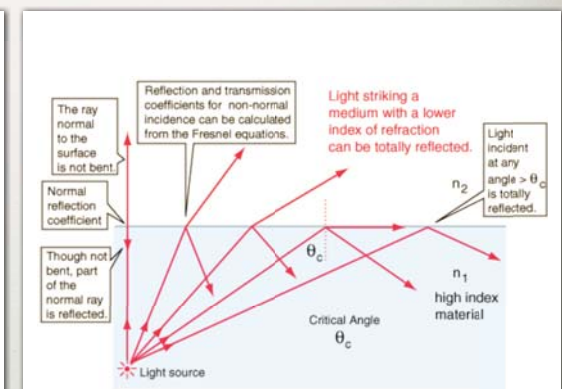
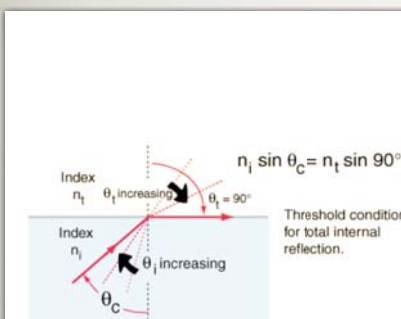
- Radiation: optical ray or beam
- Ray optic diagram: direction of energy propagation indicated as vectors
- Principle of reversibility: energy propagation is assumed to be reversible along the beam

## Image formation (ray optics diagram)



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

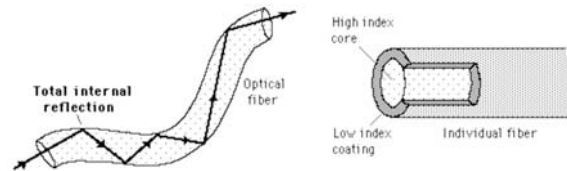
# TOTAL INTERNAL REFLECTION



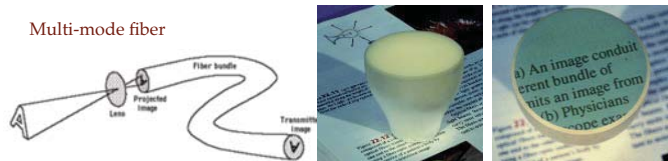


## BIOMEDICAL APPLICATION OF TIR: OPTICAL FIBERS

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

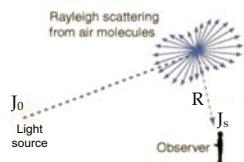
- **Arthroscopy:** diagnostic and therapeutic examination of joints (arthroscopic surgery)
- **Bronchoscopy:** examination of the trachea and bronchi
- **Colonoscopy:** examination of the colon
- **Colposcopy:** examination of the vagina and cervix
- **Cystoscopy:** examination of urinary bladder, urethra 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



## LIGHT SCATTERING



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

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

$J_s$ =intensity of scattered light  
 $J_0$ =intensity of incident light  
 $N$ =number of scattering particles  
 $\alpha$ =polarizability (dipole moment per electric field)  
 $\lambda$ =wavelength of light  
 $R$ =distance between scatterer and observer  
 $\Theta$ =angle of scattered light

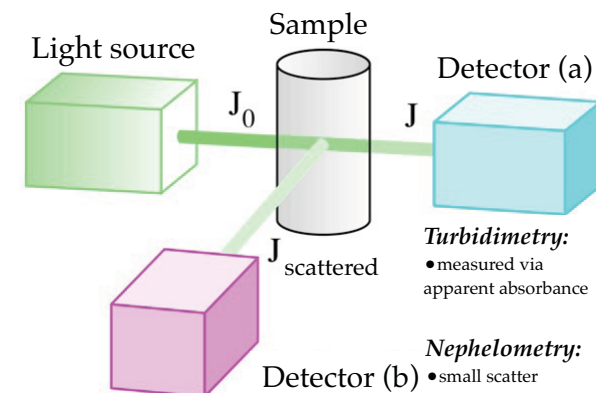


Strong wavelength dependence -> enhancement of short wavelengths -> blue sky



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

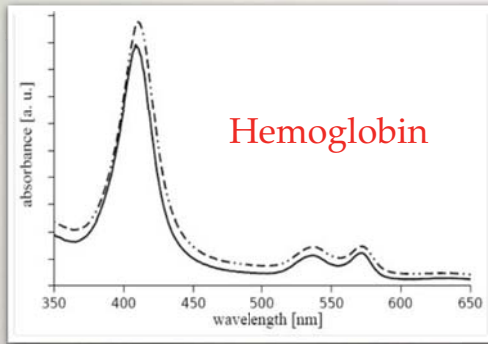
## BIOMEDICAL APPLICATIONS OF LIGHT SCATTERING



**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

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

Lambert-Beer's Law

$\epsilon_\lambda$  = molar extinction coefficient  
c = concentration

## INTERACTION OF IONIZING RADIATIONS WITH MATTER

### Classification possibilities

#### Nuclear radiation

Energy from atomic nucleus.  
e.g.,  $\alpha$ ,  $\beta$ ,  $\gamma$ , p, n, ...

#### X-ray

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

#### Particle radiation

Rest mass positive.  
e.g.,  $\alpha$ ,  $\beta$ , p, n, ...

#### Electromagnetic radiation

No rest mass.  
e.g., X-ray,  $\gamma$

#### Direct ionizing radiation

Charged particles.  
e.g.,  $\alpha$ ,  $\beta$ , p, ...

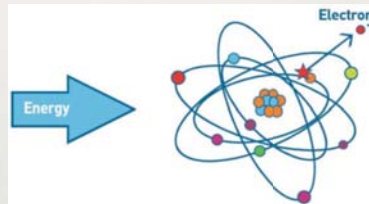
#### Indirect ionizing radiation

No charge.  
e.g., X-ray,  $\gamma$ , n

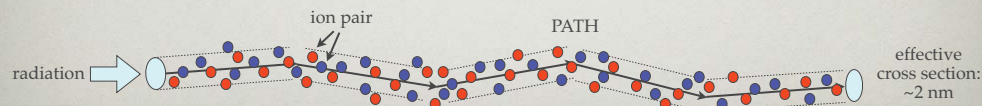
## IONIZATION

- 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  
( $5.44 \times 10^{-18}$  J = 5.44 aJ)  
energy is required to  
generate one ion pair.



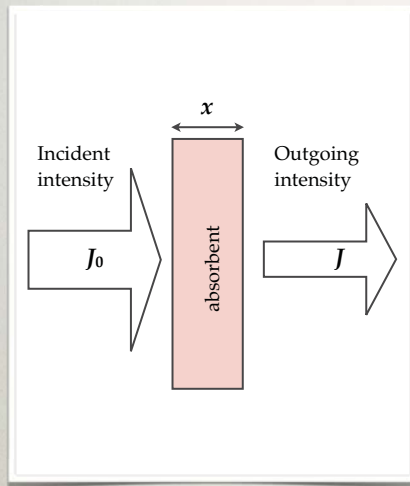
Ionizing radiations exert their effect on the interacting matter via generation of ion pairs:



## IONIZING ELECTROMAGNETIC RADIATIONS

- **Types:**  
X-ray  
 $\gamma$ -radiation
- **Source:**  
electron shell (X-ray)  
nuclear decay ( $\gamma$ -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



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

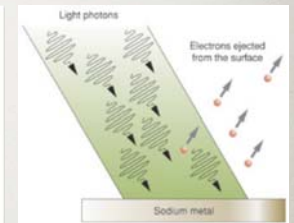
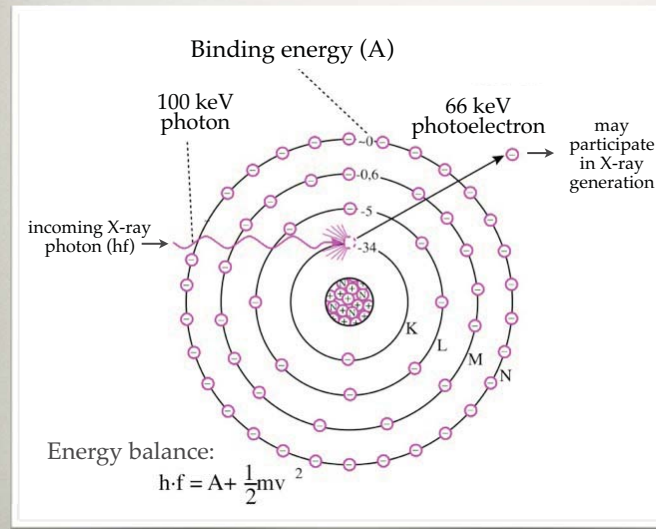
Exponential attenuation principle

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

$$\mu = \mu_m \rho$$

$\mu$ =attenuation coefficient  
 $\mu_m$ =mass attenuation coefficient ( $\text{cm}^2/\text{g}$ )  
 $\rho$ =density ( $\text{g}/\text{cm}^3$ )

# X-RAY PHOTOEFFECT

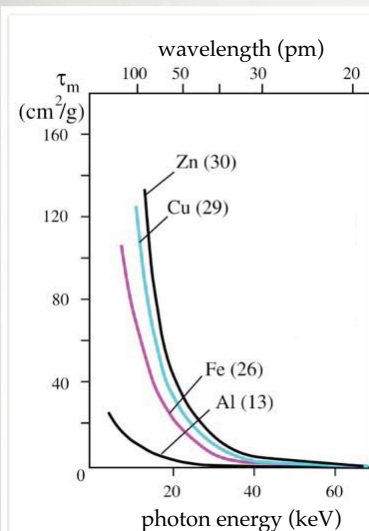


Photoeffect attenuation coefficient:

$$\tau = \tau_m \rho$$

$\tau_m$ =photoeffect mass attenuation coefficient

# PHOTOEFFECT ATTENUATION DEPENDS STRONGLY ON ATOMIC NUMBER



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

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

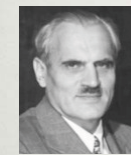
$$Z_{\text{eff}} = \sqrt[n]{\sum_{i=1}^n w_i Z_i^3}$$

$\epsilon$ =photon energy  
 $Z$ =atomic number  
 $w$ =mole fraction  
 $n$ =number of components

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

For further info: see chapter on X-ray

# COMPTON SCATTER

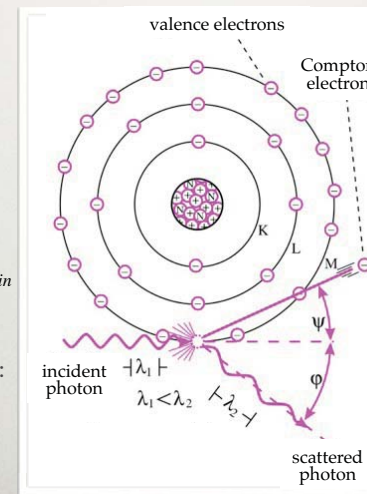


Energy balance:  
 $hf = A + hf_{\text{scatt}} + E_{\text{kin}}$

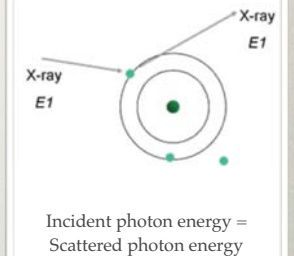
Compton scatter attenuation coefficient:

$$\sigma = \sigma_m \rho$$

$\sigma_m$ =Compton scatter mass attenuation coefficient

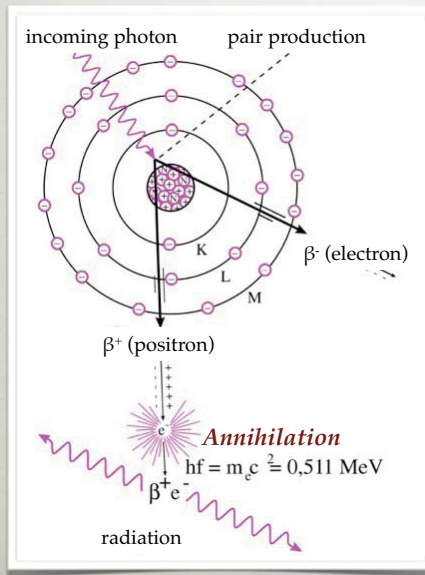


Note:  
 Elastic scatter





# PAIR PRODUCTION



Energy balance:

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

$m_e$ =mass of electron  
 $c$ =speed of light

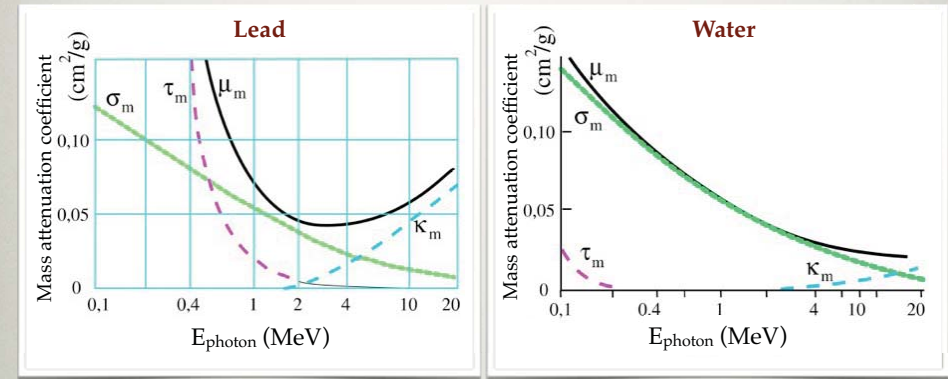
Pair production  
attenuation coefficient:

$$\kappa = \kappa_m \rho$$

$\kappa_m$ =pair production mass  
attenuation coefficient

# ATTENUATION MECHANISMS

Dependence on photon energy and material



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

$\mu_m$ =mass attenuation coefficient  
 $\sigma_m$ =Compton effect mass attenuation coefficient

$\tau_m$ =photoeffect mass attenuation coefficient  
 $\kappa_m$ =pair production mass attenuation coefficient

# SUMMARY OF ATTENUATION MECHANISMS

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

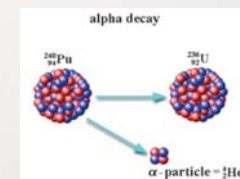
Given the usual photon energy range, the main contrast mechanism in diagnostic X-ray: photoelectric effect ( $\sim Z^3$ )

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

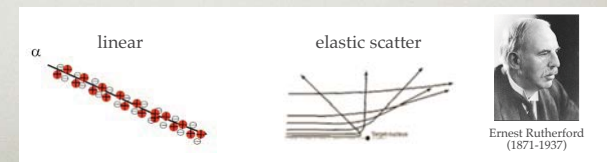


Properties:

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



Propagation path:



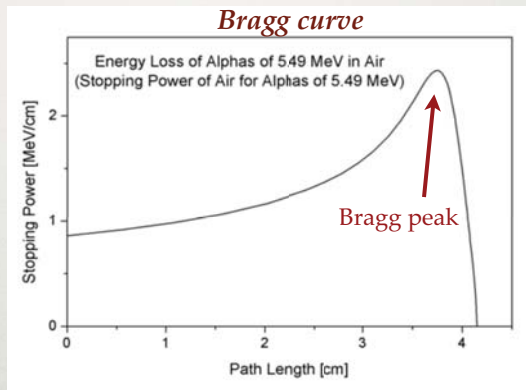
# EFFECTS OF ALPHA RADIATION: IONIZATION

Energy loss of ionizing radiation as it travels through matter

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

**Stopping power:**  
average energy loss  
per unit path length  
( $\Delta E / \Delta x$ ) ( $\text{eV} / \text{cm}$ )  
=

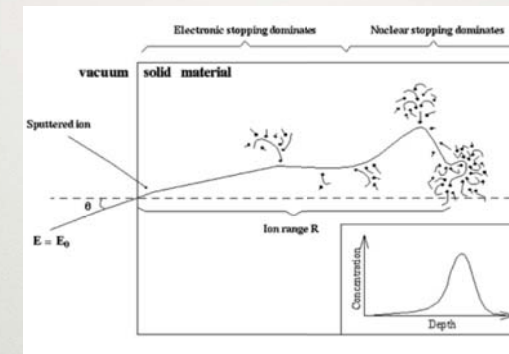
**Linear energy  
transfer:** ratio of  
energy lost and path  
length



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

# MECHANISMS OF CHARGED PARTICLE DECELERATION IN MATTER

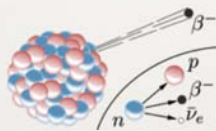
Particle energy gradually decreases - interaction cross section increases.



**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:  $\nu_e$

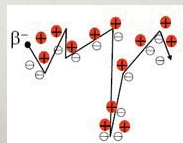
**Properties:**

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

Linear ion density: 1000 times smaller than that of alpha

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

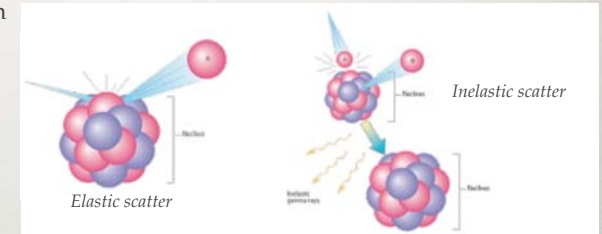
**Propagation path:** contortuous, winding  
(electrostatic effects)



# 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)

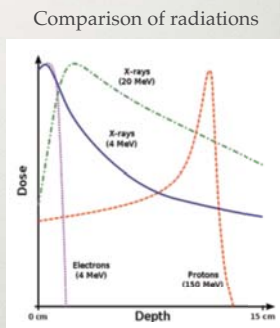
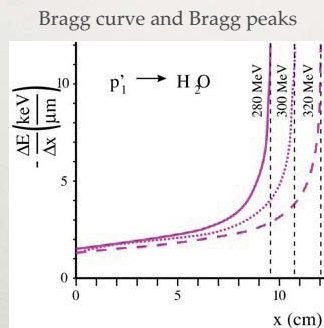
*Nuclear fission* (>100 MeV): nuclear fragments, neutrons,  $\gamma$ -radiation are generated



# PROTON RADIATION

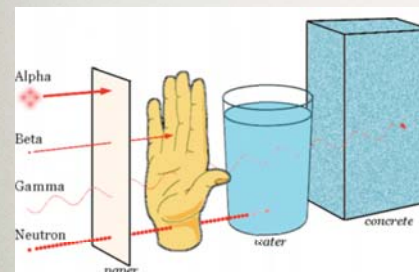
The **proton** is a subatomic particle (symbol  $p$  or  $p^+$ ) with a positive electric charge of 1 elementary charge.  
One or more protons are present in the nucleus of each atom.

Propagation in matter is very similar to that of alpha radiation

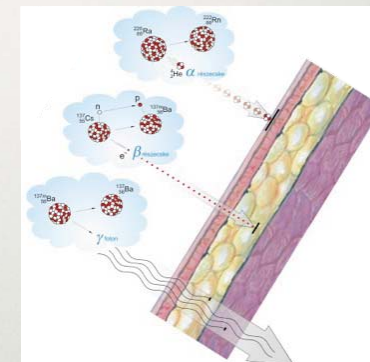
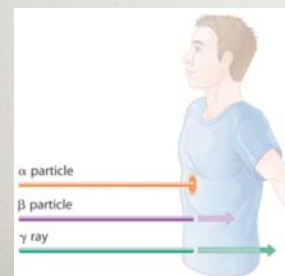


Therapeutic significance: proton radiation therapy of cancer

# BIOMEDICAL IMPORTANCE AND APPLICATIONS

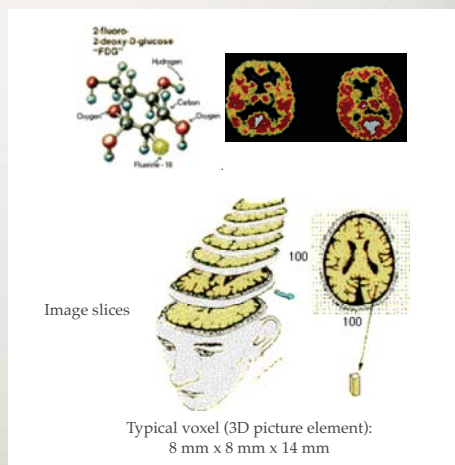
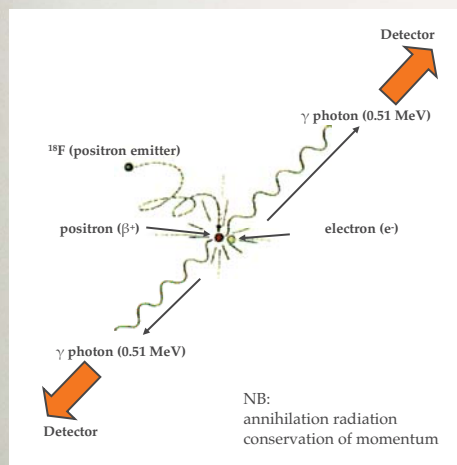


Penetration depth: depends on radiation energy and mass attenuation coefficient



Note: protection against the effect of ionizing radiations!

# POSITRON EMISSION TOMOGRAPHY



# SUPERPOSED MRI AND PET SEQUENCE



PET activity: during eye movement  
Volume rendering