Radiation physics, dosimetry

Dr. István Voszka

Semmelweis University, Department of Biophysics and Radiation Biology

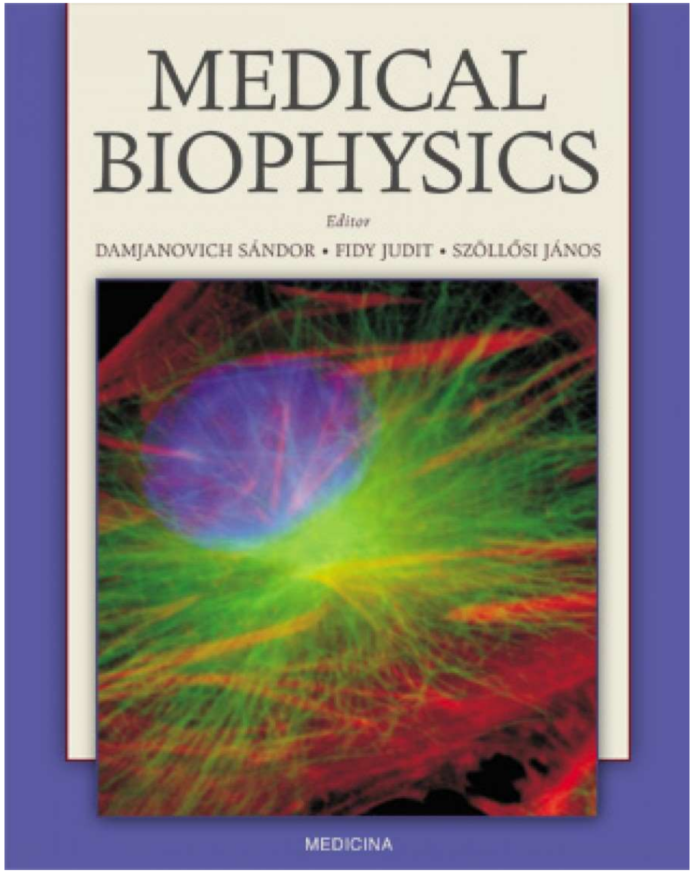
SEMMELWEIS UNIVERSITY 1769

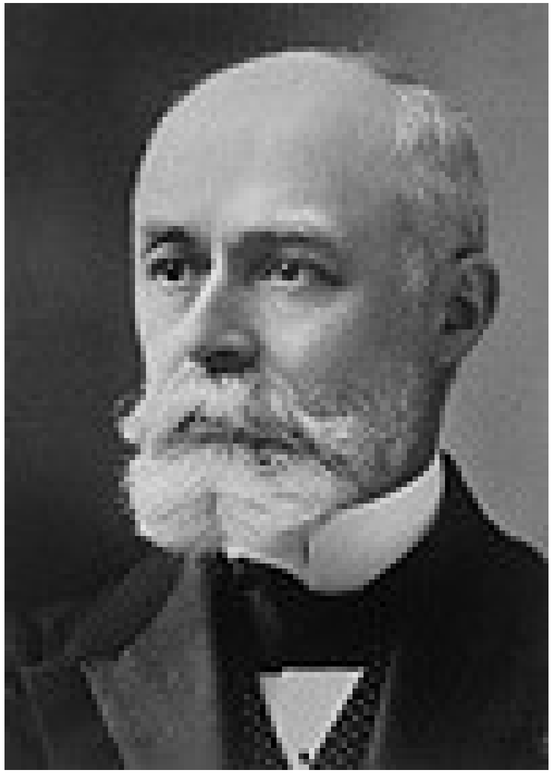
Dr. István Voszka

E-mail: voszka.istvan@semmelweis.hu

Homepage of the department:
biofiz.semmelweis.hu

Damjanovich – Fidy – Szöllősi: Medical biophysics
Chapters: II., VIII., IX.

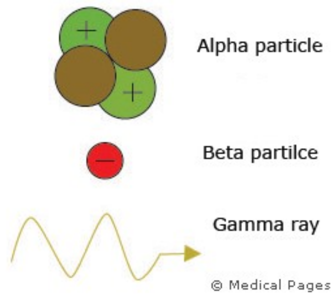




Wilhelm Conrad Röntgen
1845-1923

Antoine Henri Becquerel
1852-1908

Ionizing radiations

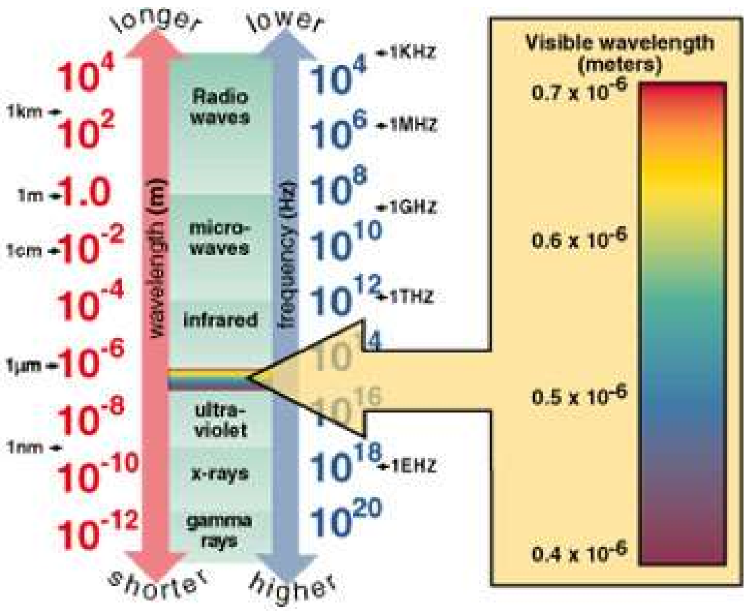


a) corpuscular: formed by particles having rest mass

E.g.: α, β, proton, neutron

b) electromagnetic: formed by photons without rest mass

γ, X-



$E = hf = hc/\lambda$

1. The structure of atom, ionization, excitation

Nucleus: d = 10^{-15}-10^{-14} m

contains protons

(number of protons → atomic number-Z)

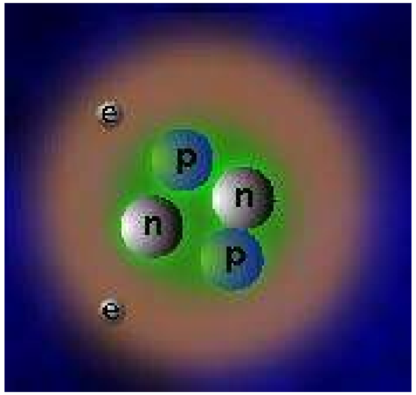
neutrons (number of protons + neutrons [nucleons] → mass number-A)

Nuclear radiations: α, β, γ

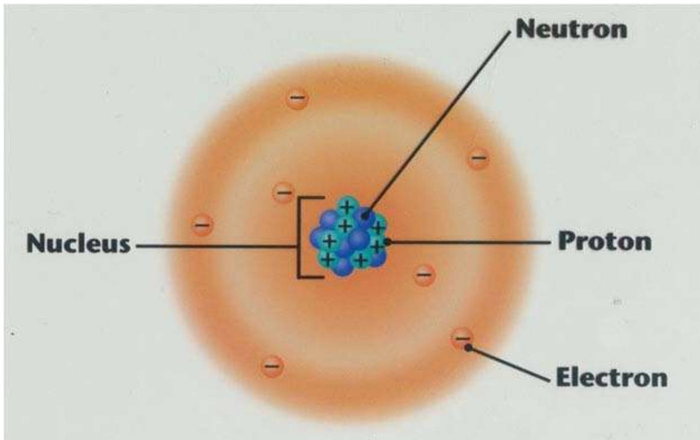
Electron shell: d ≈ 10^{-10} m

number of electrons = number of protons

electrons are positioned on special energy levels (in quantized form)



$^{56}_{26}Fe$

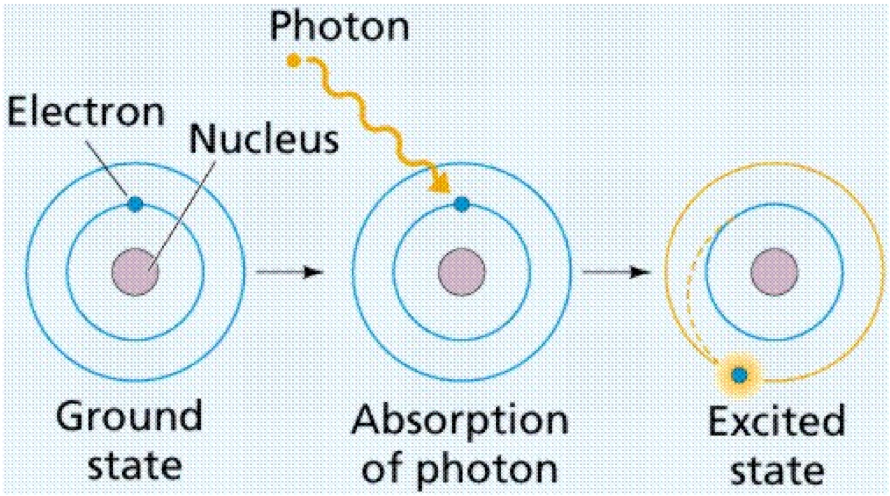


Excitation: $\Delta E = hf = h\,c / \lambda$

Ionization: $hf \geq \Delta E$

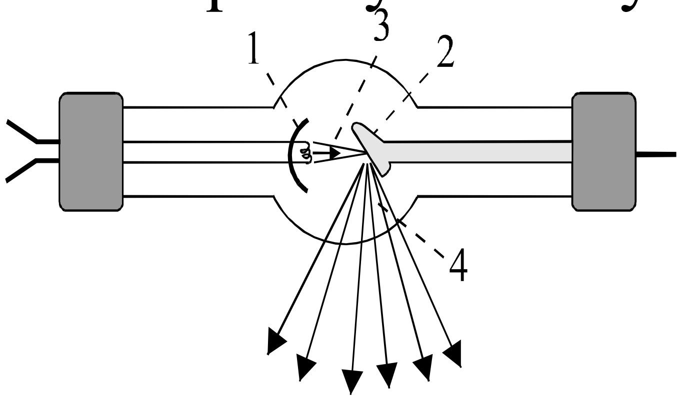
Radiation originating from the electron shell:

X-ray



2. Production of X-radiation

most frequently in X-ray tube

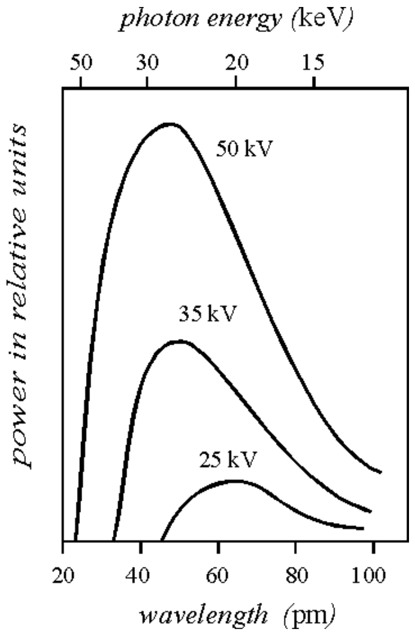


Types: **Bremsstrahlung (braking radiation)**

- continuous spectrum with minimum wavelength
- the radiation becomes harder with increasing U, the emitted X-ray power increases (proportionally with U^2)

$P = c\, U^2 I Z \qquad \eta = c\, U\, Z$

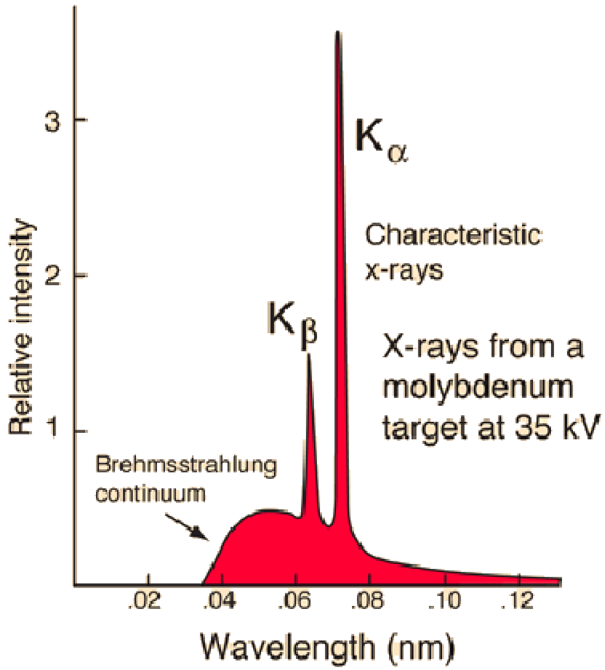
Application: X-ray imaging



characteristic radiation

- only at high accelerating voltage
- line spectrum characteristic for the anode

Application: osteodensitometry, identification of material, examination of molecular structure



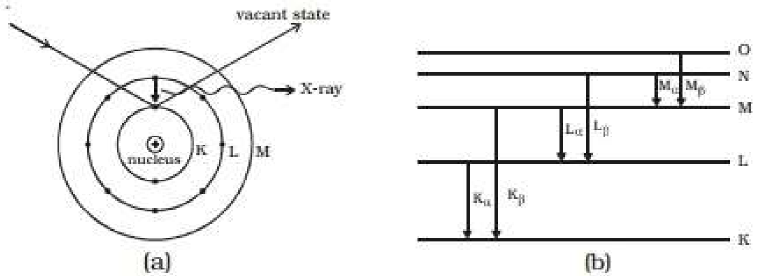
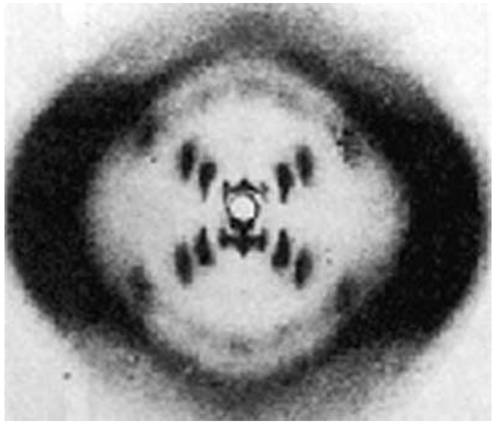
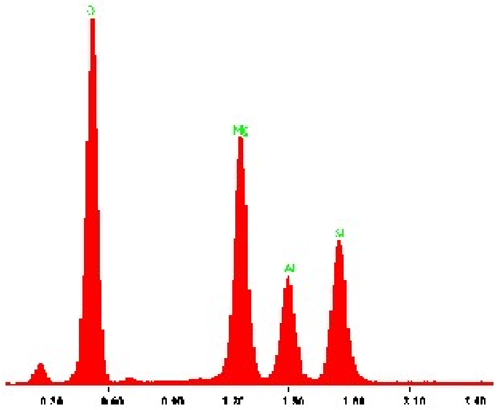


Fig Characteristic X-ray spectra


OSTEOVIEW

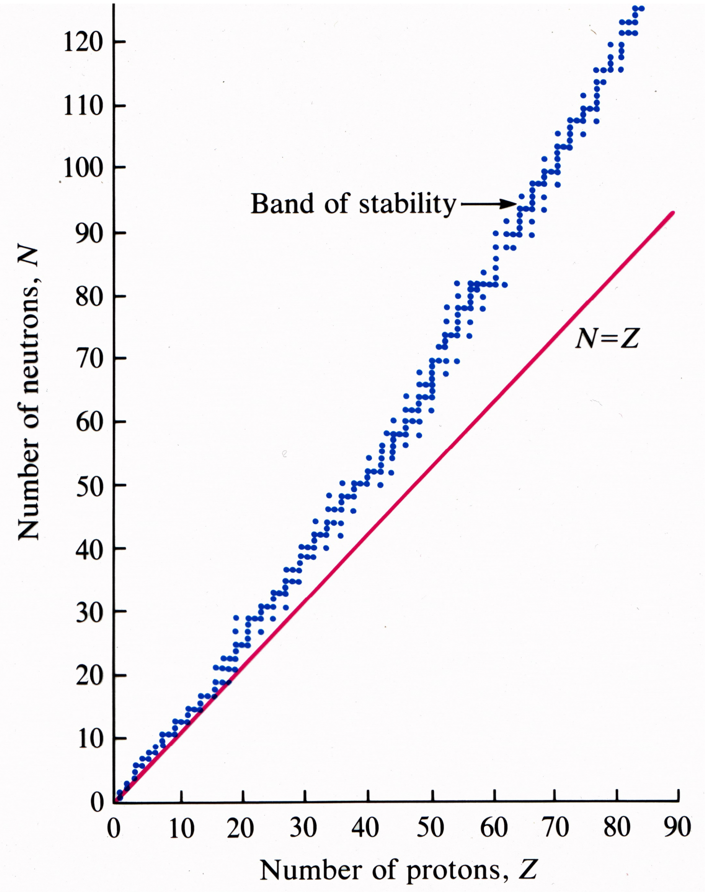

EDAX

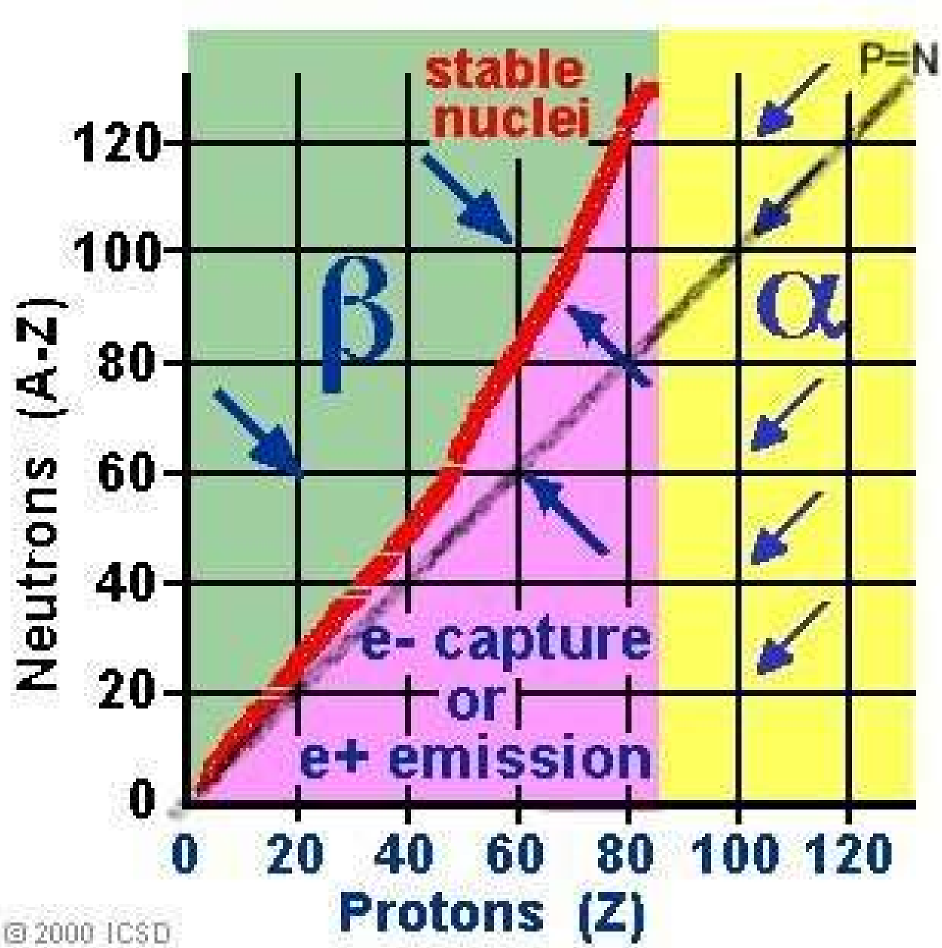



O
Mg
Al
Si

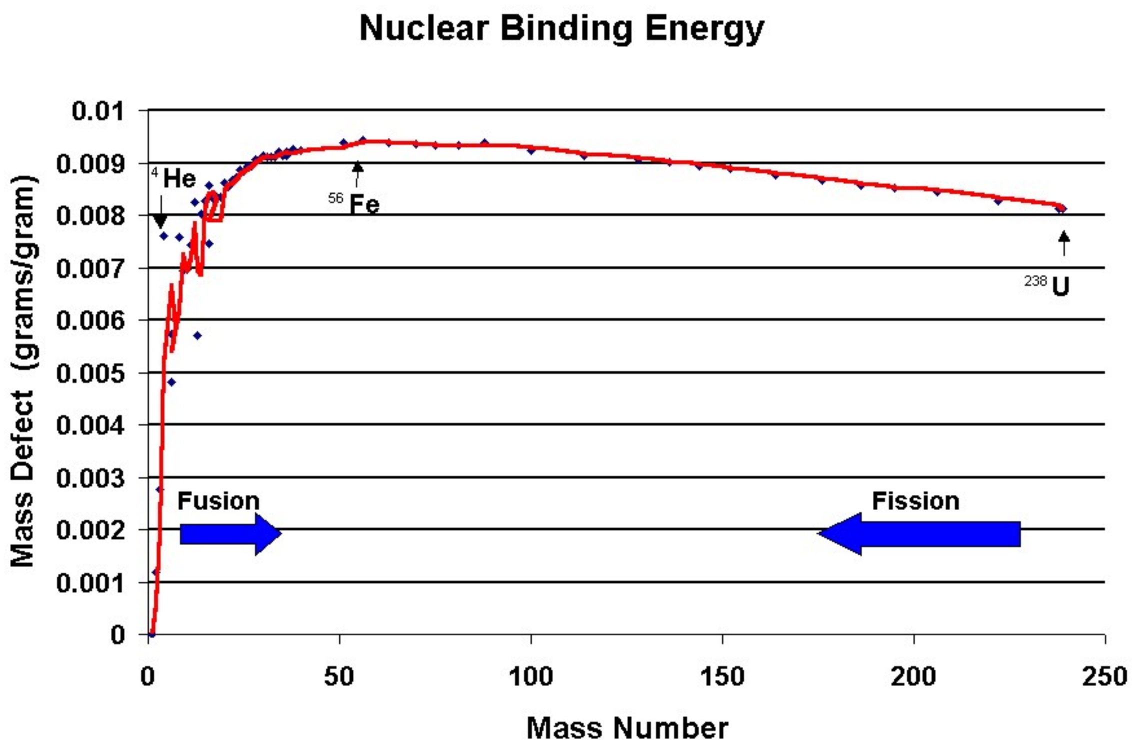
3. Nuclear forces, stability of the nucleus

There are attractive and repulsive forces between protons and neutrons

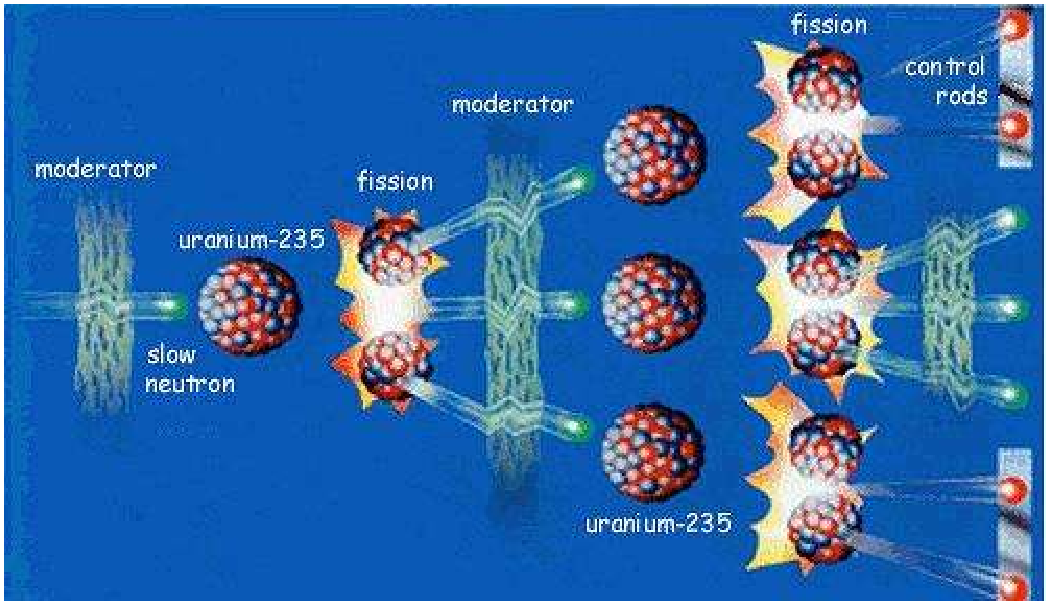




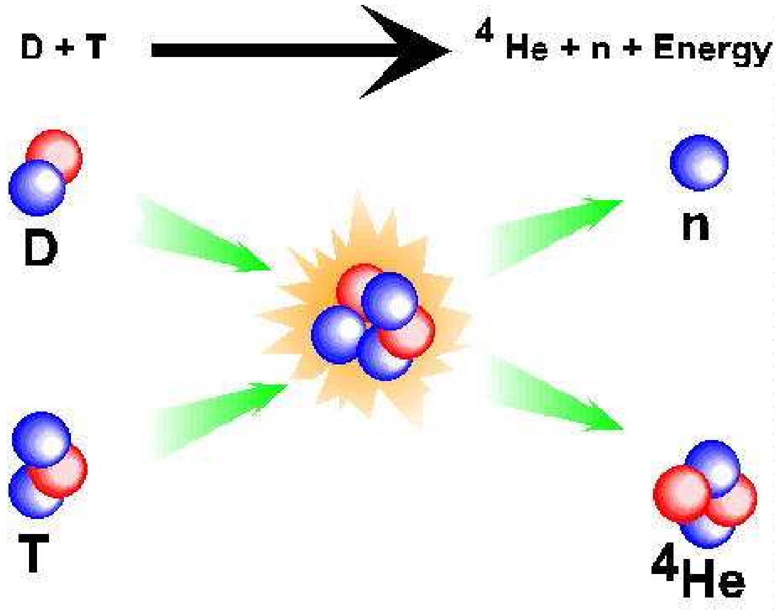
The bond energy related to one nucleon is the highest in case of medium size nuclei (the most stable nuclei)

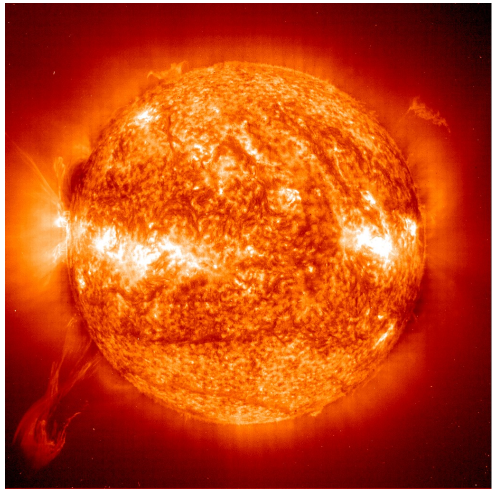


This stable state can be reached by fission of heavy nuclei: nuclear reactor, atomic bomb



By fusion of light nuclei
- fusion reactor, H-bomb

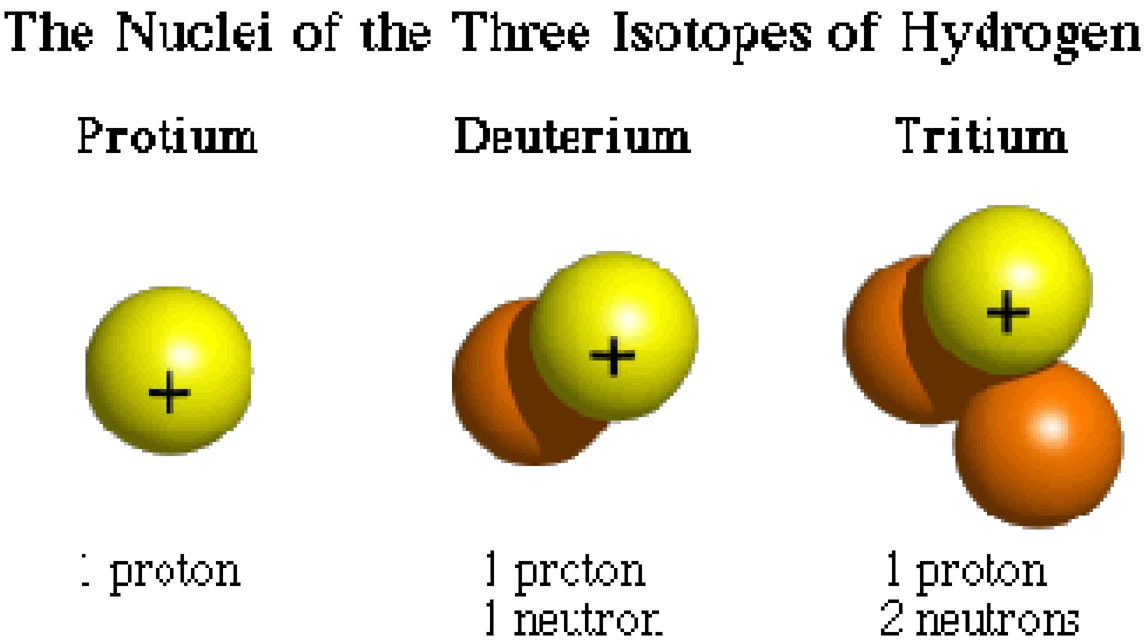




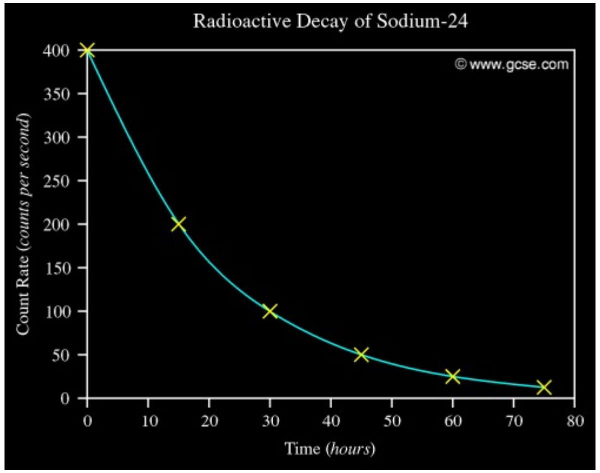
Isotopes: identical atomic number, but different mass number
(it can be stable or radioactive)

↙ ↘

natural artificial



4. Radioactive decay, activity



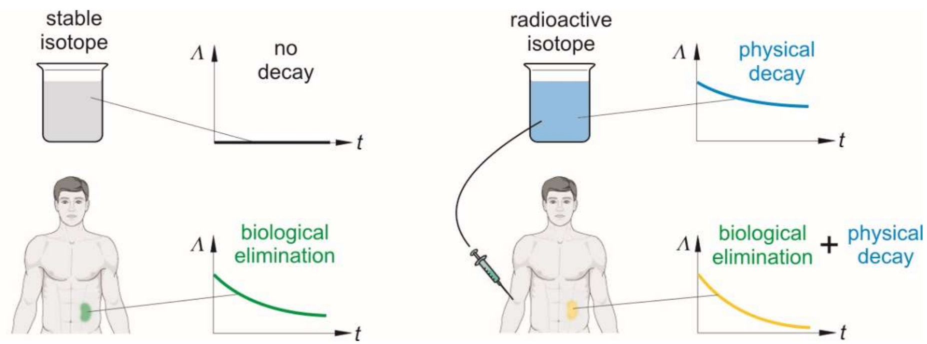
Decay rate: $\frac{dN}{dt} = -\lambda N$ $\frac{dN}{dt} = \Lambda$ (activity)

[decay/s = 1/s = Bq (becquerel)]

(1 Ci (curie) = $3{,}7 \times 10^{10}$ Bq)

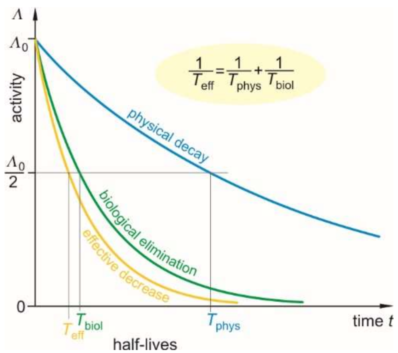
$$N = N_0 e^{-\lambda t} \qquad \lambda = \frac{0{,}693}{T}$$

$$\lambda = \frac{1}{\tau} \qquad \Lambda = \Lambda_0 e^{-\lambda t}$$



Connection between half-lives:

$$\frac{1}{T_{eff}} = \frac{1}{T_{phys}} + \frac{1}{T_{biol}}$$

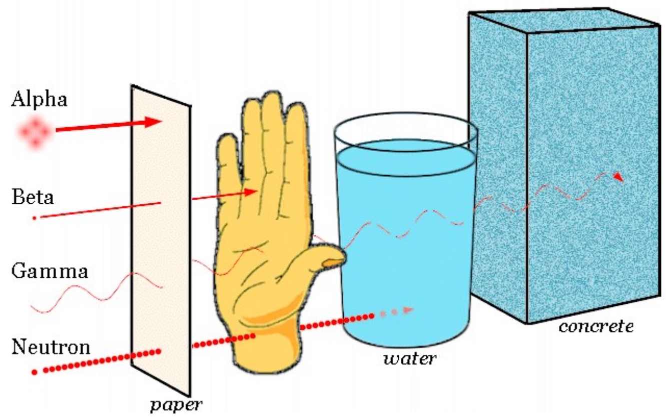


5. Types of decay

Alpha decay

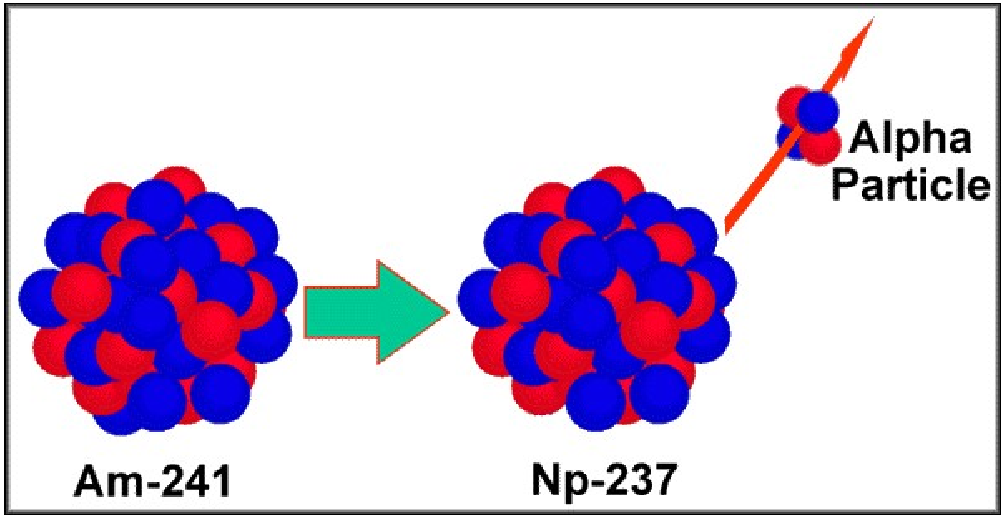
Z decreases by 2, A by 4

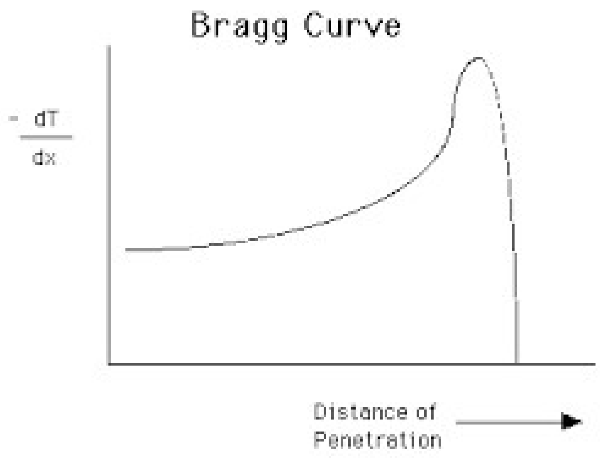
e.g. $^{226}_{88}Ra \rightarrow ^{222}_{86}Rn + ^{4}_{2}\alpha$



- energy is well defined (line spectrum)
- short effective range (in water or soft tissues several 10 μm)

Application: only therapy

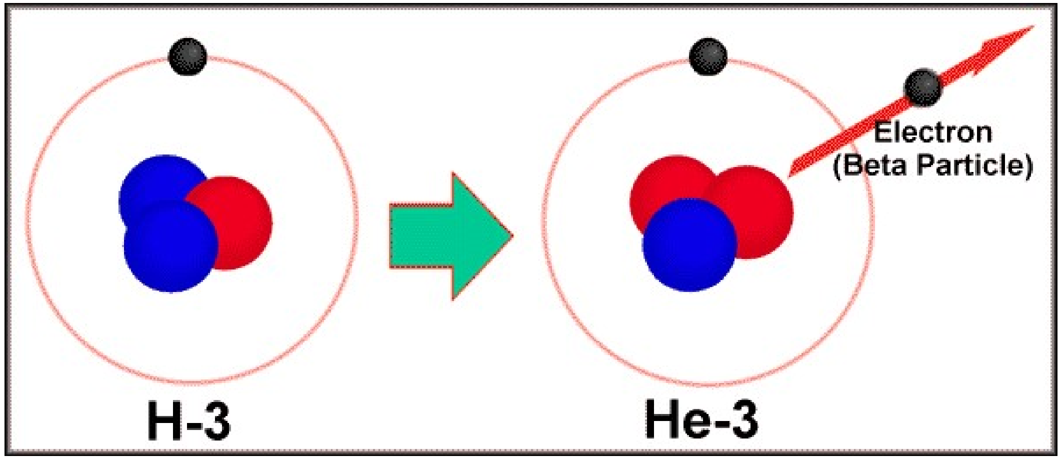




Beta decay

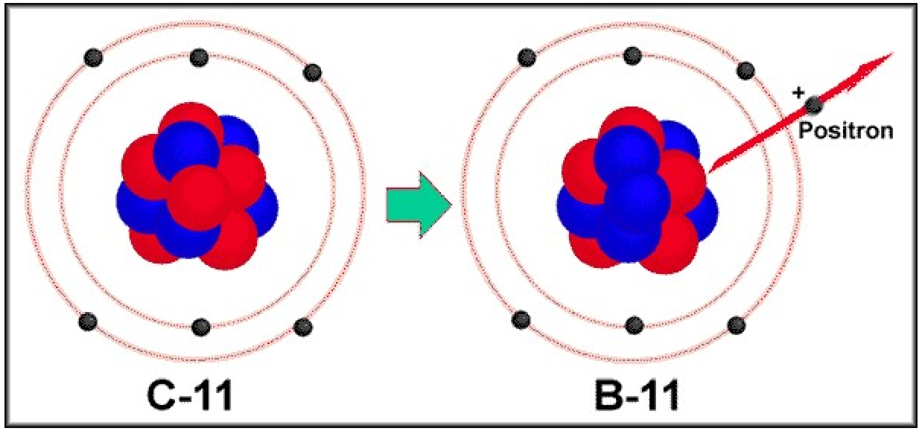
- negative β-decay: Z increases by 1

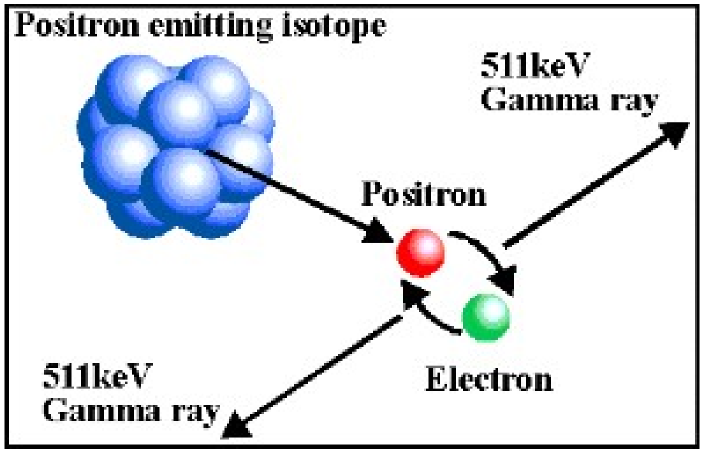
e.g.: $^{32}_{15}P \rightarrow ^{32}_{16}S + ^{0}_{-1}\beta$



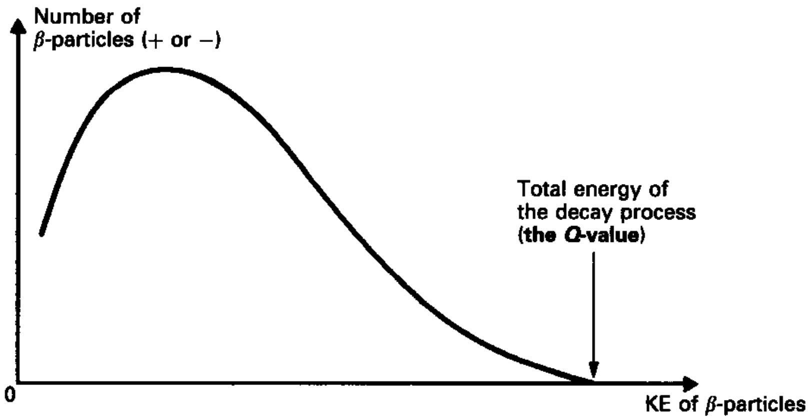
- positive β-decay: Z decreases by 1

e.g.: $^{30}_{15}P \rightarrow ^{30}_{14}Si + ^{0}_{+1}\beta$





The nucleus looses a given amount of energy, but the spektrum is continuous. Its reason is the neutrino.



Application: β^-: therapy and in vitro diagnostics

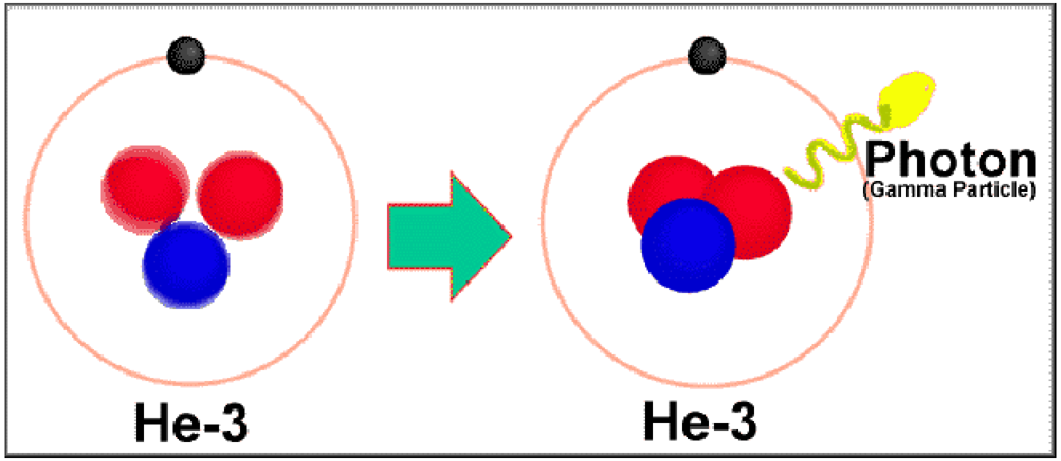
β^+: PET

Gamma radiation

After α -or β-decay the nucleus gives down its excess energy in the form of electromagnetic radiation

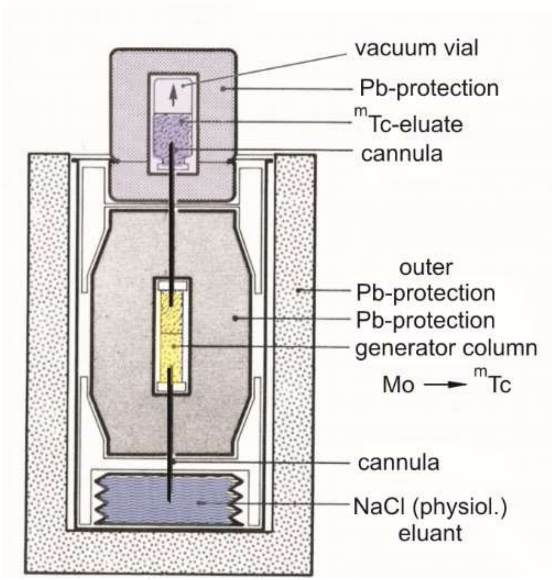
- prompt γ-radiation:
  within 10^{-13}-10^{-18} s after the particle radiation

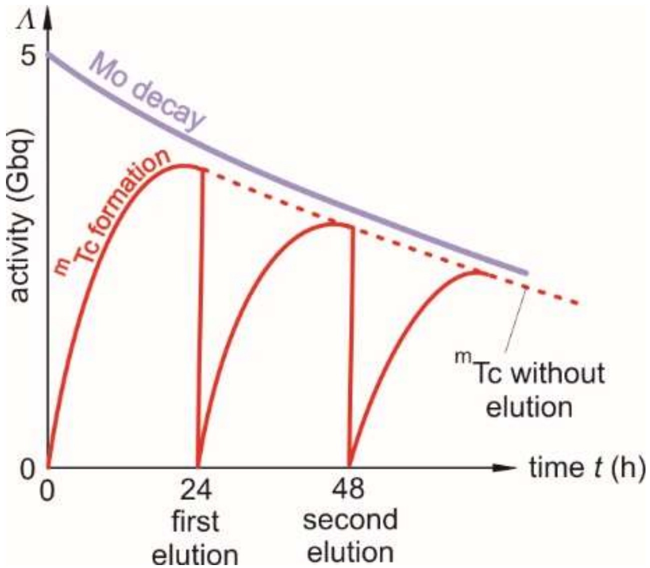
- isomeric transition:
  follows the particle radiation with longer, measurable half-life
  Advantage: the two types of radiations can be separated, pure gamma-radiating isotope can be obtained



E.g.: $^{99}_{42}Mo \xrightarrow[\beta]{} {}^{99m}_{43}Tc \xrightarrow[\gamma]{} {}^{99}_{43}Tc$

Application: in vivo diagnostics (very widely used)



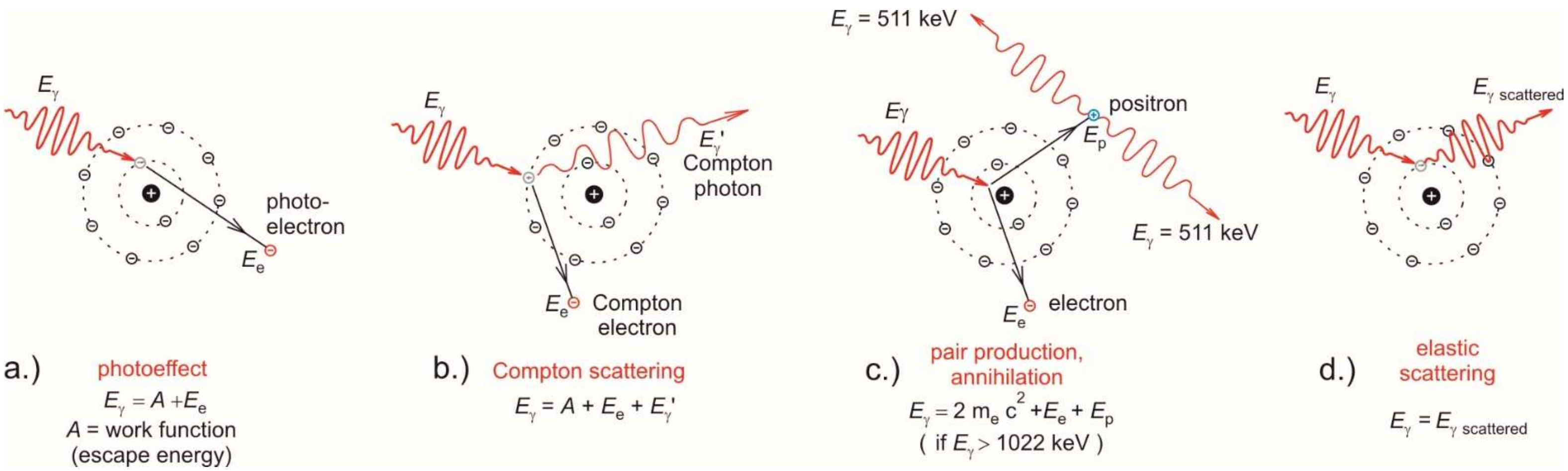


Interactions of ionizing radiations with matter

Ionizing radiations

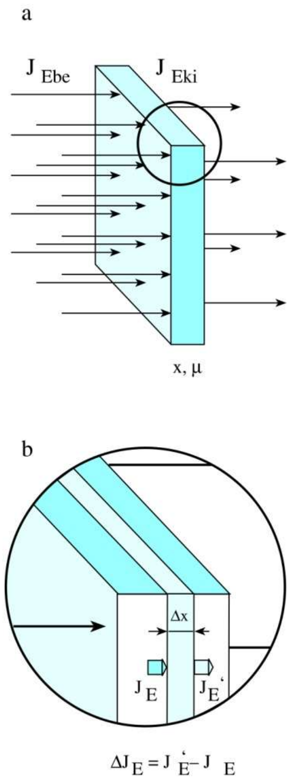
- Direct ionizing radiations: charged particles e.g. α, β.

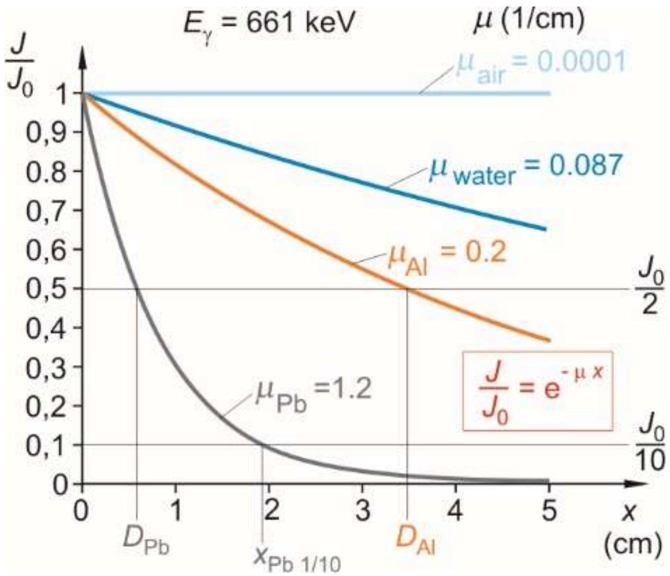
- Indirect ionizing radiations: the high kinetic energy electron produced in photoeffect, Compton-effect, or pair production will ionize, e.g. γ, X.



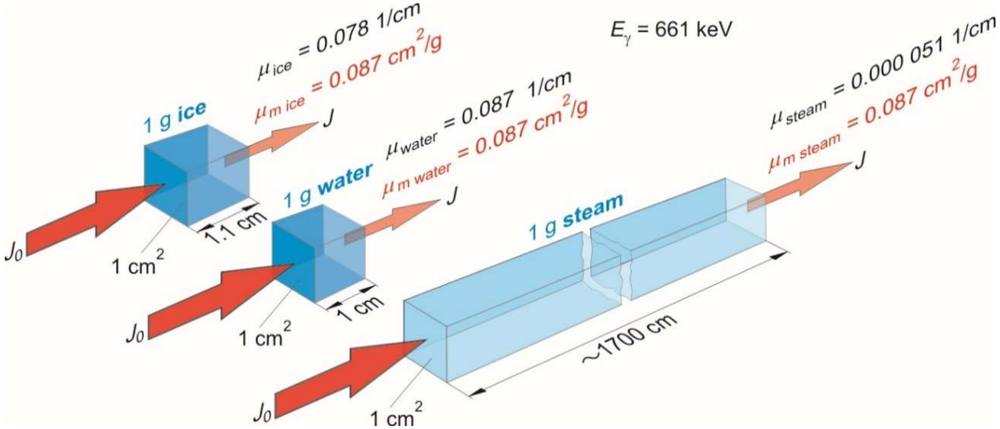
The radiation intensity decreases due to interaction.

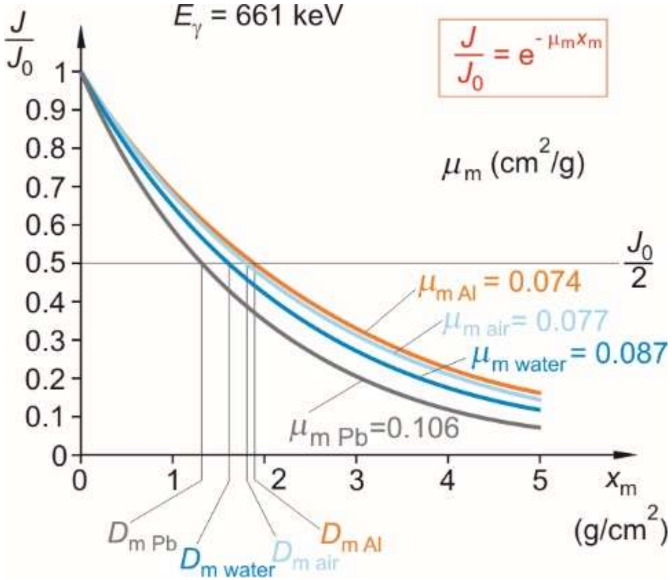
$$I = I_0 e^{-\mu x} \qquad \mu = \frac{1}{\delta} \qquad \mu = \frac{0{,}693}{D}$$

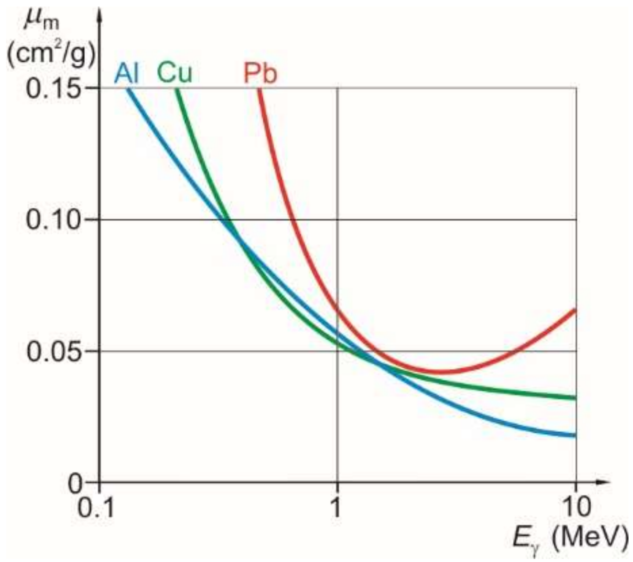




$$\mu_m = \frac{\mu}{\rho}$$

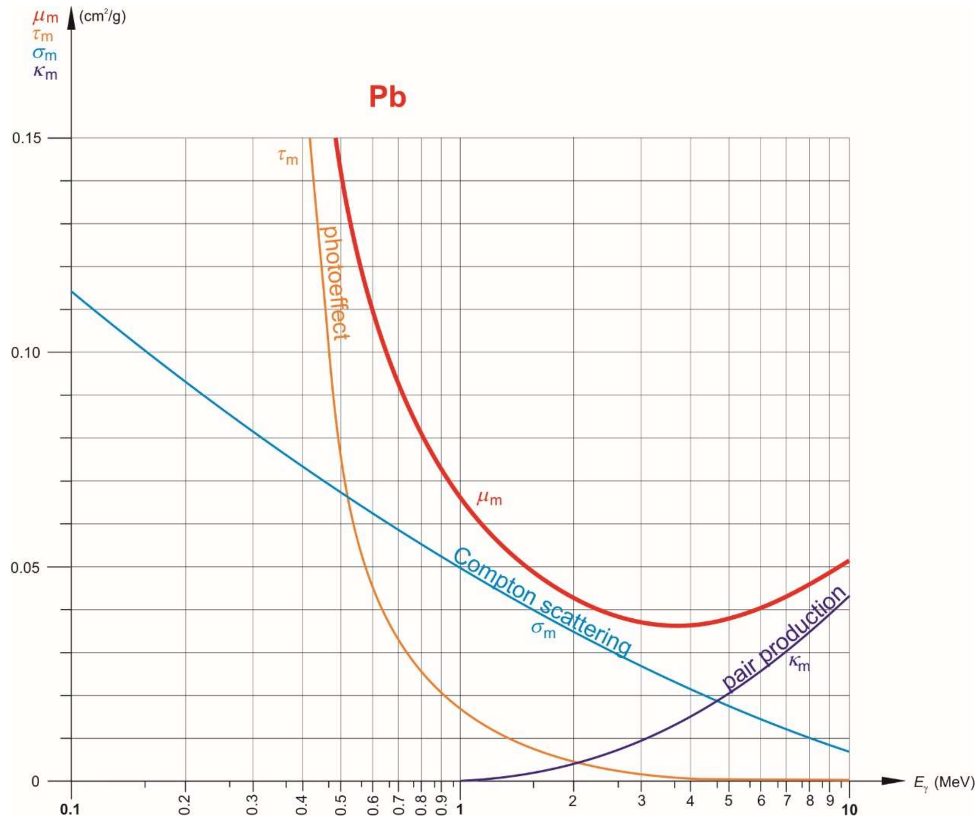




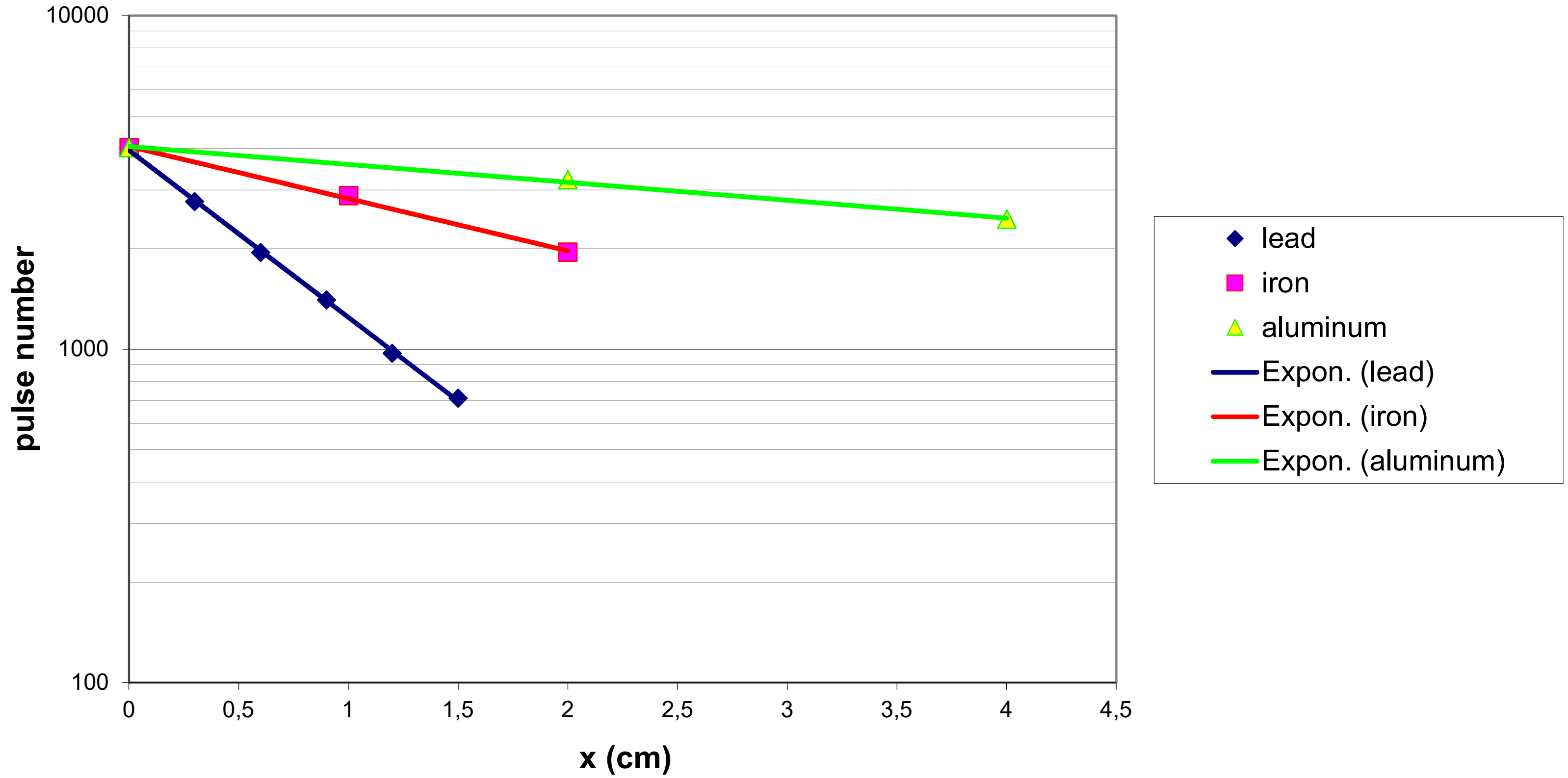


$$\mu = \tau + \sigma + \kappa \quad \text{and} \quad \mu_m = \tau_m + \sigma_m + \kappa_m$$

The ratio of components depends on the photon energy and on the material of absorbent.

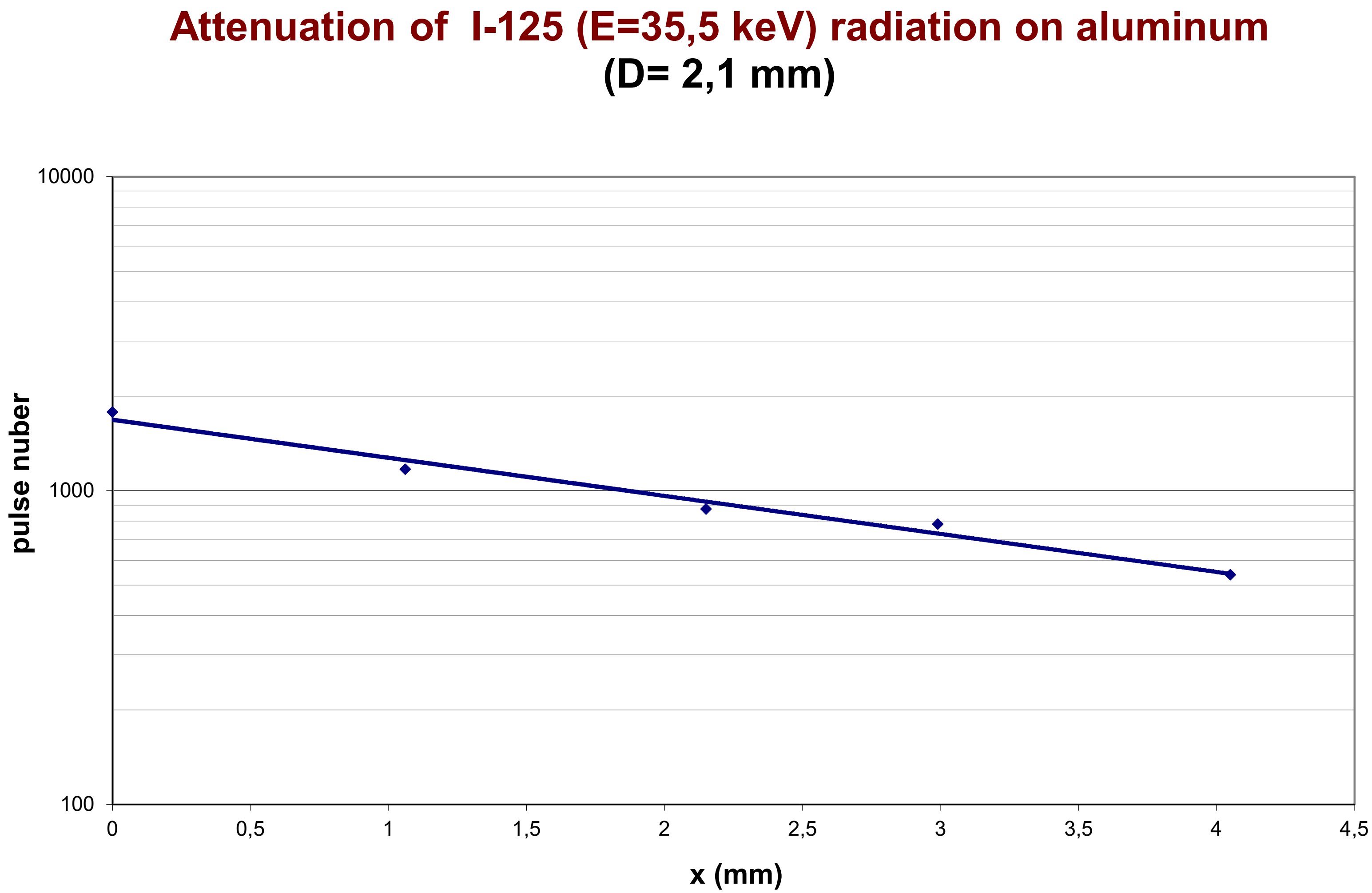


Attenuation of Cs-137 (E=661 keV) gamma radiation on different materials



Data characterizing the attenuation of radiation in case of Cs-137 gamma radiation (E = 661 keV)

	density (g/cm^3)	D (cm)	μ (1/cm)	μ_m (cm^2/g)
Pb	11,3	0,6	1,15	0,102
Fe	7,9	1,92	0,36	0,046
Al	2,7	5,6	0,12	0,046

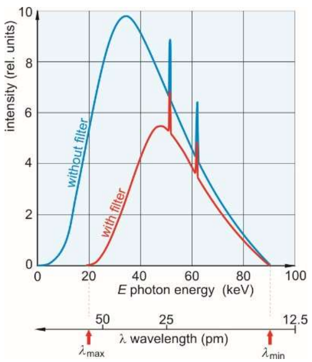

Attenuation of I-125 (E=35,5 keV) radiation on aluminum
(D= 2,1 mm)
pulse nuber
10000
1000
100
0
0,5
1
1,5
2
2,5
3
3,5
4
4,5
x (mm)

At low photon energies (diagnostic X-ray and γ), and at absorbents with higher atomic number (e.g. Pb, bone) mainly photoeffect.

For this: $\tau_m = c\,\lambda^3 Z^3$

At absorbents with lower effective atomic number (water, soft tissues) mainly Compton-effect ($Z_{eff,water} = 7{,}69$, $Z_{eff,air} = 7{,}3$)

For this: $\sigma_m \sim Z$



Practical consequences:

- radiation protection with materials of high atomic number
- filters
- X-ray diagnostics (contrast of image, contrast materials)
- therapy: low energy – body surface
- high energy – in depth

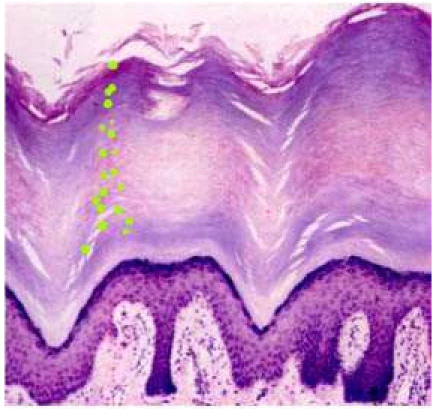
effective range: depends on photon energy (air ~ 100 m, water ~ dm)

Specific ionization is less, than for β

Interaction of ionizing radiations with matter

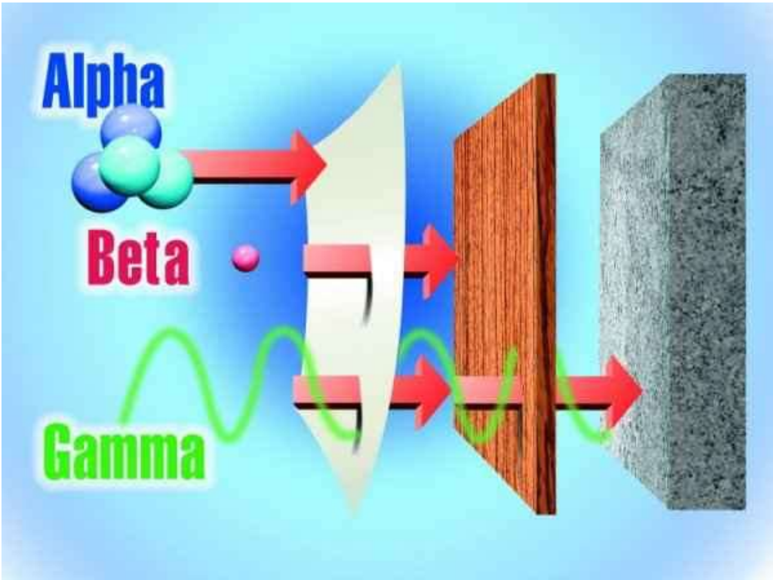
Characteristic parameters:

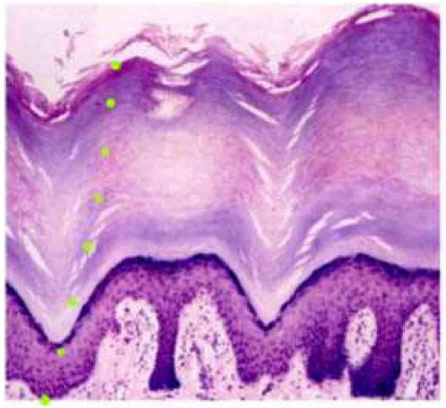
- *effective range*
- *linear ion density* $\frac{n}{l}$



Specific Ionization by alpha particles

- *linear energy transfer (LET)* $= w\frac{n}{l}$

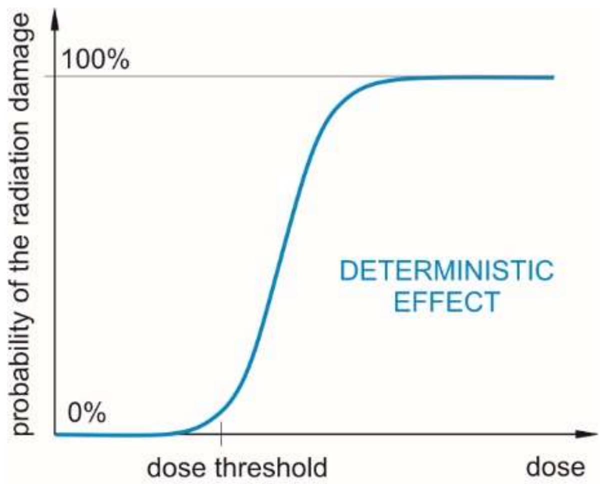




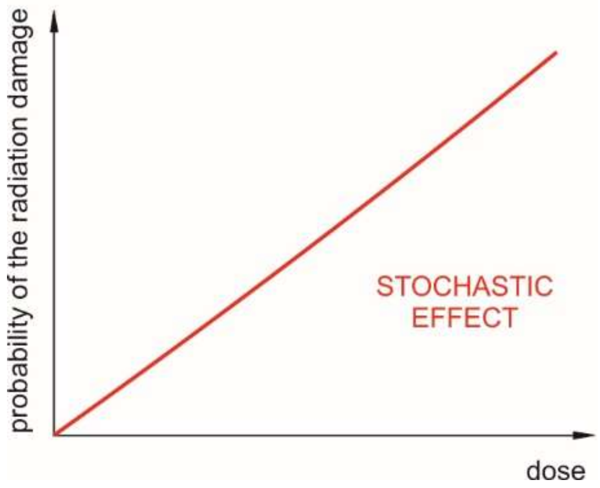
Specific Ionization by X-rays or gamma rays

Types of radiation effects:

Deterministic
- Only above a threshold dose
- The severity of damage is proportional with the dose(e.g. erythema, radiation sickness)
- Appears within some days



Stochastic
- There is no threshold dose
- The probability of damage is proportional with the dose(e.g. tumor production)
- Appears within years or decades



10^{15} Energy deposition

Excitation/ionization — PHYSICAL INTERACTIONS

10^{12} Initial particle tracks

10^{9} Radical formation

Diffusion, chemical reactions — PHYSICO-CHEMICAL INTERACTIONS

10^{6} Initial DNA damage

TIME (sec)

10^{3} 1 ms DNA breaks / base damage

10^{0} 1 second

Repair processes

Damage fixation

10^{3} 1 hour Cell killing — BIOLOGICAL RESPONSE

1 day Mutations/transformations/aberrations

10^{6} Proliferation of "damaged" cells

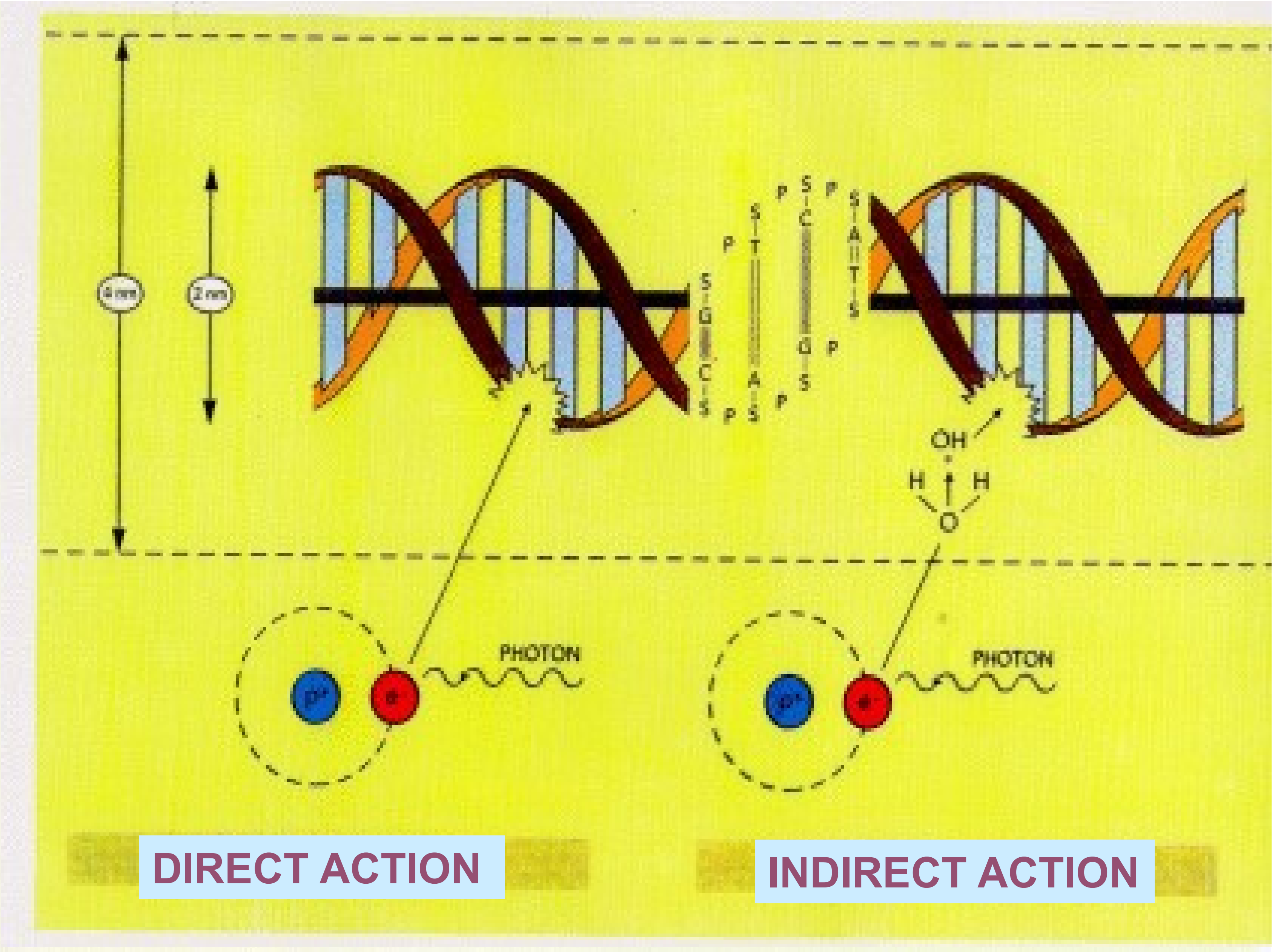
1 year Promotion/completion

10^{9} Teratogenesis — MEDICAL EFFECTS

Cancer

100 years Hereditary defects

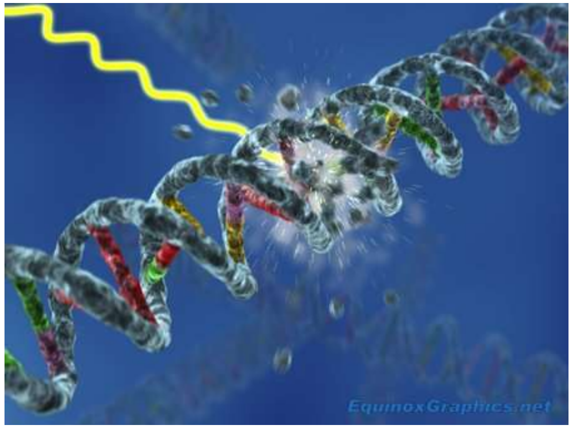
Timing of events leading to radiation effects.

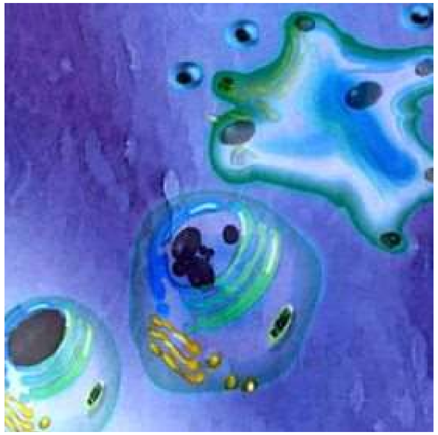

PHOTON
PHOTON
OH
H
H
O
DIRECT ACTION
INDIRECT ACTION

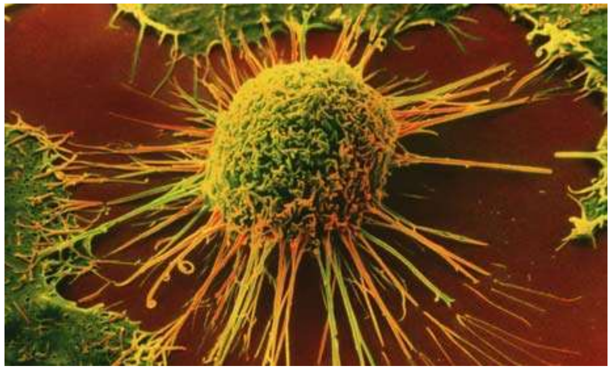
Outcomes after cell exposure

DAMAGE TO DNA

- **DAMAGE REPAIRED**
- **CELL NECROSIS** OR **APOPTOSIS**
- **TRANSFORMED CELL**





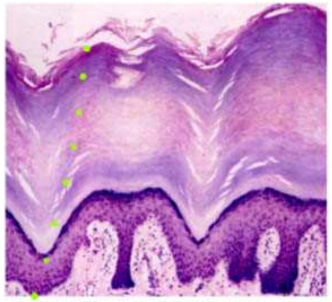


Radiosensitivity(RS)

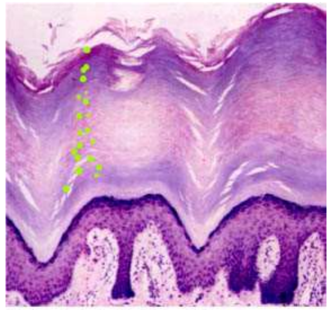
High RS	Medium RS	Low RS
Bone Marrow Spleen Thymus Lymphatic nodes Gonads Eye lens Lymphocytes (exception to the RS laws)	Skin Mesoderm organs (liver, heart, lungs…)	Muscle Bones Nervous system

Factors affecting the radiosensitivity

- Physical
  - LET (linear energy transfer): ⇑ RS
  - Dose rate: ⇑ RS
- Chemical
  - Increase RS: OXYGEN, cytotoxic drugs.
  - Decrease RS: SULFUR (cys, cysteamine…)
- Biological
  - Cycle status:
    - ⇑ RS: G2, M
    - ⇓ RS: S
  - Repair of damage (sub-lethal damage may be repaired e.g. fractionated dose



Specific Ionization by X-rays or gamma rays



Specific Ionization by alpha particles

Aim of dosimetry is the quantitative characterization of the biological effects of radiation.

Only the absorbed radiation causes biological effect.

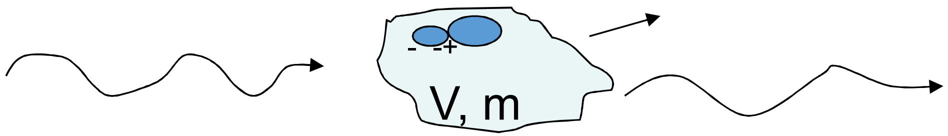
Absorbed dose:

$$D = \frac{\Delta E}{\Delta m} \cdots unit \cdots \frac{J}{kg} = Gy$$

Absorbed dose is valid for every kind of radiation and for every kind of absorbent, but it can not be measured.

The lethal dose (6 Gy) causes $1.5*10^{-3}$ °C temperature increase.

Exposure (X)



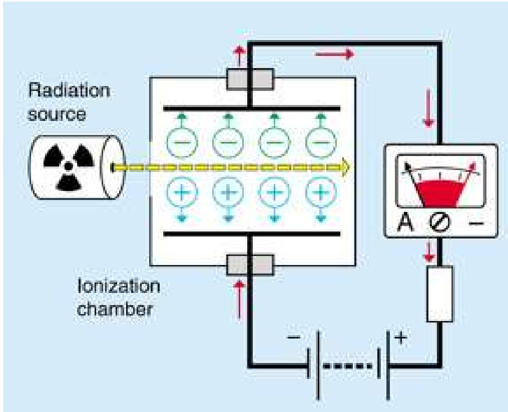
Only for X-ray and γ in air

- $X = \Delta Q / \Delta m$,

  where Q is the amount of produced electric charges in *m* mass of air.
- SI unit: $C \cdot kg^{-1}$ (C: coulomb)

Exposure can be measured easily by ionization chamber.

The absorbed dose can be calculated from it:



$D_{air} = f_0 X$ $\quad$ $f_0 = 34$ J/C

$$D_{tissue} = D_{air} \frac{\mu_{m,tissue}}{\mu_{m,air}}$$

Equivalent dose: $H_T = D_{T,R}\, w_R$ unit: J/kg = Sv

w_R: radiation weighting factor. It gives, how many times the given radiation is more effective, than γ-, or X-radiation.

The radiation weighting factor of the most frequent radiations:

Radiation type	**Radiation weighting factor W_R**
Photons, all energies	1
Electrons, myons, all energies	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (see equation)

Effective dose: $E = \Sigma H_T w_T$ unit: J/kg = Sv

w_T: tissue weighting factor. It characterizes the radiation sensitivity of the given tissue.

The radiation sensitivity of the given tissue depends on the multiplication activity of the cells.

Tissue weighting factors:

Tissue or organ	*ICRP-1990/ IBSS-1996*	*ICRP-2007*
Gonads	0.20	0.08
Bone marrow, red	0.12	0.12
Colon	0.12	0.12
Lung	0.12	0.12
Stomach	0.12	0.12
Bladder	0.05	0.04
Breast	0.05	0.12
Liver	0.05	0.04
Esophagus	0.05	0.04
Thyroid	0.05	0.04
Skin	0.01	0.01
Bone surface	0.01	0.01
Brain	-	0.01
Salivary glands	-	0.01
Remainder	0.05	0.12
Total	1.00	1.00

Dose rate: any kind of dose related to unit time.

The dose rate influences the biological consequences:
the same dose given in shorter time causes much more severe biological effect, than the same dose obtained during longer time:

Reason: the repair mechanisms can work, if certain dose is given in longer time.

Connection between the activity of gamma radiating isotope and the absorbed dose in air:

$$D_{\text{air}} = K_{\gamma} \frac{\Lambda t}{r^2}$$

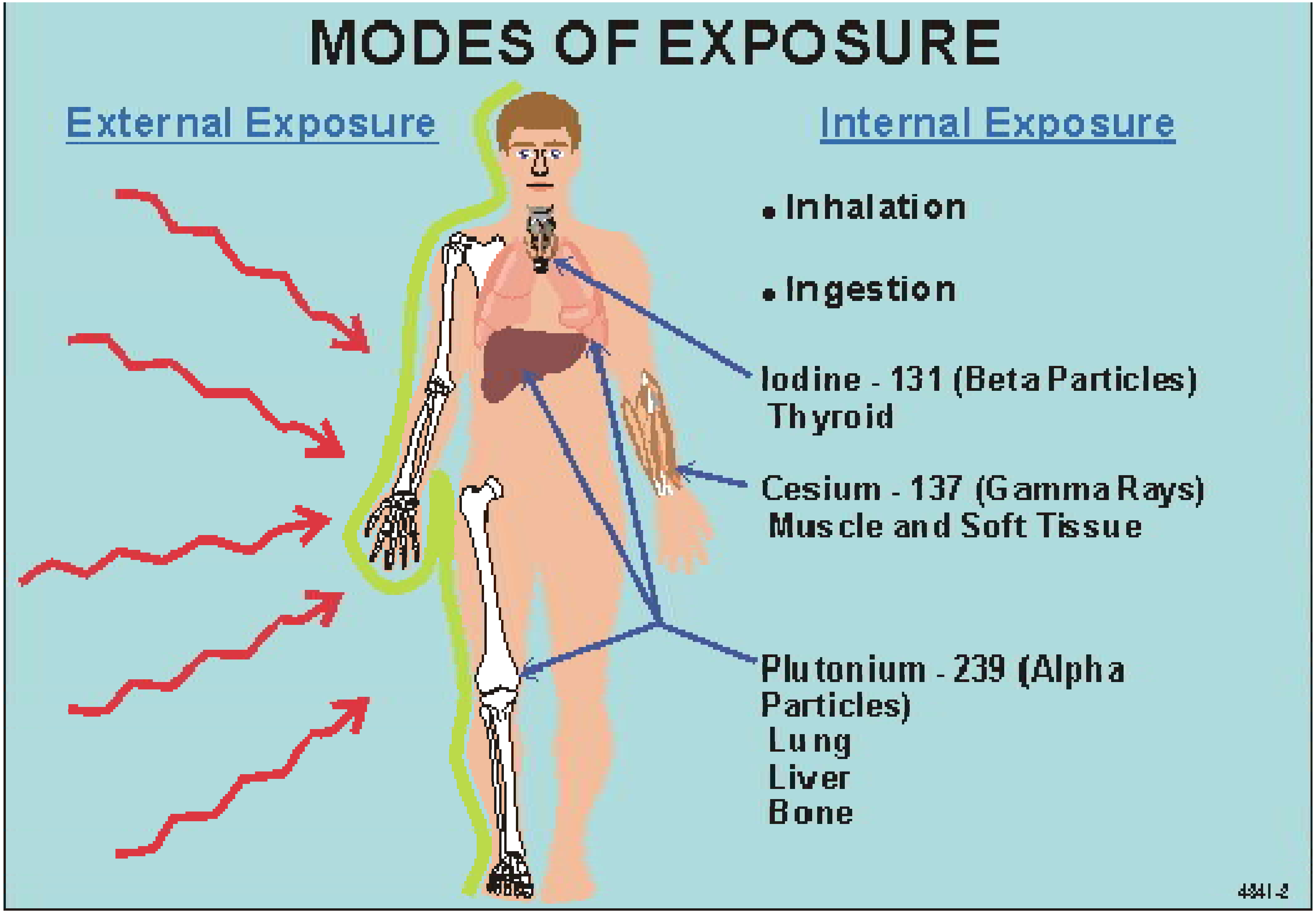
K_{γ}: dose constant. Its value depends on the photon energy.

Occupational dose limit for whole body: 20 mSv/year

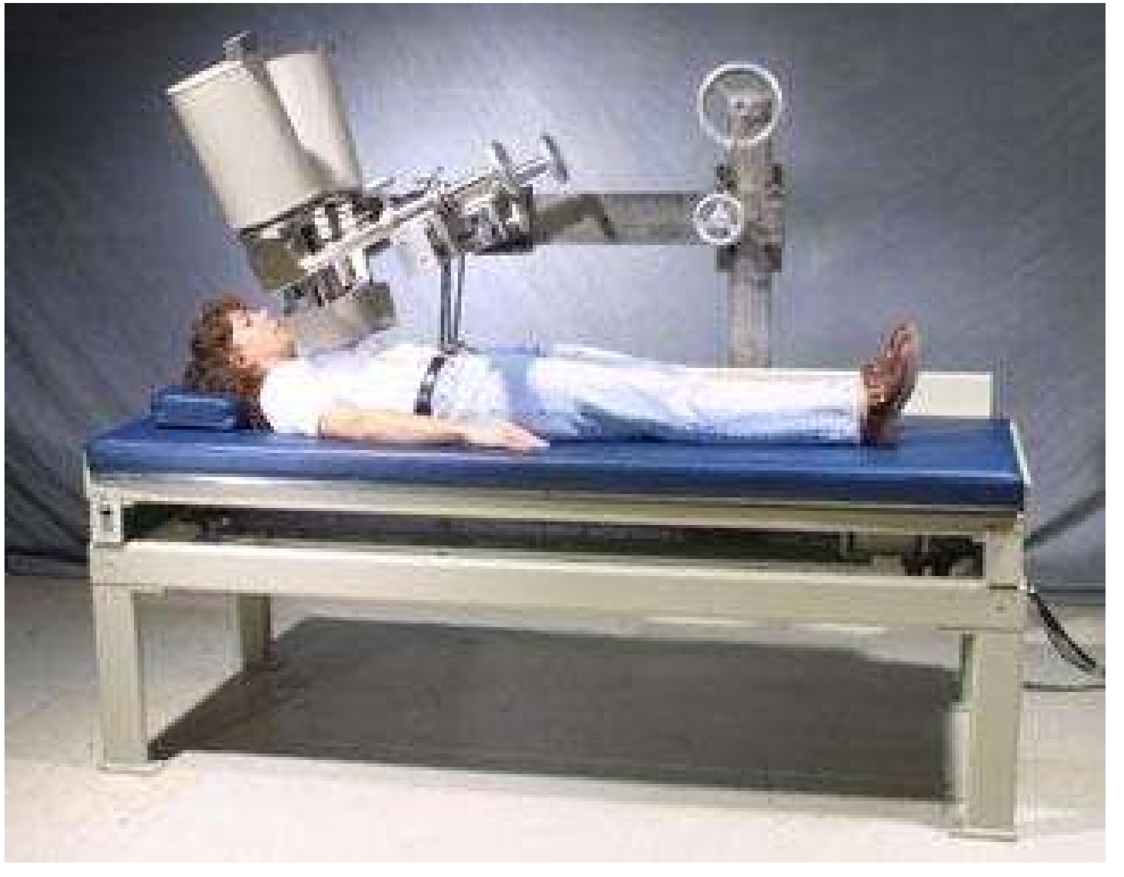
Some dose values obtained during medical application

In vivo isotope examinations usually: 4 – 5 mSv
Dental X-ray examination: 2 – 16 μSv
Chest X-ray screening: 0.1 mSv
Skull CAT-scan: 1.5 – 2 mSv
Chest or abdominal CAT-scan: 7 -8 mSv
Interventional radiology: several 10 mSv

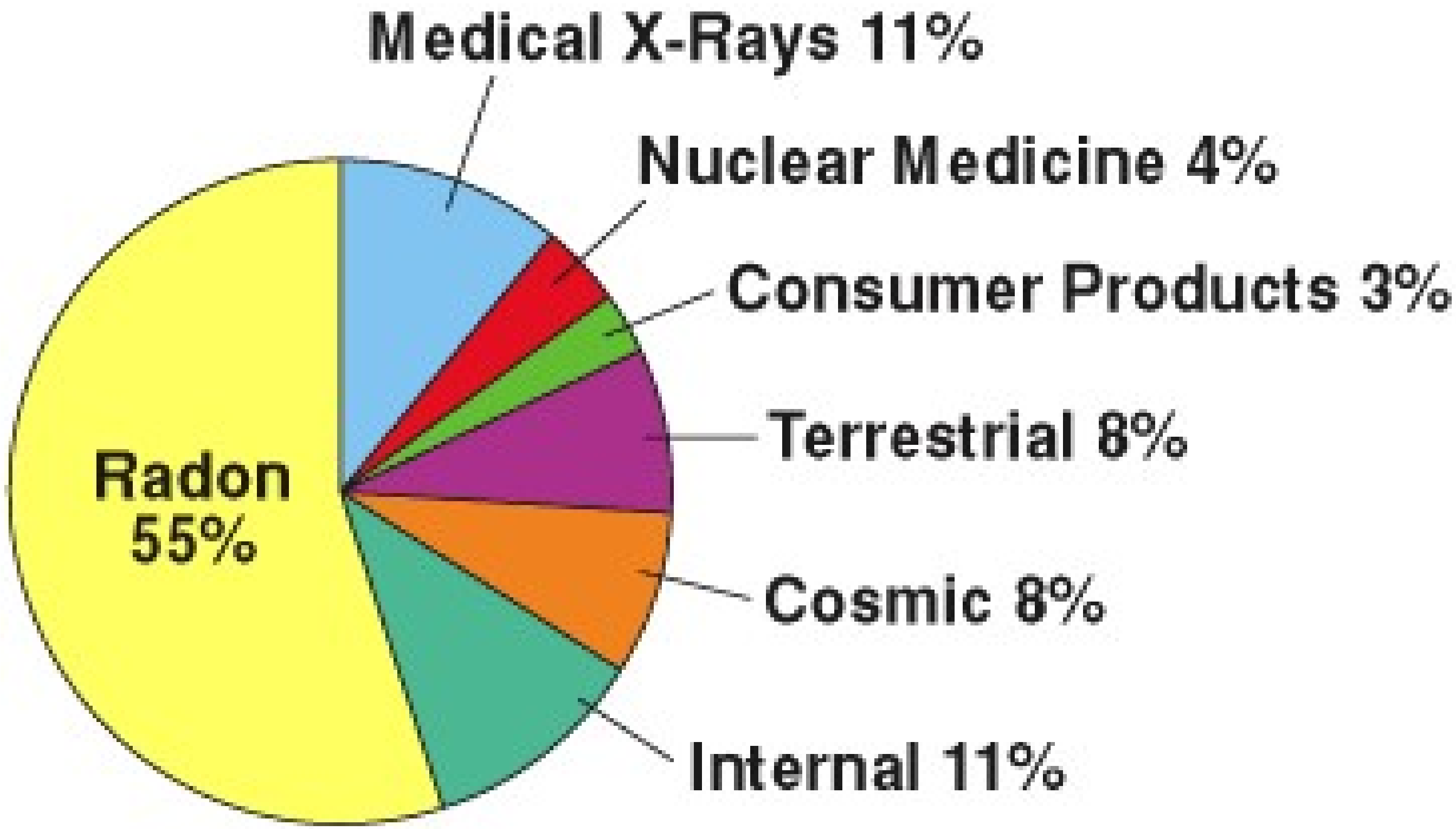
Average background radiation in Hungary: 3.1 mSv/year
Average background radiation in the World: 2.4 mSv/year
(2.5 μGy/day on the Earth's surface, 180 μGy/day on ISS
Average w_R for cosmic radiation is 2.5 $\rightarrow$ E $\approx$ 450 μSv/day)


MODES OF EXPOSURE
External Exposure
Internal Exposure
• Inhalation
• Ingestion
Iodine - 131 (Beta Particles)
Thyroid
Cesium - 137 (Gamma Rays)
Muscle and Soft Tissue
Plutonium - 239 (Alpha Particles)
Lung
Liver
Bone
4841-2

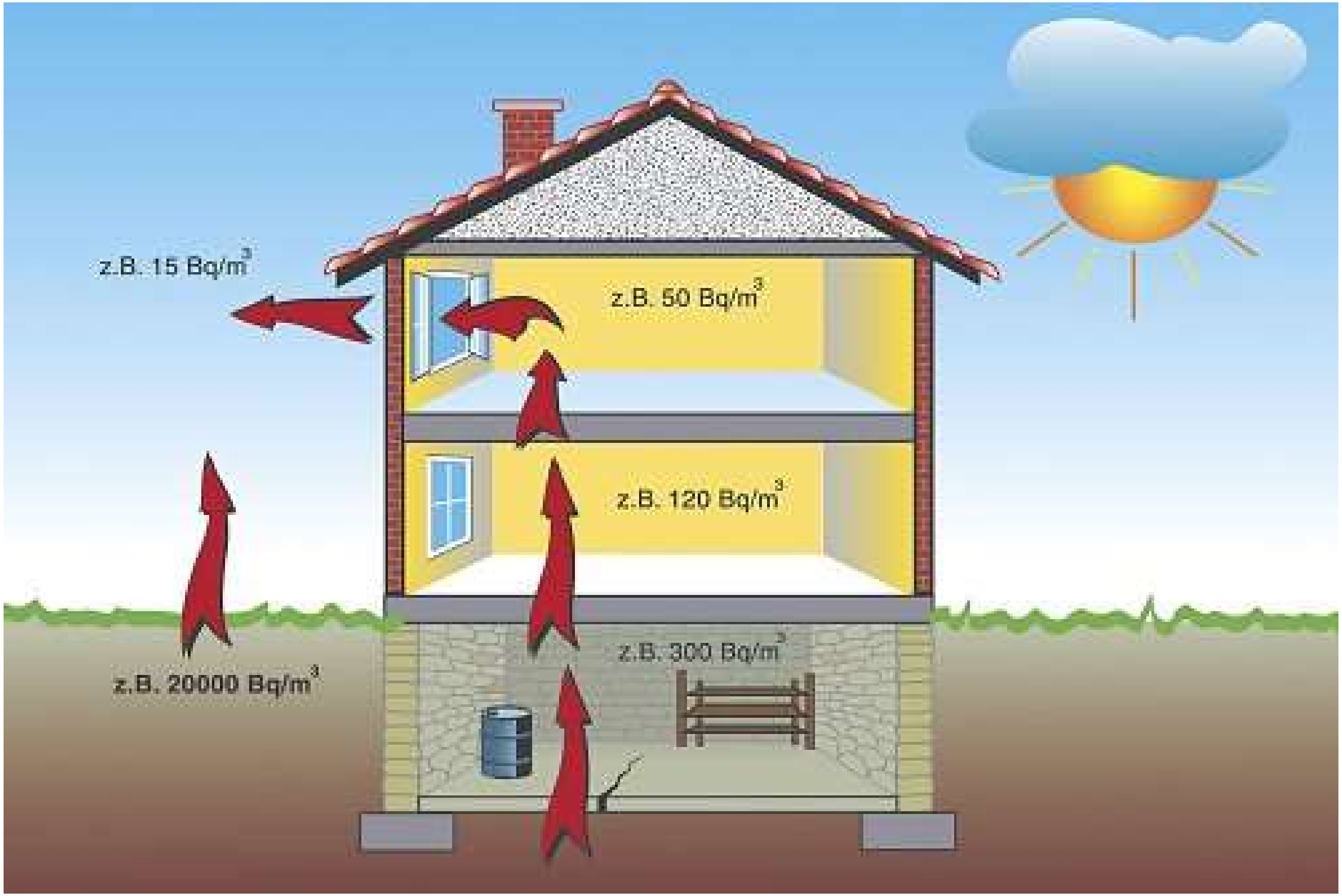
Checking the incorporated radioisotope by whole body counter



Sources of exposition of population

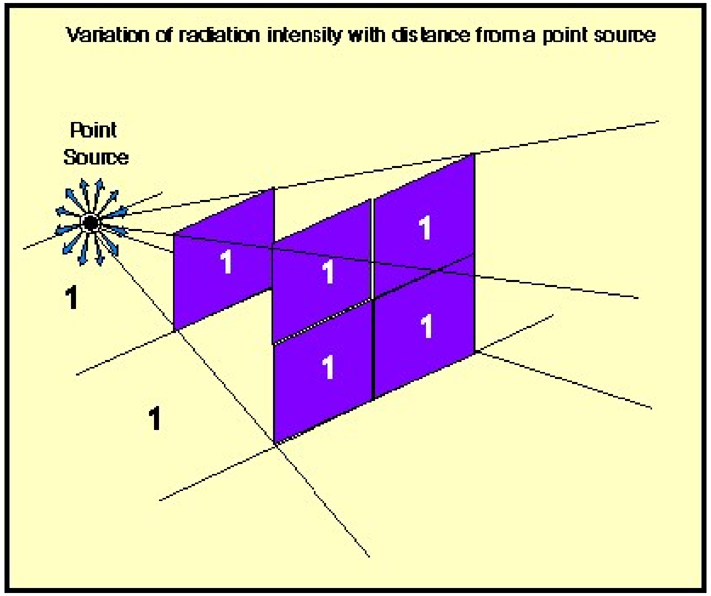


Path of Rn



Possibilities to decrease the exposure from radiation source outside the body

- Increase the distance
- Decrease the exposition time
- Application of shielding



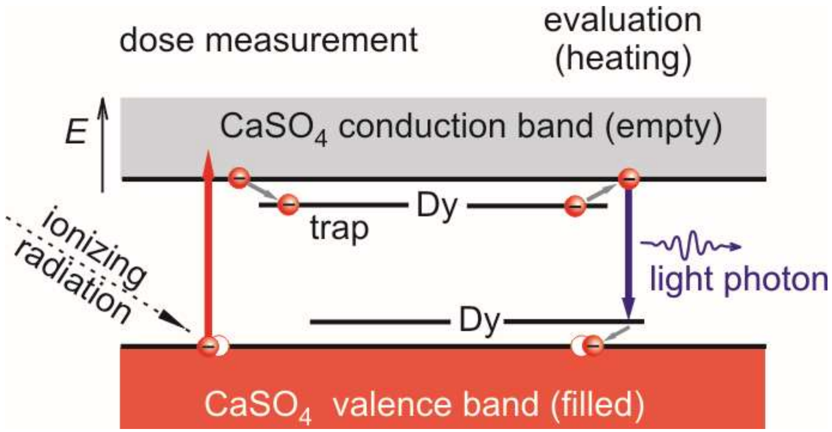
Radiation protectional viewpoints during work with ionizing radiation

1. Justification – the application of ionizing radiation must be useful: the risk of application should be lower than the risk of not applying the radiation – this must be considered from the viewpoint of the patient.

2. Optimization – the dose caused by the application should be As Low As Reasonably Achievable (ALARA-principle). This must be considered both from the viewpoint of the patient and the personnel.

3. Dose limits – the probable doses should not exceed the individual dose limits that are safe. This must be considered from the viewpoint of the personnel.

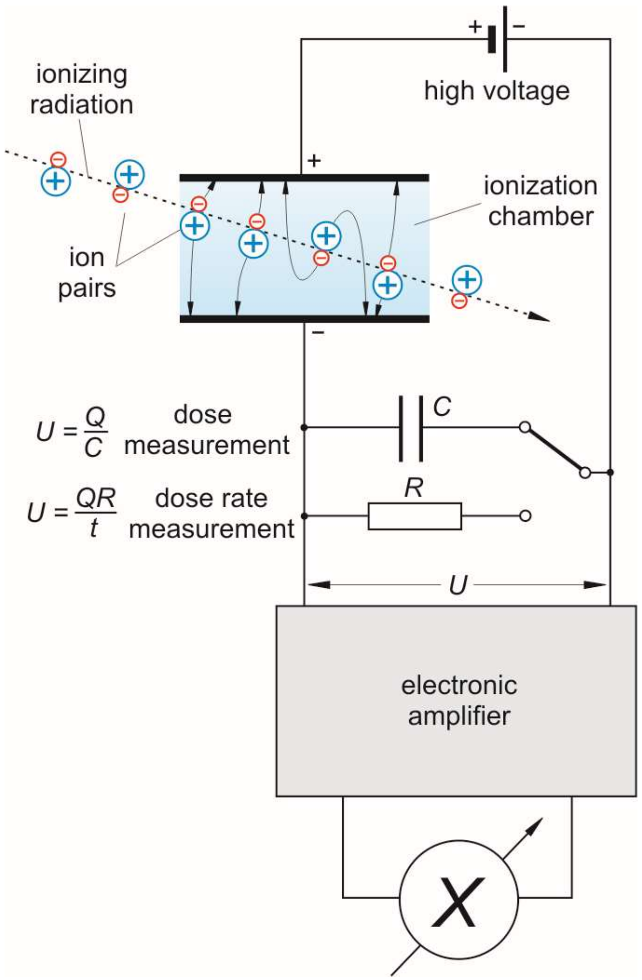
Dose/dose rate measuring devices
1. Thermoluminescent dosimeter



Pille dosimeter

Thermoluminescent dosimeter is the obligatory dose measuring device in the places, where people work with ionizing radiation.
If there is a hazard, that somebody can get high dose during short time, electronic operative dosimeter must also be used, that displays the result immediately.

2. Devices based on gas ionization



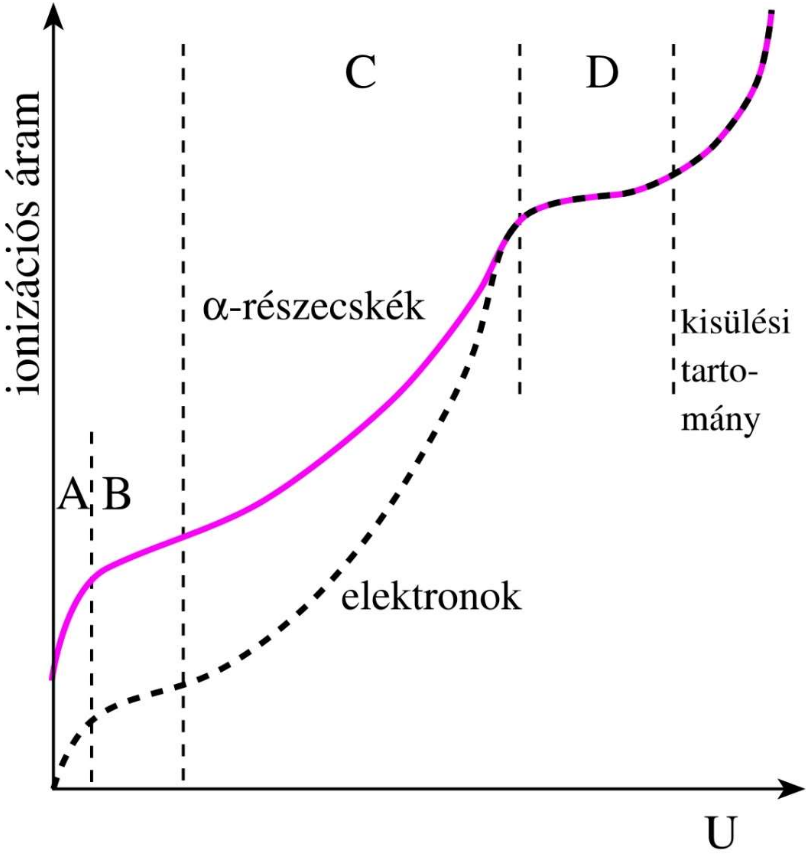
Dose measurement: capacitor is swithed into the circuit

$$U = \frac{Q}{C} \sim X$$

Dose rate measurement: resistor is swithed into the circuit

$$U = IR = \frac{Q}{t} R \sim \frac{X}{t}$$

Devices based on gas ionization

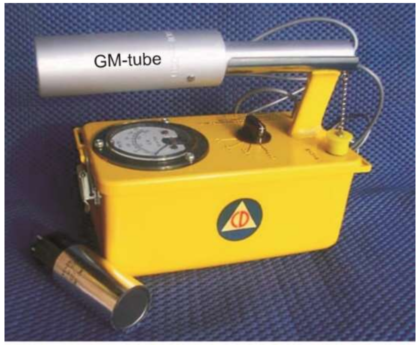


A – recombination range

B – ionization chamber range

C – proportional range

D – Geiger- Müller range



Thank you for your attention

Dr. István Voszka

SEMMELWEIS
UNIVERSITY 1769