Medical University of Białystok
Department of Biophysics

PRE-COURSE (PHYSICS)

RADIOACTIVITY 1.2

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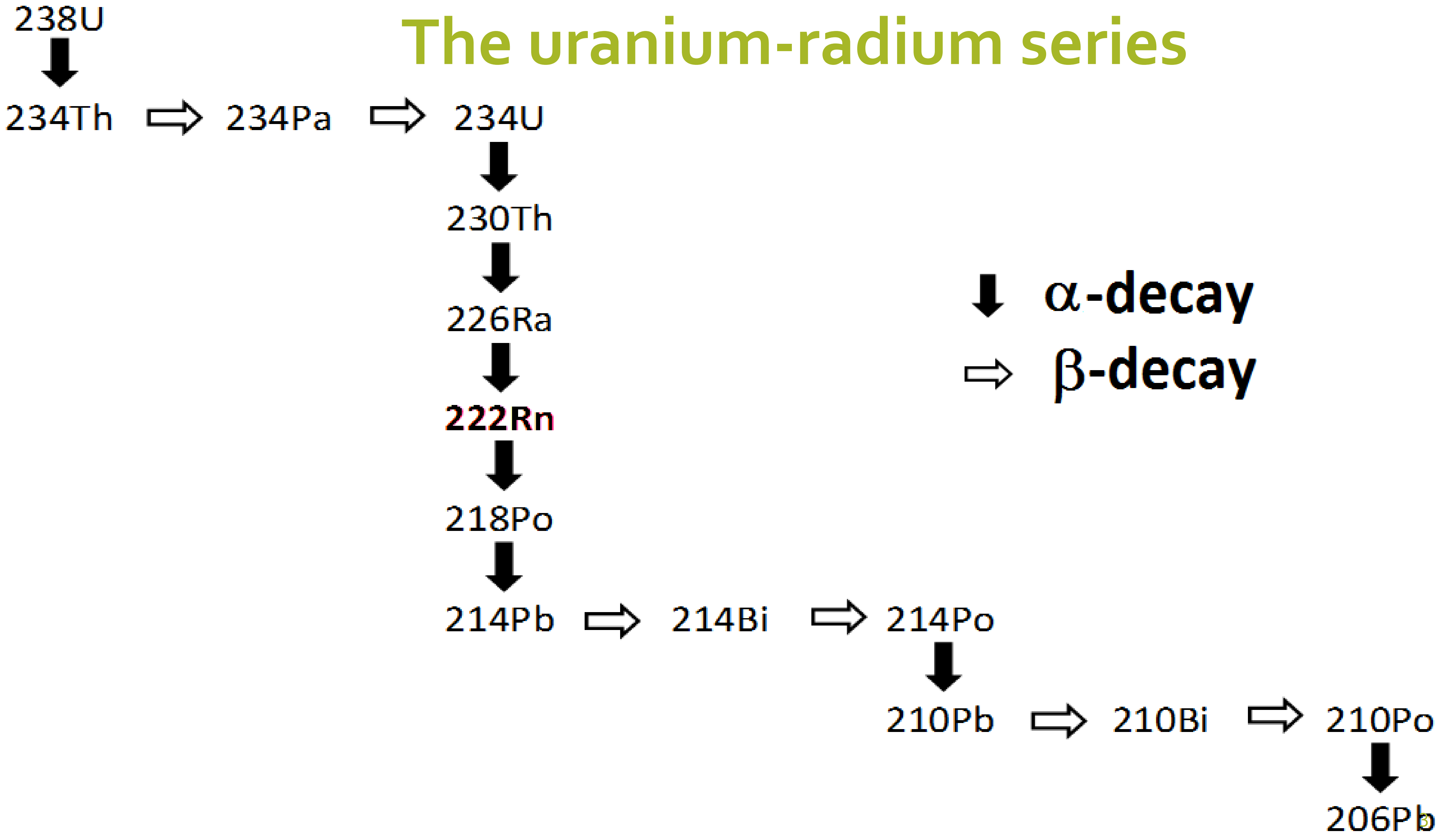
Radioactive equilibrium

If a substance is radioactive, its disintegration product is often radioactive, so that a radioactive series is built up. There are three main natural radioactive series:

1. the thorium series,
2. the uranium-radium series and
3. the actinium series.

The other series, man-made, is the plutonium series. Each series ends at stable isotope of lead.

The uranium-radium series

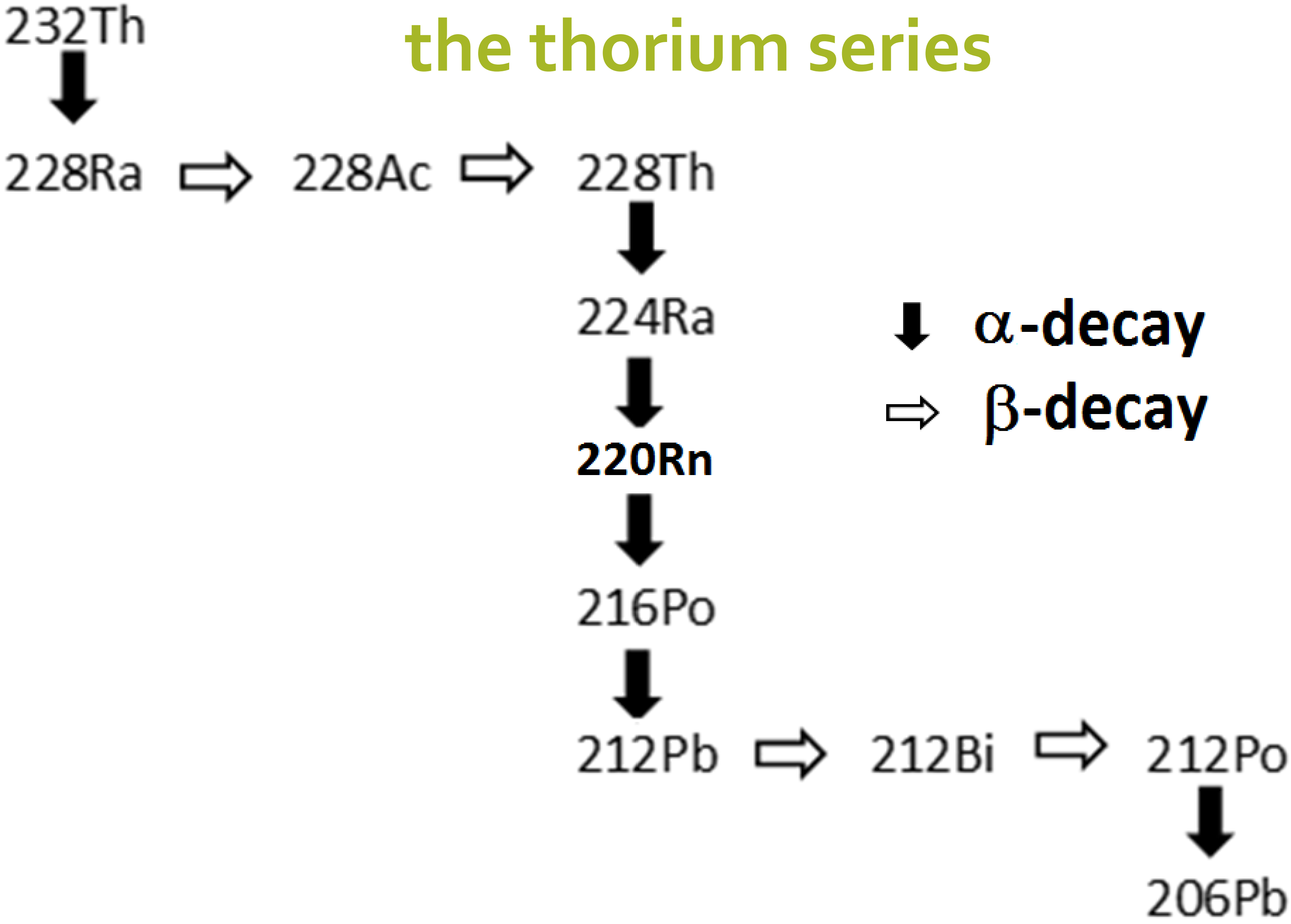


238U
⬇
234Th ⇨ 234Pa ⇨ 234U
⬇
230Th
⬇
226Ra
⬇
222Rn
⬇
218Po
⬇
214Pb ⇨ 214Bi ⇨ 214Po
⬇
210Pb ⇨ 210Bi ⇨ 210Po
⬇
206Pb

⬇ α-decay

⇨ β-decay

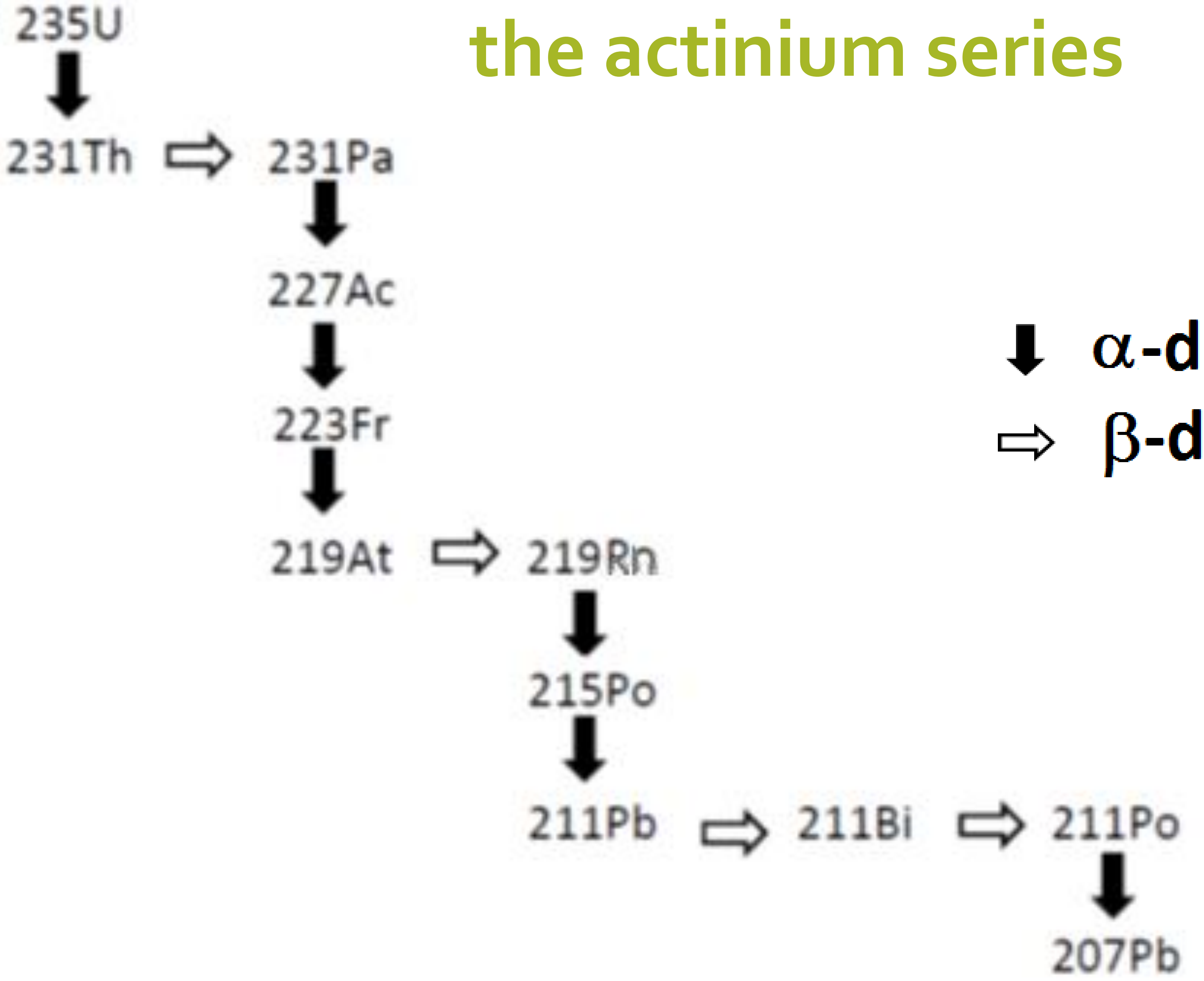
the thorium series



232Th
⬇
228Ra ⇨ 228Ac ⇨ 228Th
⬇
224Ra
⬇
220Rn
⬇
216Po
⬇
212Pb ⇨ 212Bi ⇨ 212Po
⬇
206Pb

⬇ **α-decay**
⇨ **β-decay**

the actinium series



235U
⬇
231Th ⇨ 231Pa
⬇
227Ac
⬇
223Fr
⬇
219At ⇨ 219Rn
⬇
215Po
⬇
211Pb ⇨ 211Bi ⇨ 211Po
⬇
207Pb

⬇ α-decay

⇨ β-decay

Radioactive equilibrium

When a mother and a daughter substance are in radioactive equilibrium, there are as many atoms of the mother substance as of the daughter substance disintegrating per second. If N_1 and N_2 are the numbers of atoms of the two substances present, and λ_1 and λ_2 are, their decay constants, then radioactive equilibrium is when:

$$\lambda_1 \cdot N_1 = \lambda_2 \cdot N_2 \qquad (6)$$

This means that the number of atoms of more quickly decaying substance (which has the greater value of λ) is less than that which decays more slowly.

The activity (A)

- An earlier unit of activity was 1 Curie [Ci] defined by the following relationship:

- 1 Ci = $3.7 \cdot 10^{10}$ disintegrations per second

- One gram of radium Ra-226 has $3.7 \cdot 10^{10}$ disintegrations per second (approximately) so its activity is 1 Ci.

The activity (A)

$$\boldsymbol{A = \lambda \cdot N} \longrightarrow \boldsymbol{N = \frac{A}{\lambda}}$$

$$\boldsymbol{A_0 = \lambda \cdot N_0} \longrightarrow \boldsymbol{N_0 = \frac{A_0}{\lambda}}$$ **and** $$\boldsymbol{N = N_0 \cdot e^{-\lambda \cdot t}}$$

$$\boxed{A = A_0 \cdot e^{-\lambda \cdot t}}$$

Some of the natural radioactive isotopes found in the human body.

isotope	Total activity [Bq]	Type of radiation emitted
^{3}H hydrogen	70	β
^{14}C carbon	3100	β
^{40}K potasium	4400	β, γ
^{87}Rb rubid	600	β
^{210}Po polonium	≈40	α, γ
^{226}Ra radium	≈2	α,γ

The activity (A)

If there are *n* moles in the sample, then the number of atoms in the sample is:

$$N = n \cdot N_A$$

Where:

N_A = 6.023 · 10^{23} [mol^{-1}] - Avogadros number - is the number of atoms in a mole.

The activity of the sample is:

$$A = \lambda \cdot n \cdot N_A = \frac{\ln 2}{T_{1/2}} \cdot n \cdot N_A \qquad (8)$$

Calculating activity on the basis of measurements

The results of measurements of the radioactive samples (frequency of pulses I) depend on many factors:

- the efficiency of the detector used,
- the kind and energy of the emitted radiation,
- the shape of both the detector and the sample,
- the density of the sample and others.

Efficiency of measurments

When we are calculating the activity of the sample, we should use the standard activity (A_s) for determining efficiency calibration of the detector.

$$\eta = \frac{I_s}{A_s} \qquad (9)$$

where:

A_s - the activity of the standard (known) [Bq]

I_s - the frequency of pulses from the measured standard [pulses per sec]

Calculating activity on the basis of measurements

If both samples, the standard and the measured sample, have similar geometry, we can use the following formula:

$$A_x = \frac{I_x}{I_s} \cdot A_s \qquad (9)$$

where:

A_x - the activity of the measured sample (unknown) [Bq]

A_s - the activity of the standard (known) [Bq]

I_x - the frequency of pulses from the measured sample [pulses per sec]

I_s - the frequency of pulses from the measured standard [pulses per sec]

Ionizing radiation

- **Ionizing radiation has sufficient energy to ionize atoms or molecules. An atom is ionized when one or more electrons are separated from the atom.**
- **Binding energy of electrons is more than 10 eV**

One electron-volt is the energy gained by
a particle having one elementary charge ($1e = 1.610^{-19}C$)
moving between two surfaces
with a potential difference of one volt (1V) in vacuum.

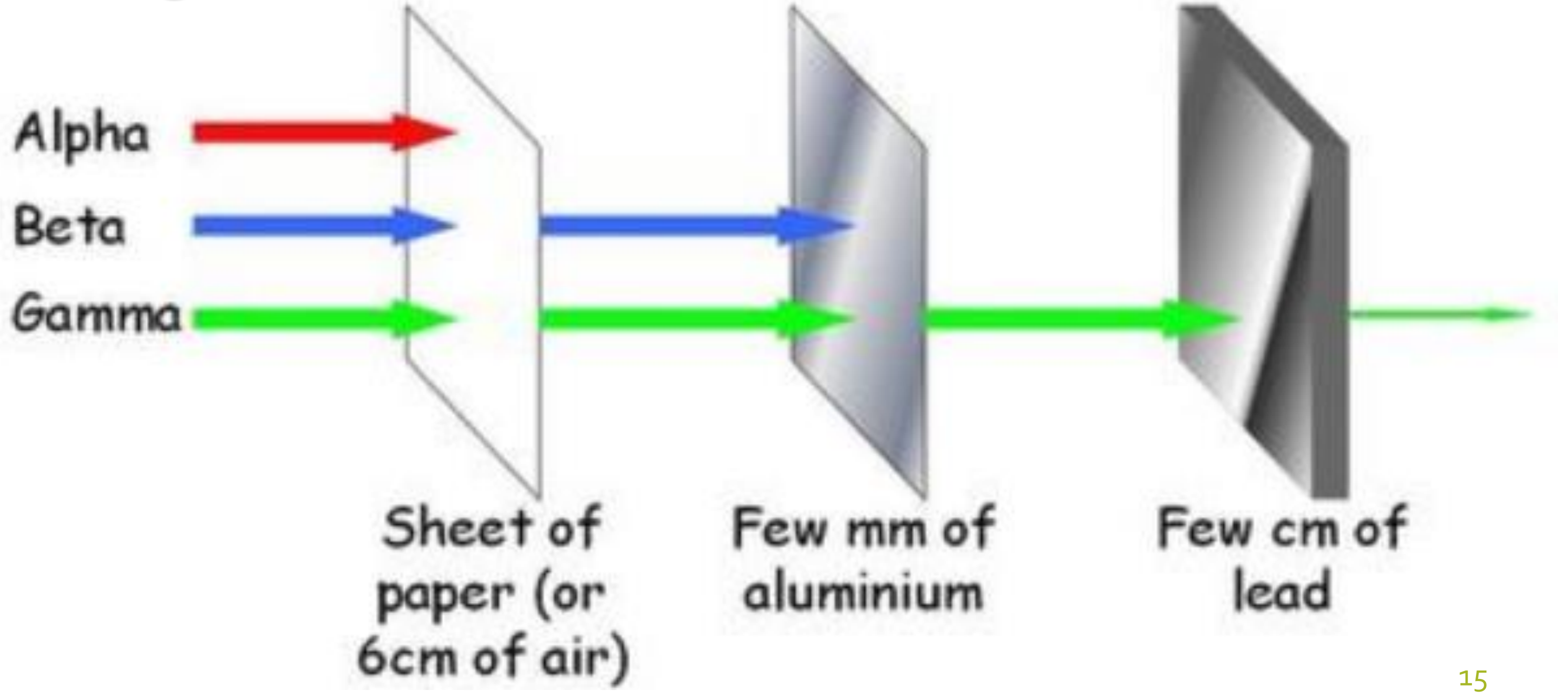
Ionizing radiation

- These kinds of radiation **differ in**:

a) methods of production

b) interaction with atoms

c) penetration ability through matter



Ionizing radiation

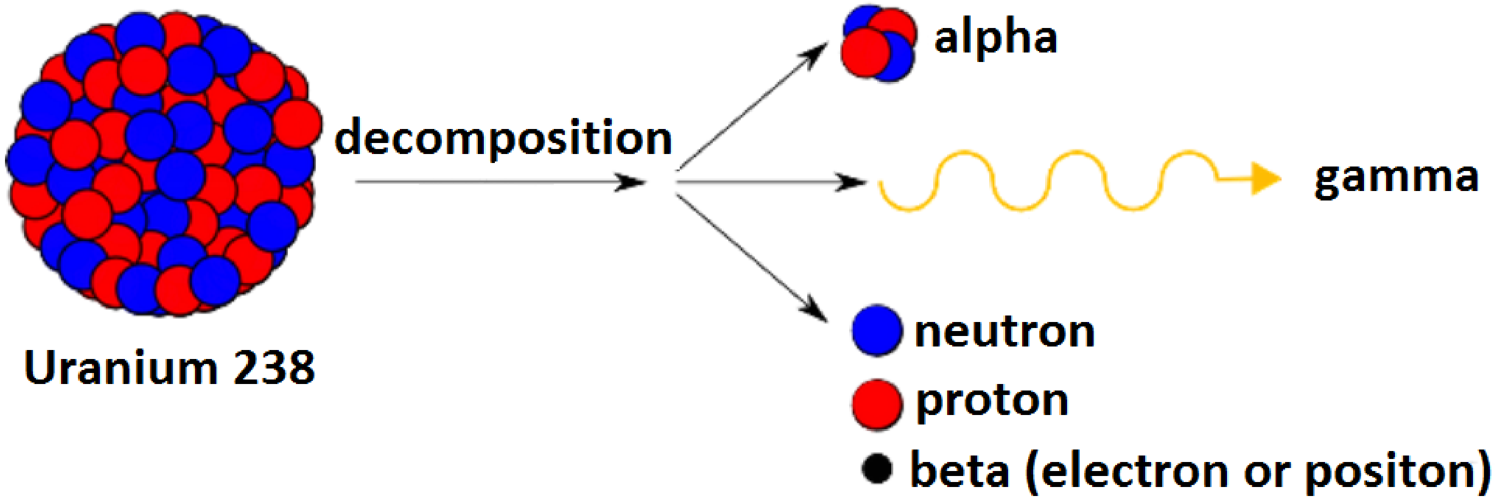
- The principal kinds of ionizing radiation are:

a) gamma rays and X-rays

b) beta particles (high speed electrons or positrons)

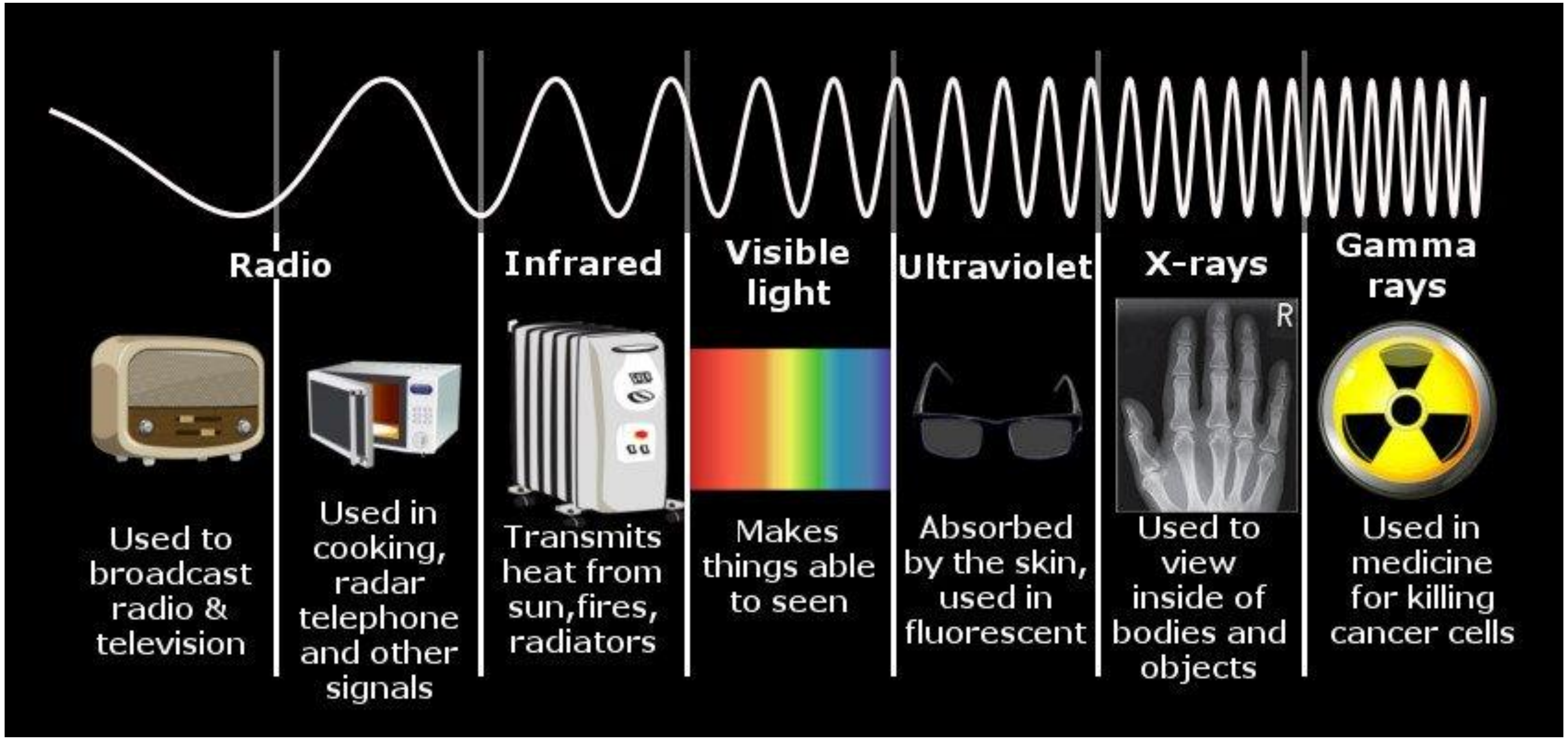
c) alpha particles (high speed $^{4}_{2}\mathrm{He}$ nuclei)

d) neutrons (uncharged particles, mass nearly equal to $^{1}_{1}\mathrm{H}$ atoms)



electromagnetic radiation

- **Gamma rays and X-rays consist of tiny packets of energy known as photons which travel with the speed of light. They have identical properties and differ by the mechanisms which produce them. They have no mass, nor electric charge.**



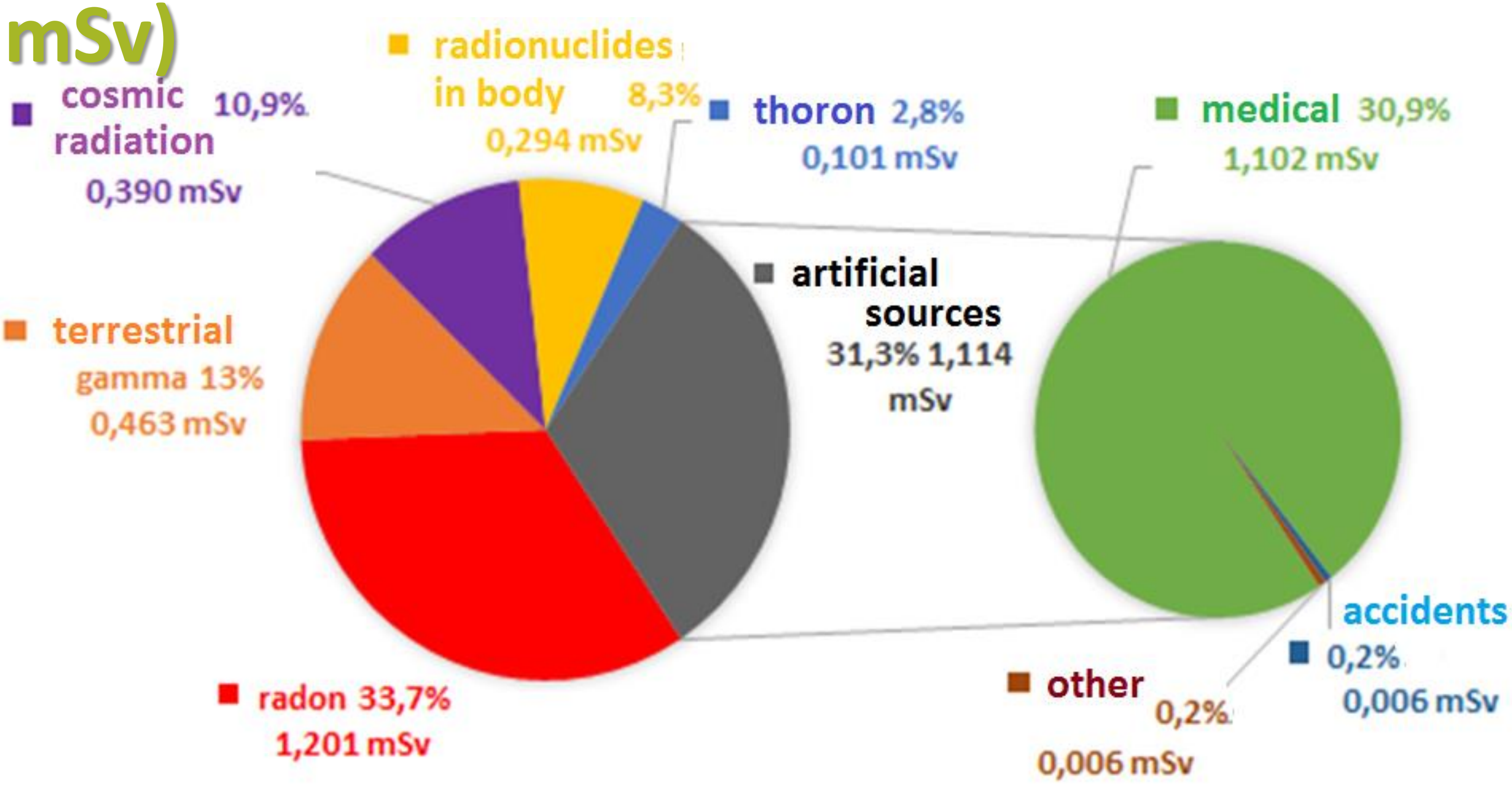
corpuscular radiation (α β^+ β^- ${}_1^1p$)

- α β^+ β^- ${}_1^1p$
- **Alpha particles, beta particles are basic components of the atoms and all possess: mass and electric charge**

corpuscular radiation $({}_{0}^{1}\mathrm{n})$

- **neutrons are basic components of the atoms and all possess mass, NO electric charge**

The ionizing radiation sources in the average annual effective dose per statistical inhabitant of Poland (3,56 mSv)



ionizing radiation

- The energy carried by ionizing radiation is measured in units of kilo-electron-volts (keV) and mega-electron-volts (MeV) and is much greater than the amount of energy necessary to cause ionization of an atom, therefore the ionizing radiation produces a large number of ionizations.

Dosimetry

Exposure - is the ability of the radiation beam to ionize air.

$$X = \frac{\Delta Q}{\Delta m} \qquad \frac{\text{charge of 1 sign}}{\text{mass of air}} \tag{10}$$

where:

X - exposure [C·kg^{-1}]

ΔQ - charge of 1 sign ions occurs at the site of energy transfer of the photon beam in air [C]

Δm - mass of air [kg]

Exposure (X)

It is a historical quantity.

By convention, applied only to photon beams.
Practical to measure only for E < 3 MeV.

Pre-SI unit of exposure

1 Roentgen [R] = $2.58 \cdot 10^{-4}\ \mathrm{C \cdot kg^{-1}}$

Dosimetry

Absorbed dose - is the amount of energy absorbed per unit of mass of absorber.

$$D = \frac{\Delta E}{\Delta m} \qquad (11)$$

where:

D - absorbed dose [Gy]

ΔE - energy of radiation imparted to element of irradiated material [J]

Δm - the mass of the element of material [kg]

The unit of absorbed dose is the joule per kilogram, it is called gray [Gy] (1 Gy = 1J/1kg).

Dosimetry

Most radiations exposures cause different absorbed doses in different parts of the human body.

Absorbed doses from different types of radiation have different biological effectiveness, and the organs and the tissues in the body have different sensitivities.

It is useful to combine the absorbed doses from different types of radiations to provide a further quantity called equivalent dose.

Dosimetry

Equivalent dose - in a human tissue or organ is the absorbed dose weighted by a radiation weighting factor Q that ranges from 1 for low LET radiation to 20 for alpha particles.

$$H_t = D_t \cdot Q \qquad (12)$$

where:

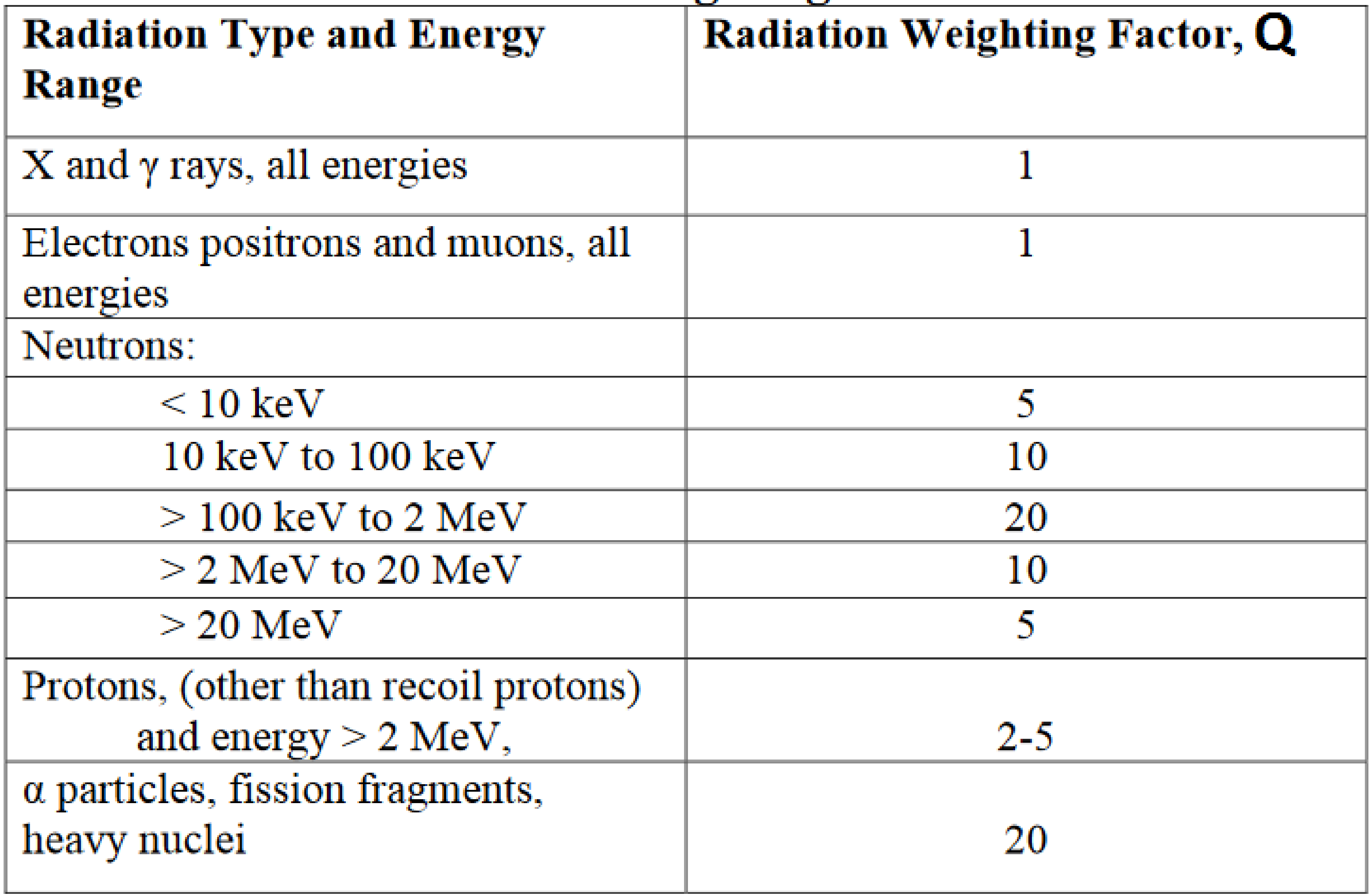
H_t- the equivalent dose [Sv]

D_t- the absorbed dose [Gy]

Q - radiation weighting factor (earlier Quality Factor)

The unit of equivalent dose is called sievert (Sv).

Radiation Weighting factors



Radiation Type and Energy Range	**Radiation Weighting Factor, Q**
X and γ rays, all energies	1
Electrons positrons and muons, all energies	1
Neutrons:	
< 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5
Protons, (other than recoil protons) and energy > 2 MeV,	2-5
α particles, fission fragments, heavy nuclei	20

Dosimetry

Various organs and tissues in the body differ in their response to exposure to radiation. To allow for this the effective dose is used.

- **Effective dose - is the sum of equivalent dose in each tissue or organ multiplied by a tissue weighting factor H_t over the whole body. The unit of effective dose is sievert (Sv).**

where:

$$H_{ef} = \sum H_t \cdot w_t \qquad (13)$$

H_{ef} - the effective dose [Sv]

H_t- the equivalent dose [Sv]

w_t- the tissue weighting factor

The unit of effective dose is sievert (Sv).

The effective dose is an indicator of the total detriment due to stochastic effects in the exposed individual and his or her descendants.

The tissue weighting factors for some human organs:

organ	The tissue weighting factors (w_t)
reproductive organs	0.25
red marrow	0.12
lungs	0.12
liver	0.05
thyroid	0.03
skin	0.01

Dosimetry

Dose rate - is a dose divided by a time of irradiation (the formula includes all kinds of doses), for example:

$$\dot{D} = \frac{D}{\Delta t} \qquad (14)$$

where:

$\dot{D}$ - absorbed dose rate [Gy·s^{-1}]

D - absorbed dose [Gy]

Δt— time of irradiation [s]

Levels of exposure

1. <u>Exposures of natural sources</u>

Source of exposure	Annual effective dose [mSv]
Cosmic rays	0.39
Terrestrial gamma rays	0.46
Radionuclides in the body (except ^{222}Rn)	0.29
^{222}Rn and its decay products	1.3
Total	2.44

Levels of exposure

Exposures of natural sources

- The cosmic ray dose rate depends on height above sea level and latitude –
  - annual doses in areas of high exposure are about five times average.
- The terrestrial gamma-rays dose rate depends on local geology with a high level being about 10 times the average.
- The dose from radon and its decay products depends on local geology and housing constructions and use, with the dose in some regions being about 10 times the average.

Medical Exposures

- Radiation is used in diagnostic examinations and in treatments.
- X-ray procedures account for about 90% of the radiation dose to the population from all artificial sources of radiation. In all of these procedures exposure is to a part of the body, not to the whole body.

Medical Exposures

- Medical examinations providing information on the functioning of specific organs are also performed by administering to patients small amounts of radioactive materials (more than 90% of medical procedures employ Tc-99m)
- The average effective dose is of the order 1 mSv.
- The equivalent dose to individual patients undergoing radiotherapy is very much higher than in diagnosis - typically about 60 Sv to the tumor-bearing tissue over a period of 6 weeks.
- Lethal effective dose is about 7 Sv (whole body exposition).

Typical levels of patient effective dose from X-ray examinations

Examination	Effective dose [mSv]	Equivalent period of natural radiation
Extremities (arms, legs)	<0.01	1.5 days
Dental	0.02	3 days
Chest	0.04	1 week
Skull, mammography	0.1	2 weeks
Hip	0.3	2 months
Abdomen	1.4	8 months
CT head	1.8	10 months
Intravenous urography	4.6	2 years
CT chest	8.3	4 years

Thank you for your attention