Medical University of Białystok
Department of Biophysics

PRE-COURSE (PHYSICS)

RADIOACTIVITY (2)

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INTERACTION OF PHOTONS AND CHARGED PARTICLES WITH MATTER

Ionazing radiation

The following categories of radiation are of interest to us:

- **gamma (γ) rays**
- **X-rays,**
- **neutrons**
- **charged particles:** **- alpha (α) particles**

  - beta (β) particles

  - protons

Ionazing radiation

When the ionising radiation passes through matter, it loses energy in:

- **radiation,**
- **ionisation**
- **photonuclear interactions.**

Gamma-rays and X-rays

Gamma rays and X-rays are absorbed by collisions with electrons to which their energy is transferred (photoelectric effect and Compton scattering)

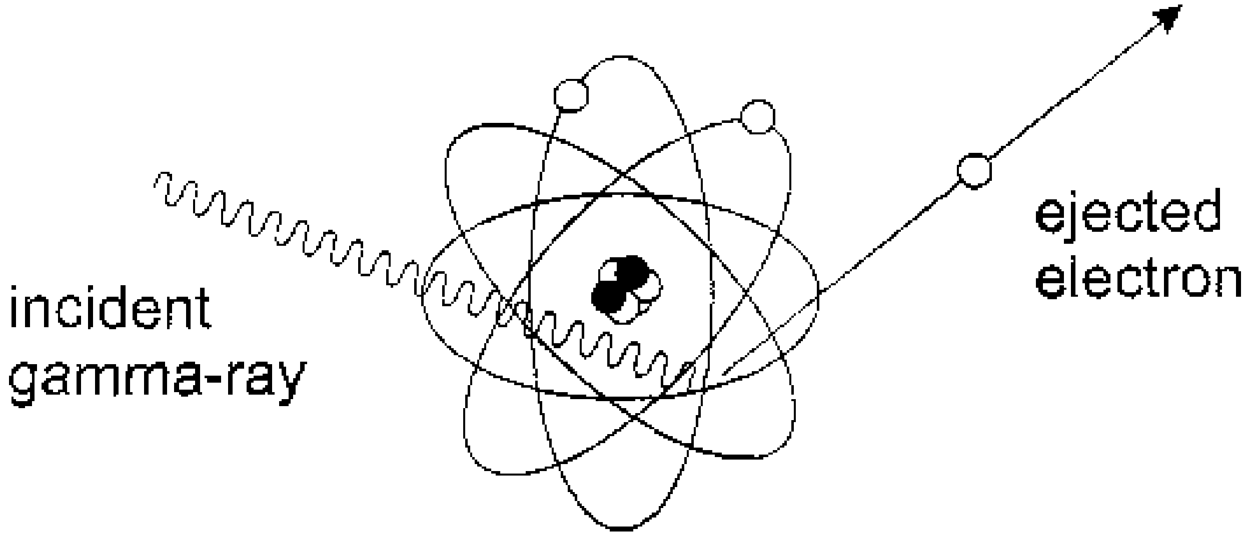
and in the reaction $h\nu \rightarrow e^- + e^+$, which can take place in the Coulomb field of a nucleus (pair production).

These electrons subsequently lose their energy in ionizing events, which are relatively widely spaced.

Photoelectric effect

Photoelectric effect is the process in which a photon collides with a bound electron causing ejection of the electron from the atom. The photon is absorbed by the atom.

$$E_e = h\nu - E_B$$



E_e - The electron energy

$h\nu$ - photon energy

E_B - binding energy – minimum amount of energy necessary to free electron from metal (different value for different material)

The photon energy

- $E_{photon} = h \cdot \nu = \frac{h \cdot c}{\lambda}$

- c - speed of light in a vacuum ($c = 3 \cdot 10^{8}$ m/s)
- ν – light wave frequency (1Hz = 1/s)
- λ - light wavelength (1nm = $1 \cdot 10^{9}$ m)

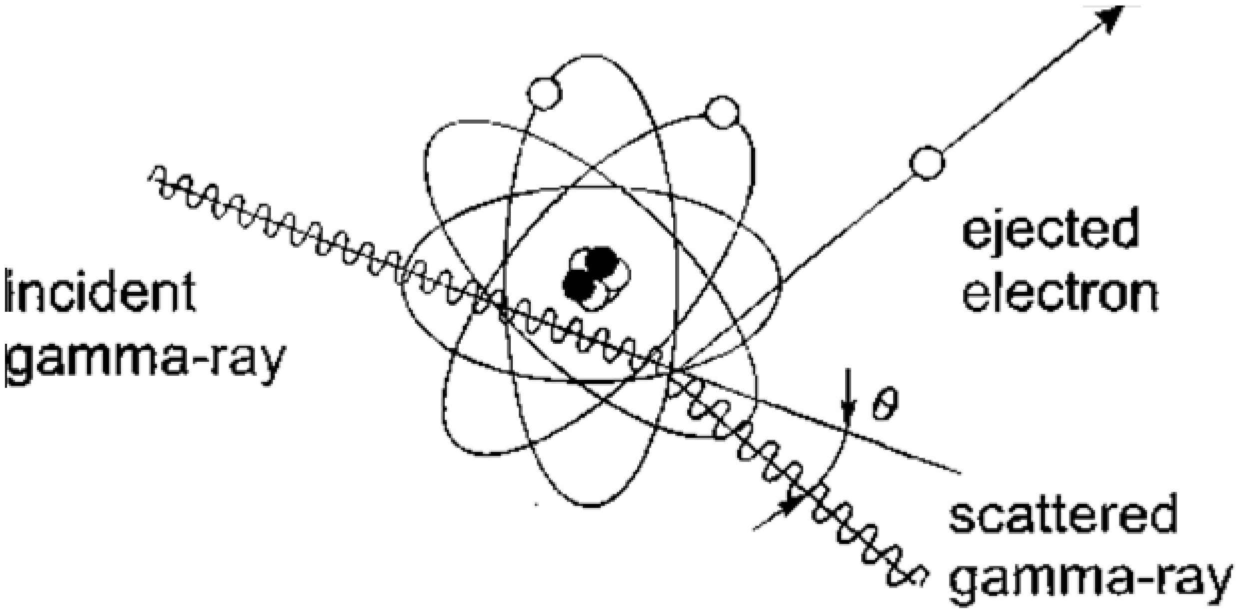
- **For tissues, since the binding energies are small, almost all the energy goes to the photoelectron. The photoelectric probability increases strongly with Z of material and decreases at higher energies.**

Photoelectric effect

- **The presence of the atom is required to conserve momentum because it is impossible to balance both momentum and energy for a photon completely absorbed by a free electron.**
- **After a photoelectric interaction, the atom is left in an excited state due to vacancy created when the electron is ejected.**
- **The atom relaxes by electronic transition from a higher orbital to the vacant orbital.**

Compton scattering

In incoherent Compton scattering the photon collides with a (free or weakly bound) electron, losing energy to the electron and scattering in a different direction.



Compton scattering

The energy of electron and the energy of scattered photon are given by:

$$h\nu' = h\nu\left[1 + \frac{h\nu}{m_e c^2}(1 - \cos\Theta)\right]^{-1}$$

$$E_e = h\nu - h\nu'$$

where:

$h\nu$ - incident photon energy,

$h\nu'$ - scattered photon energy

E_e- electron energy,

m_e- electron mass,

c - velocity of light

Θ - angle between incident and scattered gamma ray directions

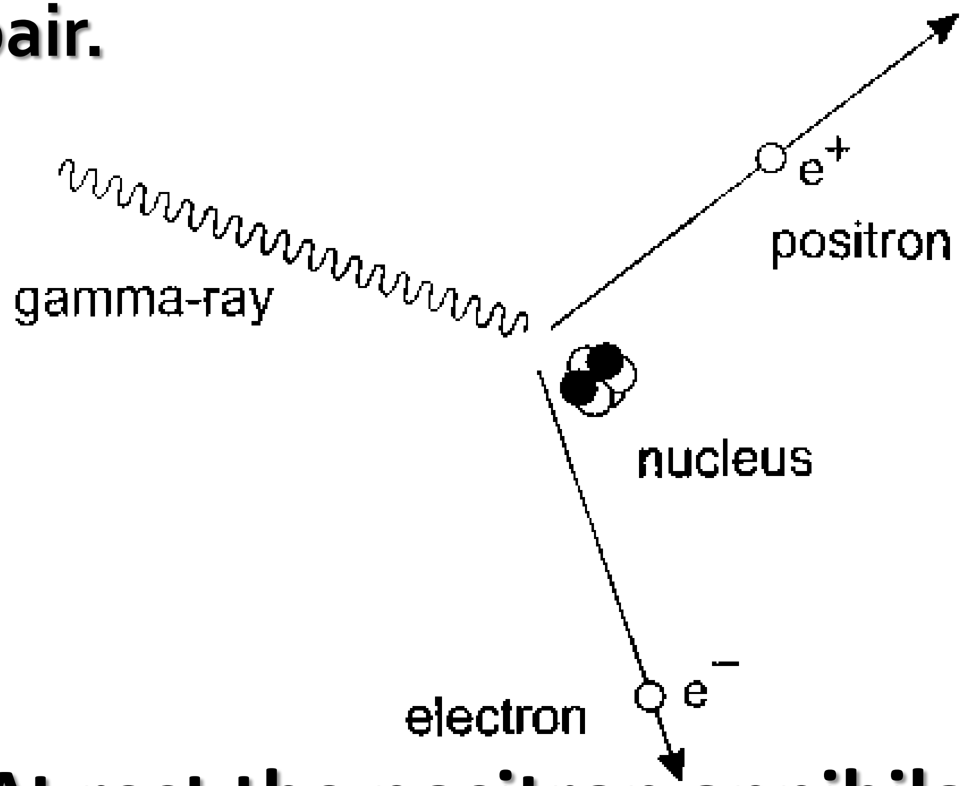
- Θ = 0 there is no energy transfer
- Θ = 180° there is maximum energy transfer.
- The electron is never scattered backwards.

differences between Photoelectric effect and Compton scattering

- https://www.youtube.com/watch?v=lzuiPoJffV4

Pair production

Pair production is the process by which a positron - electron pair is created when a photon interacts in the Coulomb field of a nucleus. At least 1.022 MeV = $2m_ec^2$ of a photon energy is required to create a positron - electron pair.



Energy conservation:

$$Ee+Ep = h\nu - 2m_ec^2$$

where:

E_c , E_P - electron and positron energy,

$h\nu$ - photon energy

$2m_ec^2$ - energy equivalent of mass of electron and positron

At rest the positron annihilates with electron creating two photons of 0.511 MeV emitted at 180°.

Pair production

The pair production can also take place in the Coulomb field of an electron, termed historically „triplet" production, since there are three particles in motion (the two that are created and the original electron). The threshold energy for triplet is $4m_ec^2$. Triplet production is a small fraction of the pair production and is usually included with it.

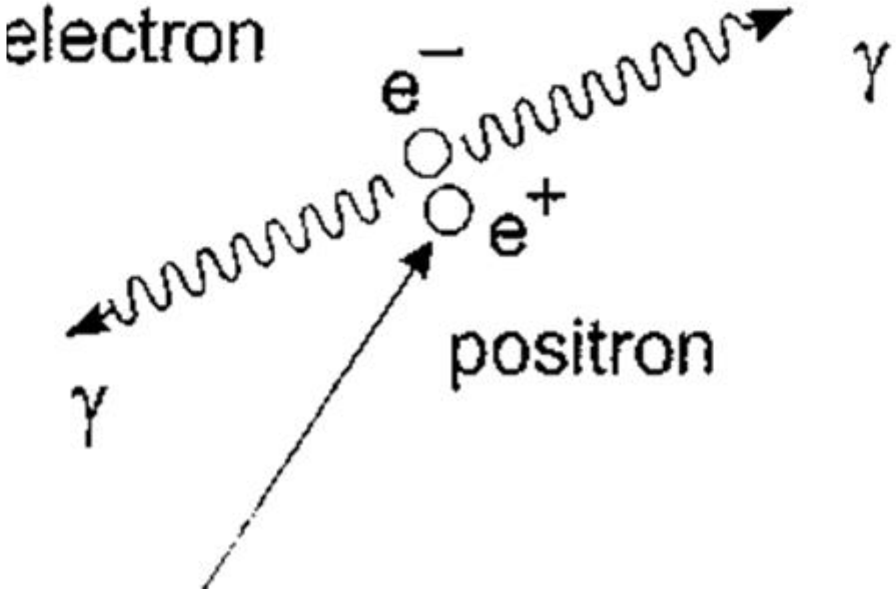
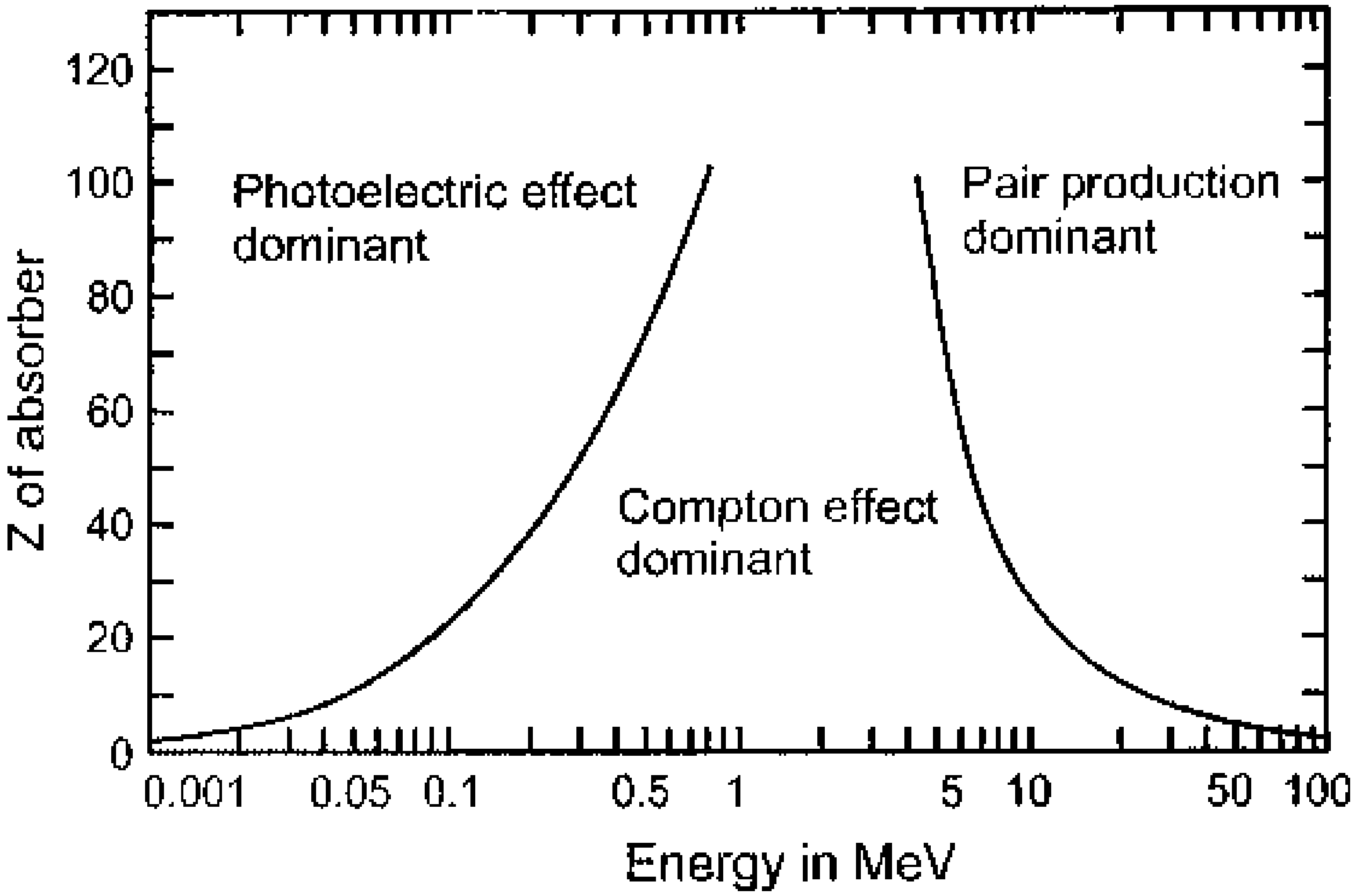


Table shows the distribution of the types of photon interactions in water in function of energy of photons.

hν	% energy transferred		
(keV, MeV)	Photo	Compton	Pair
10 keV	99.9	0.1	0.0
30	93.2	6.8	0.0
50	62.8	37.2	0.0
100	10.4	89.6	0.0
200	1.0	99.0	0.0
500	0.1	99.9	0.0
1 MeV	0.0	100.0	0.0
1.5	0.0	99.9	0.1
2	0.0	99.3	0.7
5	0.0	89.6	10.4
10	0.0	71.9	28.1
20	0.0	49.3	50.7
50	0.0	24.6	75.4
100 MeV	0.0	13.3	86.7

Figure shows the relative importance of three major types of gamma-ray interaction with the matter. The <u>lines</u> show the values of atomic number Z and gamma ray energy *hv* for which the two neighbouring effects are <u>equal</u>.



Attenuation coefficient (μ)

The probability of interacting with matter in one of these three processes (photoelectric effect, compton scattering, pair production**)can be expressed as an attenuation coefficient μ.**

The attenuation coefficient for a beam of gamma rays is related to the number of gamma rays removed from the beam, either by absorption or scattering. For all the three processes the total attenuation coefficient μ is the sum of the three partial attenuation coefficients:

$$\mu = \mu_{photo} + \mu_{Compt} + \mu_{pair}$$

The attenuation coefficient is often called absorption coefficient

The law of attenuation

The number of photons removed from a beam „dn” of „n” primary photons on the distance-travelled „dx” is:

$$dn = -n \cdot \mu \cdot dx \quad \text{or} \quad dI = -I \cdot \mu \cdot dx$$

which integrates to:

$$n = n_0 \cdot e^{-\mu \cdot x} \quad \text{or} \quad I = I_0 \cdot e^{-\mu \cdot x}$$

where:

n – final numer of photons, I – final beam intensity

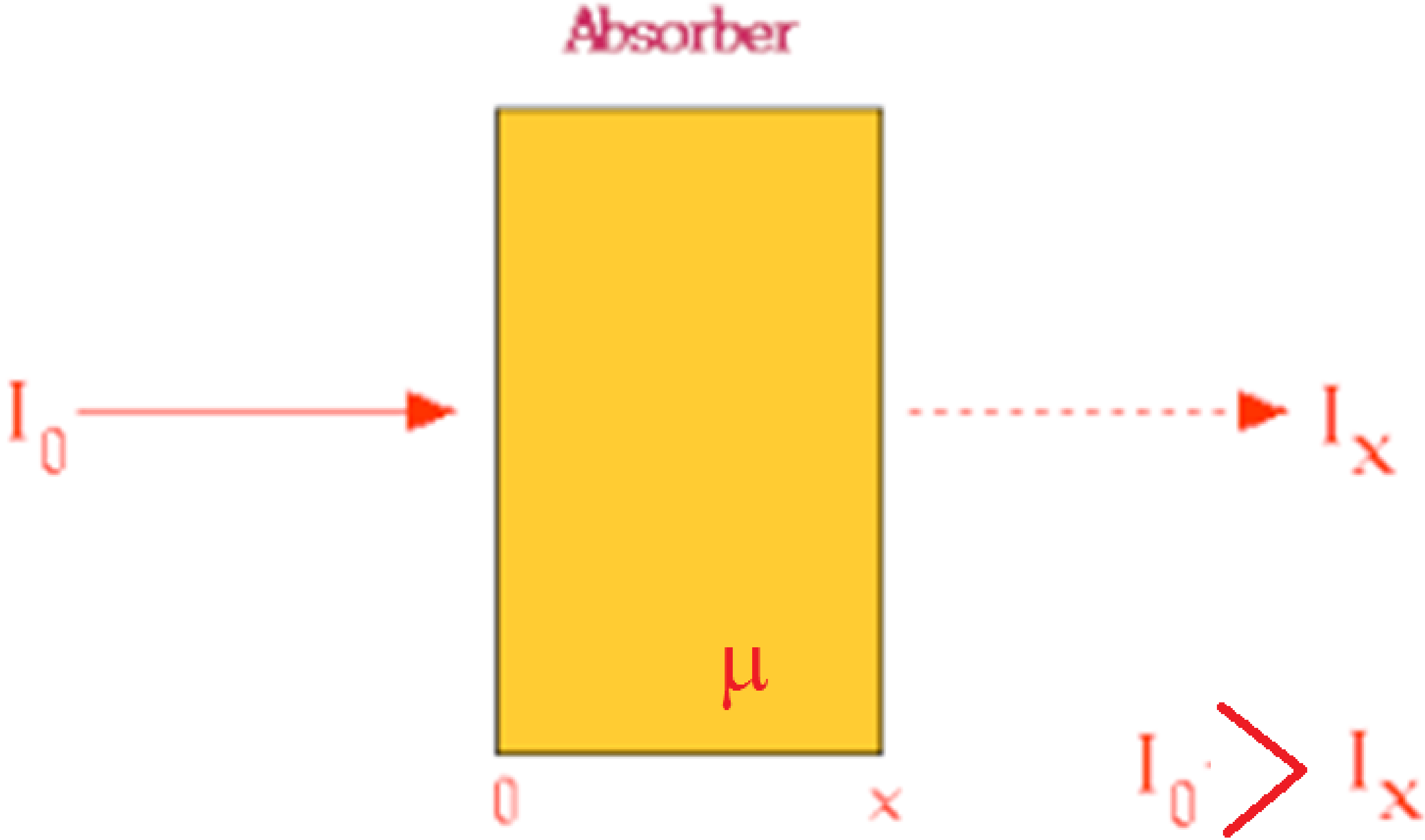
n_0 – an initial number of photons, I_0 – an initial beam intensity

μ - the total attenuation coefficient [m^{-1}]

x - thickness of material [m]

The law of attenuation

$$I_x = I_0 \cdot e^{-\mu \cdot x}$$



The law of attenuation

For the surface density defined as „$\rho \cdot x$" the previous formulas are:

$$n = n_0 \cdot e^{-\frac{\mu}{\rho}\cdot(\rho\cdot x)}$$

or

$$I = I_0 \cdot e^{-\frac{\mu}{\rho}\cdot(\rho\cdot x)}$$

where:

n - final number of photons, (I - final beam intensity)

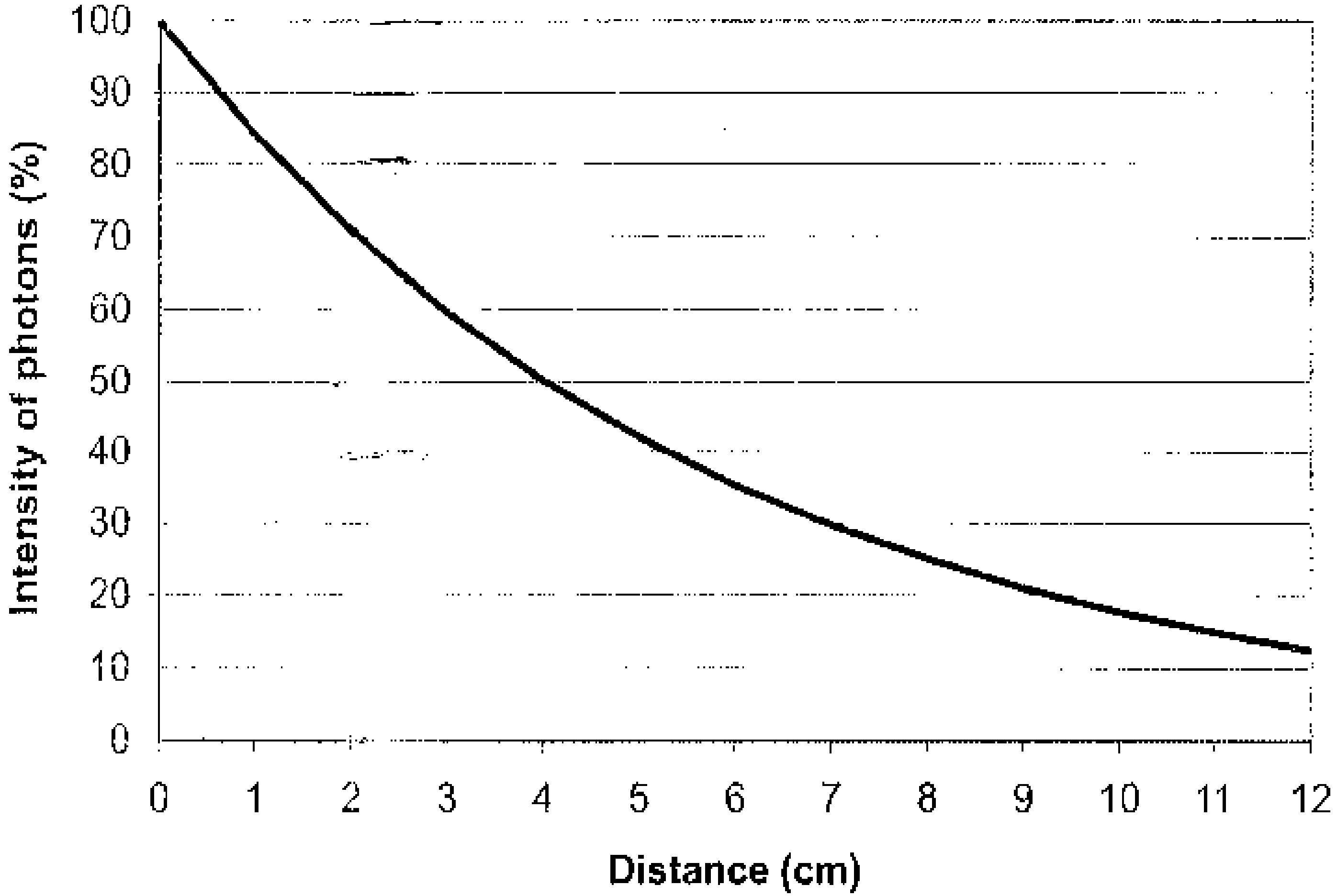
n_0- initial number of photons, (I_0 - initial beam intensity)

$\mu \cdot \rho^{-1}$ - mass attenuation coefficient ($m^2 kg^{-1}$)

ρ - density of absorber ($kg \cdot m^{-3}$), $\rho \cdot x$ - surface density ($kg \cdot m^{-2}$)

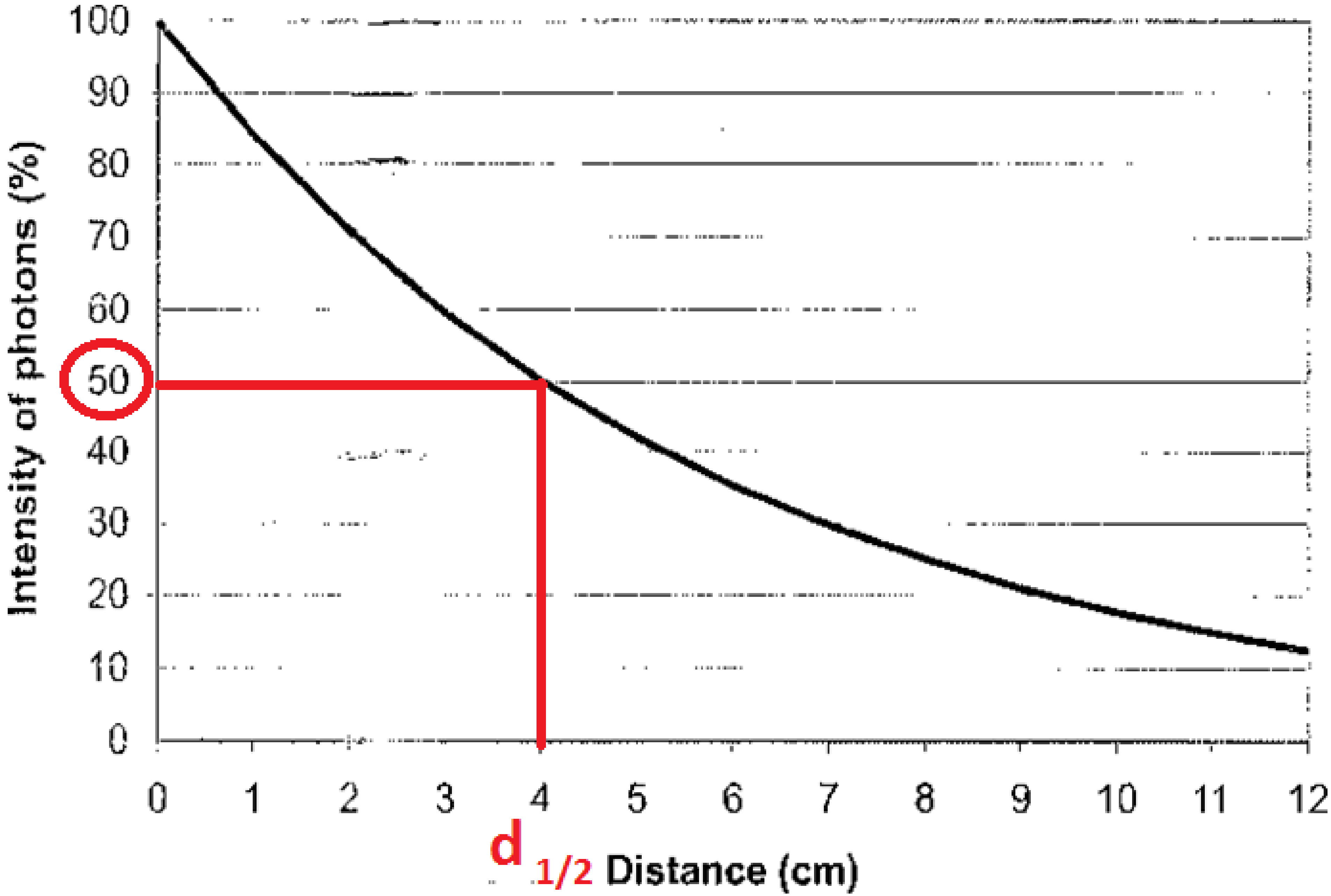
The law of attenuation

The Figure shows the percentage changes of intensity of photons γ in function of travelled distance in matter



$$I = I_0 \cdot e^{-\mu \cdot x}$$

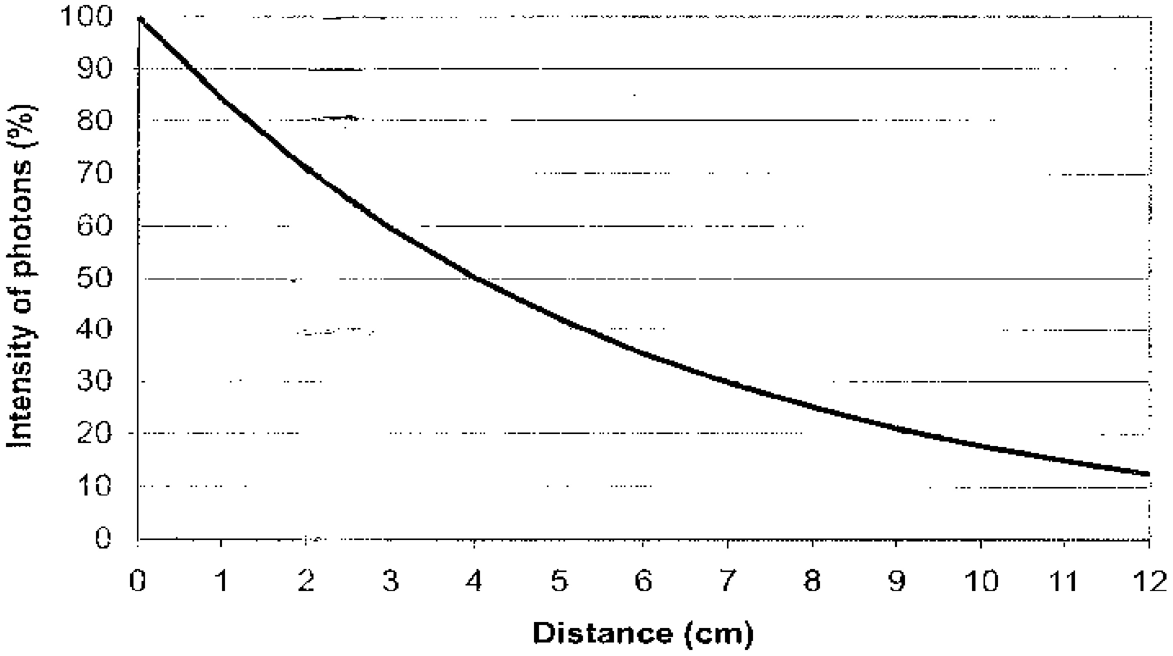
$$\frac{I}{I_0} \cdot 100\% = e^{-\mu \cdot x}$$


Intensity of photons (%)
100
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
8
9
10
11
12
d 1/2 Distance (cm)

half-thickness ($d_{1/2}$)

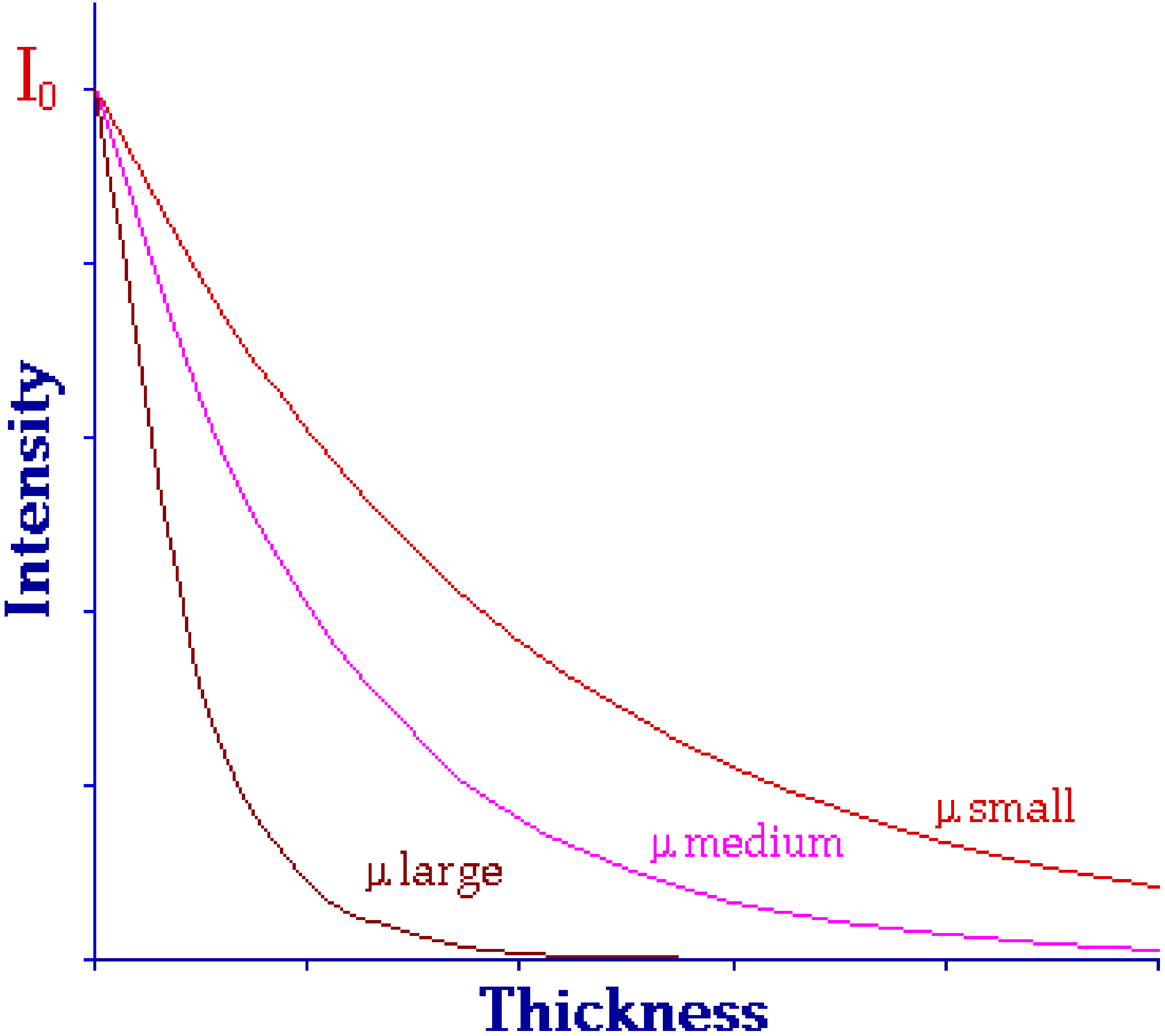
It is the thickness for which the intensity of a beam of parallel gamma rays given energy E is reduced by factor 2. It is easily verified that:

$$d_{1/2} = \frac{ln(2)}{\mu}$$

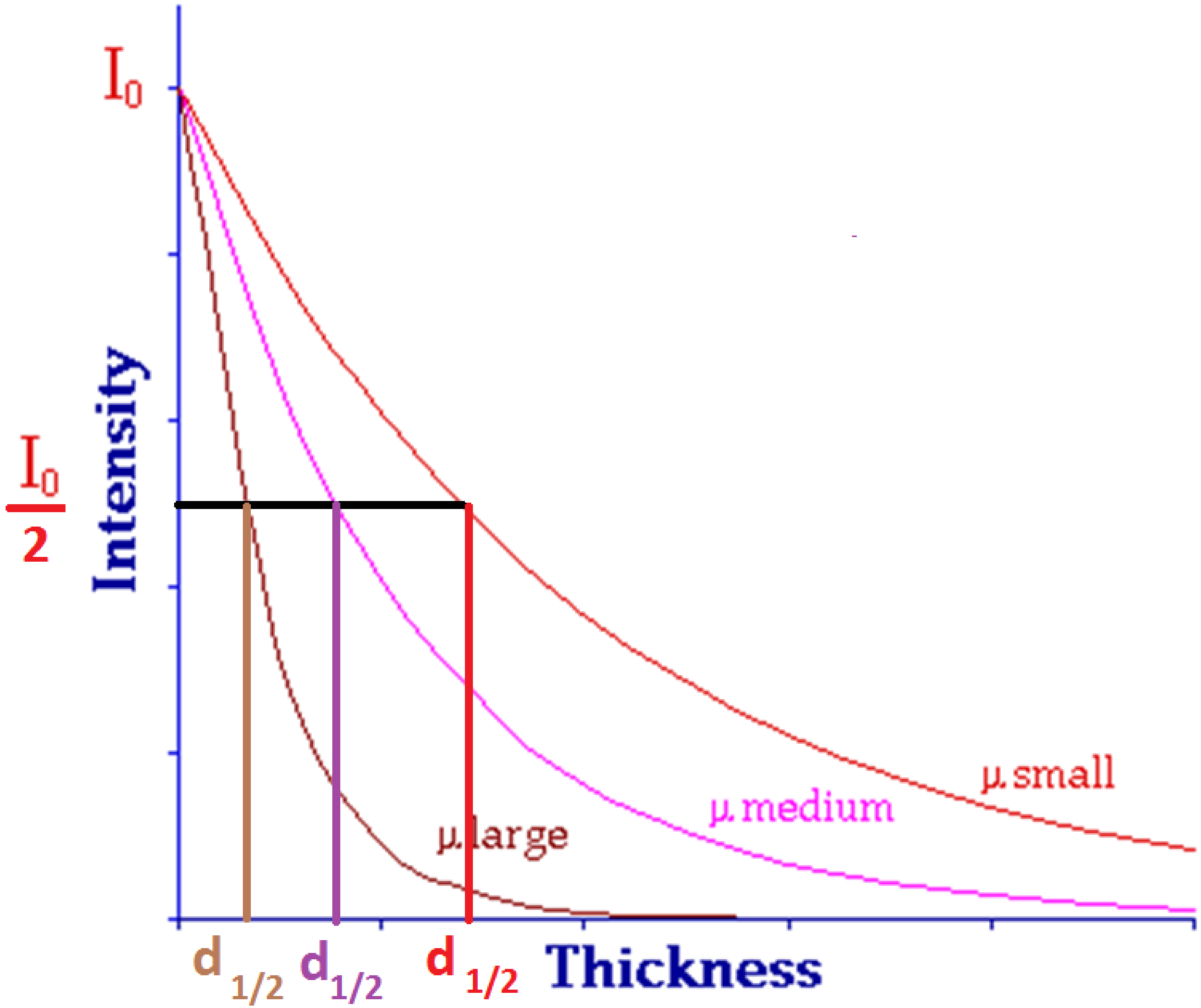


Where:

- $d_{1/2}$ **- half-thickness [m],**
- μ **– the linear absorption (attenuation) coefficient [m^{-1}],**
- $ln(2)$ **– natural logarithm of 2**



I_0
Intensity
μ small
μ medium
μ large
Thickness


I_0
$\frac{I_0}{2}$
Intensity
μ.small
μ.medium
μ.large
d 1/2
d 1/2
d 1/2
Thickness

The linear energy transfer (LET)

High values of LET signify that ionisations are produced much closer together in an absorber than is the case with low values of LET.

LET is an important radiation characteristic because it determines the amount of damage produced by the absorption of a given amount of radiation energy.

bremsstrahlung

Beta particles have energies up to few MeV.

They lose not only their energy by:

- ionisation and
- excitation of atoms,

but also by emitting a continuous electromagnetic radiation called **bremsstrahlung**, which appears when a high energy electron is stopped in the Coulomb field of nuclei.

The efficiency of bremsstrahlung (the probability for the electron to lose part of its energy by radiation) varies nearly as Z^2.

radiation yield (Y)

The total amount energy dissipated under the form of bremsstrahlung is determined by the radiation yield, Y.

Radiation yield is the average fraction of the electron's kinetic energy that an electron radiates as bremsstrahlung if completely stopped. It is given by:

$$Y = \frac{A}{A+1}$$

where: $A = 6 \cdot 10^{-4} \cdot Z \cdot E_k$

Z - the atomic number of the stopping material

E_k- the kinetic energy of the electrons (MeV)

radiation yield (Y)

To keep the bremsstrahlung low, low Z materials should be used for stopping beta particles.
For example:
a 2MeV electron loses a fraction of

- **Y=0.015 (1.5%) in Al (Z=13) and**
- **Y=0.09 (9%) in Pb (Z=82) by bremsstrahlung.**

The positron (β^+ particle) at rest will annihilate with an electron resulting in the emission of two gamma ray photons of 511 keV emitted in coincidence at 180° of each other.

radiation yield (Y)

Electrons and beta particles will penetrate distances in the body ranging from a small fraction of millimetre up to a few centimetres depending on their energy.

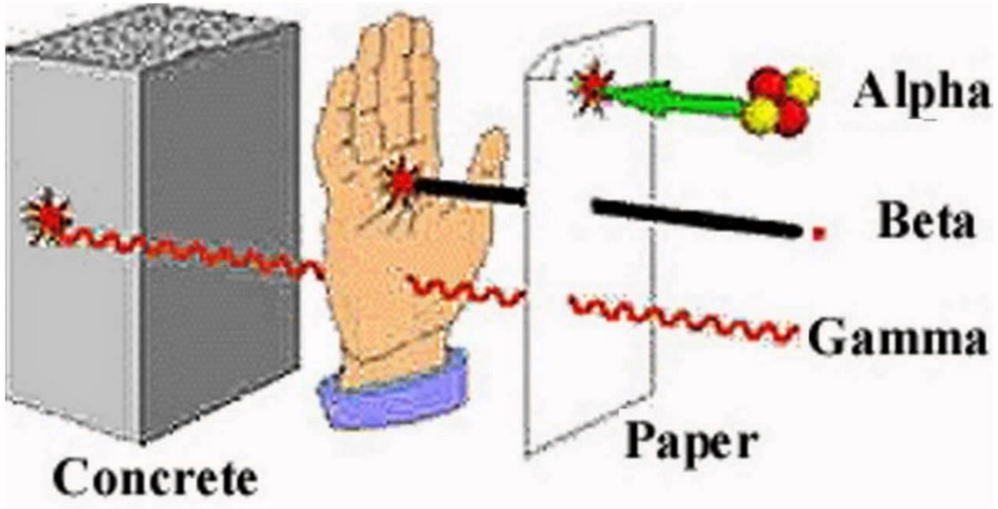
A 1 MeV electron has a range with water (or soft tissues) of 0.4 cm.

$$\boldsymbol{LET = \frac{1MeV}{0.4cm} = 2500\frac{keV}{cm} = 0.25\frac{keV}{\mu m}}$$

Alpha particles (α)

Alpha particles have a strong ionisation power and thus a very short range. They deposit their energy in very short distances and they are said to have a high LET (approximately 200 keV per micron in water). Alpha particles with a few MeV of energy are absorbed in:

- **a few centimetres of air**
- **a sheet of paper**
- **a few contiguous cells**



Alpha particles (α)

They will not penetrate the skin and only constitute a hazard in the case of intake of the radioactive material inside the body.

When the E_k of alpha particle decreases to about 1 MeV, the particle acquires two e^- and becomes helium He^4 atom (and stops in a short distance after a few collisions).

Fast neutrons

Fast neutrons are also classified as high LET radiation because their interactions with matter produce heavy charged particles (fast protons) that have a high LET (approximately 40 keV per micron in water).

However, the neutrons themselves carry no electrical charge, so they can travel relatively large distances between interactions and can penetrate many centimetres of the body - as do gamma rays and X-rays.

constance	symbol	Value with unit
Planck constance	h	$6.63 \cdot 10^{-34}$ J·s = = $4.14 \cdot 10^{-15}$ eV·s
The speed of light in a vacuum	c	$3 \cdot 10^{8}$ m/s
elementary charge	e	$1.602 \cdot 10^{-19}$ C
resting mass of the electron	m_e	$9.109 \cdot 10^{-31}$ kg

Thank you for your attention