Department of Medical Physic

Basic Physics, Part 2

Lecture 5

Medical physics

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Radioactive decay

The decay of a nuclide is exponential i.e. it theoretically never reaches zero. The S.I unit of radioactivity is the Becquerel (Bq):

$$1 \text{ Bq} = 1 \text{ transformation per second}$$

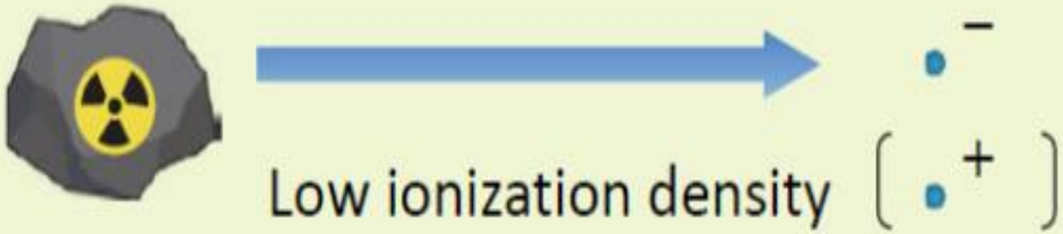
Types of radiation

When a nuclide undergoes radioactive decay it breaks down to fall into a lower energy state expending the excess energy as radiation. The radioactivity released can be:

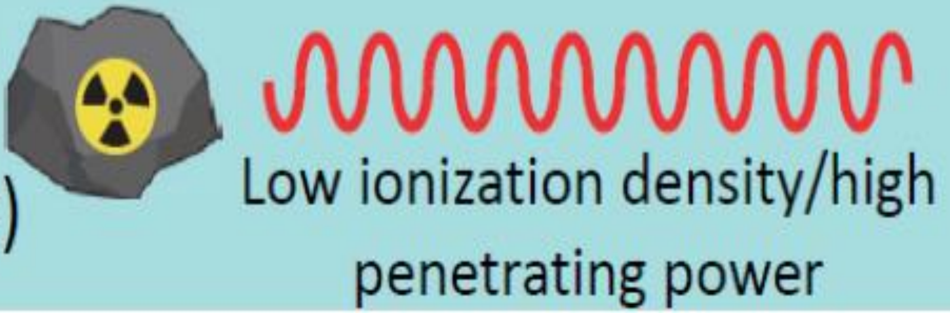
1. **Alpha particles**
2. **Beta particles**
3. **Gamma particles (or photons)**
4. **Others**

- **α-particles**
  - Two protons plus two neutrons
  - Helium (He) nuclei
  - Charged particles (2+)

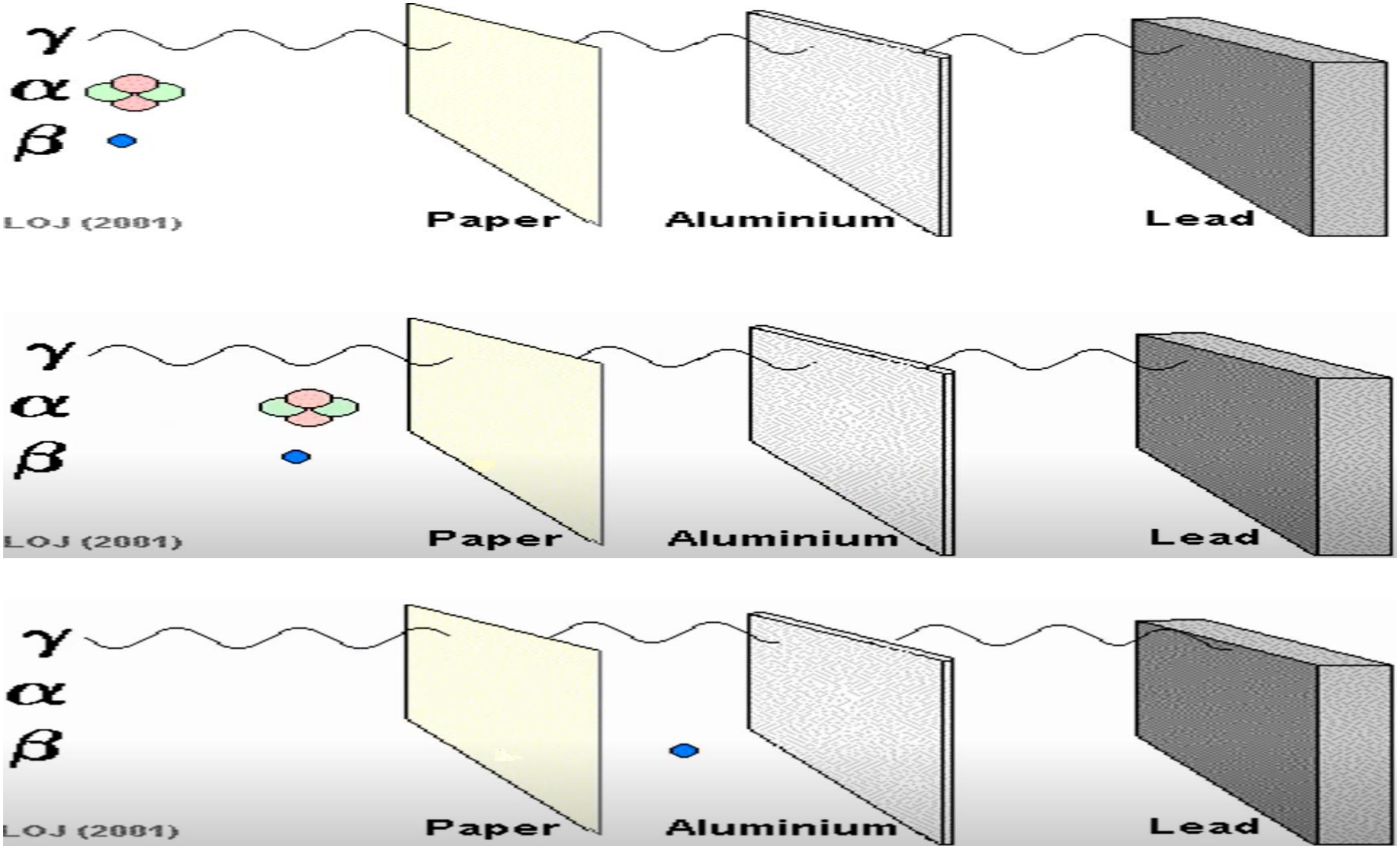
- **β-particles**
  - Electrons (or positrons)
  - Charged particles (- or +)

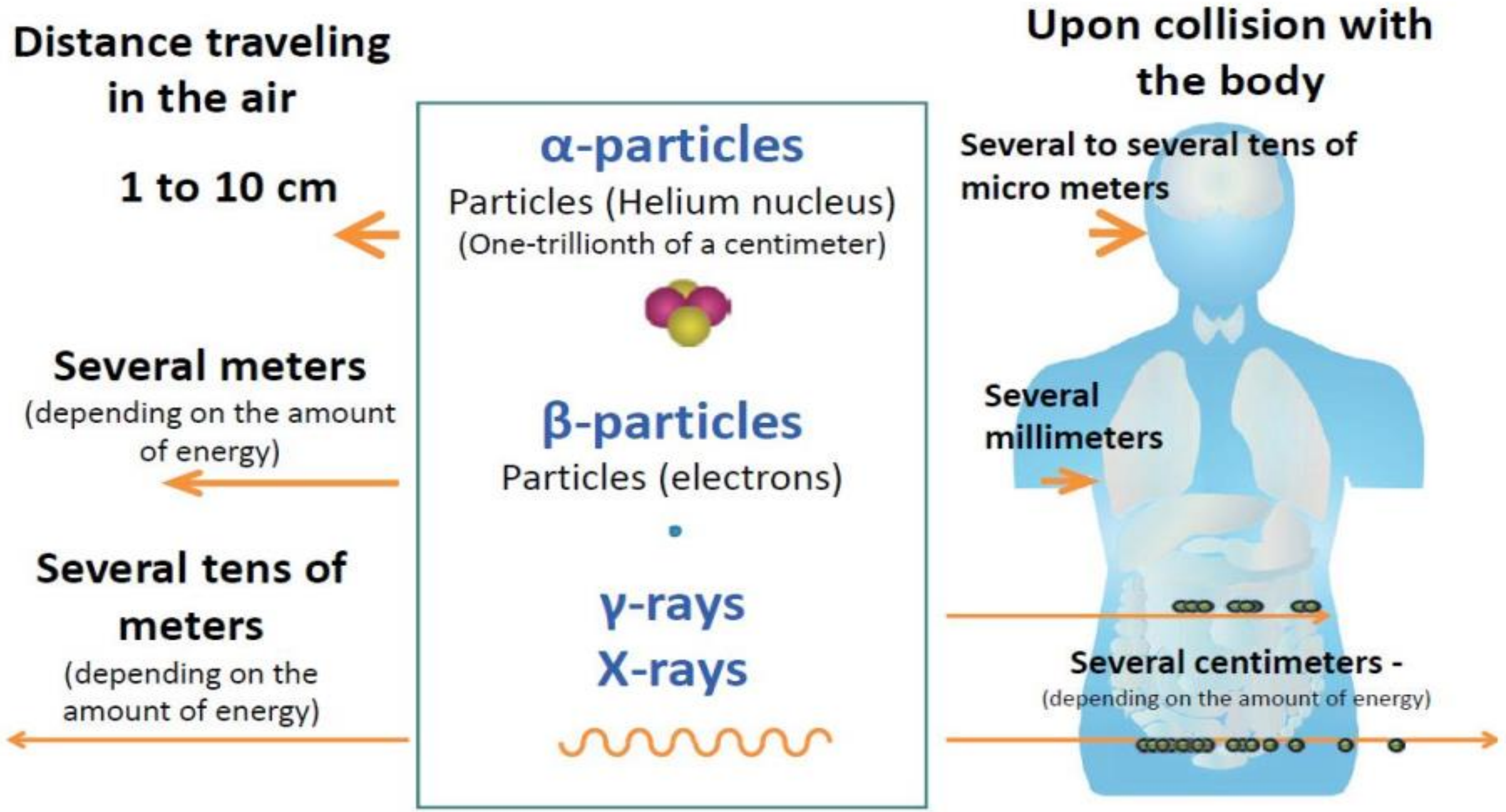


- **γ-rays and X-rays**
  - Electromagnetic waves (photons)

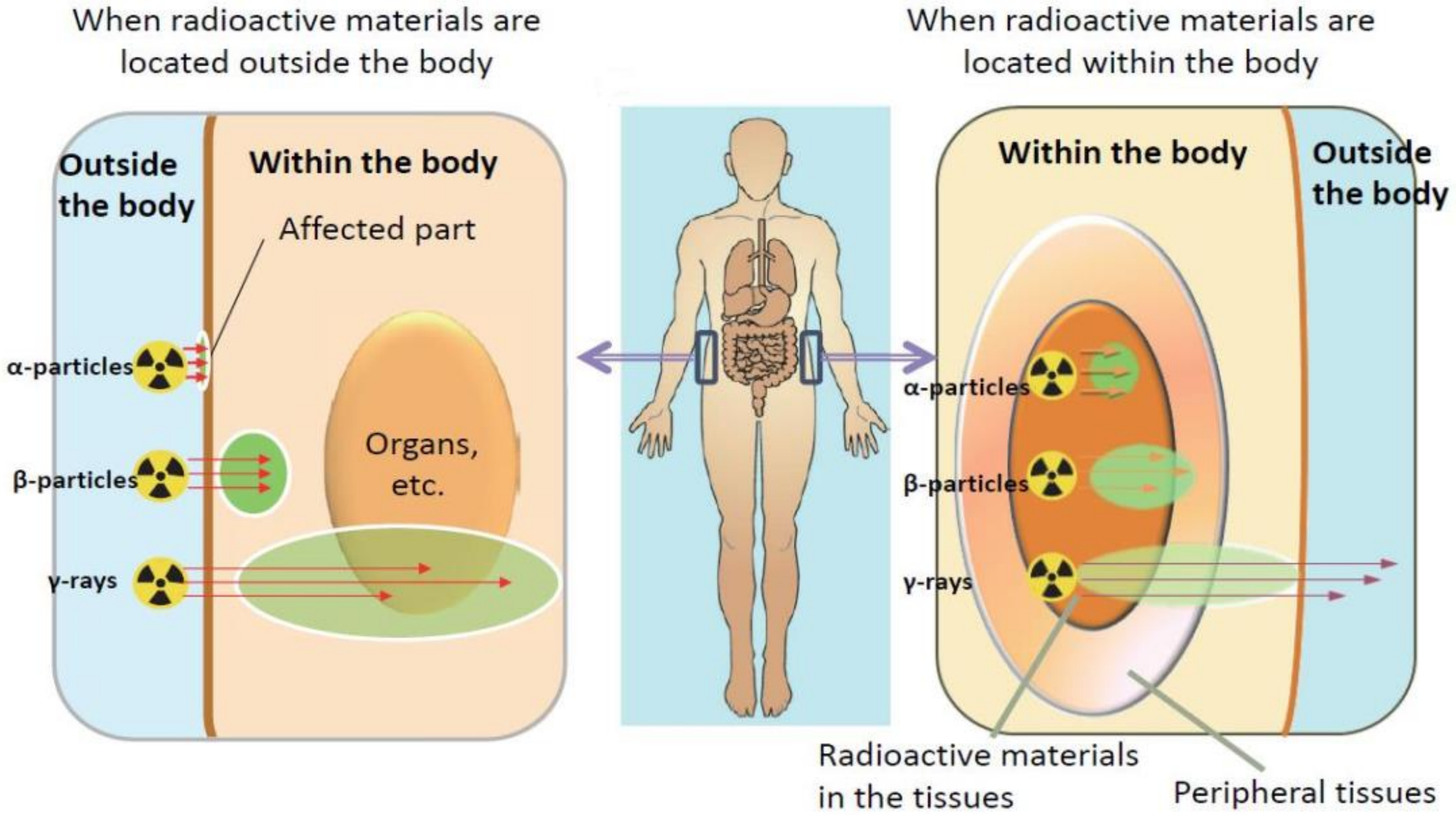


Penetration of different types of radiation





Distance traveling in the air
1 to 10 cm
Several meters
(depending on the amount of energy)
Several tens of meters
(depending on the amount of energy)
α-particles
Particles (Helium nucleus)
(One-trillionth of a centimeter)
β-particles
Particles (electrons)
γ-rays
X-rays
Upon collision with the body
Several to several tens of micro meters
Several millimeters
Several centimeters -
(depending on the amount of energy)


When radioactive materials are located outside the body
Outside the body
Within the body
Affected part
α-particles
β-particles
γ-rays
Organs, etc.
When radioactive materials are located within the body
Within the body
Outside the body
α-particles
β-particles
γ-rays
Radioactive materials in the tissues
Peripheral tissues

1. Alpha particles

- Symbol: α
- Formed of 2 protons and 2 neutrons (i.e. a helium atom)
- Positively charged
- Relatively heavy
- Short range of travel

2. Beta particles

- Symbol: β
- Electrons emitted from radioactive nuclei
- Carry negative charge
- Split into β- (negatron) and an antimatter equivalent β+ (positron)
- Lighter and smaller than α

3. Gamma particles

- Symbol: γ
- Identical to x-rays except for the origin (x-rays originate from electron bombardment, gamma particles from radioactive atoms)
- Result of transition between nuclear energy levels
- Very high energy and range of travel

4. Others

- X-rays
- Internal conversion: γ ray energy transferred to inner shell electron which is then emitted from the nucleus
- Auger electron: ejected from electron shells as a result of same radioactive decay processes that create electron shell vacancies. Competes with emission of x-rays.
- Neutrinos and anti-neutrinos: electrically neutral particles with very little mass emitted from atomic nuclei during β+ and β- decay respectively.
- Spontaneous fission: very heavy nuclides are so unstable they split into two smaller nuclides emitting neutrons in the process.

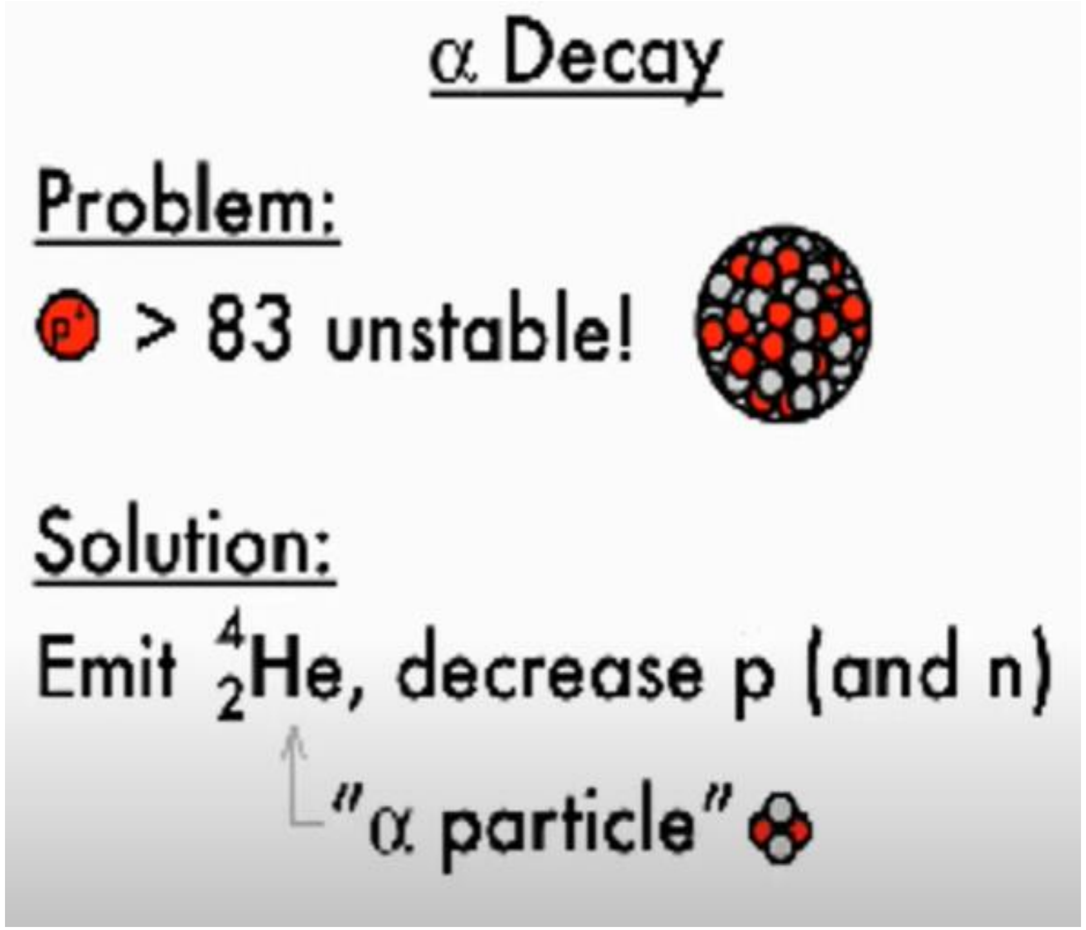
1- Alpha (α) decay

This occurs in heavier nuclides with too many nucleons. The parent nuclide emits a helium atom (α particle). This type of decay occurs in the nuclides in area **C** of the decay model graph that are very heavy.

$$^{A}_{Z}\text{Parent} \longrightarrow {}^{A-4}_{Z-2}\text{Daughter} + {}^{4}_{2}\text{He}$$

An alpha particle is a helium nucleus.

- It has a relative charge of +2.
- Its penetration power is the lowest among the three types of particles and can be blocked by a piece of paper or a few cm of air.
- Its ionizing power is the highest among the three types of particles.



2- Beta minus (β-) decay

This occurs in nuclides in area **B** of the decay model graph that have too many neutrons. The neutral neutron decays into a positive proton (which is retained in the nucleus), a negative electron and an electron antineutrino (i.e. the charge on both sides of the equation remains the same).

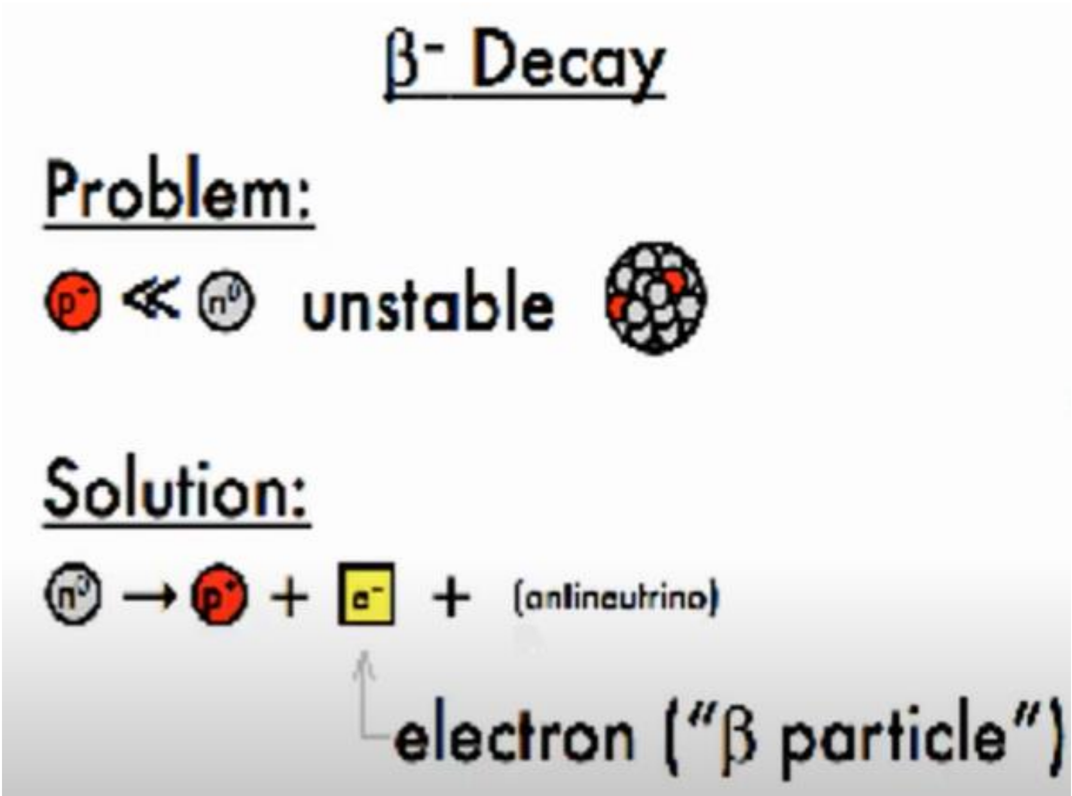
$$n \rightarrow p + e^{-} + \bar{v}e$$

$$^{A}_{Z}\text{Parent} \longrightarrow {}^{A}_{Z+1}\text{Daughter} + e^{-} + \bar{v}e$$

(Z=53) I-131 ⟶ Xe-131(Z=54)

A beta particle is an electron or a positron.

- It has a relative charge of -1 or +1.
- Its penetration power is in the middle among the three types of particles and can be blocked by a thin sheet of aluminum.
- Its ionizing power is in the middle among the three types of particles.



3- Beta plus (β+) decay aka positron emission

This occurs in nuclides in area **A** of the decay model that have too few neutrons. The extra proton decays into a neutron (which is retained in the nucleus), a positron (β+ or e) and an electron neutrino (ve). This from of radioactivity with the production of a positron is important in PET imaging.

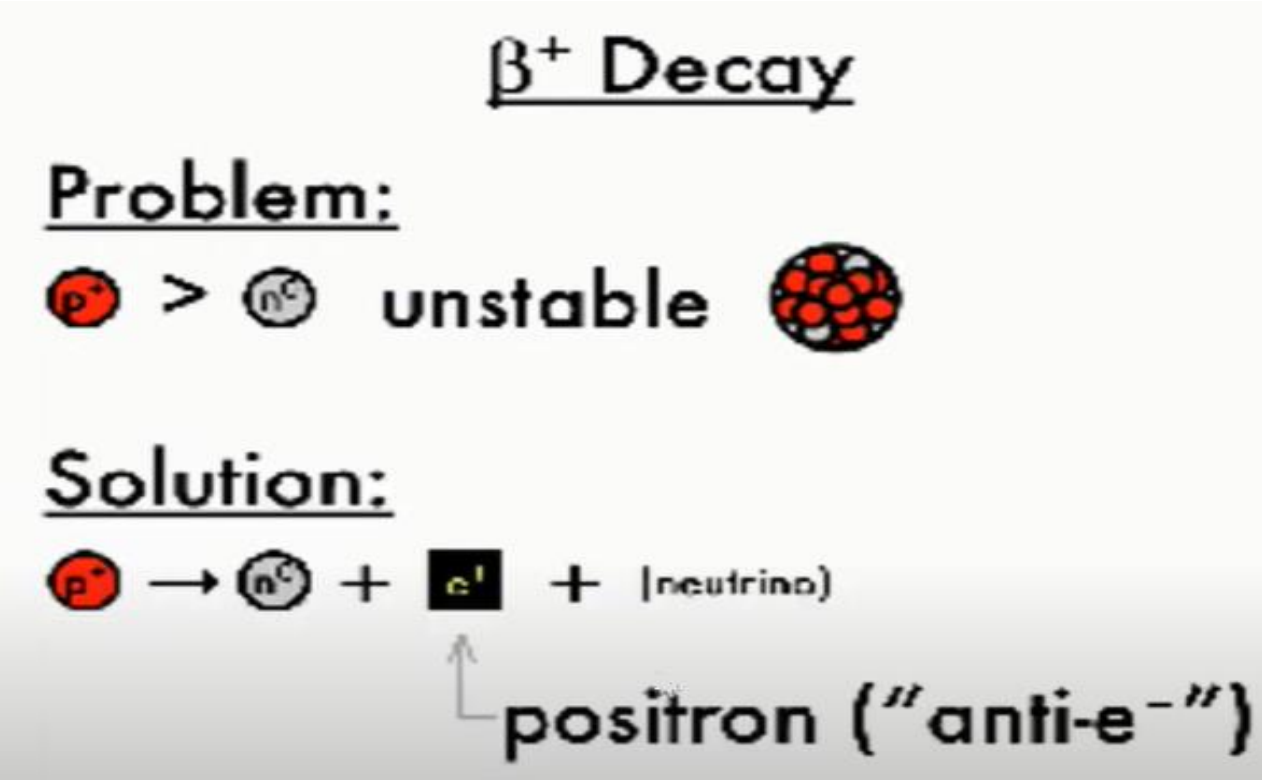
$$p \rightarrow n + \beta^{+}/e + ve$$

$$^{A}_{Z}\text{Parent} \longrightarrow {}^{A}_{Z-1}\text{Daughter} + e + ve$$

4- Electron capture

This competes with β+ decay as it also occurs in proton-rich nuclei. If the energy difference between the parent and daughter nuclides is too low for positron emission an inner shell electron is captured by the nucleus converting a proton into a neutron (i.e. positive + negative = neutral).

$$p + e^{-} \rightarrow n$$



The electron capture

The daughter nuclide will emit K-characteristic X-rays when an electron from an outer shell fills the hole created in the K- shell. If the daughter nuclide is left in an excited state, it will also emit gamma rays. For example, iodine – 123 (^{123}I) decays wholly by electron capture and emits 160 KeV gamma and 28 KeV X- rays but no positive beta particles.

5. Isomeric transition

A radionuclide in a metastable excited state decays to its ground state by isomeric transition and the number of protons and neutrons remain the same. The energy difference (energy released) is emitted as γ radiation. The Z and A remain unchanged.

e.g. Tc-99m → Tc-99 + 140 keV γ rays

99mTc & 99Tc are isomers that have different energy states and different half-lives

6. Gamma (γ) decay

Released by a hyperexcited nucleus to move to lower energy state after β or α decay.

- Gamma rays are photons.
- It does not have a charge.
- Its penetration power is the highest among the three types of particles and can be blocked by several cm of lead.
- Its ionizing power is the lowest among the three types of particles

Internal conversion the gamma rays emitted by some nuclei do not leave the atom but are photoelectrically absorbed within its K-shell. As a result of this internal conversion , such radionuclides (e.g. iodine-125, ^{125}I) emit both photoelectrons and characteristic X-rays, usually of fairly low energy (less than 35KeV in this case). As an example, figure 8.1 gives the simplified photon spectrum for another iodine isotope, ^{125}I , which is more useful for imaging than (^{123}I) because of its higher- energy photon emission and shorter half- life (around 13h).

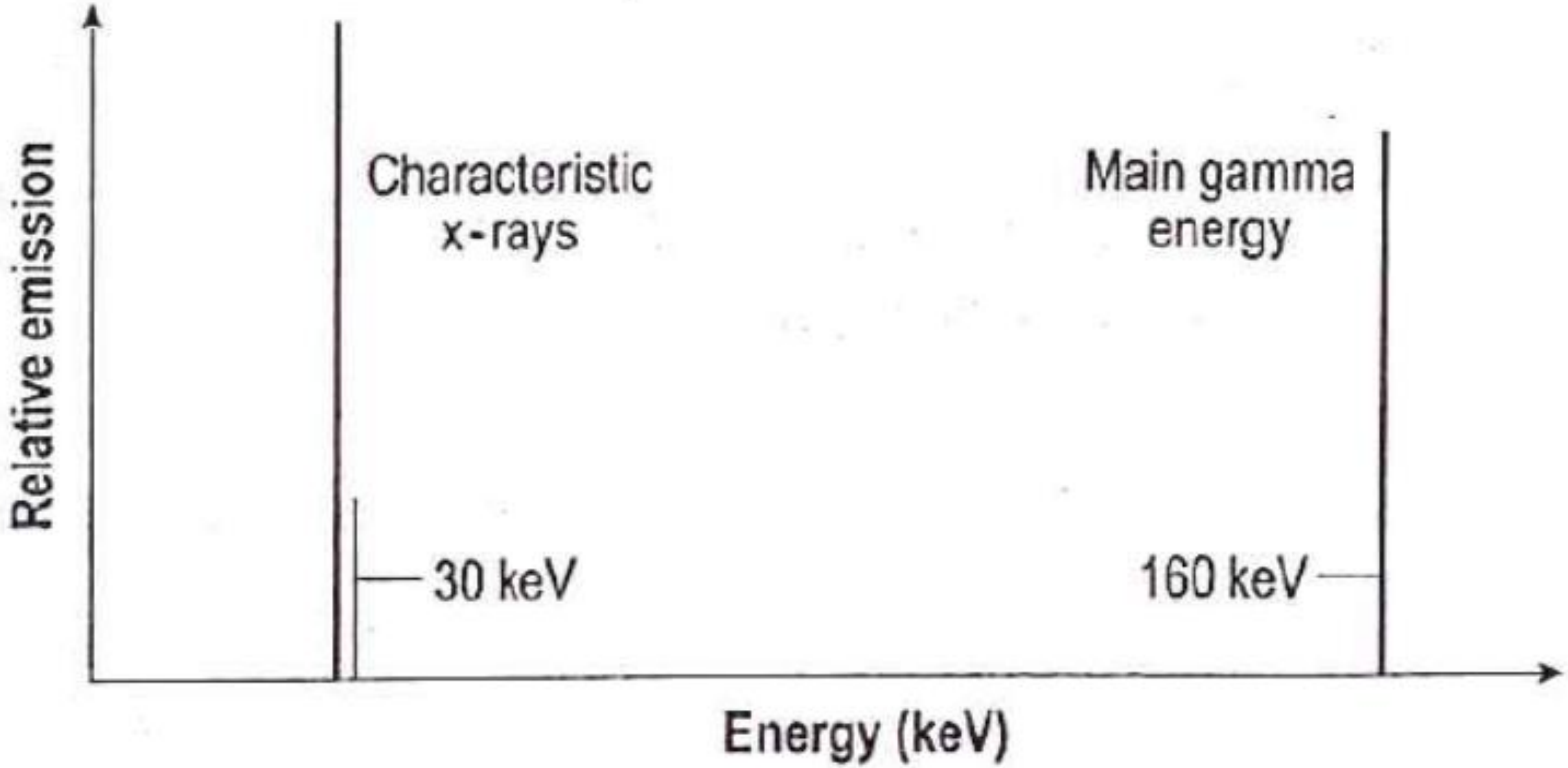
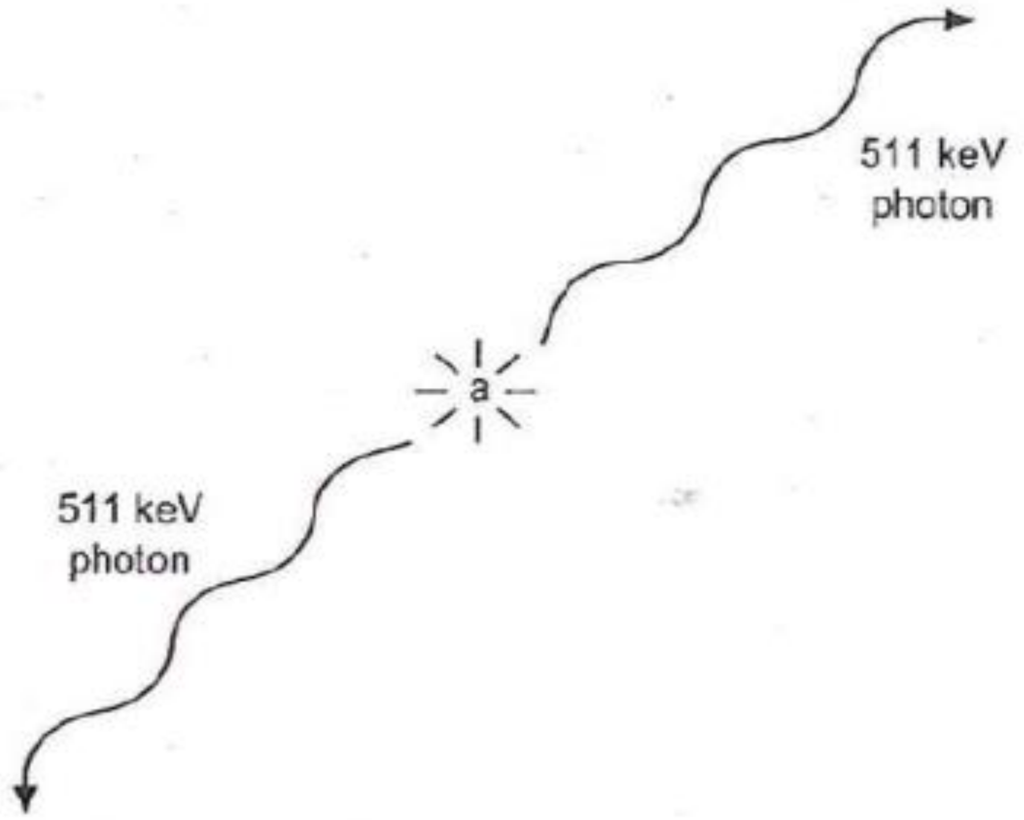


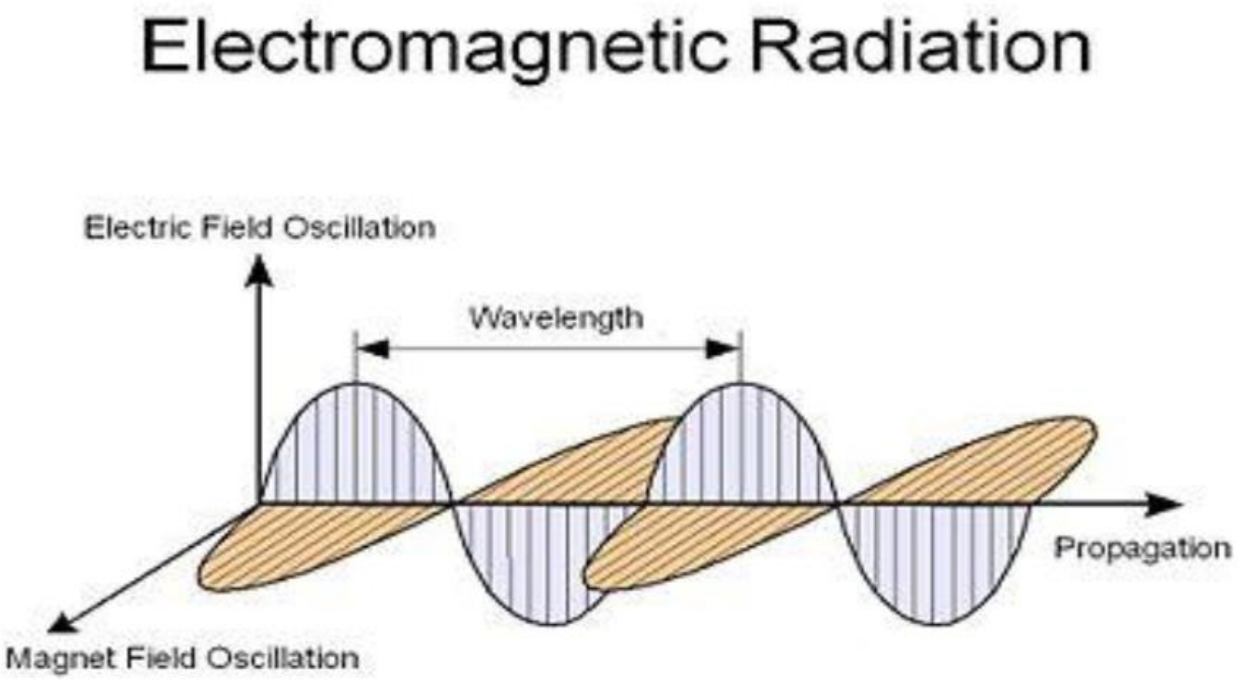
Figure 8.1 Photon line spectrum for iodine-123.



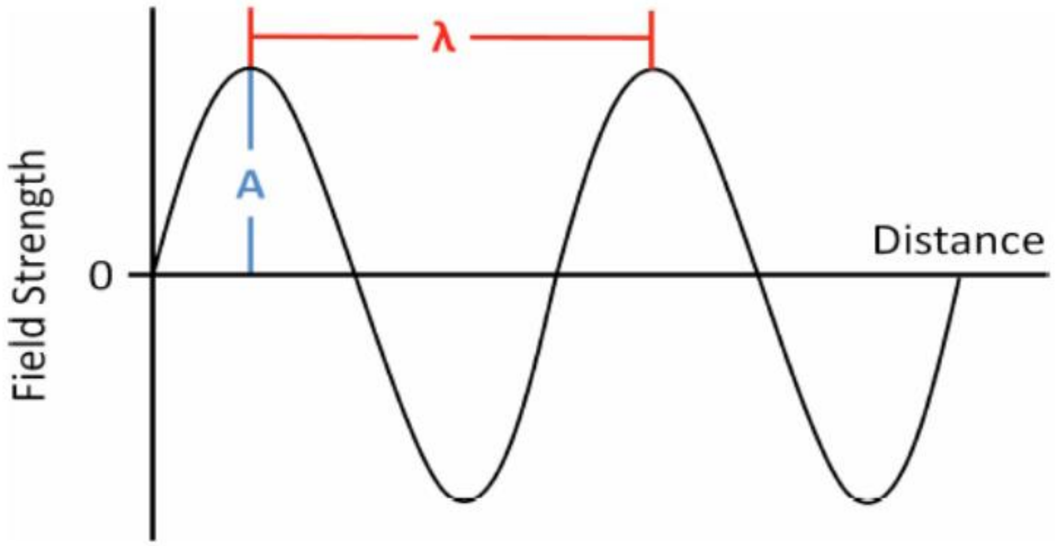
Positron annihilation: a is the point where positron meets electron and they annihilate.

> Electromagnetic radiation

• Electromagnetic (EM) radiation arises from oscillating electric and magnetic fields. It can be considered either as a stream
of quanta (photons, particles) or waves.
• EM radiation as waves Concerning the wave aspect, it is a sinusoidally varying electric and magnetic field vector pointing at right angles to one another and to the direction of the travel of the wave



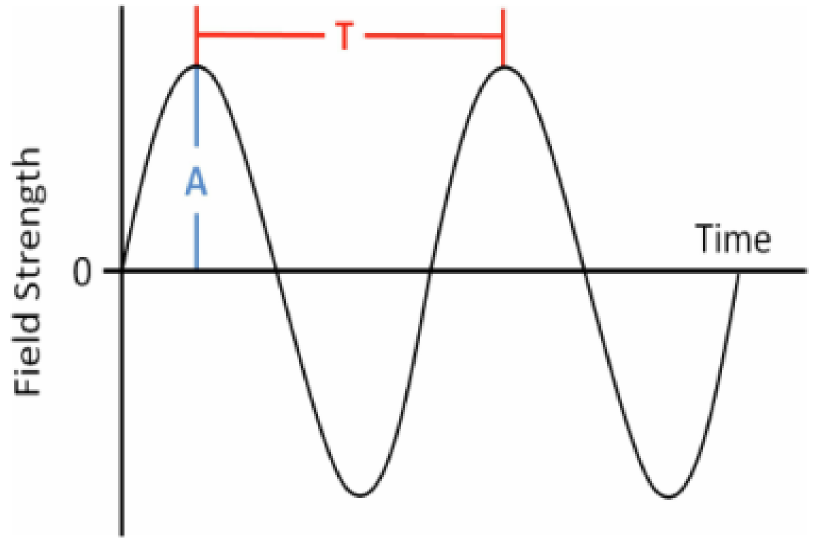
Graph Showing Wave Strength Over Distance



Graph Showing Wave Strength Over Time

Definitions

Amplitude (A)	peak field strength	
Wavelength (λ)	distance between successive peaks	Units = m (metres)
Time (T)	time between successive peaks	Units = seconds
Frequency (f)	the number of peaks passing a given point in one second	f = 1/T Units = s^{-1} (per second) or Hz (hertz, 1Hz = 1 cycle per second)
Velocity (c)	the distance travelled by a peak in one second	v = f x λ (velocity = frequency x wavelength)



EM radiation as particles

When considering EM radiation as particles, the particles are small packets, or quanta, of energy called photons that travel in straight lines. The energy of the photon packet is measured in joules but this is inconveniently small when describing EM radiation so the unit of electron-volt is used.

$$1 \text{ ev} = 1.6 \times 10^{-19} \text{ J}$$

Intensity

The intensity (i.e. photon energy or field strength) is related to the characteristics of the wave by **Planck's constant.**

$$E = hf$$

Key:
E = photon energy
h = Planck's constant
f = frequency

Rearranging the earlier equation of velocity = $f\lambda$ and assuming that the velocity if fixed (i.e. 1) gives you:

$$f = 1 / \lambda$$

In other words, the frequency is inversely proportional to the wavelength. Substituting this into the Planck's constant equation gives you:

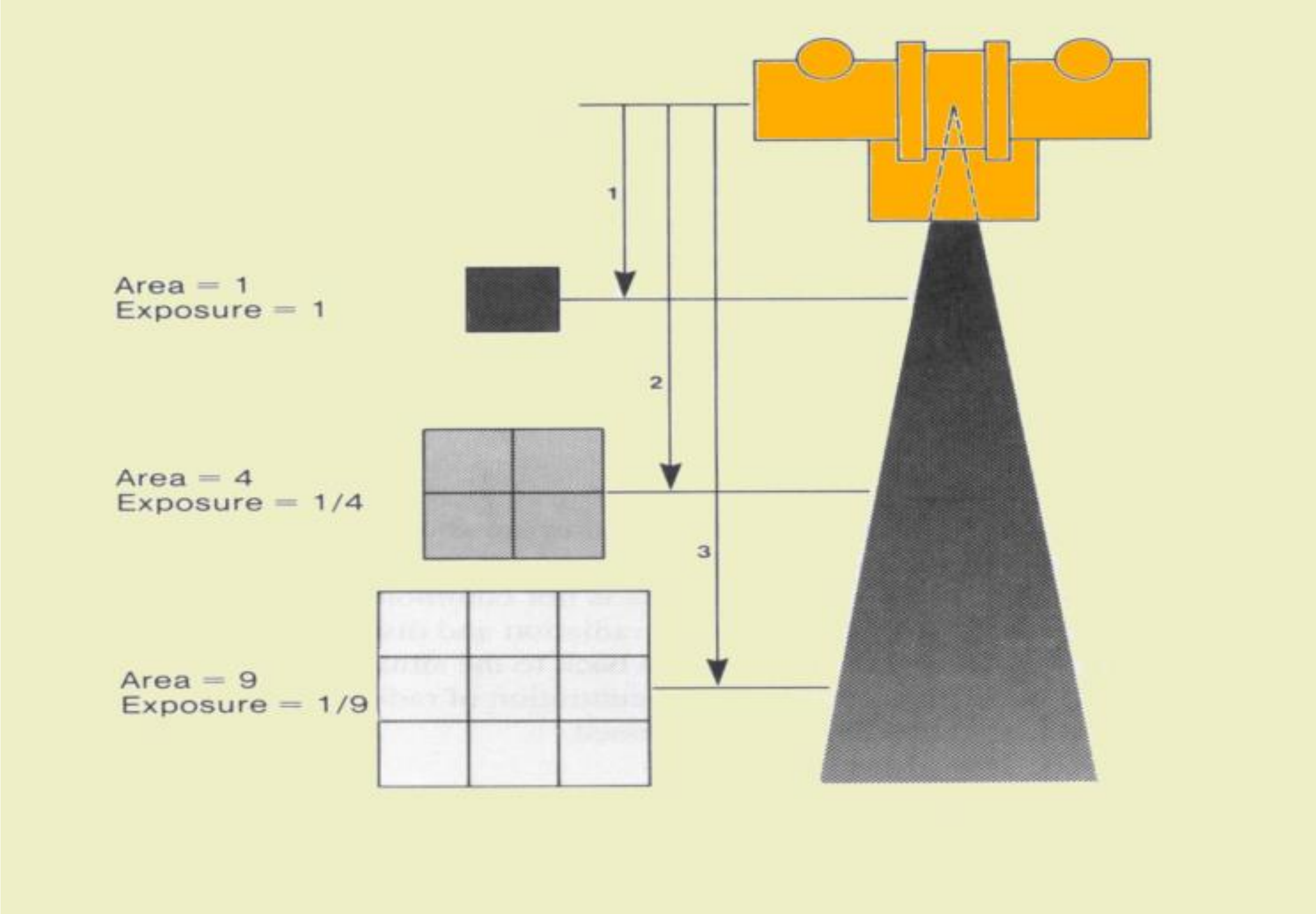
$$E = h / \lambda$$

i.e. the photon energy is inversely proportional to the wavelength.

The types of radiation are listed in Table in order of increasing photon energy, increasing frequency, and decreasing wavelength.

	Wavelength	Frequency	Energy
Radio waves	30-6 m	10-50 MHz	40-200 neV
Infrared	10000-700 nm	30-130 THz	0.12-1.8 eV
Visible light	700-400 nm	430-750 THz	1.8-3 eV
Ultraviolet	400-100 nm	750-3000 THz	3-12 eV
X- and gamma	60-2.5 pm	$5 \times 10^6 – 120 \times 10^6$ THz	20-500 keV

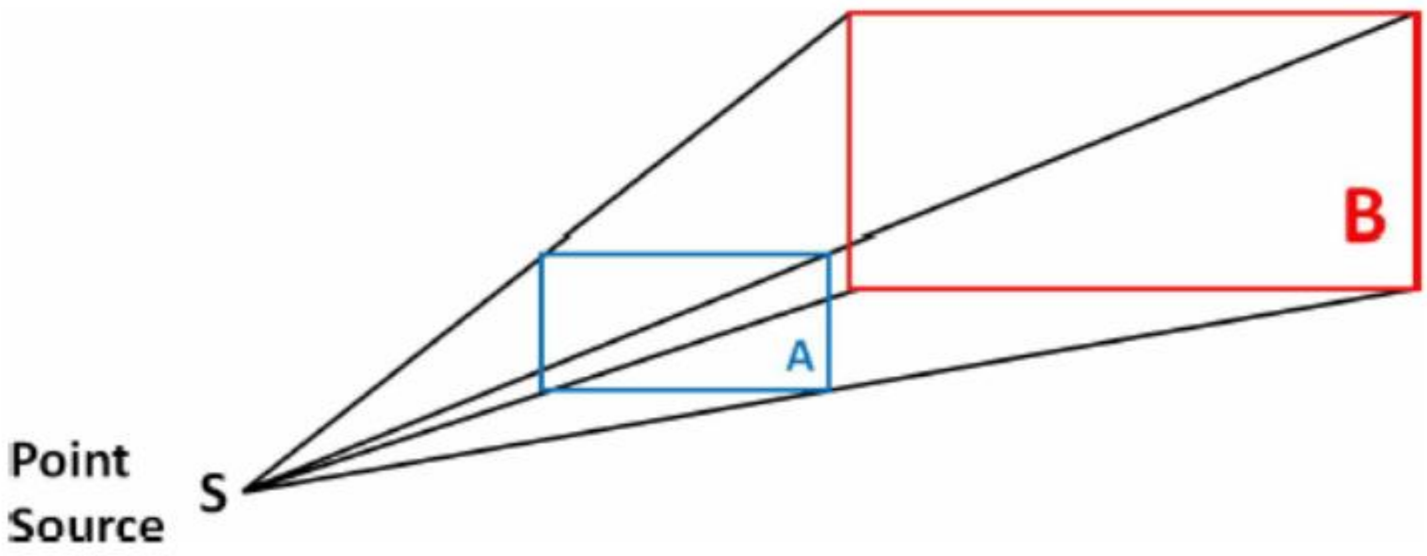
Inverse Square Law



- **the total amount of radiation does not change but its concentration Decreases**

- **We can conclude that the concentration of radiation is inversely related to the square of the distance from the source. This is commonly known as the inverse-square law**

Definitions



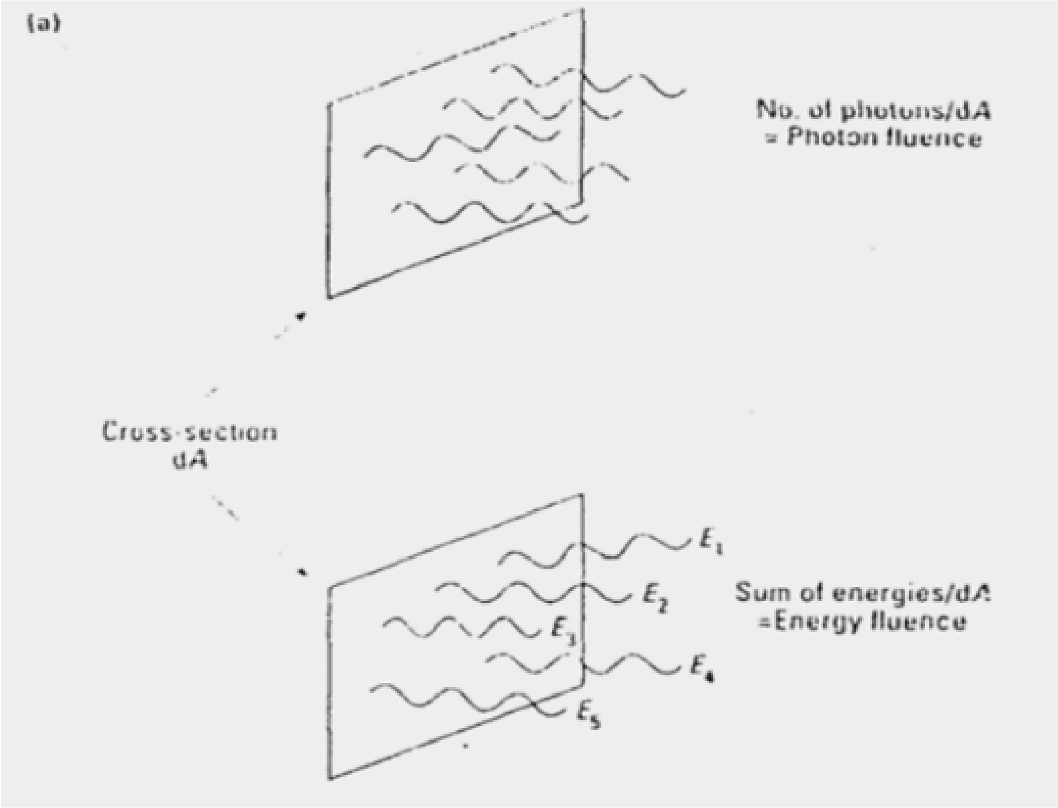
The diagram represents a beam emanating from a point source (S). As the beam moves further from the source it spreads (area B is larger than area A)

Photon fluence = number of photons per unit area at a given time and given cross-section of beam (e.g. **number** of photons in area A or B).

Energy fluence = total amount of **energy** of different photons at a given time at a given cross-section of the beam per unit area (**total energy** of photons in area A or B).

Energy fluence rate (aka beam intensity) = total **energy per unit area** passing through a cross section **per unit time** (watts/mm^2) (**total energy per second** of photons in area A or B).

Beam intensity =energy fluence rate is the total amount of energy per unit area traveling per unit time (strength of the beam)



Inverse square law

As the beam moves further from the source the area of the beam increases.
The area of the beam is the distance squared.

$$A \propto d^2$$

Key:
A = area
d = distance

This means the same number of photons are spread over a larger area and the strength of the beam decreases (the intensity is inversely proportional to the area).

$$\text{intensity} \propto 1 / A$$

Putting the two equations together gives:

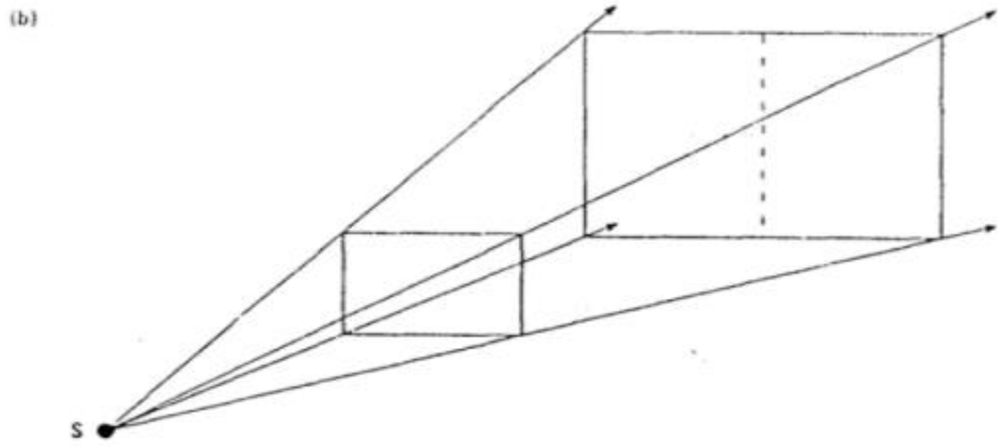
$$\text{intensity} \propto 1 / d^2$$

This relationship between the distance from the source and the energy of the beam is the **inverse square law** as the intensity is inversely proportional to the distance from the source squared.

Energy fluence and intensity are not easy to measure directly. Instead, an easier indirect measurement is made:

☒ ***'Air kerma'*** instead of energy fluence. ☒ ***"Air kerma rate"*** instead of intensity.

INVERSE SQUARE LAW



- ***The intensity of the radiation is inversely proportional to the square of the distance from a point source***
- When the distance is changed:

$$\frac{\text{New intensity}}{\text{Old intensity}} = \frac{(\text{Old distance})^2}{(\text{New distance})^2}$$

or

$$\frac{\text{New air kerma rate}}{\text{Old air kerma rate}} = \frac{(\text{Old distance})^2}{(\text{New distance})^2}$$

∴ ***Halving*** the distance quadruple's the intensity or air kerma rate & ***doubling*** the distance reduces them by a factor of 4.

N.B.

Only the intensity of the x-ray will decrease with distance but the energy of the photons not change.

- Electromagnetic rays originate from a point source and diverge out, traveling in a straight line, unless attenuated.
- The inverse square law states that the intensity of radiation emitted from a point source will reduce in intensity, proportional to the square of the distance from that point, i.e. the area covered by the beam increases as the rays are diverging from a point; however, the number of photons remains the same and hence their intensity reduces.

- Important points to remember regarding the inverse square law are:

i. Radiation comes from a point source.

ii. There is no absorption or scatter of radiation between a source and point of measurement.