EBreast II

Radiation physics

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Introduction

- Physical constants, definitions and prefixes
- Subatomic particles
- Properties of electromagnetic radiation
- The electromagnetic spectrum
- Types of ionising radiation

Introduction

- The atomic model
- Excitation, ionisation and binding energy
- Radionuclides and radioactivity
- Production of x-rays

Introduction

- The inverse square law
- Attenuation and half-value layer
- Interactions between photons and matter
- Interaction between charged particles and matter

Introduction

- Absorbed dose
- Equivalent dose
- Effective dose
- Depth dose curves
- Monitor Unit (MU)

Physical constants

- Planck's constant: $h \approx 6.63 \cdot 10^{-34}$ J·s
- Speed of light: $c \approx 3.0 \cdot 10^{8}$ m/s
- Elementary charge $e \approx 1.6 \cdot 10^{-19}$ C

Definitions

- 1 eV equals the amount of kinetic energy one electron will gain when it is accelerated from rest through an electric potential difference of 1 V in vacuum.
- 1 eV ≈ $1.6 \cdot 10^{-19}$ J

- The resting energy (E) of a particle is the rest mass (m) of the particle multiplied by the speed of light squared (c):
- $E = mc^2$

(1)

Prefixes

The most common prefixes are

- Giga (G) : one billion $=10^9$
- Mega (M): one million $=10^6$
- Kilo (K): one thousand $=10^3$
- milli (m): one thousandth $= 10^{-3}$
- micro (μ): one millionth $=10^{-6}$
- nano (n): one billionth $=10^{-9}$

Subatomic particles

Particle	Symbol	Comments
Proton	p	Nucleon (found in the nucleus of atoms)
Neutron	n	Nucleon (found in the nucleus of atoms)
Alpha-particle	α	Two protons and two neutrons, ejected in α-decays of heavy radioactive nuclei
Electron	e^- or β^-	Located in the atomic shells. Ejected in β-decays of radioactive nuclei
Positron	e^+ or β^+	Antiparticle of the electron, produces annihilation radiation when the two interact. Ejected in β^+-decays of some short-living artificial produced radioactive nuclei
Neutrino	υ	Emitted during β-decays, has very weak attenuation in matter
Photon/ quantum	h·υ	Travels at the speed of light, electromagnetic radiation

Subatomic particles

Particle	Symbol	Rest mass [kg]	Rest energy [MeV]	Charge *
Proton	p	$1.672 \cdot 10^{-27}$	938	+1
Neutron	n	$1.675 \cdot 10^{-27}$	939	0
Alpha-particle	α	$6.645 \cdot 10^{-27}$	3718	+2
Electron	e^- or β^-	$9.109 \cdot 10^{-31}$	0.511	-1
Positron	e^+ or β^+	$9.109 \cdot 10^{-31}$	0.511	+1
Neutrino	υ	0?	0?	0
Photon/ quantum	h·υ	0	0	0

* Number of elementary charges (1)

What is radiation?

- Radiation is emission of energy from a radiative source to another medium or through space.
- The energy is in the form of waves or subatomic particles

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Radiation

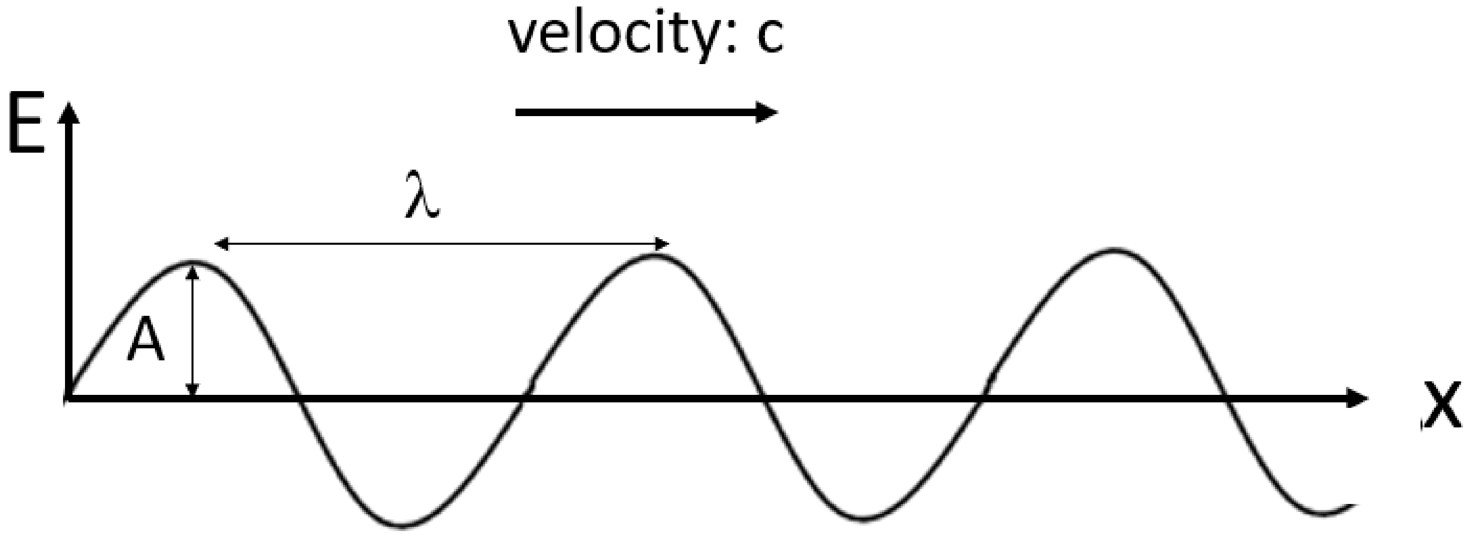
- Ionising versus non-ionising radiation
  - Only ionising radiation is used in the treatment of cancerous tumours
- Electromagnetic radiation versus particle radiation
- Indirect versus direct ionising radiation

(1,2)

Properties of electromagnetic radiation

- Wave-like properties:
  - cycle
  - wavelength λ
  - frequency ν
  - amplitude A
- $c = \lambda \cdot \nu$

- Particle-like properties:
- Photon energy $E = h \cdot \nu$
- $E = \frac{hc}{\lambda}$



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The electromagnetic spectrum

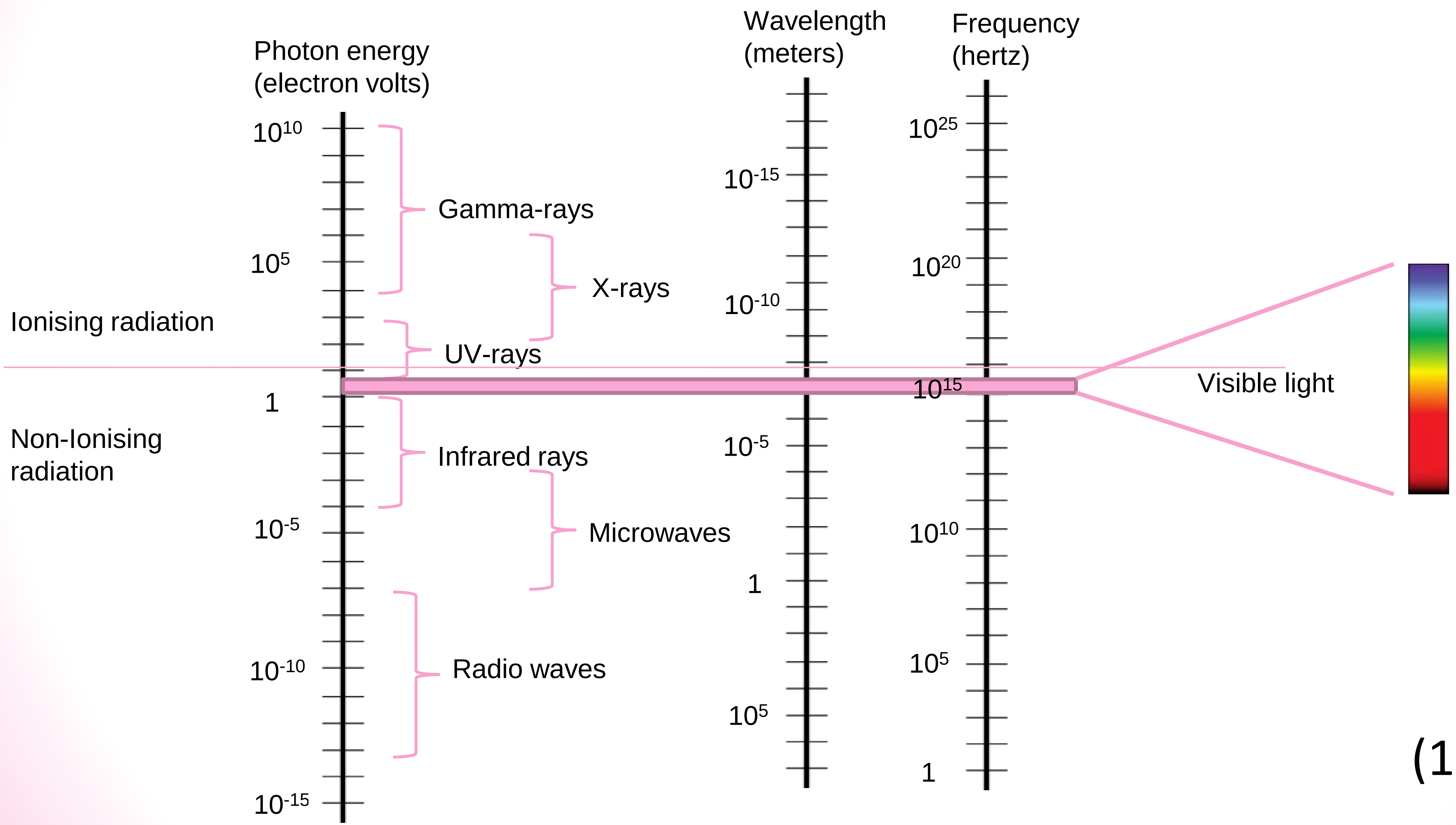
Can be divided into two parts:

1) Ionising radiation (high enough energy to ionise atoms in tissue)
   - Gamma-rays
   - X-rays
   - High-energy ultraviolet (UV) rays (energy>12 eV)

2) Non-ionising radiation
   - Low-energy ultraviolet (UV) rays
   - Visible light
   - Infrared radiation
   - Microwaves
   - Radio waves

(1,2,3)

The electromagnetic spectrum



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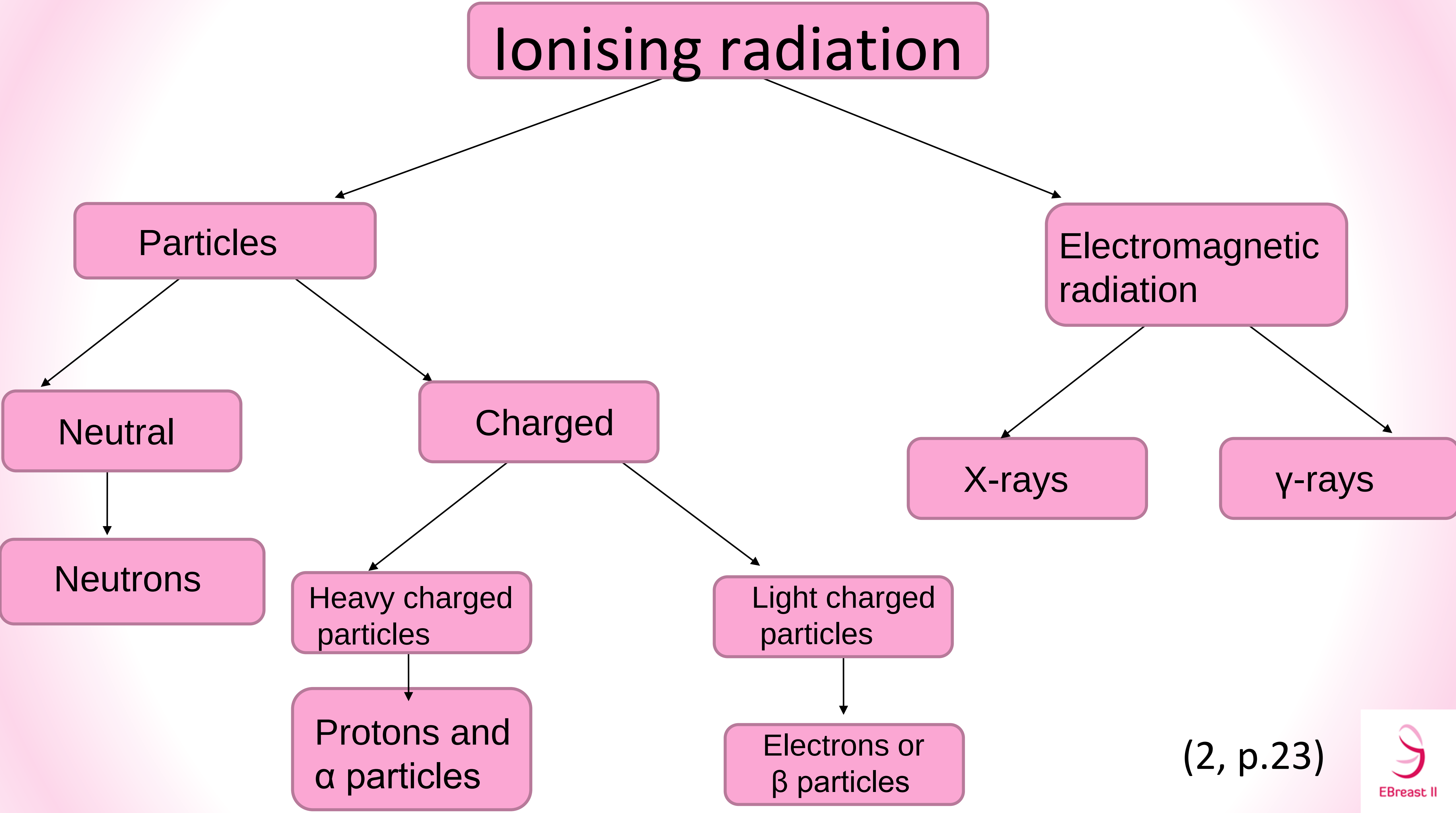
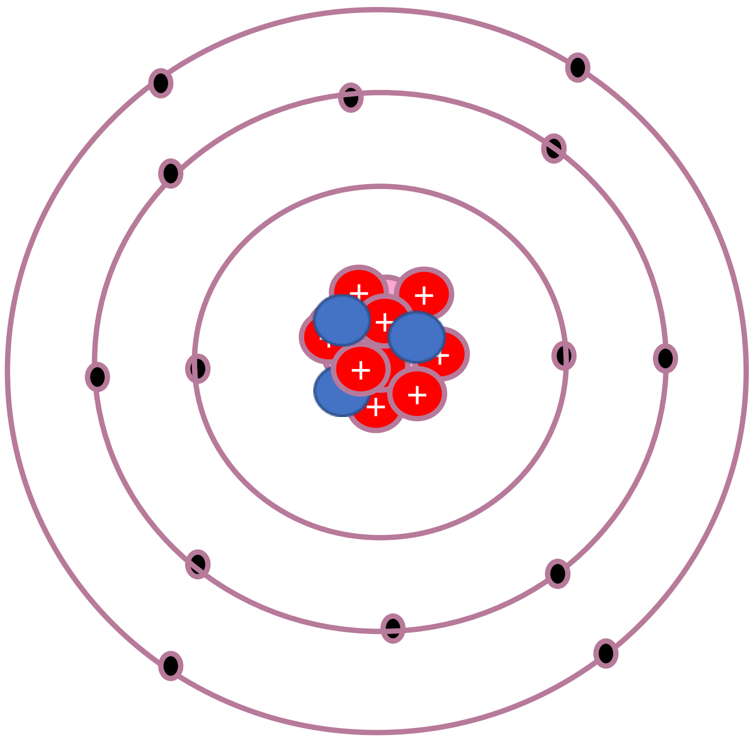

Ionising radiation
Particles
Electromagnetic radiation
Neutral
Charged
X-rays
γ-rays
Neutrons
Heavy charged particles
Light charged particles
Protons and α particles
Electrons or β particles

(2, p.23)

The atomic model



(Sizes are not in scale, colours are for demonstration purposes only)

- Positively charged nucleus, containing
  - Positively charged protons
  - Neutrons (neutral)
- Surrounded by negatively charged electrons
- Atom is neutral
- Diameter of the atom: order of magnitude 10^{-10} m
- Diameter of the nucleus: order of magnitude 10^{-14} m

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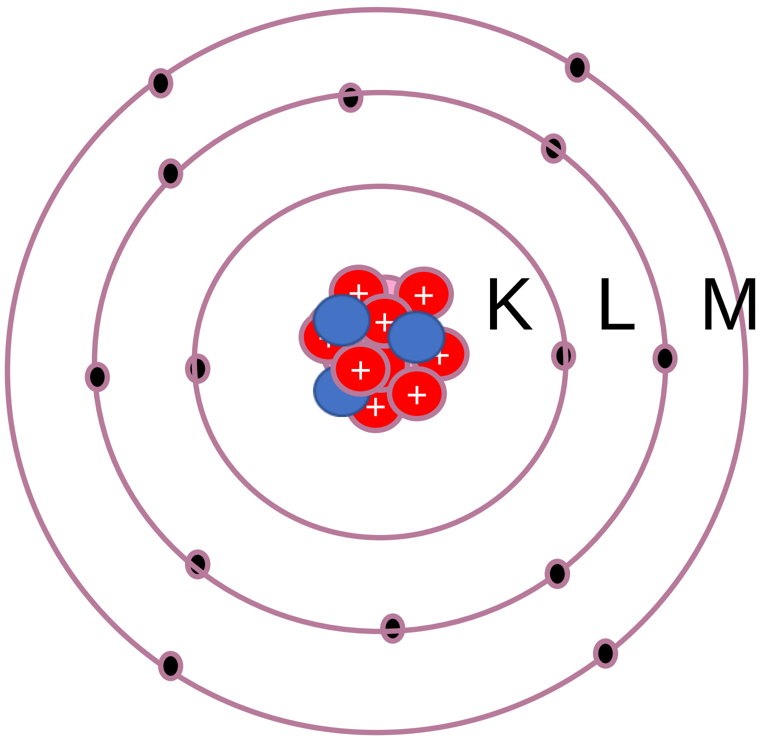
The atomic model- electron shells



Shell number (n)	Shell	Max no. of electrons	$2n^2$
1	K	2	2
2	L	8	8
3	M	18	18
4	N	32	32

- Shell number n cannot contain more than $2n^2$ electrons
- Outer shell cannot contain more than 8 electrons

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Excitation, ionisation and binding energy

- Excitation of the atom: A raise in the energy of one electron caused by collisions or interactions causes the electron to move to a shell at a higher energy level.
- Ionising of the atom: An interaction between the atom and ionising radiation causes an electron in an a shell to receive sufficient energy in order to escape the atom, creating an ion and a free electron.
- The binding energy in an atomic shell is defined as the amount of energy that the electron in the shell must receive in order to be released from the atom.
- The binding energy is larger in the K shell than in the L shell, and larger in the L shell than the M shell, and so on.

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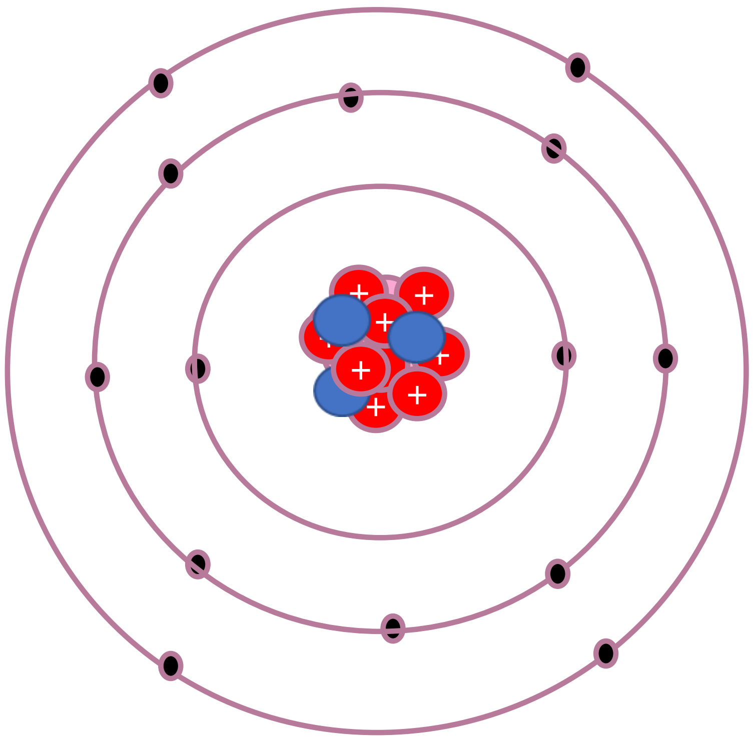
Elements and isotopes

$^{A}_{Z}X$



- An element is a nucleus with a given value of the atomic number Z.
- The isotope X has Z protons and A nucleons (protons and neutrons)
- Z is the atomic number
- A is the mass number
- Number of neutrons =A-Z
- Number of electrons in the neutral atom =Z

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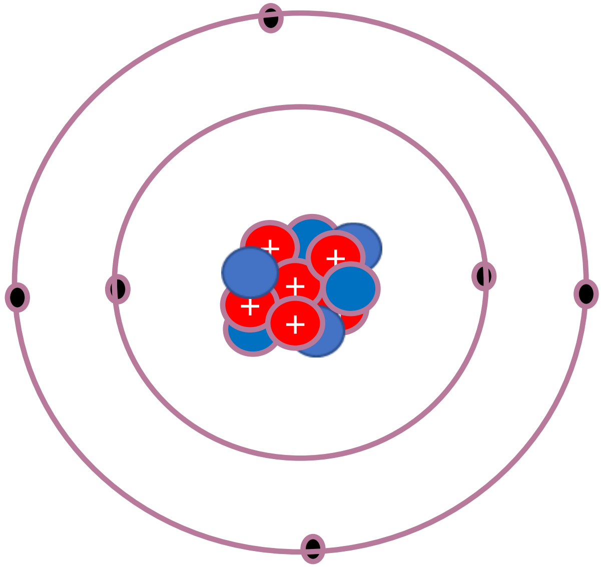
Isotopes- example

$^{12}_{6}C$



- The Carbon-12 isotope has 12 nucleons = mass number 12
- Number of protons = atomic number is 6
- Number of neutrons = 12-6 =6
- Number of electrons in the neutral carbon atom is the same as number of protons =6

(1)

Radionuclides

- Radionuclides (radioisotopes) are unstable nuclides that can emit radiation spontaneously
- This emission is also called radioactive decay, and can be particle radiation (α-, or β- decay) or electromagnetic radiation (γ- decay)
- The radionuclides are unstable because
    - the ratio between the number of protons and neutrons in the nucleus is not "ideal“
    - or because the nucleus has excess energy after emitting particle radiation

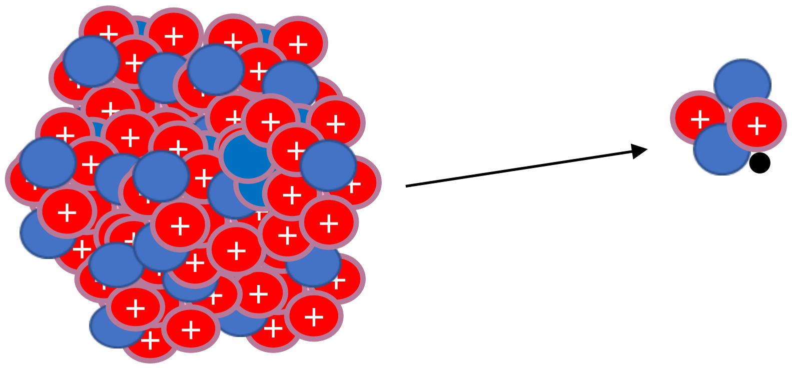
(1,2,3)

Activity and half-life

- Activity of a radioactive isotope is measured in numbers of decays per second. The unit is called Bequerel (Bq), 1 Bq is defined as 1 decay per second. (1 Bq = s^{-1})
- Half-life of a radioactive isotope is defined by the time it takes before the number of remaining nuclei that have not emitted radiation is halved.

(1,2,3)

Alpha-decay



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- Heavy unstable nuclei (A>150) with excess of protons relative to neutrons emits α-radiation
- The α-particle is a helium nucleus, consisting of two protons and two neutrons
- Daughter nucleus: Z reduced by 2, A reduced by 4

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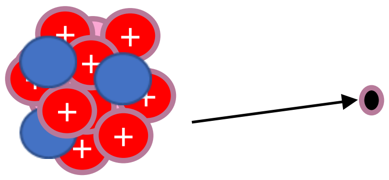
Beta minus decay



- Lighter unstable nuclei with an excess of neutrons relative to protons emits β^- -radiation
- The β^- -particle is an electron
- $n \rightarrow p + \beta^- + \bar{\upsilon}$
- Daughter nucleus: Z increased by 1

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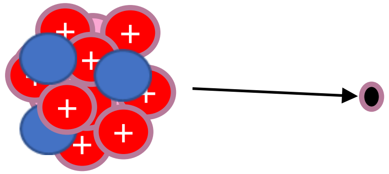
Beta plus decay



- Lighter unstable nuclei with an excess of protons relative to neutrons emits β^+ -radiation
- These radionuclides are artificially produced in cyclotrons
- The β^+ -particle is a positron, the anti-particle of the electron
- $p \rightarrow n + \beta^+ + \upsilon$
- Daughter nucleus: Z decreased by 1

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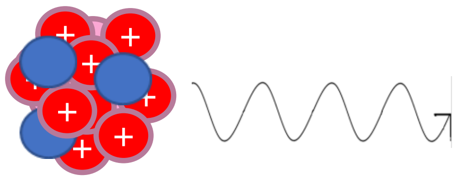
Gamma decay



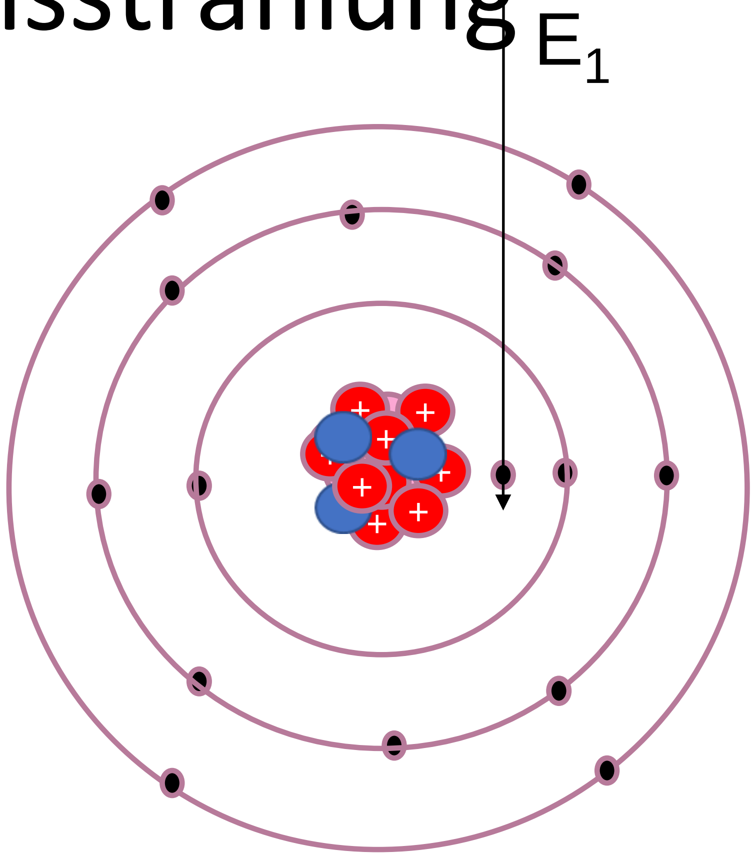
- Nuclei with excess energy after emitting particle radiation
- Excess energy is emitted as electromagnetic radiation, photons, γ-rays

The formation of X-rays

- Electrons are accelerated to high kinetic energy in the linear accelerator (LINAC) or in an x-ray tube and hits a target of heavy metal (often Tungsten)
- Interactions between the electrons and target atoms leads to the formation of X-rays by these two processes:
    - Bremsstrahlung
    - Characteristic radiation

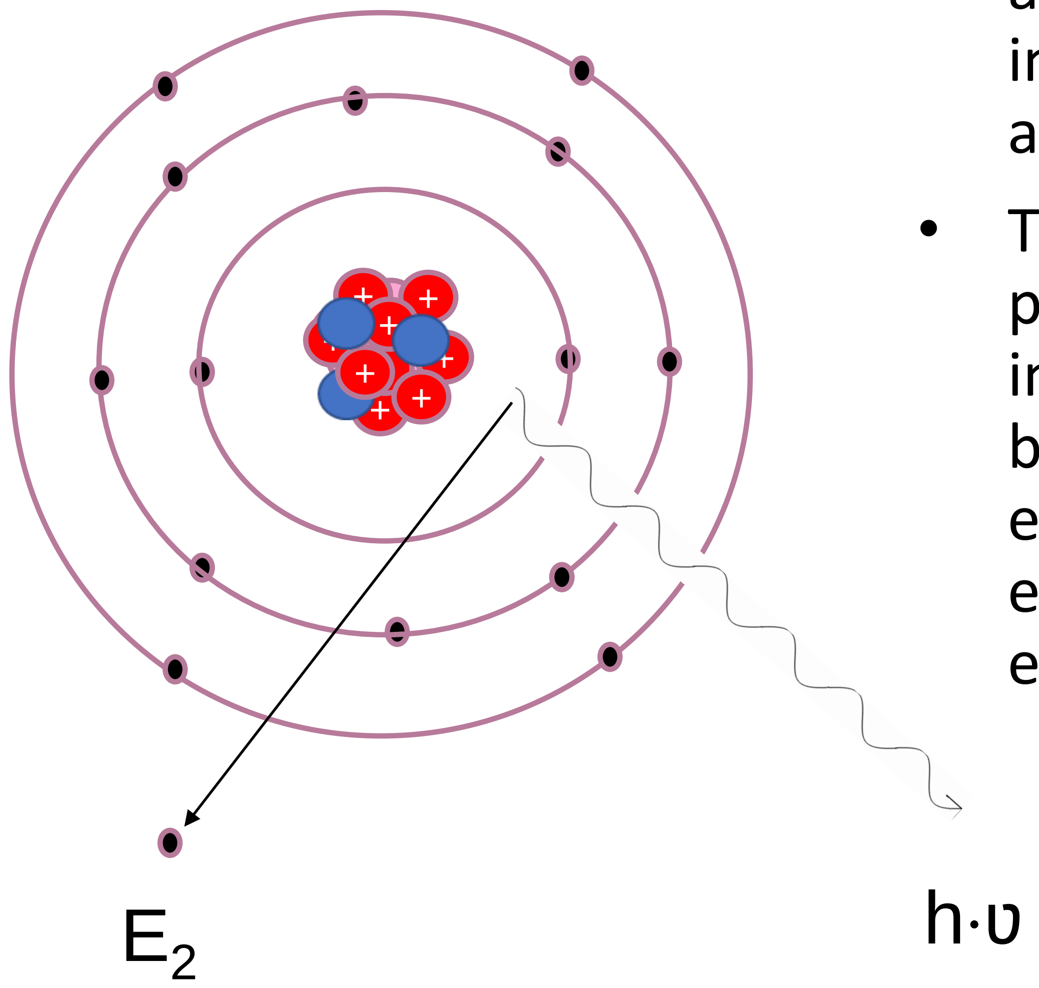
(1,2,3)

Bremsstrahlung



- Bremsstrahlung, or braking radiation, is produced when the incoming electron passes near the nucleus of the target atom.

Bremsstrahlung



- The electron loses kinetic energy, and this energy loss is converted into photon energy in the form of an X-ray photon.
- The total energy is conserved in the process, so the energy of the incoming electron E_1, is divided between the X-ray photon and the electron after the process. The electron continues with a reduced energy E_2.

$$E_1 = E_2 + h \cdot \upsilon$$

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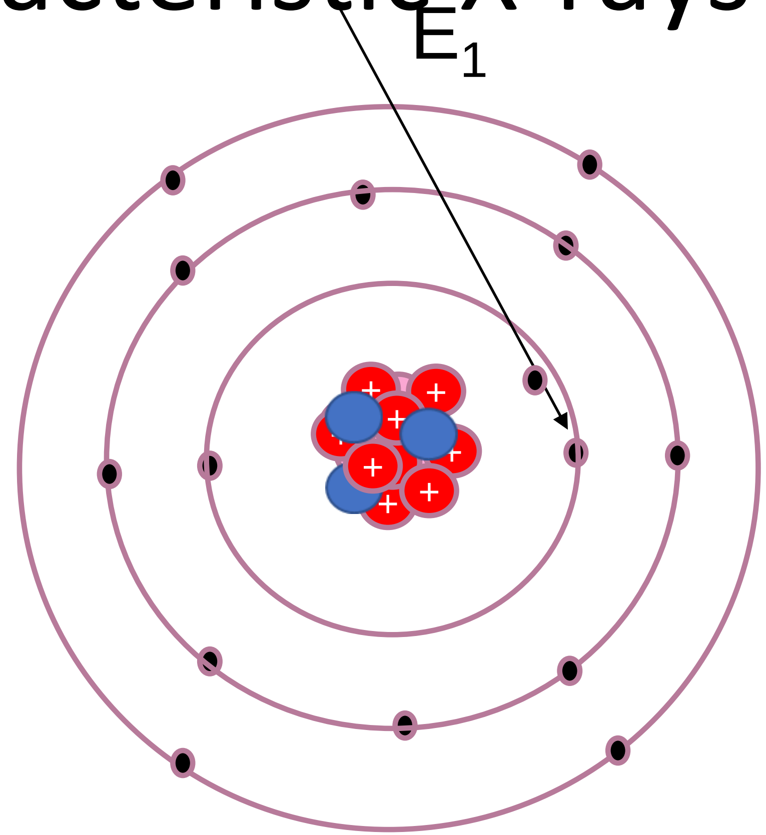
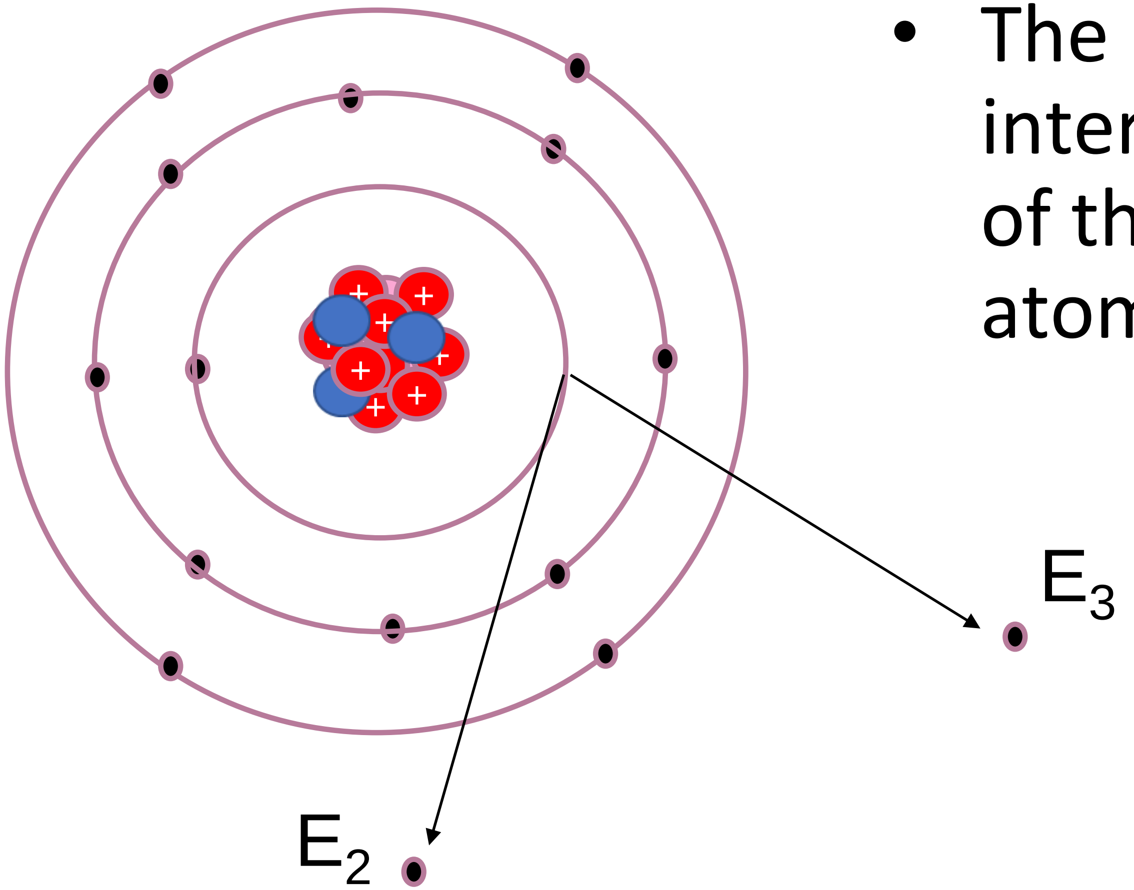
Characteristic X-rays



- Characteristic radiation is created after an ionising process.

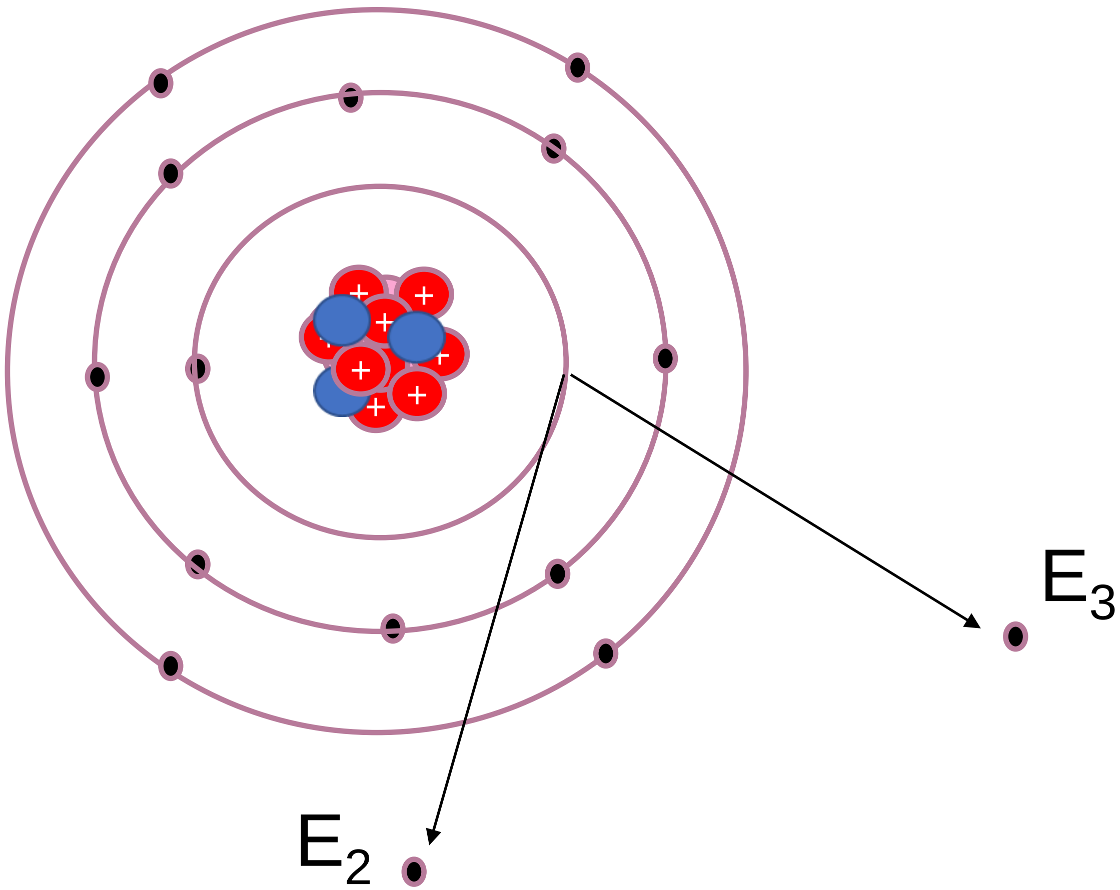
Characteristic X-rays



- The incoming electron interacts with an electron of the target atom, and the atom is ionised.

$$E_1 = E_2 + E_b + E_3$$

Characteristic X-rays



- The total energy is conserved in the process, so that the energy of the incoming electron, E_1, is divided between energy of the electron after the process, E_2, the binding energy of the electron ejected from the atom, E_b, and the kinetic energy of the ejected electron, E_3.

$$E_1 = E_2 + E_b + E_3$$

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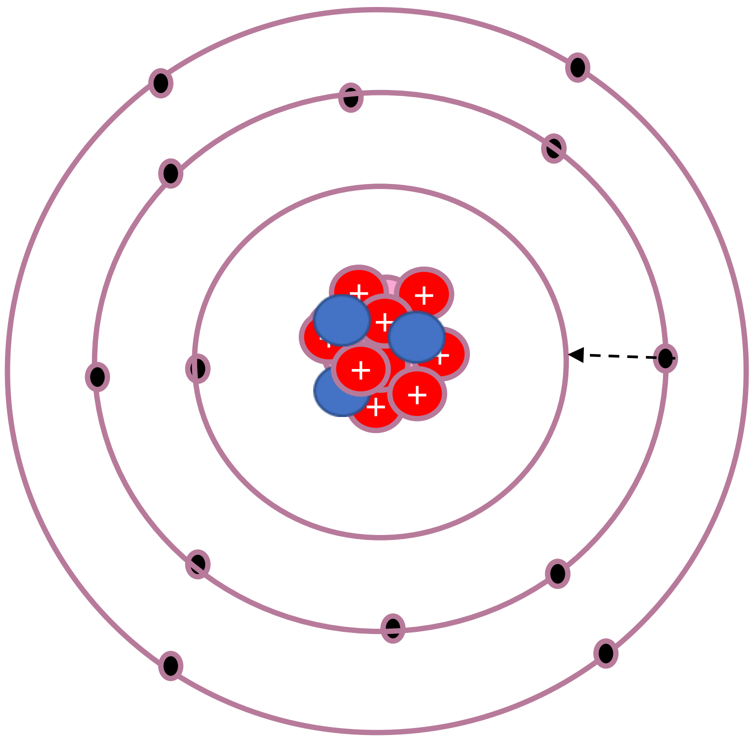
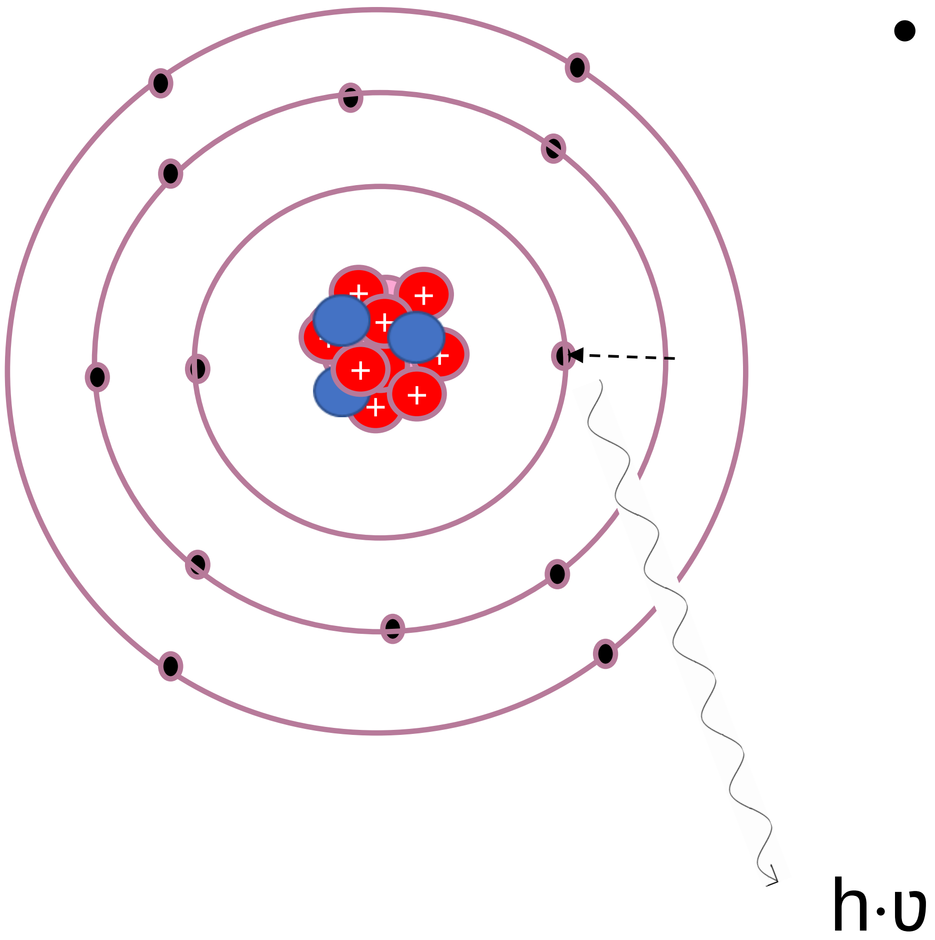
Characteristic radiation



- This ionisation process leaves a vacancy in the shell, and this is immediately filled by an electron from a shell of a higher energy level, which causes the potential energy of this electron to decrease.

Characteristic radiation



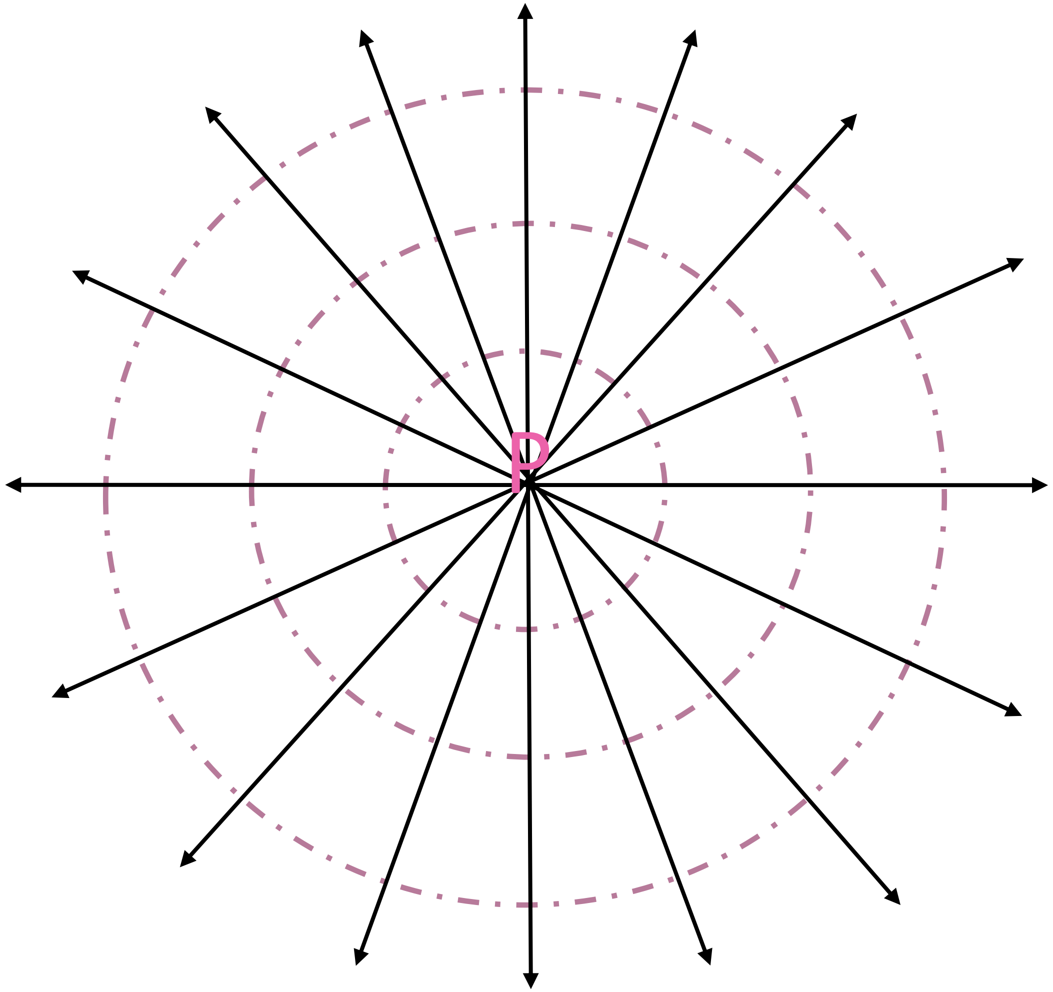
- This transition produces a characteristic X-ray photon. The energy of this photon is equal to the difference in binding energies between the two shells involved in the transition.

$$h \cdot \upsilon = E_b - E_{b2}$$

Radiation intensity

- The intensity of radiation can be defined as the energy associated with radiation that is emitted per unit of surface area and per unit of time.

The inverse square law

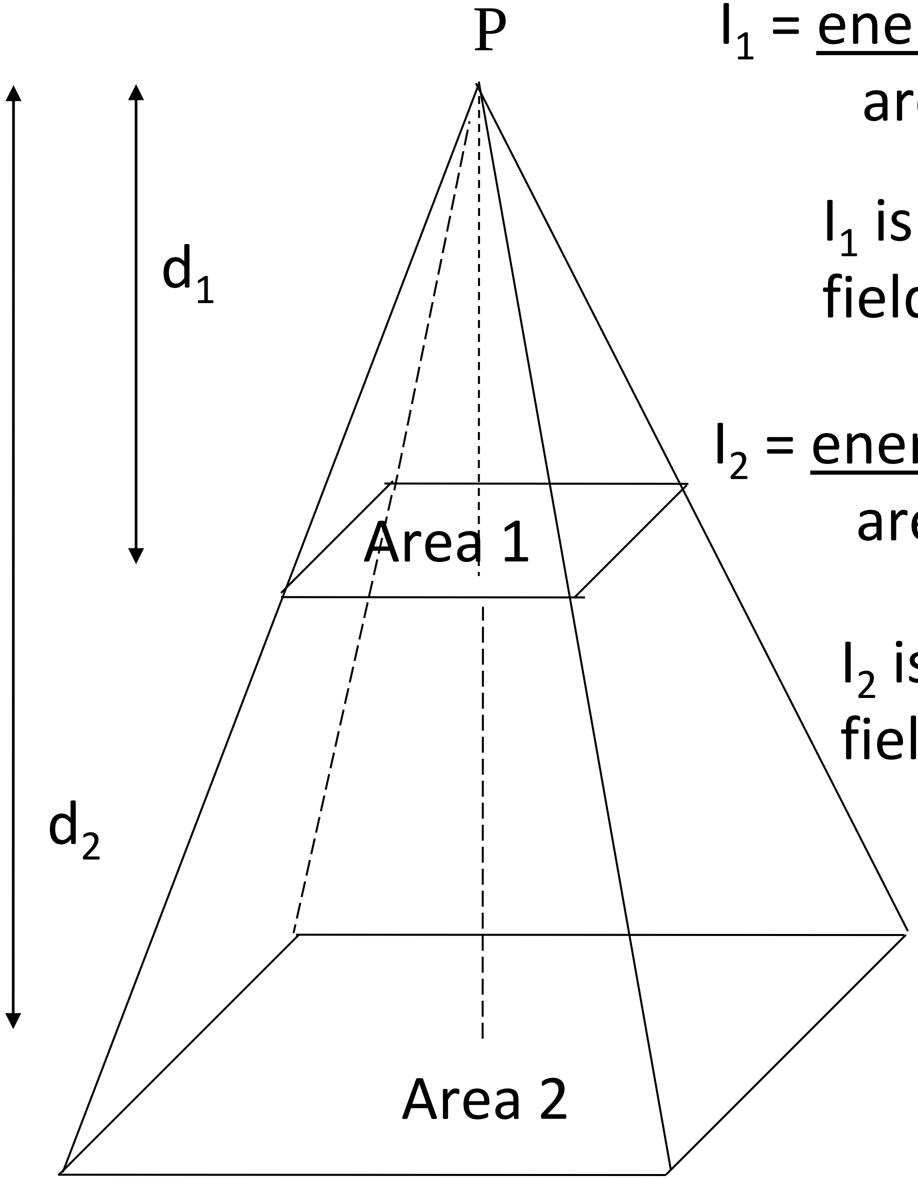


(1,2)

The inverse square law

The intensity of radiation from a point source is inversely proportional to the squared distance

$$\frac{I_2}{I_1} = \frac{Area_1}{Area_2} = \frac{d_1^2}{d_2^2}$$



$I_1 = \dfrac{\text{energy of photons per unit of time}}{\text{area 1}}$

I_1 is the intensity and $area_1$ is the field size at distance d_1

$I_2 = \dfrac{\text{energy of photons per unit of time}}{\text{area 2}}$

I_2 is the intensity and $area_2$ is the field size at distance d_2

(1,2)

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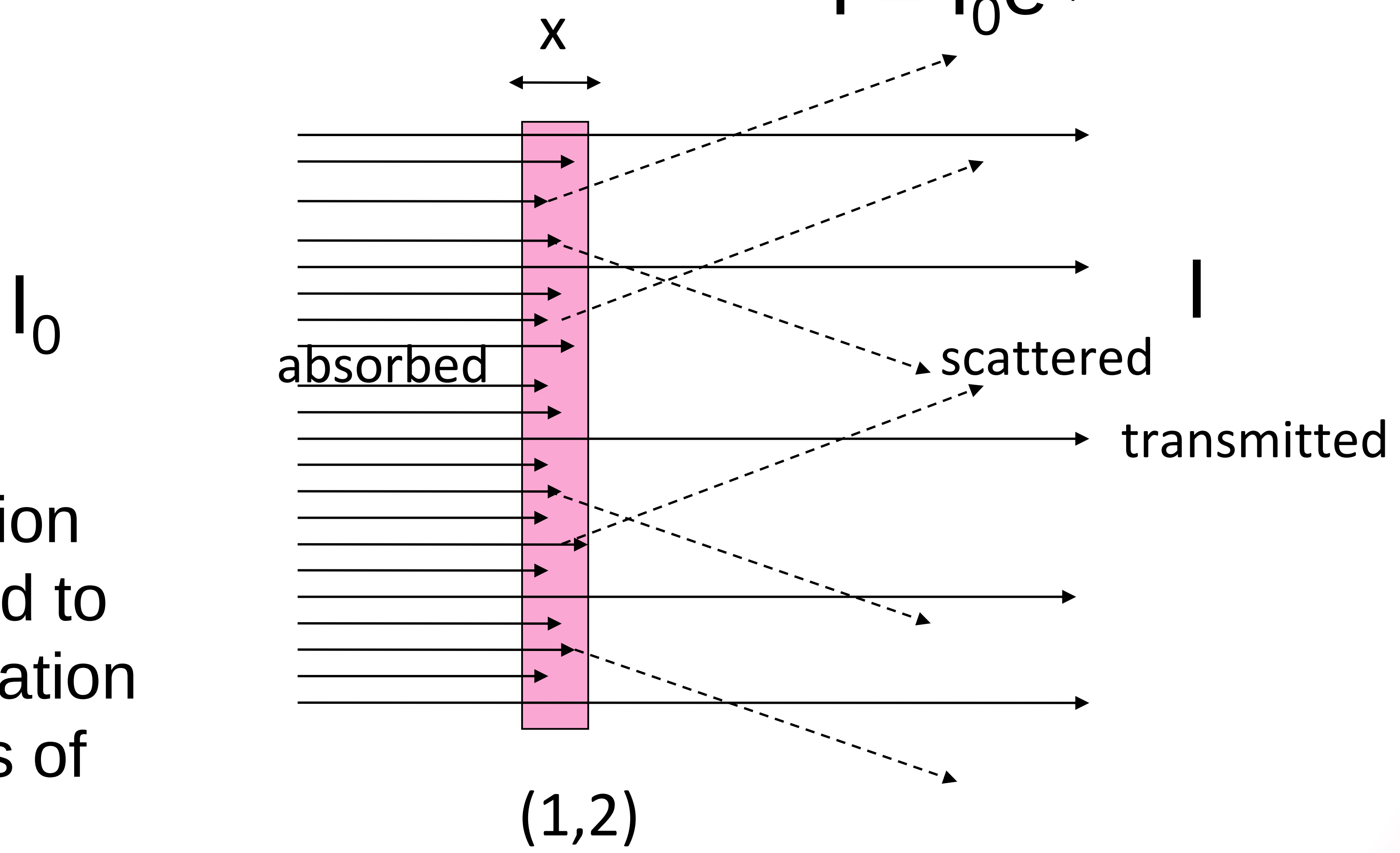
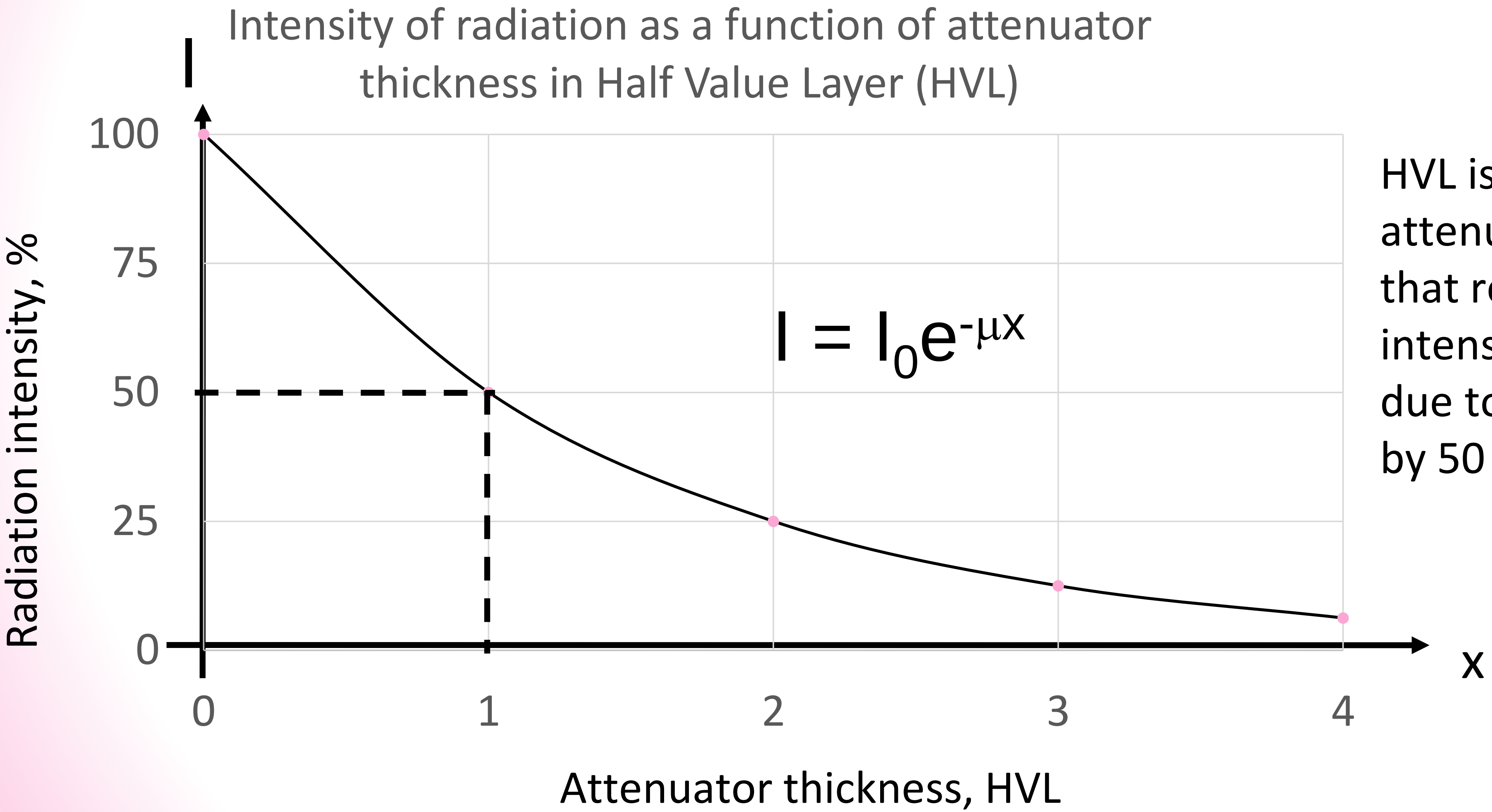
Attenuation of photons (X-rays and γ-rays) through matter

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



μ: linear attenuation coefficient, related to amount of attenuation per unit thickness of matter/tissue

Half Value Layer (HVL)



HVL is defined as the attenuator thickness that reduces the intensity of radiation due to attenuation by 50 %.

(1,2,3)

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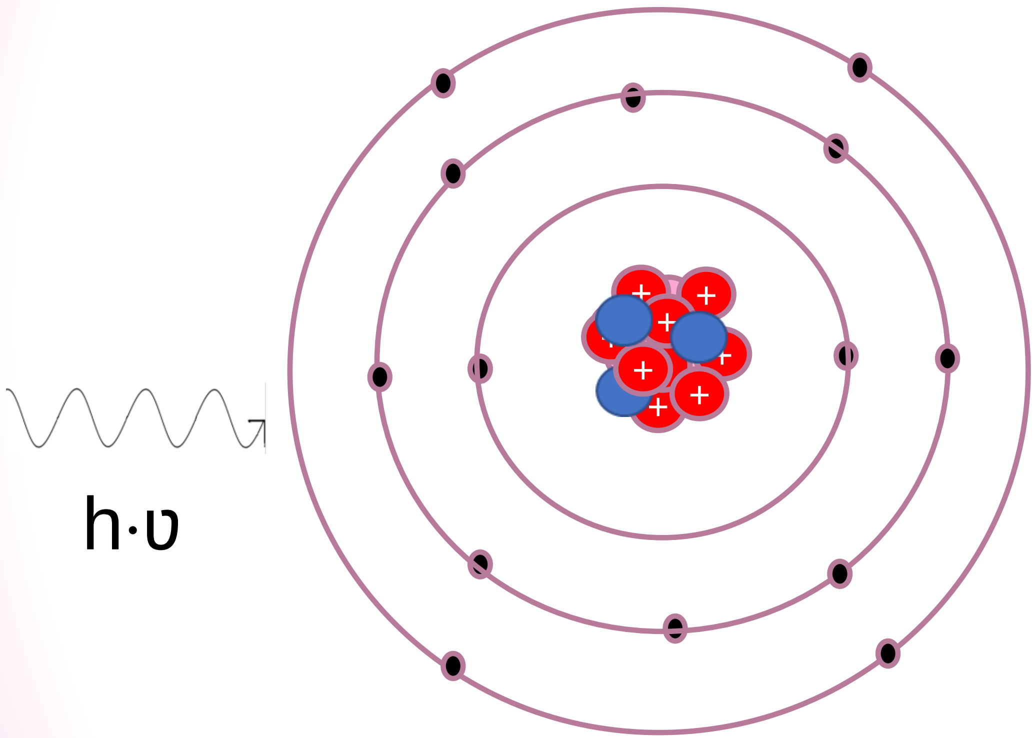
The interaction of photons with matter

- Coherent scattering
- Photoelectric effect
- Compton effect
- Pair production
- Photodisintegration

(1,2,3)

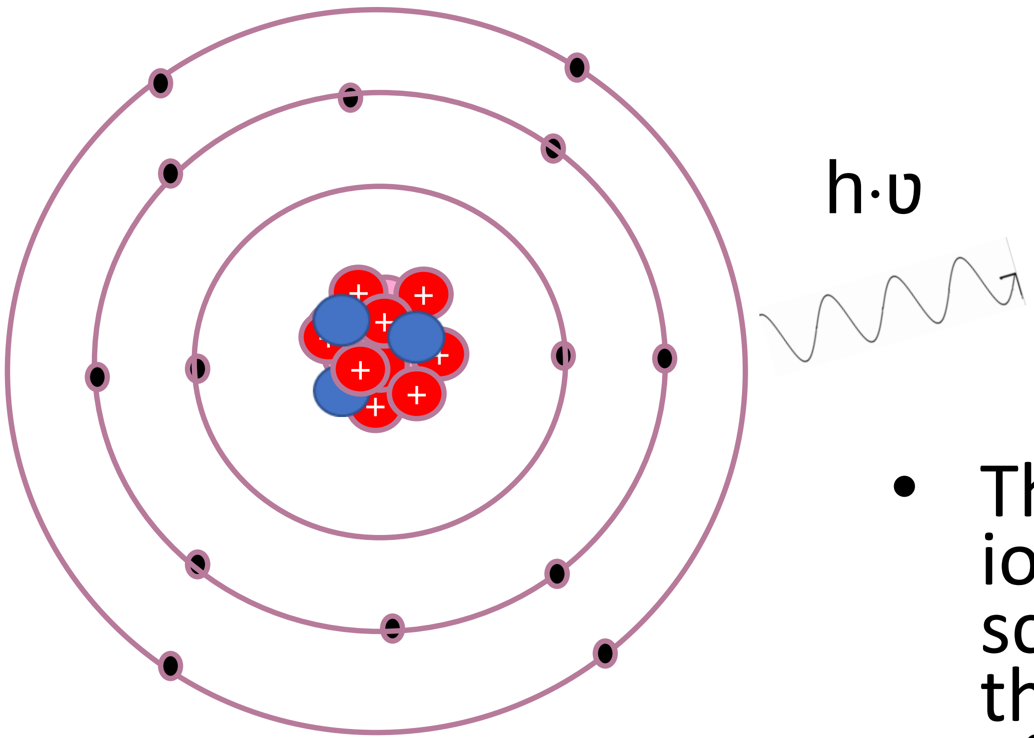
Coherent scattering



- A low-energy photon interacts with the atom, and the energy transferred to the atom is minimum.

(1,2)

Coherent scattering



- The process does not cause ionisation, it contributes to scattering as the direction of the photon is slightly changed after the interaction

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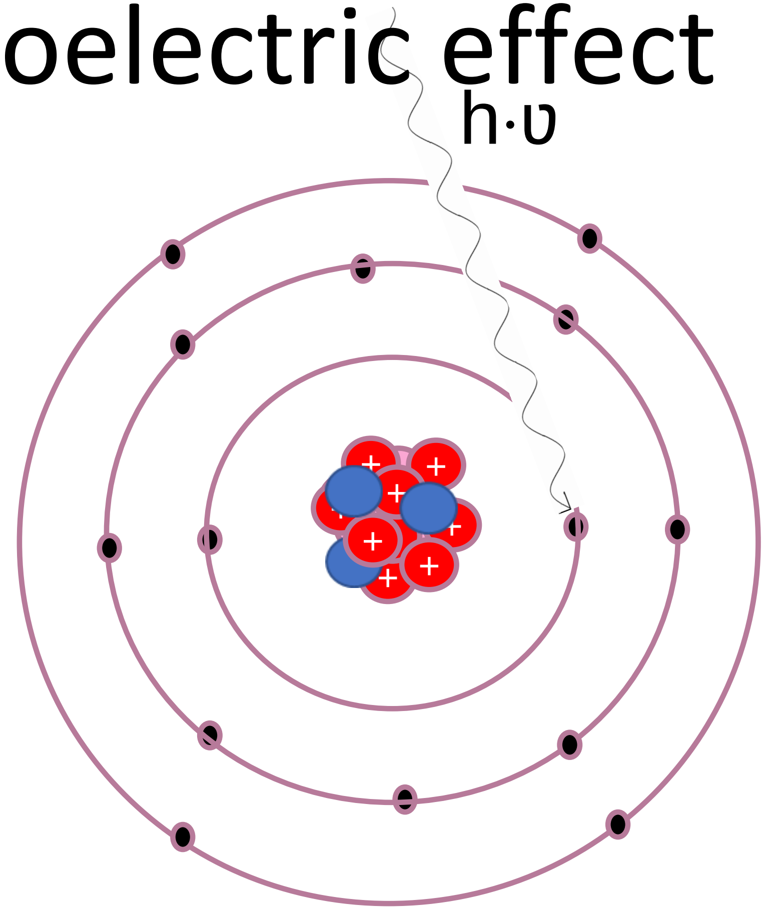
Photoelectric effect

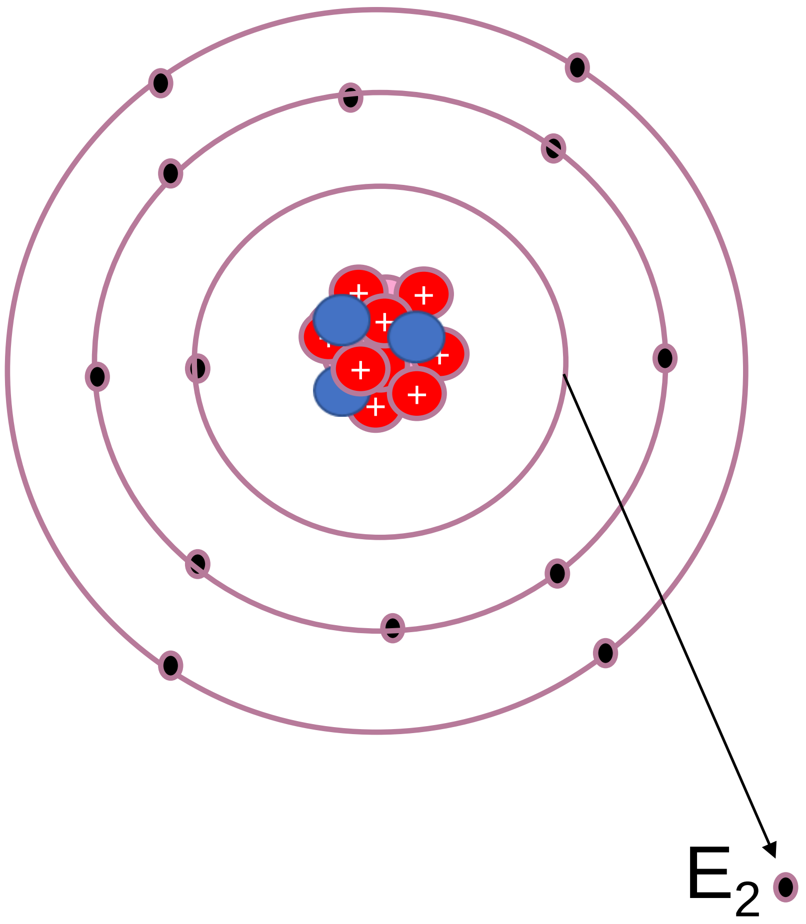


- The photon interacts with an inner orbital electron of the atom.
- All the photon energy is transferred to the electron; thus, the photon disappears.

(1,2,3)

Photoelectric effect

$$h \cdot \upsilon = E_2 + E_b$$



- Results in a positive ion and a free electron.
- $h \cdot \upsilon > E_b$
- If the photon energy ($h \cdot \upsilon$) is larger than the binding energy E_b, the rest of the energy is kinetic energy E_2 to the free electron.

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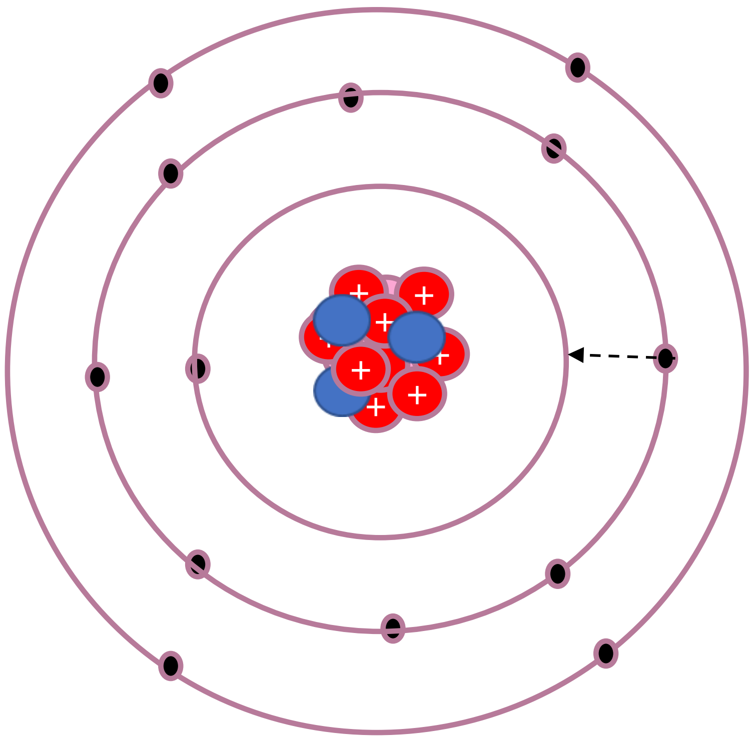
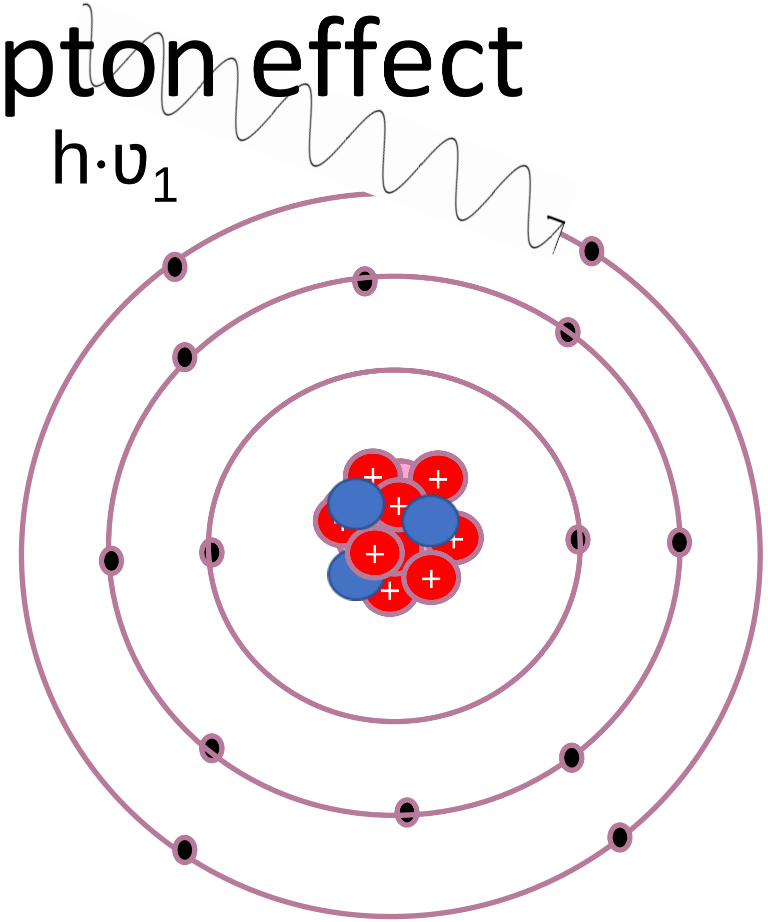
Photoelectric effect



- Vacancy in the shell => characteristic radiation
- The process is most important for lower photon energies and higher atomic numbers.

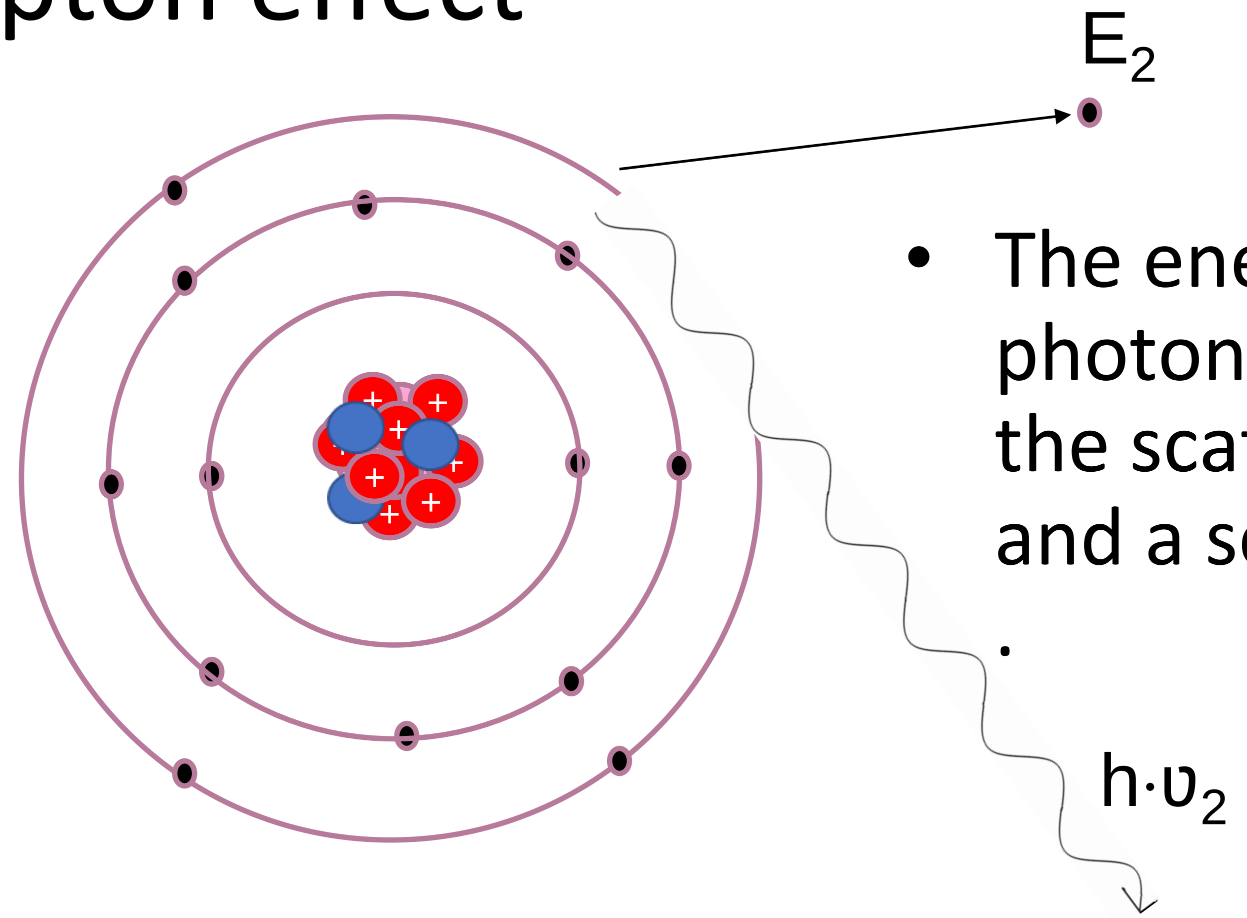
Compton effect



- $h \cdot \upsilon_1 \gg E_b$
- Interaction between a photon and a free electron

(1,2,3)

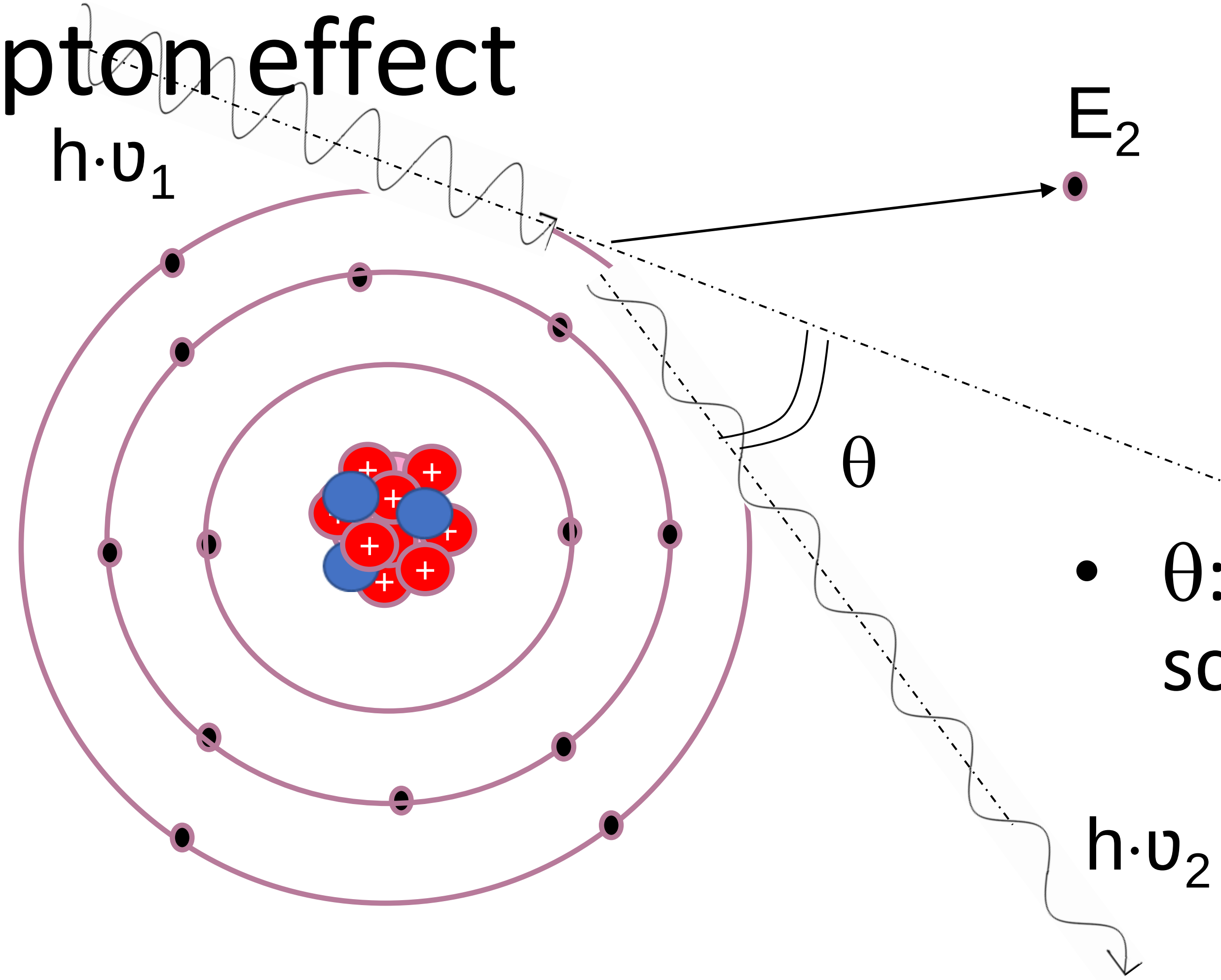
Compton effect



- The energy of an incoming photon $h \cdot \upsilon_{1,}$ is divided by the scattered electron E_2 and a scattered photon $h \cdot \upsilon_2$.

$$h \cdot \upsilon_1 = h \cdot \upsilon_2 + E_2$$

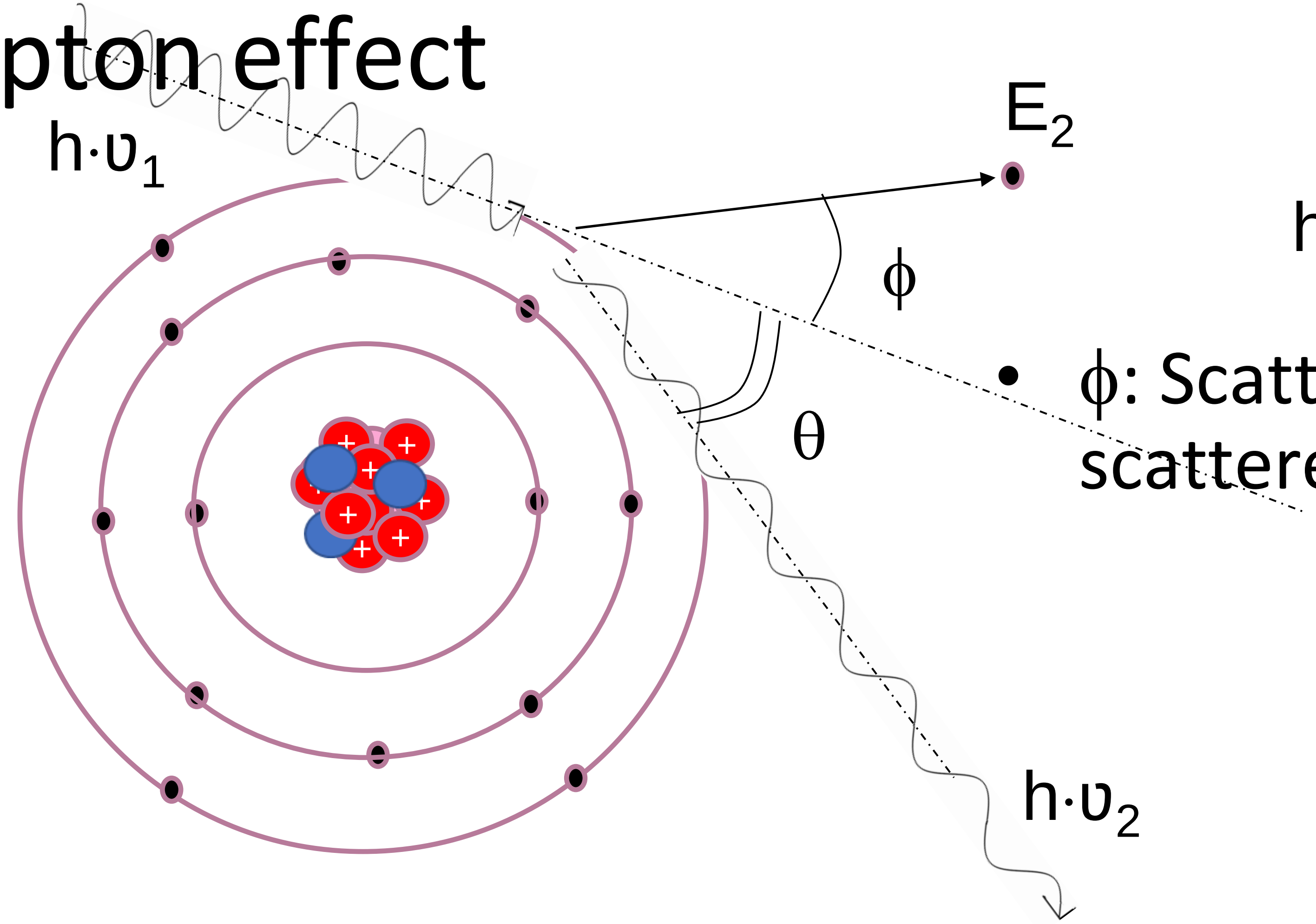
Compton effect



$$h \cdot \upsilon_1 = h \cdot \upsilon_2 + E_2$$

- θ: Scattering angle of the scattered photon

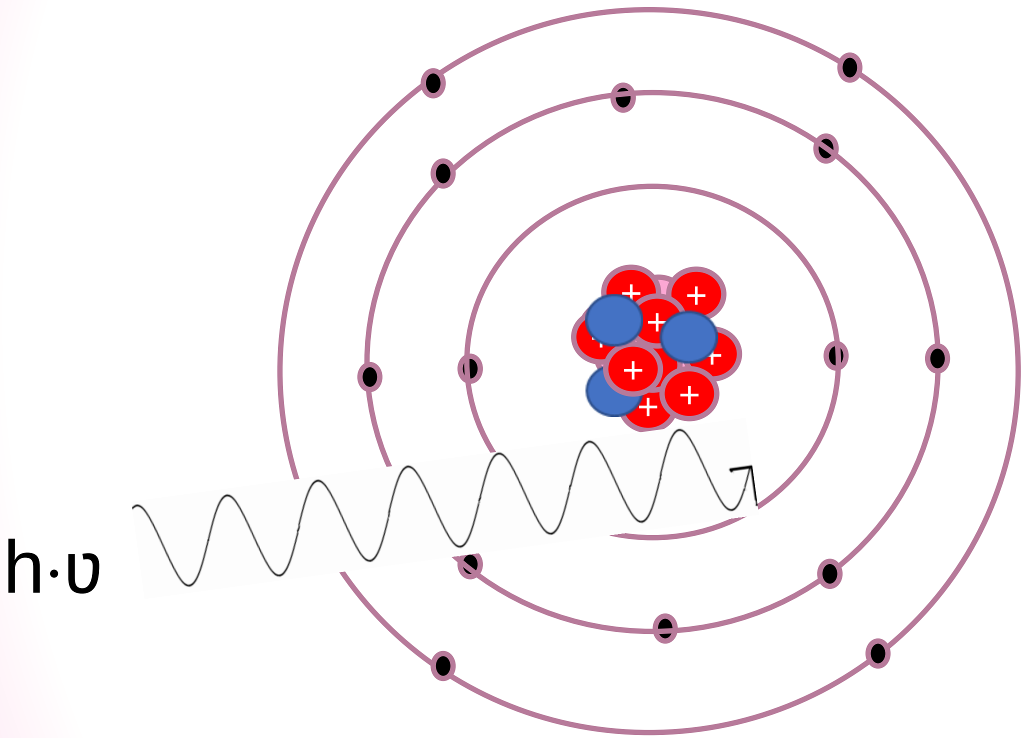
Compton effect



$$h \cdot \upsilon_1 = h \cdot \upsilon_2 + E_2$$

- ϕ: Scattering angle of the scattered electron

Pair production

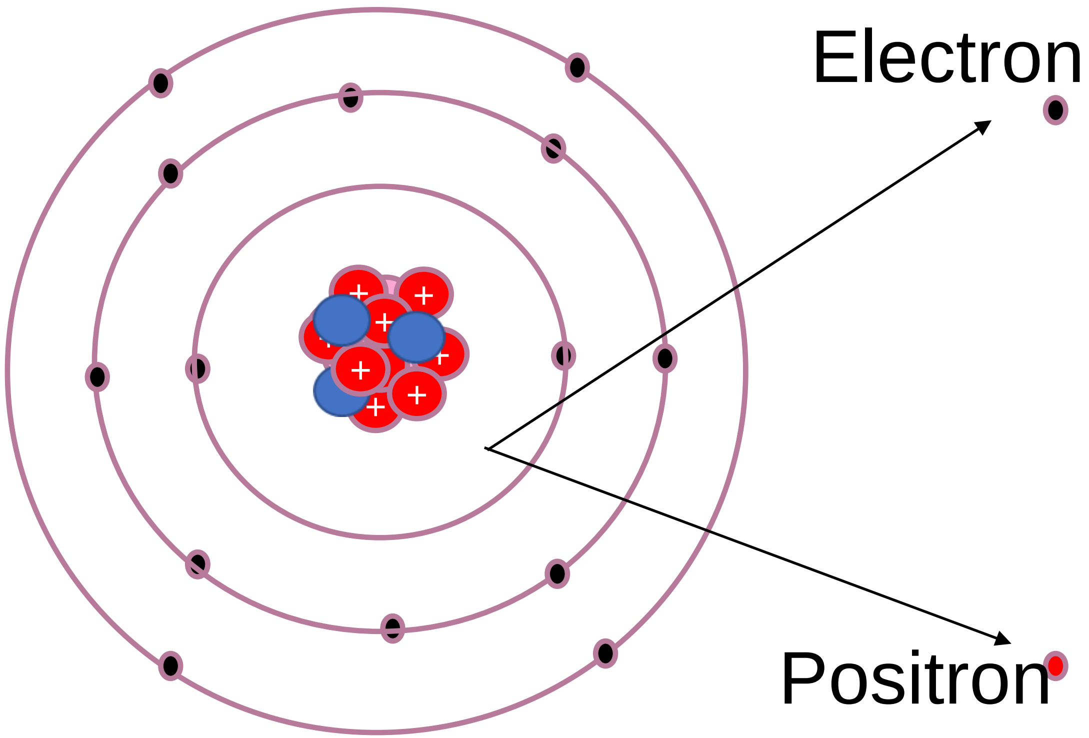


- Photon interacts with the electrical field close to the atomic nucleus

h·υ ≥ 1.022 MeV

(1,2,3)

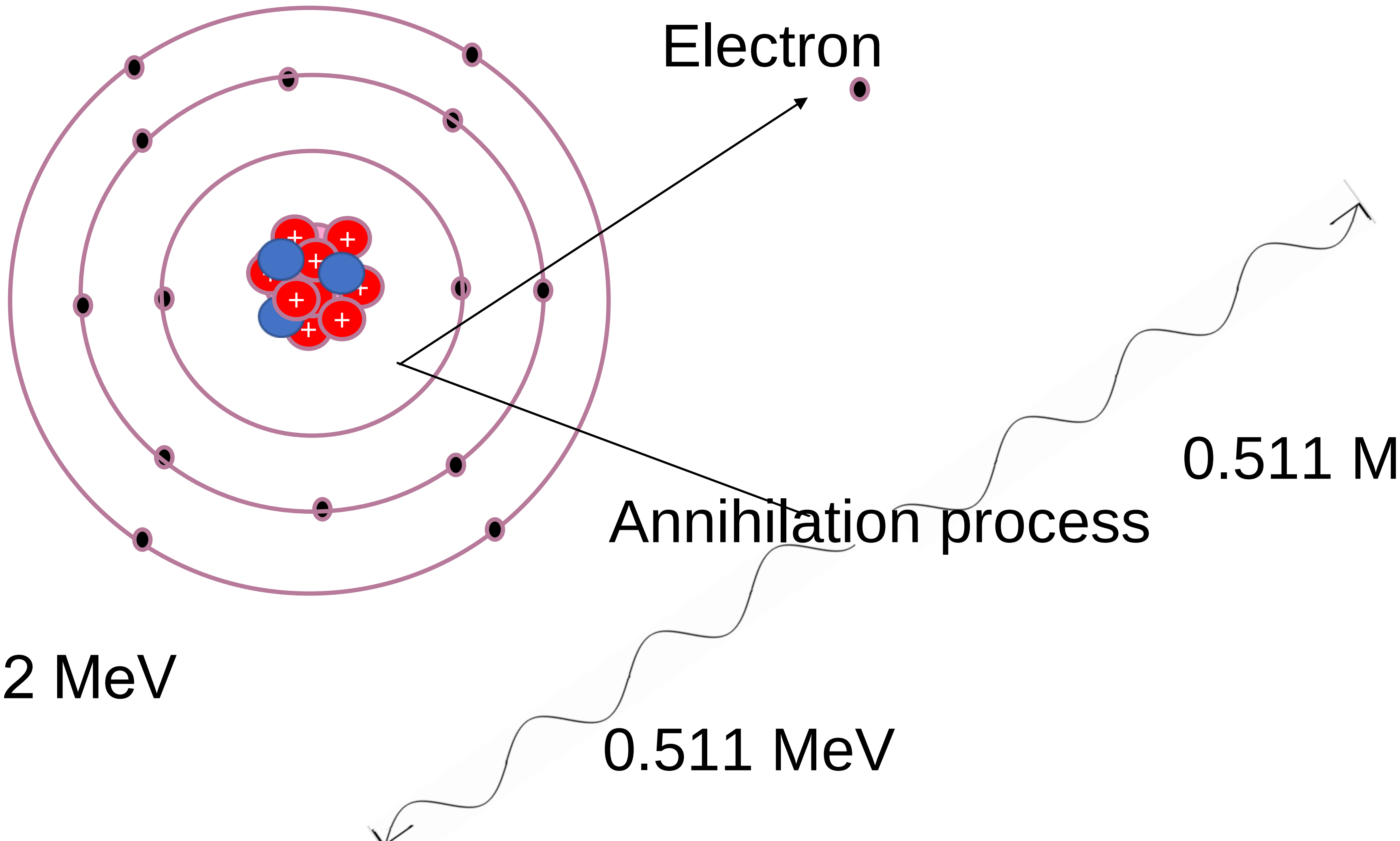
Pair production



- The photon disappears while an electron-positron pair is created.
- $h \cdot \upsilon \geq 1.022$ MeV

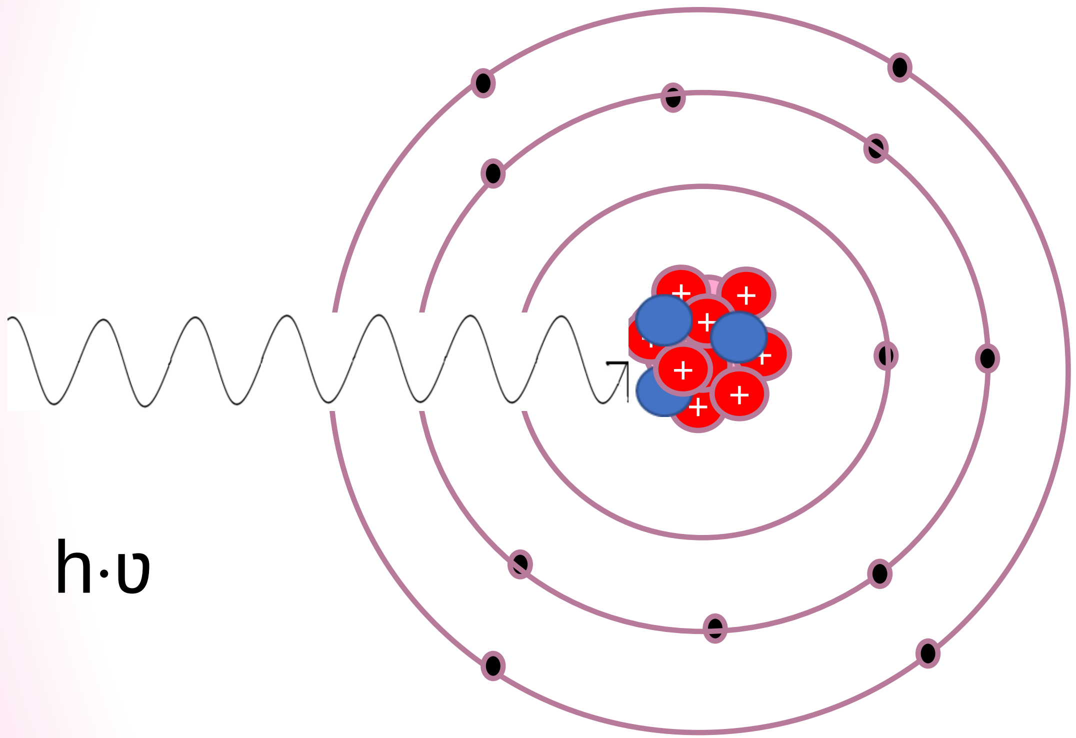
$h \cdot \upsilon \geq 1.022$ MeV

Annihilation



h·υ ≥ 1.022 MeV

Photodisintegration



h·υ ≈ 10-15 MeV

- Photon interacts with the atomic nucleus

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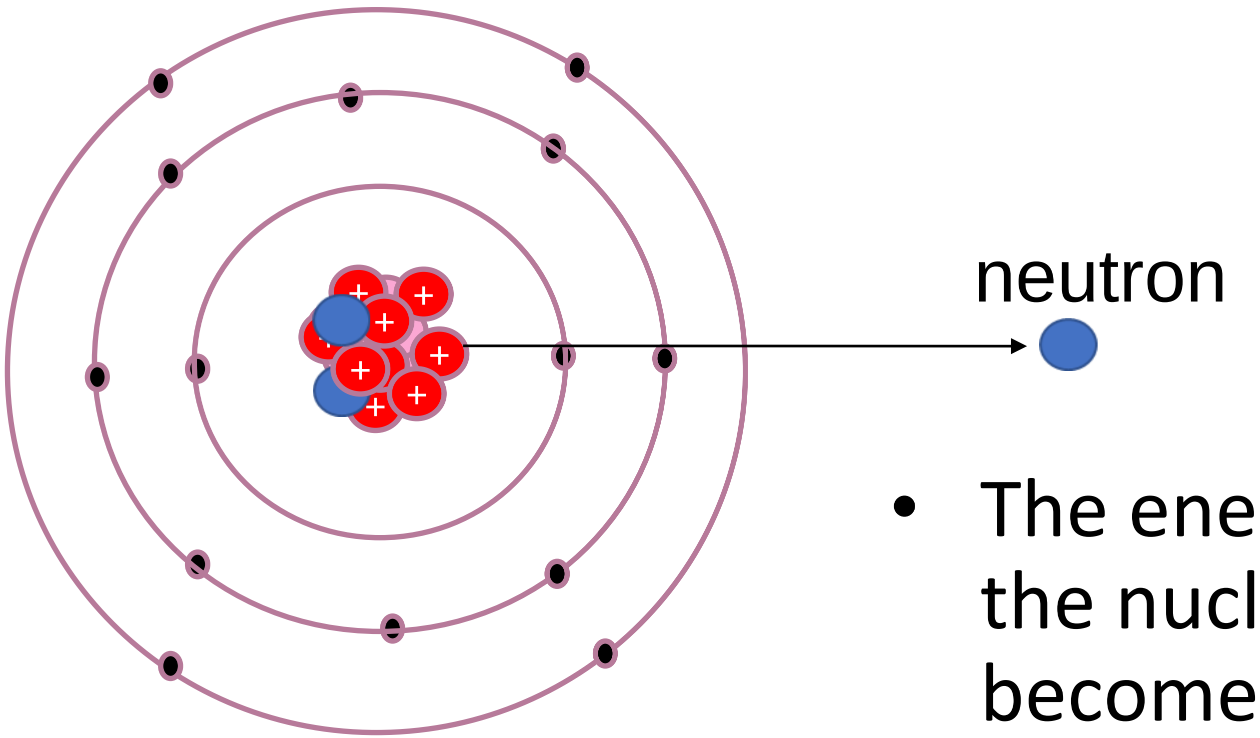
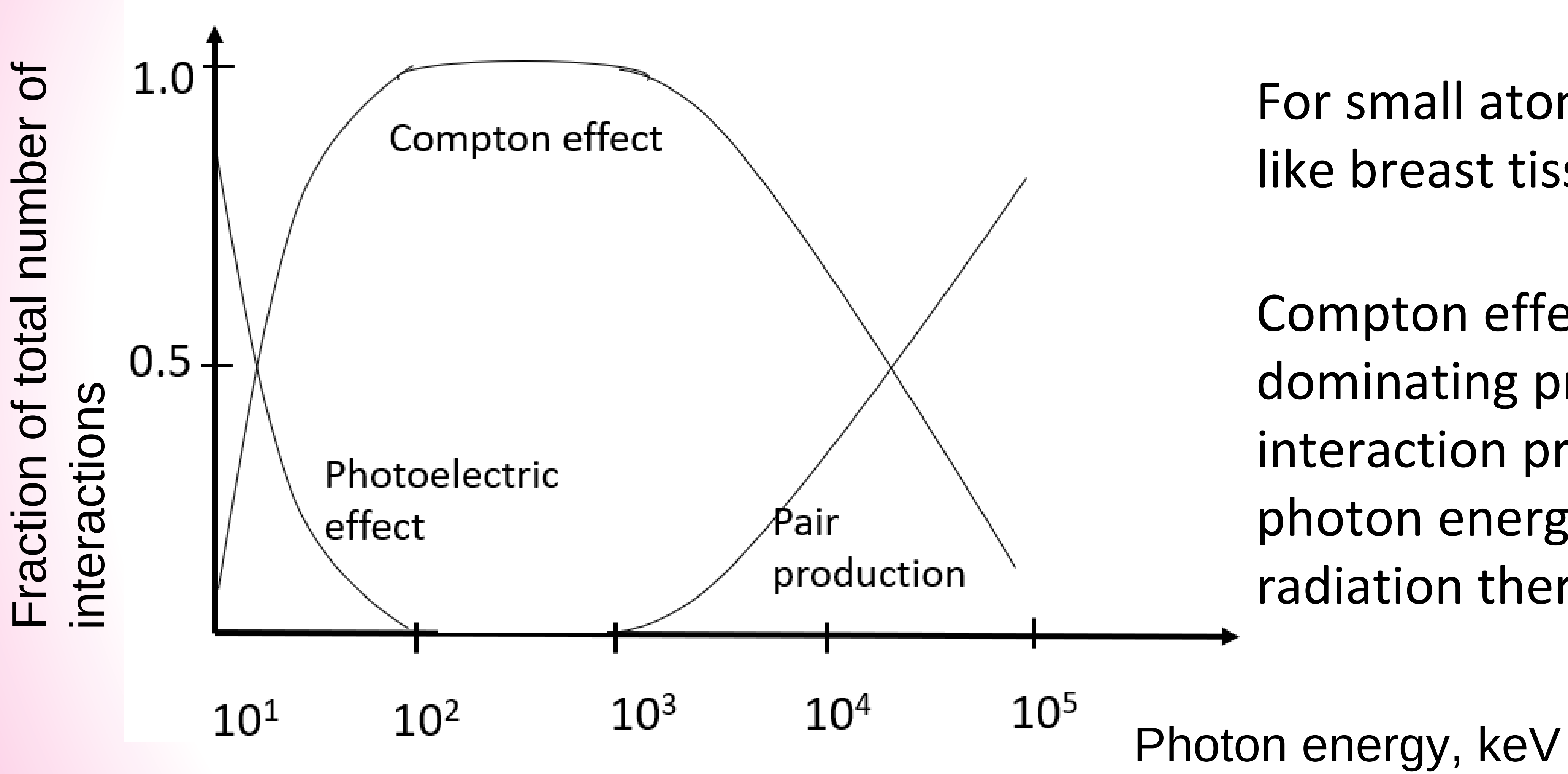
Photodisintegration



- The energy is absorbed by the nucleus, which becomes unstable, and the nucleus ejects a neutron

$h \cdot \upsilon \approx 10\text{-}15$ MeV

Relative amounts of photon interactions



For small atomic numbers, like breast tissue, Z ≈ 6-7:

Compton effect is the dominating primary interaction process for photon energies used in radiation therapy.

(2, p.54)

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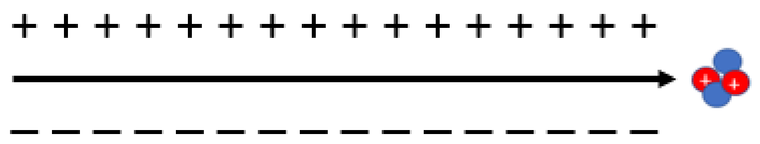
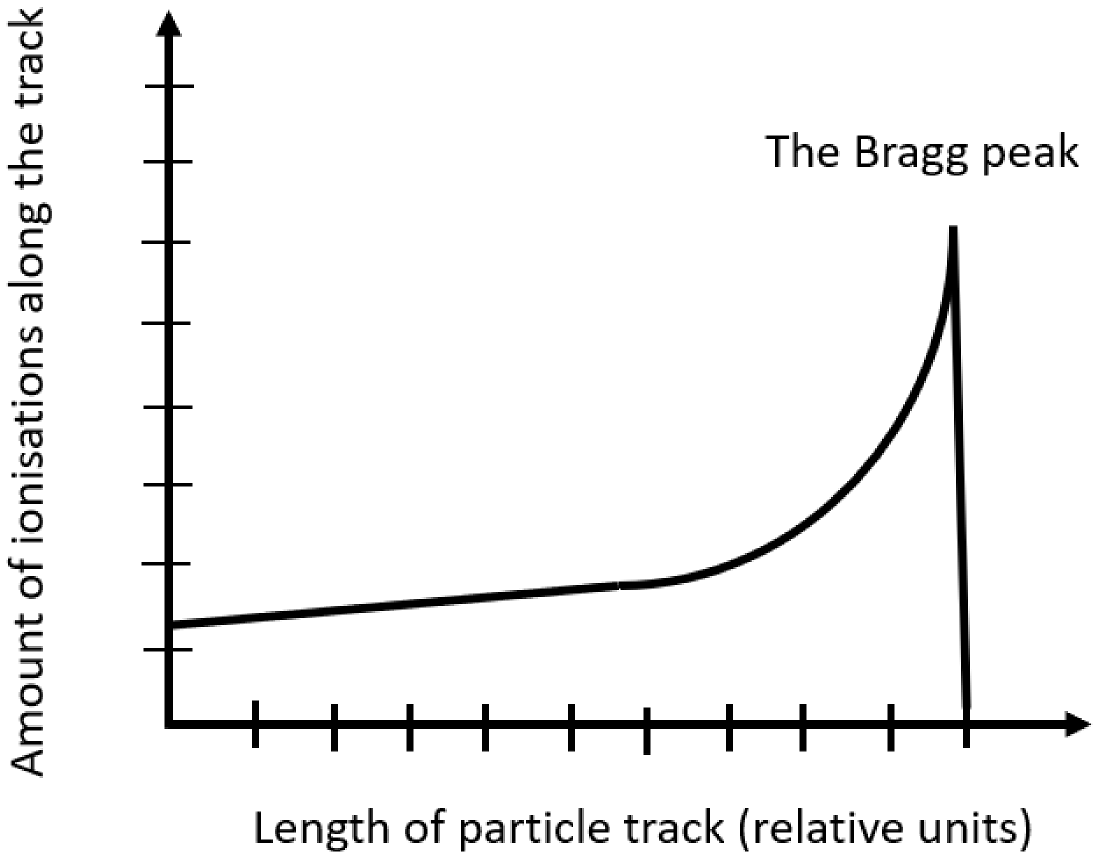
The interactions of charged particles with matter

- α-particle: Charge +2
- Loses energy by Coulomb interactions with the atomic electrons
- Loses a fraction of its energy per ionisation





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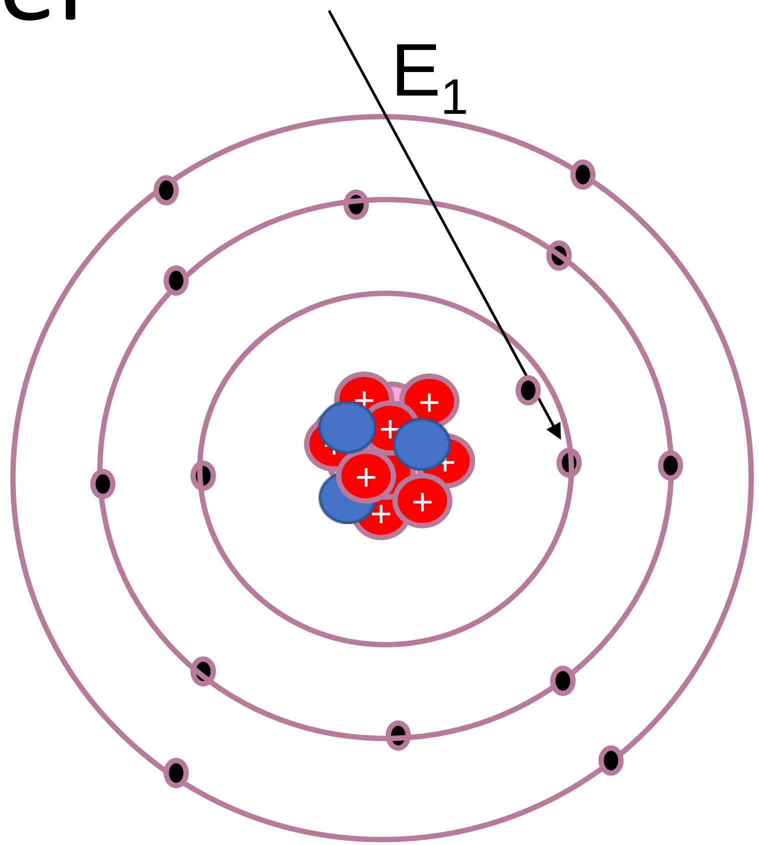
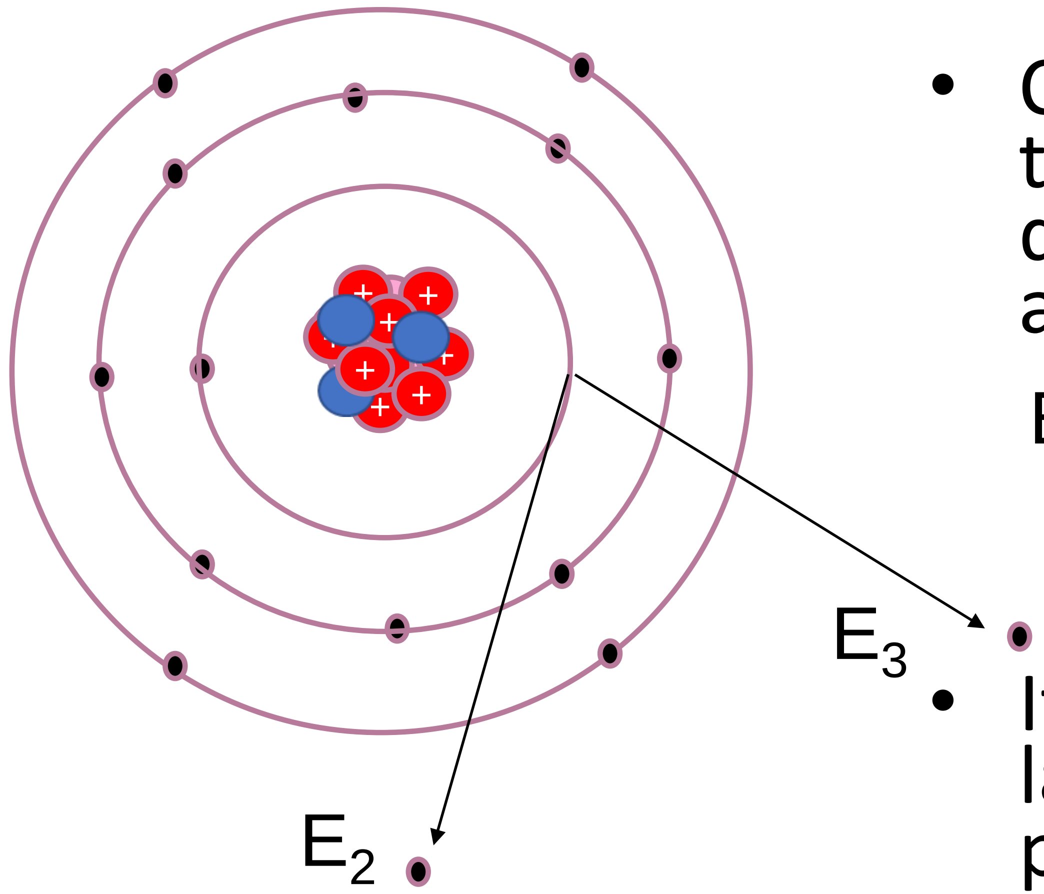
The interactions of charged particles with matter



- β-radiation (charge -1)

(2,3)

The interactions of charged particles with matter



- Compared to α-particles, the β- -particles are more deflected from their path after the ionisation.

$$E_1 = E_2 + E_b + E_3$$

- If the atomic number is large, the bremsstrahlung process also occurs.

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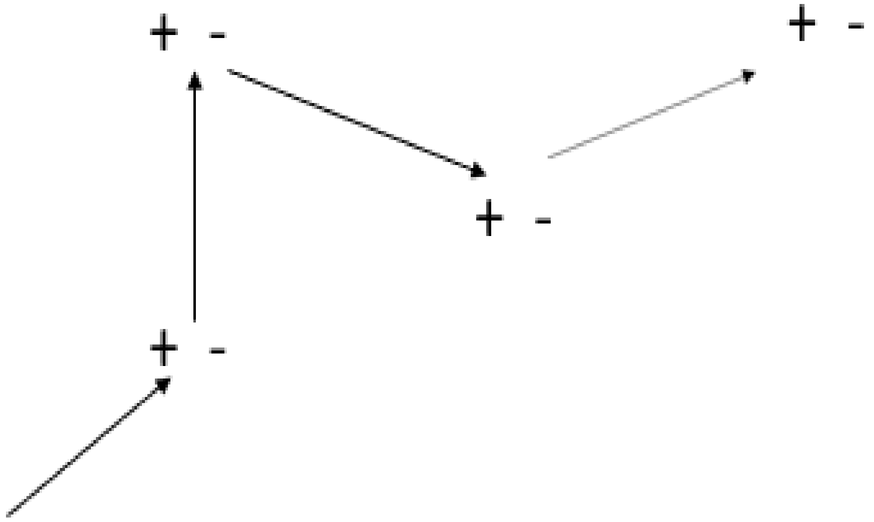
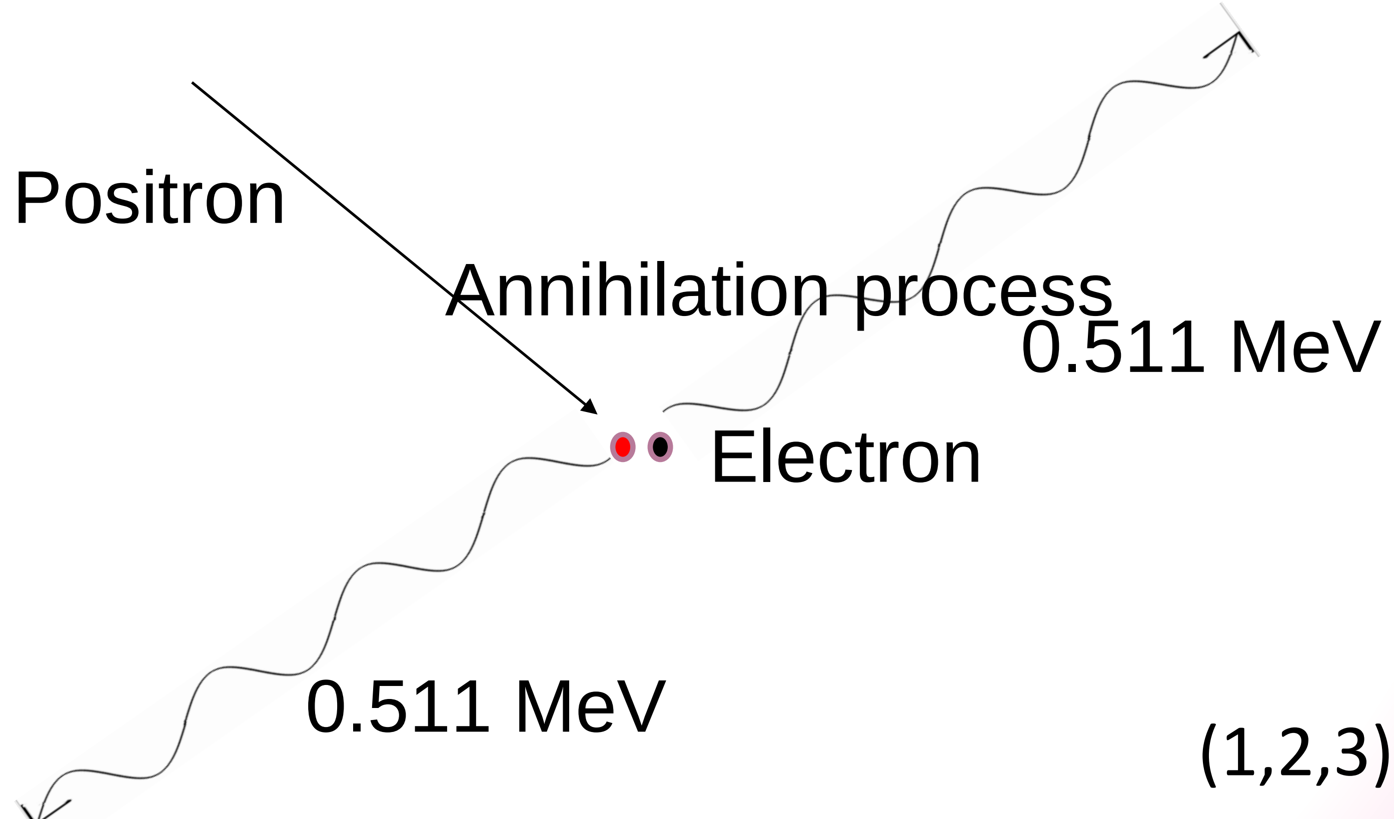
The interactions of charged particles with matter



- Path of beta radiation in matter
- The β- particle has a more "tortuous" path than the α-particle.

The interactions of charged particles with matter

- When a β+ / positron interacts with an atomic electron, they annihilate, and 2 photons with energy 0.511 MeV are created



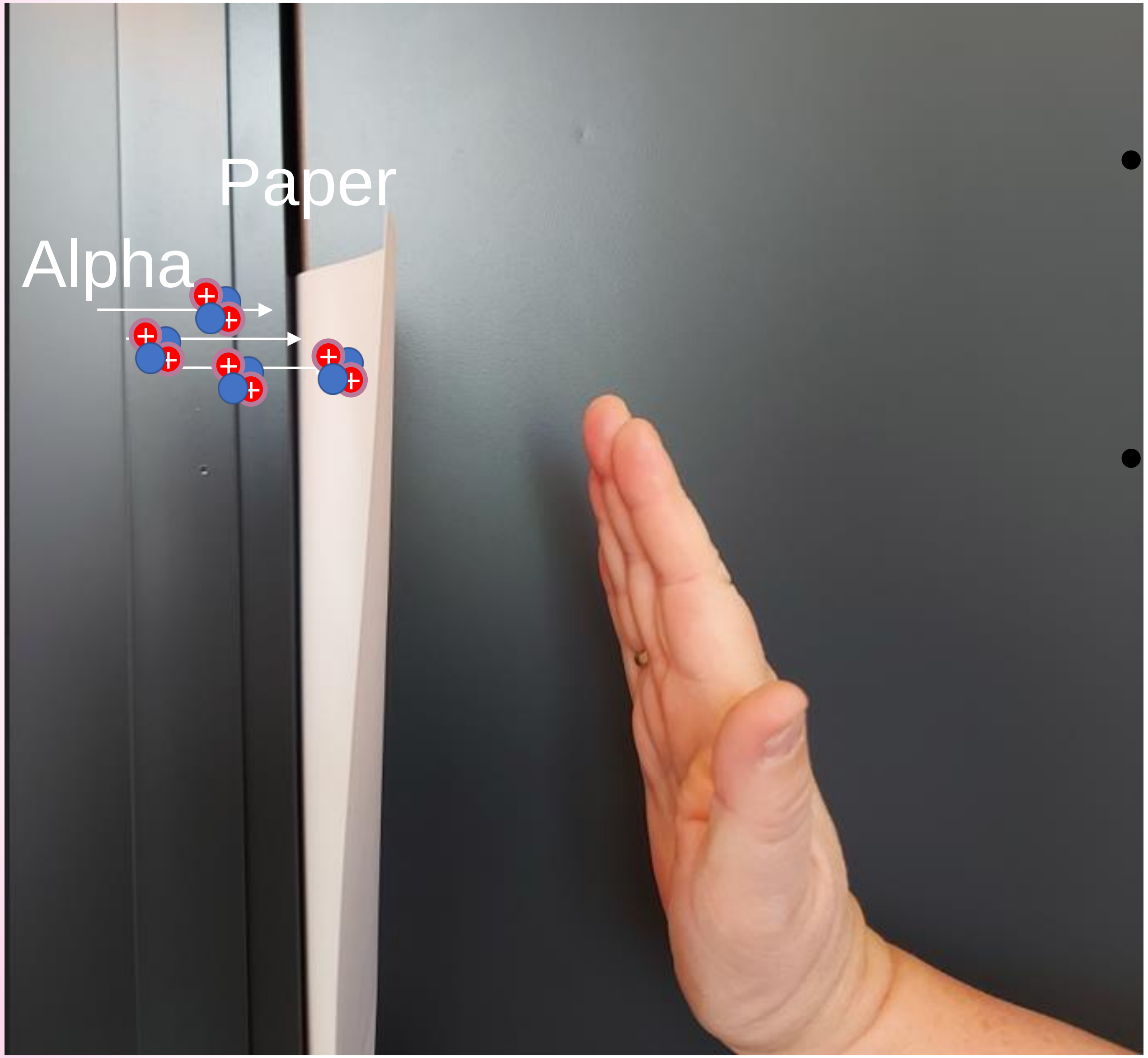
(1,2,3)

Linear energy transfer

- Linear energy transfer (LET) is defined as the mean energy that a particle deposits per unit length when it passes through a substance.
- Unit of LET: keV/µm
- For heavy charged particle radiation, LET increases with charge and decreases with the velocity of the moving particle

(3)

Penetration ranges of ionising radiation

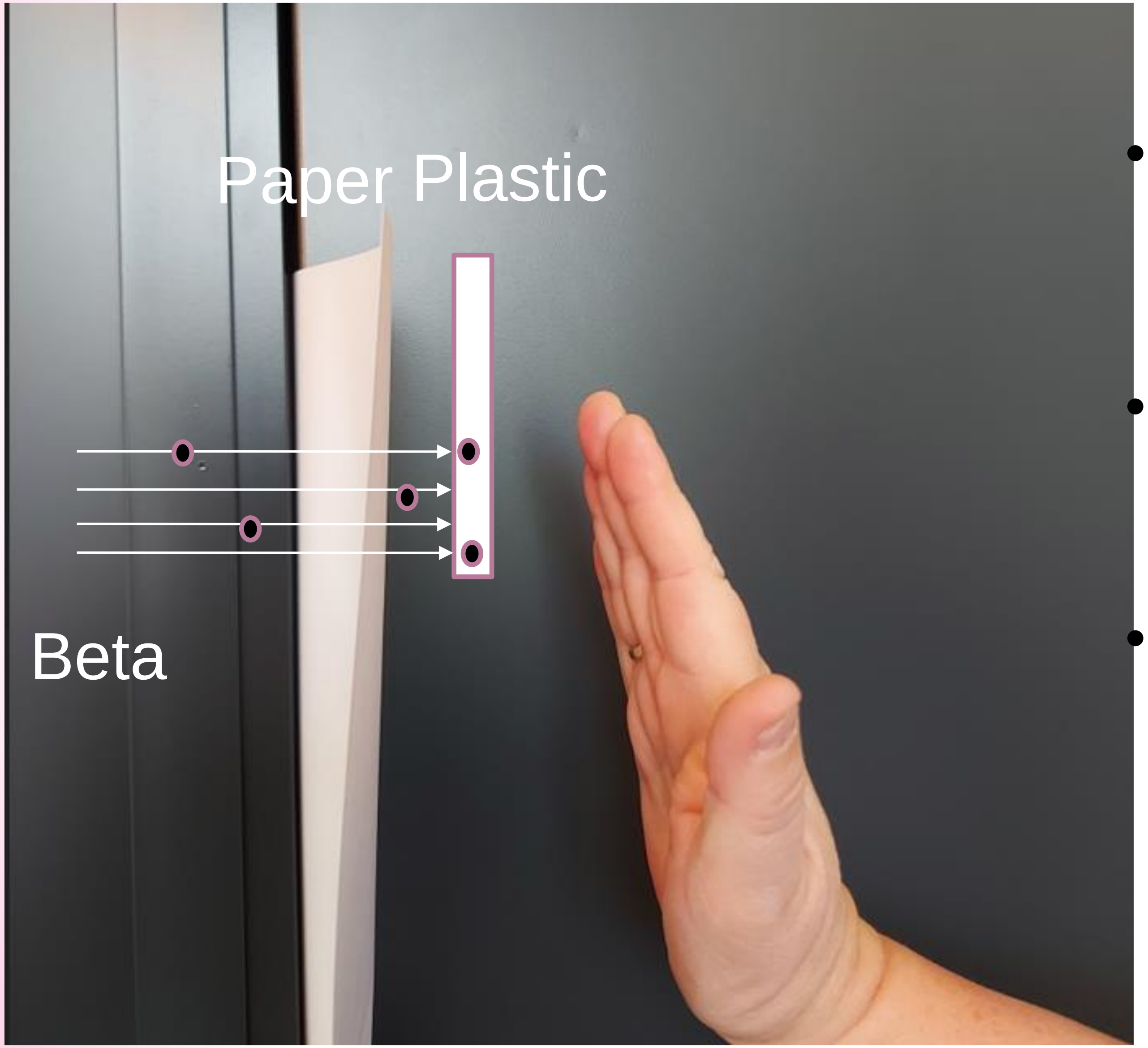


- Range of α-particles: < 10 cm in air, <100 µm in tissue
- A source of α-radiation **inside** the body may give large radiation doses!

(3)

Particle sizes are not in scale.

Penetration ranges of ionising radiation



- Range of β—particles ≈ 5 mm in tissue

- Do not use heavy metal to shield against β- radiation, this would produce brehmsstrahlung.
- β+ radiation -> annihilation radiation

(3)

(Particle sizes are not in scale)

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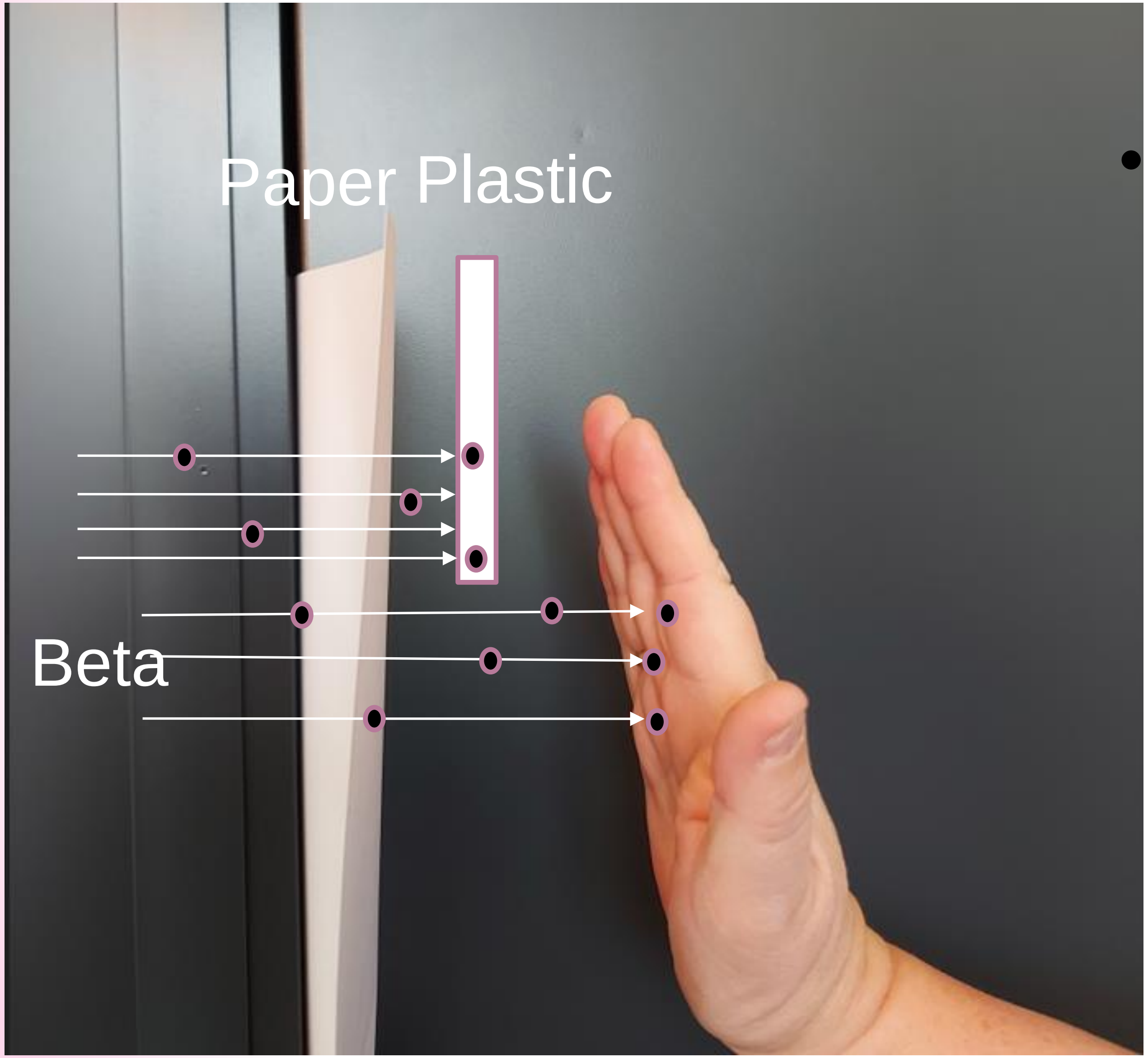
Penetration ranges of ionising radiation

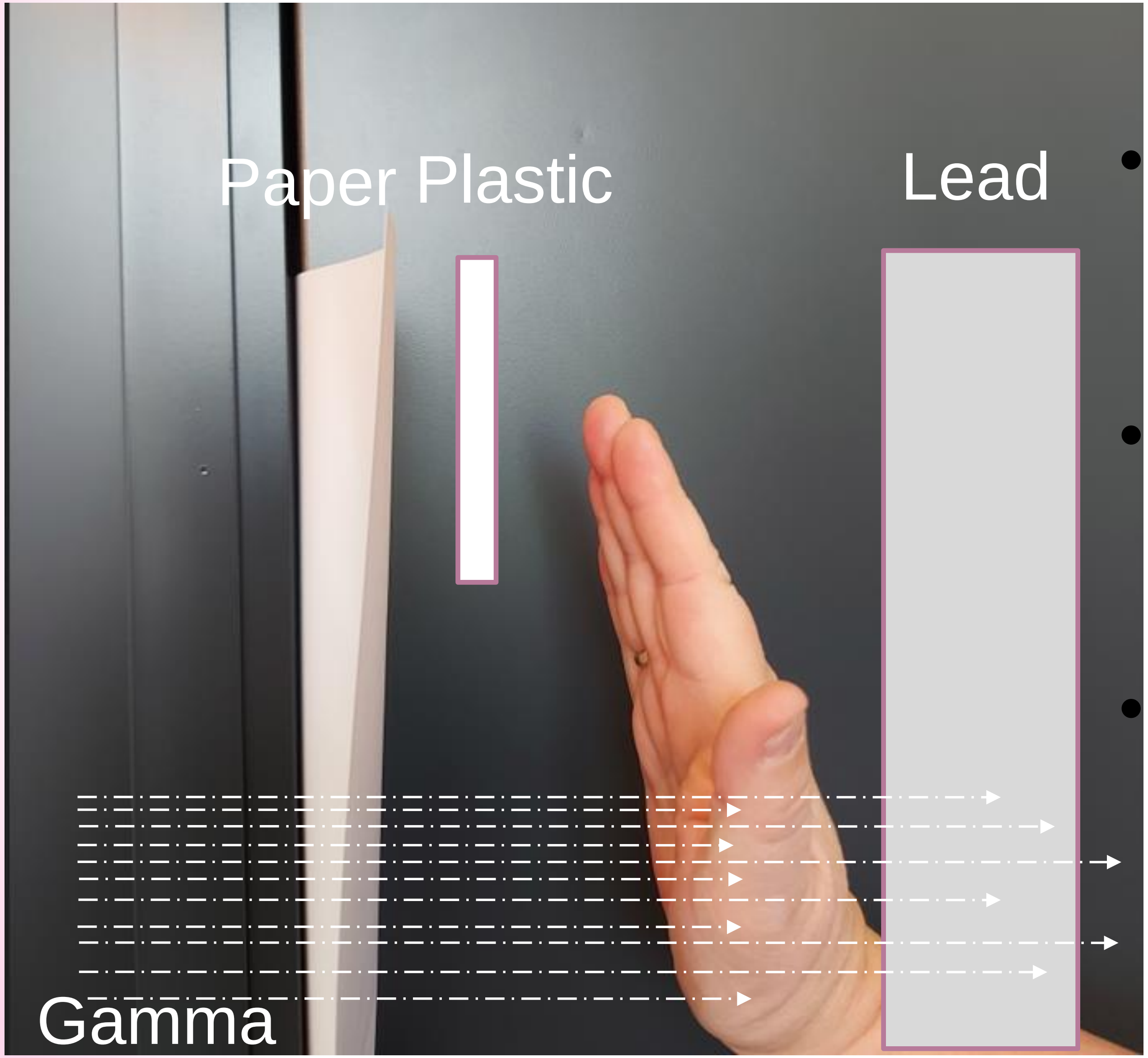


- Range of β—particles ≈ 5 mm in tissue

(3)

(Particle sizes are not in scale)

Penetration ranges of ionising radiation



- X- rays and gamma- rays have the ability to penetrate tissue
- Example: Cs-137 γ-radiation 0.662 MeV; HVL ≈ 9 cm of water
- 5 HVL reduces the intensity by about 97 %

(3)

(Particle sizes are not in scale)

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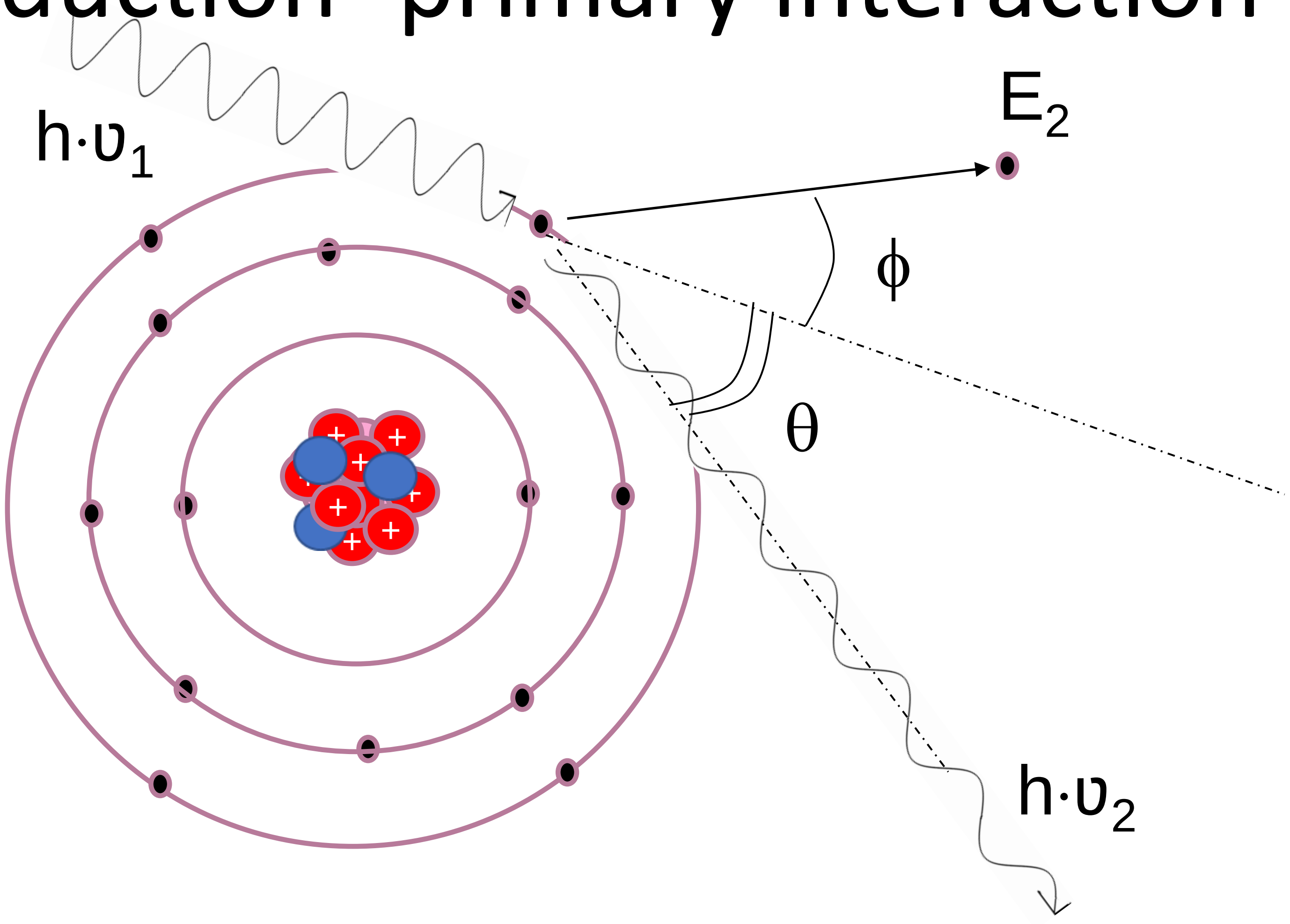
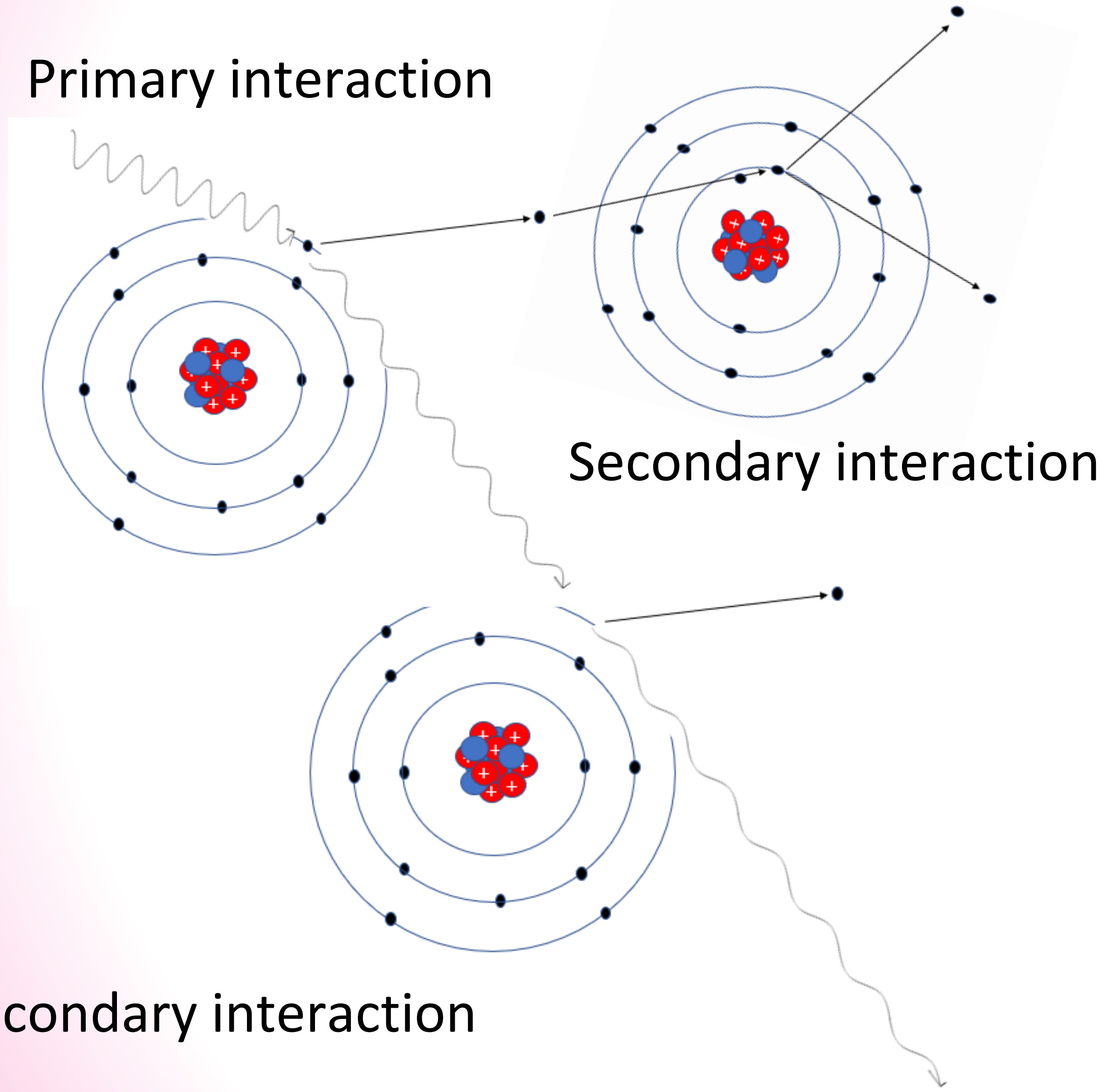
Introduction- primary interaction



$$h \cdot \upsilon_1 = h \cdot \upsilon_2 + E_2$$

Primary interaction-> secondary interactions

Primary interaction



Secondary interaction

Secondary interaction

(1, 2, 3)

....and so on.....

(1, 2, 3)

Absorbed dose

- Primary interactions
- Secondary interactions

- The absorbed dose is defined by $D = \frac{dE}{dm}$
- Unit of absorbed dose: Gray (Gy)
- 1 Gy = 1 J/kg

(1, 2, 3)

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Dose rate

- Dose rate is absorbed dose per unit of time.

- Example: If a treatment apparatus delivers 2 Gy/min at a certain distance, the dose will be 1 Gy for half a minute of treatment.

(2)

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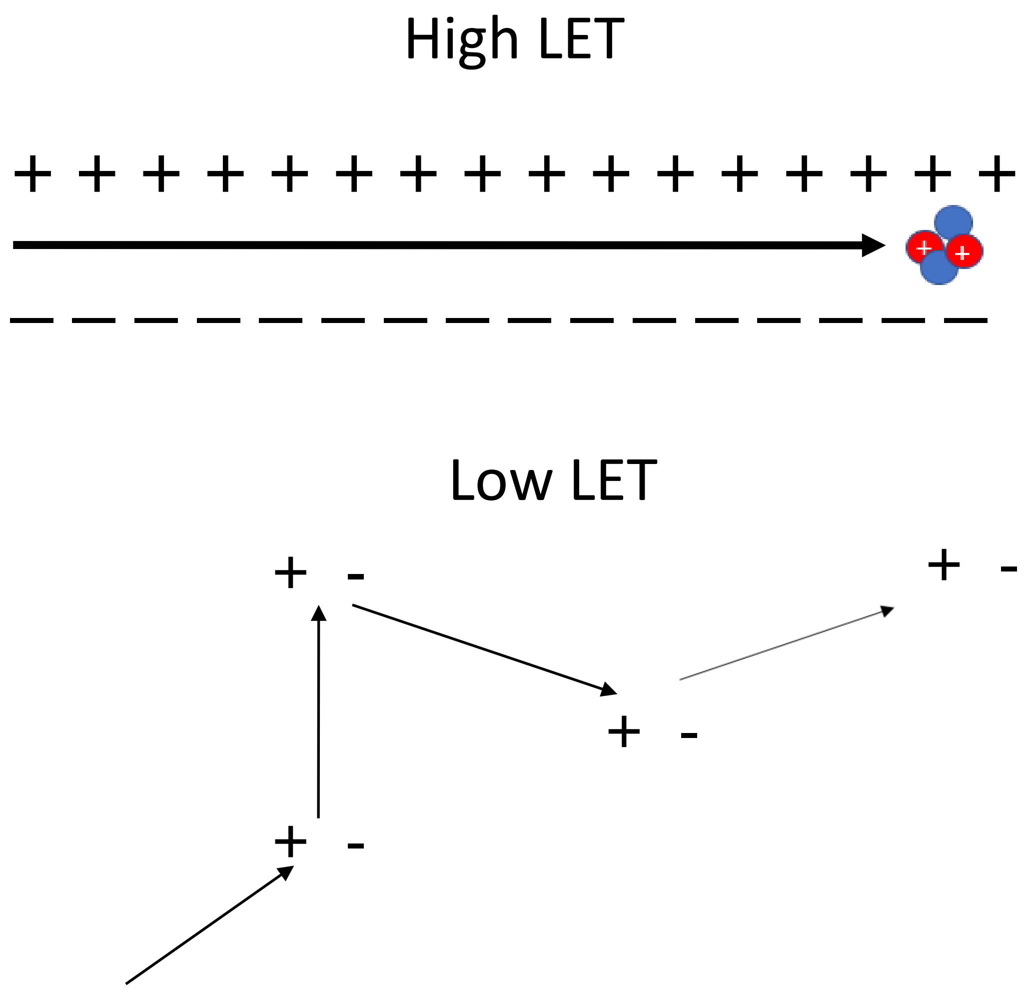
Equivalent dose

- Takes into account that different types of radiation can cause different amount of damage.
- Unit: Sievert [Sv], Sv = J/kg
- Equivalent dose [Sv] = Radiation weighting factor x Absorbed dose [Gy]
- $Sv = w_R \cdot Gy$
- w_R is the weight factor for the radiation in question.
- Related to Linear energy transfer (LET)

(3)

Radiation weighting factor



(4)

Radiation type	Weighting factor w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous curve as a function of neutron energy

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Effective dose

- Weighted sum of equivalent doses to organs

$$E = \sum_{i=1}^{N} w_i H_i \qquad (4)$$

- i goes from 1 to N, number of organs
- and w_i is the weighting factor of organ i
- Organ weighting factors are related to the radiosensitivity of the organ
- Unit: Sievert [Sv]

Organ	Organ weighting factor W_T
Breast	0.12
Bone marrow	0.12
Colon	0.12
Lung	0.12
Remainder	0.12
Stomach	0.12
Gonads	0.08
Bladder	0.04
Liver	0.04
Oesophagus	0.04
Thyroid	0.04
Bone surfaces	0.01
Brain	0.01
Salivary glands	0.01
Skin	0.01

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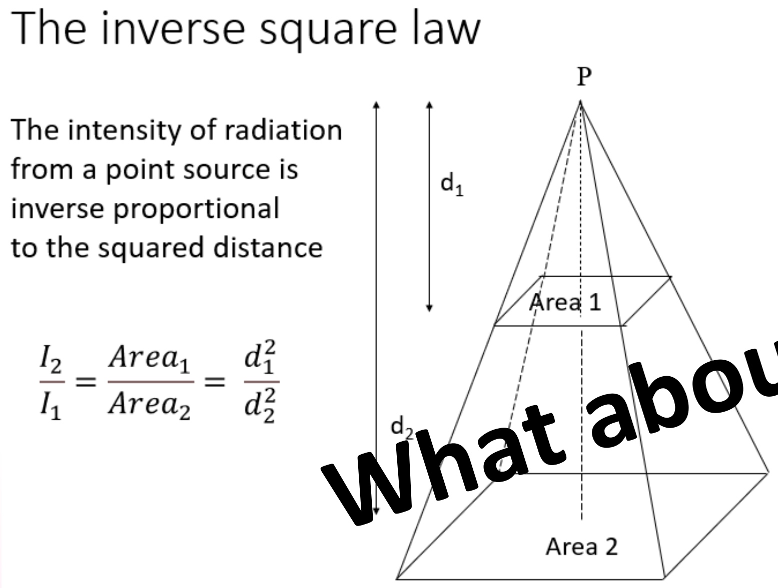
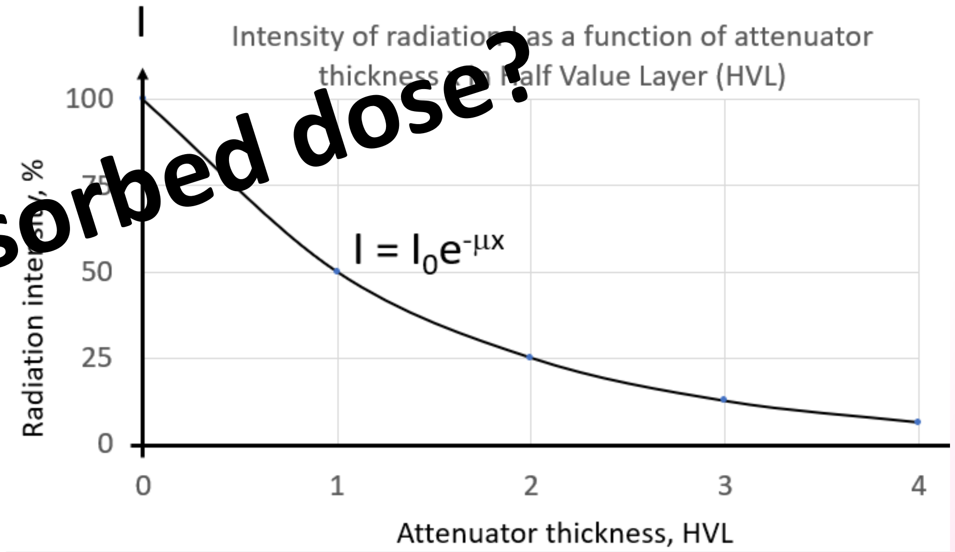
Factors affecting doses and radiation intensities

- **<u>The time of exposure</u>** is also a factor affecting the radiation dose – when all other factors are constant, radiation dose is proportional to the exposure time.

Radiation intensity and distance from the source



Radiation intensity and thickness of attenuator/tissue



What about the absorbed dose?

(1,2)

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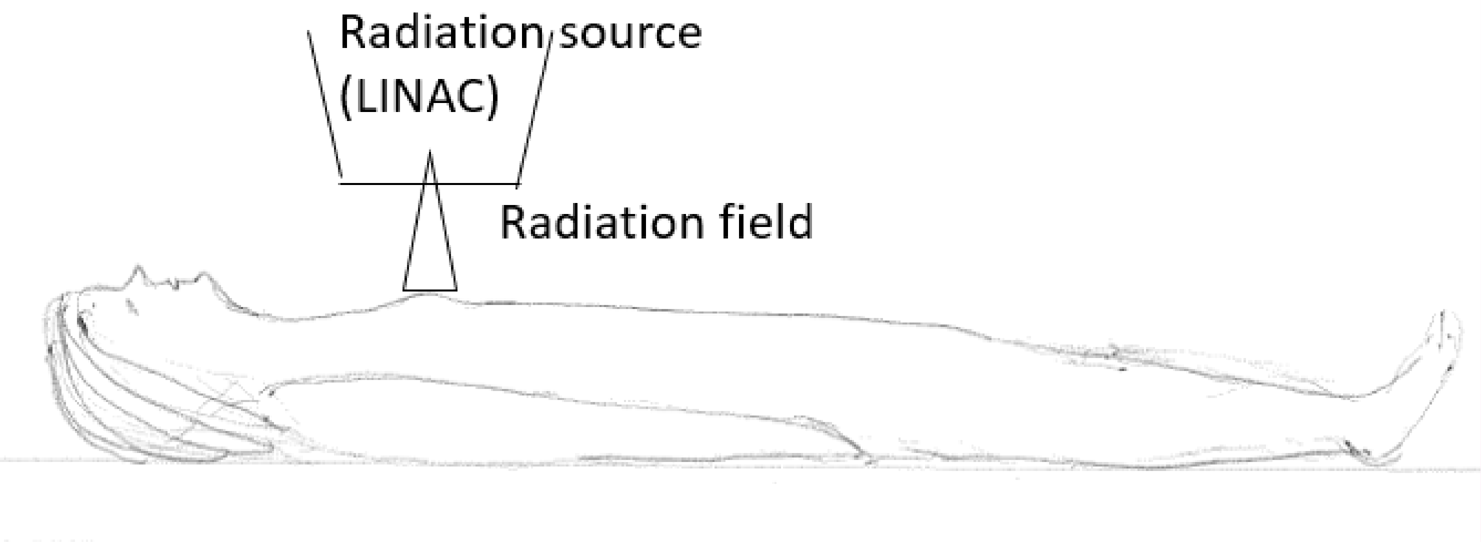
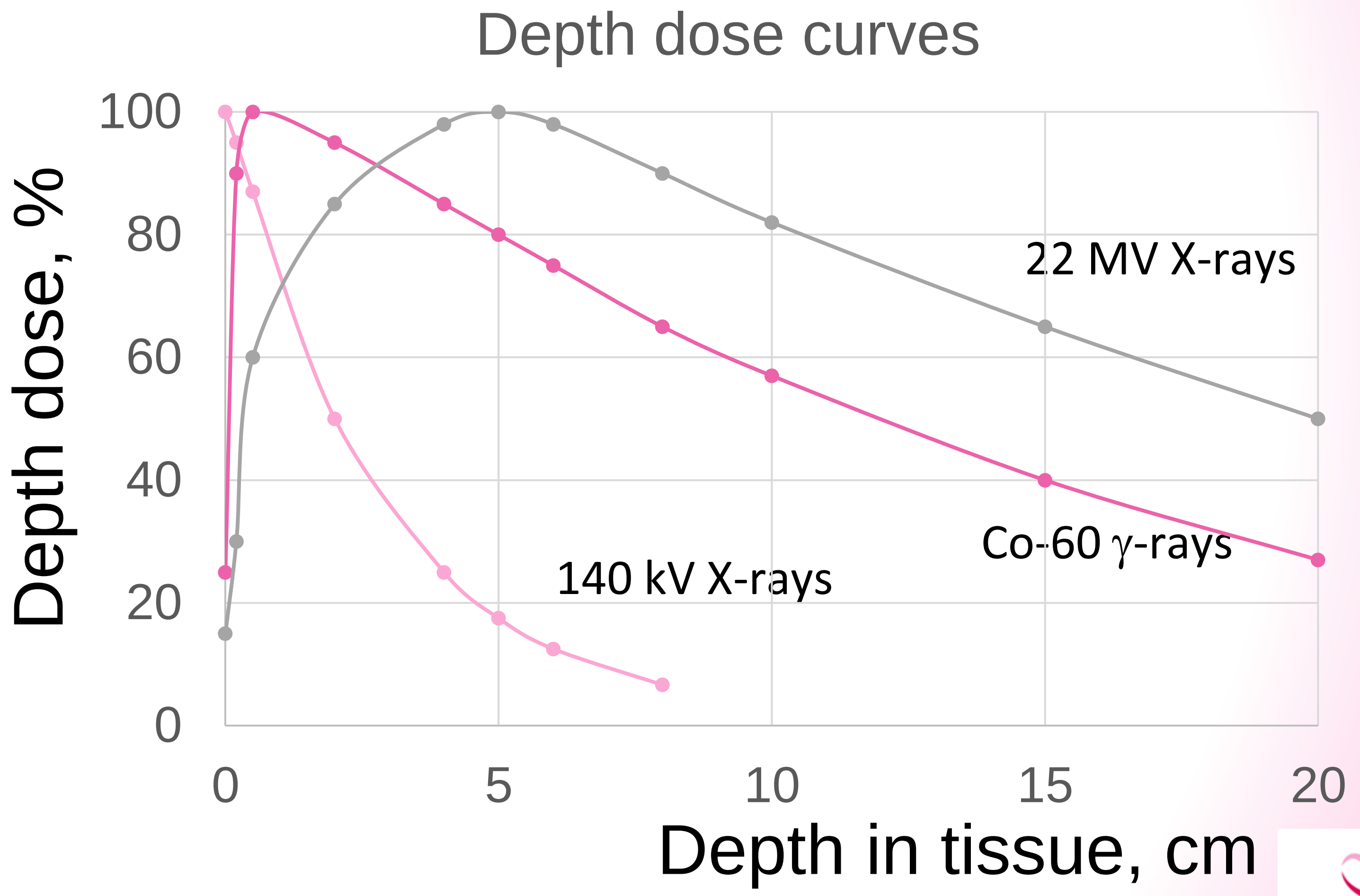
Properties of the radiation field

- Photon radiation fields
- Electron radiation fields



Depth dose curves- photon beams

- Range of secondary electrons -> build up
- Maximum absorbed dose (100%) at a depth under the skin
- Exponential decrease of absorbed dose after dose-max
- Depth of dose-max increases for increasing photon energy



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Other factors affecting the depth dose curve of photons

- Source to skin distance (SSD): The dose reduces more rapidly with short distances than longer distances. A larger SSD gives larger relative absorbed doses deeper in the patient (at depths larger than depth of dose-max)
- Field size: A larger field gives a larger number of scattered electrons, and a larger relative absorbed dose deeper in the patient (at depths larger than depth of dose-max).
- Attenuation and other factors related to the patient: The electron density of the tissues affect the attenuation.

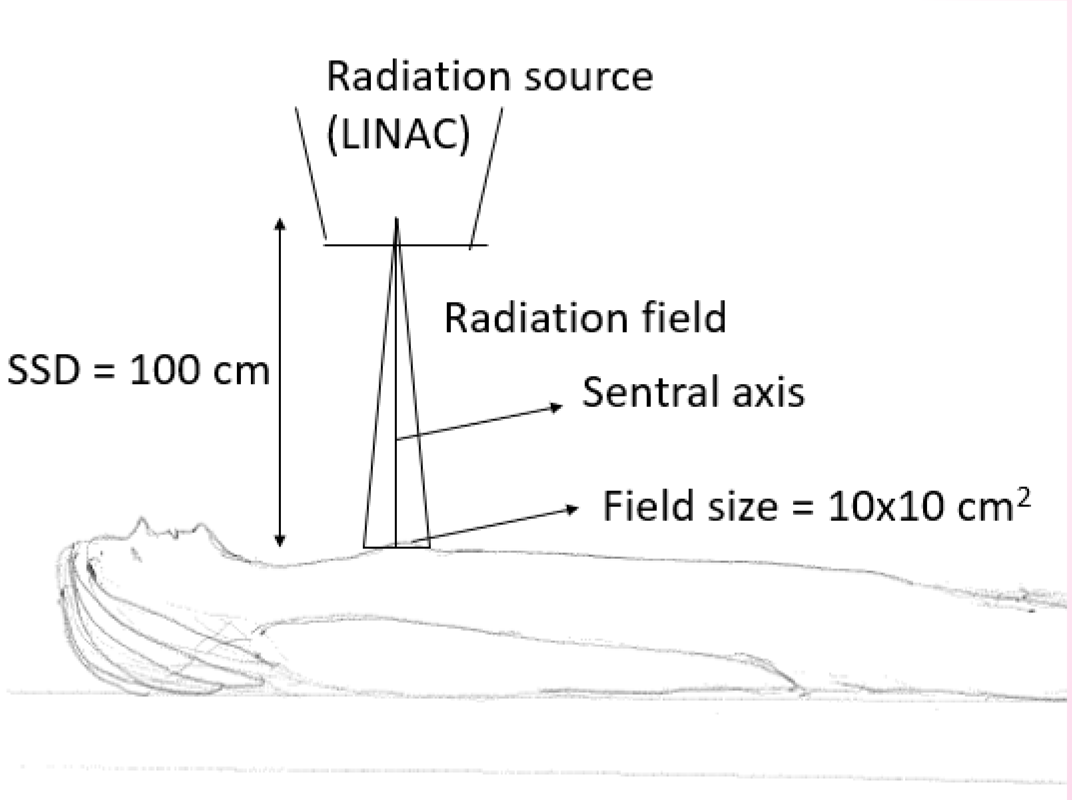
(2)

Electron beams

- Electron beams have a larger relative skin dose, have a dose-max close to the skin surface and a steeper exponential decrease in absorbed dose than photons produced by the LINAC at the same voltage.
- An electron beam is suitable for treatment of superficial tumours, and will give a lower absorbed dose in tissues deeper than the depth of tumour, compared to a photon beam produced in the LINAC at the same voltage.

Monitor Unit (MU)

- The Monitor unit (MU) is a measure of the radiation output of the LINAC in radiation therapy
- Measured by an ionisation chamber
- 100 MU is the amount of radiation that gives D_{max}= 1 Gy at the central axis for Source-to skin distance (SSD)=100 cm, field size 10x10 cm^2, and no other absorbing material in the field ɫsuch as wedges or shielding material.



(2)

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