A2 Level Physics

Chapter 21 – Medical Imaging

21.1.1 Using X-rays

Notes

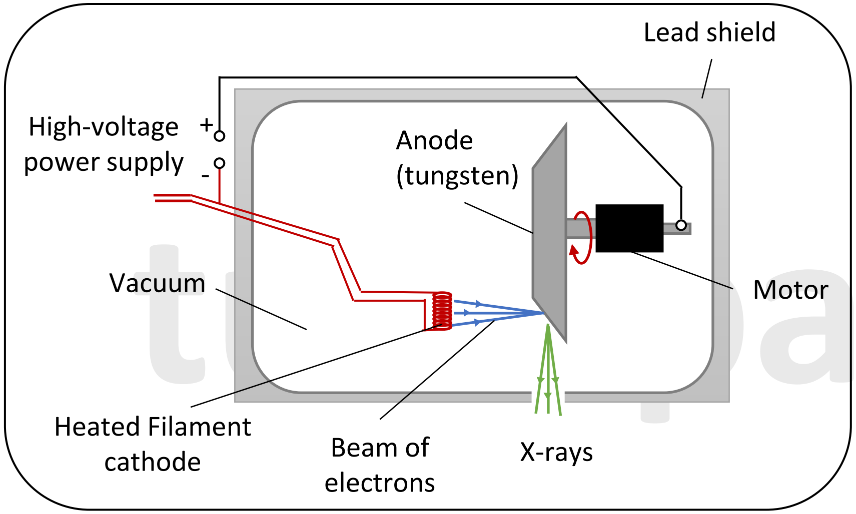
X-ray Production

X-rays are electromagnetic (EM) waves with a wavelength ranging from 10^{-8} to $10^{-13}m$, putting it between ultraviolet and gamma-rays.

The X-rays used for diagnostic imaging are produced in an evacuated rotating anode X-ray tube.

When fast-moving (high-energy) electrons collide with a heavy-metal target (e.g. tungsten), they rapidly decelerate, producing X-rays as a result.

How a rotating anode X-ray tube works?



In an evacuated tube, a very high voltage $(\approx 100kV)$ is applied across the electrodes (the cathode and the anode).

Electrons are produced at the negative electrode (cathode), which is a filament that is heated due to the electric current passing through it.

These electrons are then accelerated by the p.d. between the cathode and rotating tungsten target (the anode – positive electrode). When the electrons collide with the tungsten anode, they decelerate and some of their KE is converted into EM energy in the form of X-ray photons. The tungsten anode emits a continuous spectrum of X-ray radiation – this is called bremsstrahlung ('braking radiation').

X-ray Production

Majority of the KE of the electrons is transferred to thermal energy of the target. Therefore the target becomes extremely hot, and so it must be cooled by passing oil or water through it. Only about 1% of the KE of the electrons is converted into X-rays.

The tube is evacuated to prevent the accelerated electrons from losing energy due to collisions with gas molecules.

The energy of the X-rays produced is proportional to the accelerating voltage. Therefore, the greater the accelerating voltage, the greater is the energy of the X-rays produced.

The equation $E = hf$ (where $h = Planck's\ constant = 6.63 \times 10^{-34} Js$) relates the energy of a photon (E) to its frequency (f). Hence if the energy (E) of the X-rays produced increases, the X-ray frequency (f) increases and the wavelength (λ) decreases.

Consider an electron with a charge (e) that is accelerated through a p.d. (V) and striking a metal target, resulting in X-rays with a maximum frequency (f_{max}).

Maximum energy of X-ray photons = work done by the accelerating p.d.

$$hf_{max} = eV$$

Therefore maximum frequency is:

$$f_{max} = \frac{eV}{h}$$

In terms of wavelength (λ):

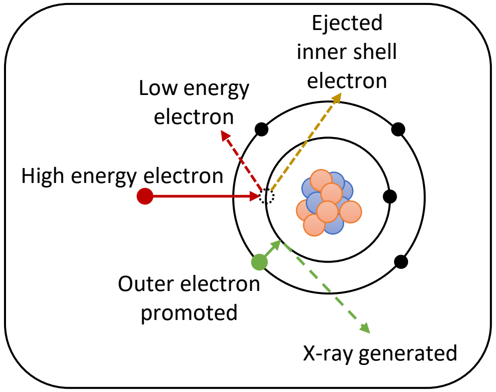
$$\frac{c}{\lambda_{min}} = \frac{eV}{h}$$

X-ray Production

There are two processes that produce X-ray photons:

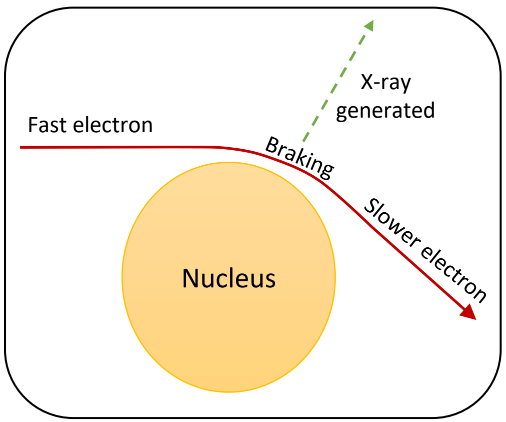
1) Characteristic X-rays

When a bombarding electron knocks an inner-shell electron out of a tungsten atom (this is known as ionisation), this causes electron transition to fill the vacancy and release energy in the form of X-ray photons. The X-ray photon is emitted when the outer electron goes to a lower energy level, rather than when the inner electron is ejected. These X-rays photons have a definite energy.



2) Bremsstrahlung (braking radiation) X-rays

These X-ray photons have a continuous range of energies. They are created when bombarding electrons are deflected (and hence decelerated) by the electric field around the nuclei of the target atoms. Energy is emitted by an accelerating charged particle.

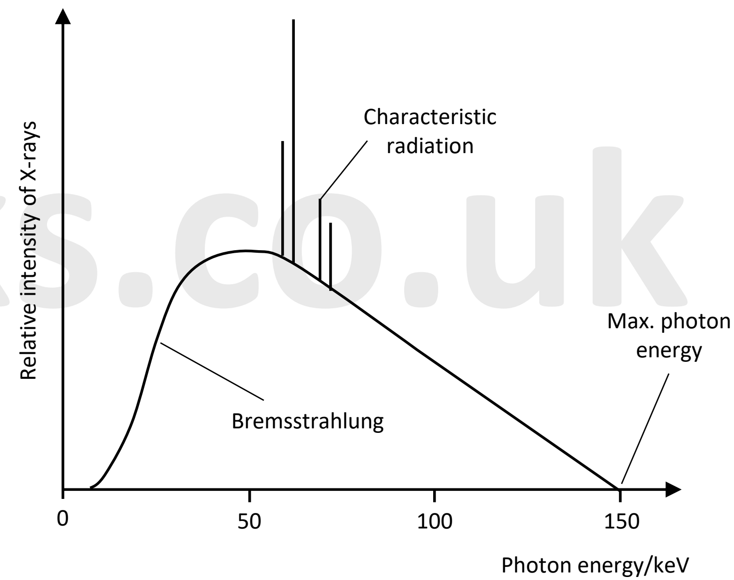


X-ray Production

X-ray Spectrum

By combining the continuous spectrum from the bremsstrahlung with the characteristic spectrum from ionisation, you obtain a line spectrum superimposed on a continuous spectrum.

The continuous curve refers to bremsstrahlung X-rays, whereas the peaks refer to characteristic X-rays.



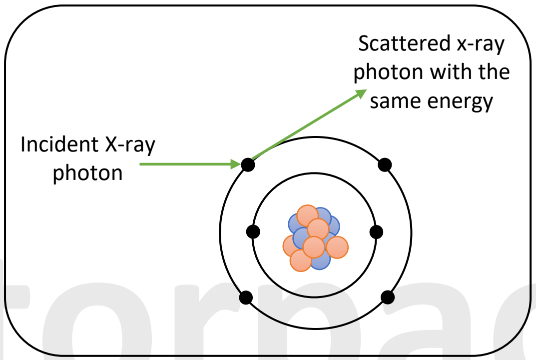
Interaction of X-rays with Matter

X-rays can be thought of as waves or particles (photons).

As an X-ray beam travels through matter, its intensity is diminished (attenuated). This occurs as a result of X-ray photon absorption or scattering. There are four main causes for attenuation:

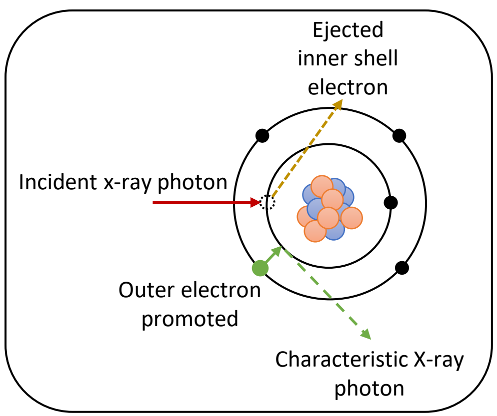
1) Simple scattering

When a low-energy X-ray photon interacts with an atom's electron, the photon's energy is insufficient to cause ionisation. Instead, the photon is deflected, but its energy remains unchanged.



2) Photoelectric effect

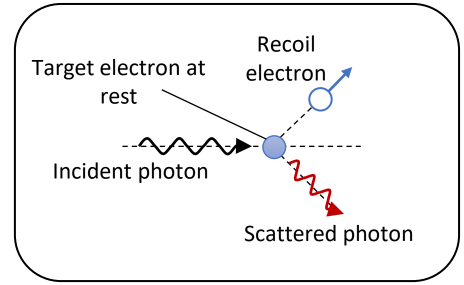
The incident X-ray photon ejects one of the orbital electrons from an atom of the absorbing material, by giving the electron its energy. An electron from the higher energy level may drop to fill the vacancy, resulting in the emission of a distinctive X-ray photon.



Interaction of X-rays with Matter

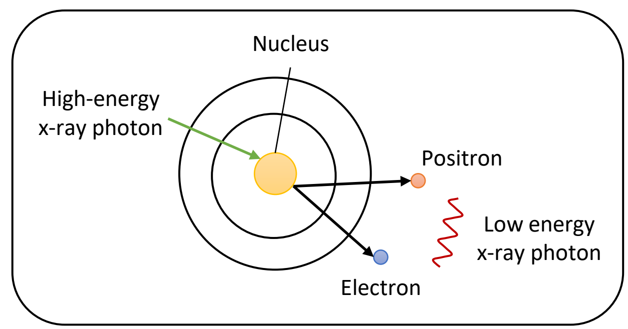
3) Compton Effect

This happens when the incident X-ray photon has a lot of energy. The incident photon is scattered by an orbital electron in an atom of the absorbing material. The electron receives some of the photon's energy and then goes in a different direction than the scattered photon. The energy of the emitted electron can range from 0 to 2/3 of the energy of the incident photon. The larger the photon's deflection, the greater the energy loss.



4) Pair production

In pair production a high-energy X-ray photon interacts with the nucleus of an atom of the absorbing material, producing an electron-positron pair. When the positron is annihilated by an electron, two identical, low-energy X-ray photons are emitted.



Intensity

The intensity of radiation is defined as the power (P) per unit cross-sectional area (A).

$$I = \frac{P}{A}$$

Where:

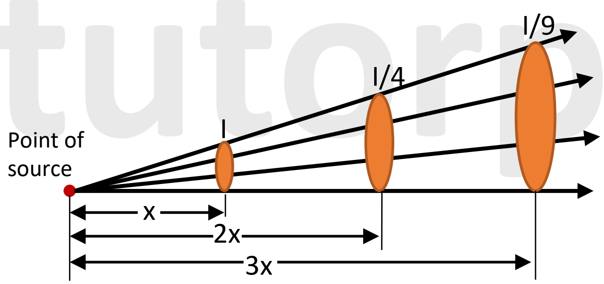
I = intensity of the radiation in Wm^{-2}

P = Power in Watts ,W

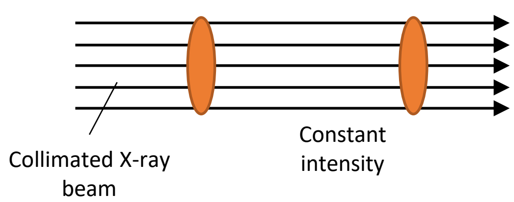
A = cross-sectional area in m^2

Note:

The inverse-square law is used if the X-ray beam is expanding out from a point source (as shown in the diagram below).



When an X-ray beam is collimated, it becomes a parallel beam with a constant intensity.



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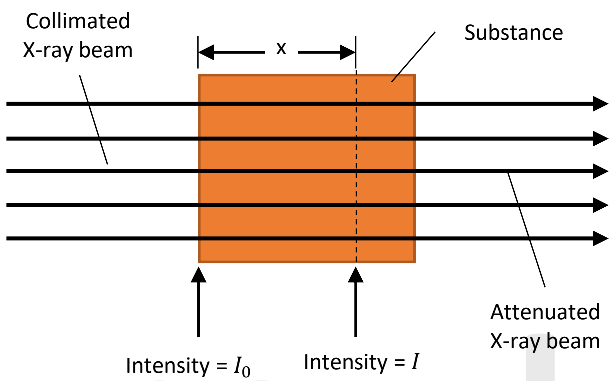
Attenuation of X-rays

X-rays are absorbed and scattered as they pass through matter (such as a patient's body). This indicates that as a collimated X-ray beam passes through a substance, its intensity drops.



The amount of absorption changes significantly depending on the X-ray frequency.

The photoelectric effect is mainly due to the low frequency (low energy) X-ray absorption. Compton scattering is the major absorption mechanism for higher frequency X-rays, while pair production is the absorption mechanism for very high frequency X-rays.

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Attenuation of X-rays

According to the material attenuation (absorption) coefficient, the intensity of the X-ray beams decreases (attenuates) exponentially with distance from the surface:

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

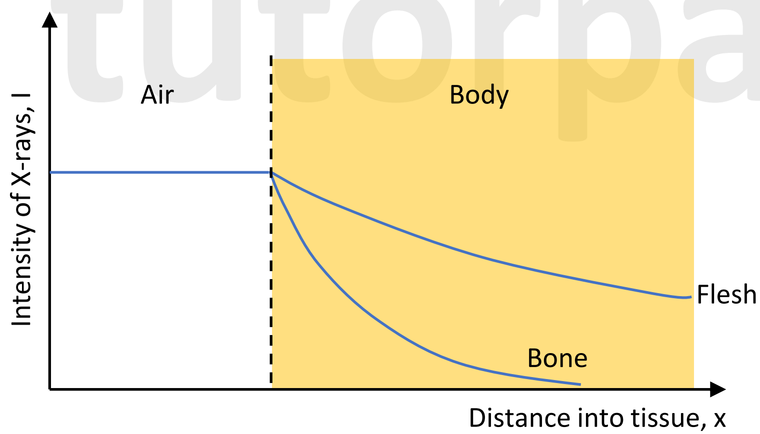
Where:

I = intensity of the X-ray beam in Wm^{-2}

I_0 = initial intensity of the X-ray beam in Wm^{-2}

μ = the material's attenuation (absorption) coefficient in m^{-1}

x = the distance from the surface in m



Attenuation of X-rays

The attenuation coefficient varies according on the substance, e.g.:

- Vacuum = $0m^{-1}$
- Muscle = $50\ m^{-1}$
- Bone = $300\ m^{-1}$

Half-Value Thickness

The thickness of material necessary to lower the x-ray beam intensity to half its original value is known as half-value thickness, or $x_{\frac{1}{2}}$.

Half-value thickness, $x_{\frac{1}{2}}$ can be derived by rearranging the equation for the intensity of the x-ray beam:

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

Half-value thickness is the point at which the initial intensity, I_0, will have decreased to half of its original value, $I_0/2$. By substituting this and $x = x_{\frac{1}{2}}$, we get :

$$\frac{I_0}{2} = I_0 e^{-\mu x_{\frac{1}{2}}}$$

Dividing both sides by I_0 gives:

$$\frac{1}{2} = e^{-\mu x_{\frac{1}{2}}}$$

Taking natural logs of both sides gives:

$$\text{In}\left(\frac{1}{2}\right) = -\mu x_{\frac{1}{2}}$$

Following that $\frac{1}{2} = 2^{-1}$ so $In\left(\frac{1}{2}\right) = In(2^{-}) = -In(2)$ using the rules, we get:

$$\text{In}(2) = \mu x_{\frac{1}{2}}$$

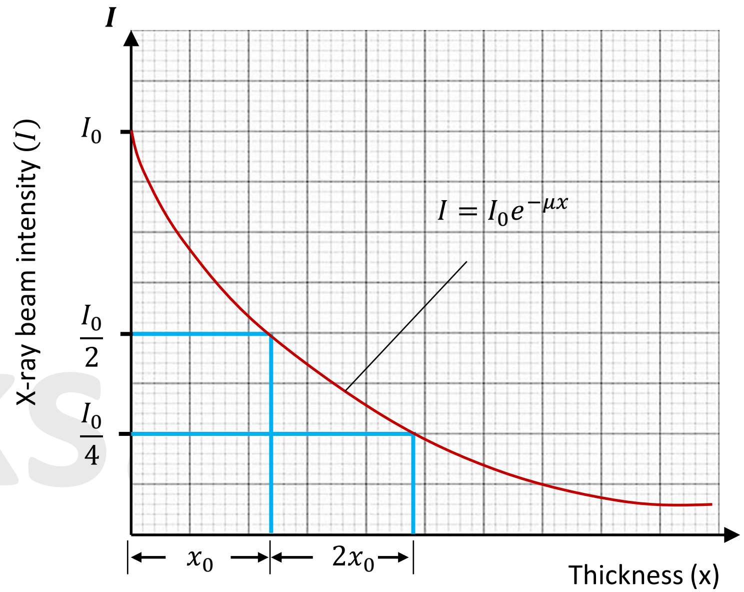
Rearranging gives us:

$$x_{\frac{1}{2}} = \frac{In(2)}{\mu}$$

When an X-ray beam passes through a given thickness of a substance, you may be asked to calculate the fraction of the X-ray intensity that is transmitted. This is provided by:

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

Half-Value Thickness



X-ray Imaging

Photographic X-ray film is used to obtain an X-ray image. Such film is developed in the usual way in a dark room to provide a negative image, so that the shadows of bones appear brighter because they absorb the X-rays more than the surrounding body tissue. This is due to bone's high attenuation coefficient, which allows it to absorb X-rays more effectively.

The image opposite shows a typical X-ray image that clearly shows the bone structure in a person's hand.

Contrast media

A contrast media is required for X-ray imaging soft tissue. This is because different types of soft body tissue have similar μ-values, and so they will absorb the X-ray in almost equal amounts. As a result, the X-ray image would be of limited use because there is little contrast between different structures.

In order to make soft tissues more visible, a contrast medium such as iodine or barium, is used. The patient consumes a drink containing barium (known as a barium meal), which, due to its high μ-value will readily absorb X-rays.

If an X-ray of the intestines is required, the patient drinks the contrast medium and the barium meal will coat the intestine's walls, allowing the outline to be seen.

X-ray Imaging

Advantages of X-rays:

- X-rays have a high resolution and allow for clear bone imaging.

Disadvantages of X-rays:

- X-rays are a type of ionising radiation that can harm cells and, in rare situations, cause cancer to develop.
- X-rays are generally unsuitable for pregnant women

Computerised Axial Tomography (CAT)

Computerised Axial Tomography (CAT) scans use computers and X-ray devices to create 3D images of the body.

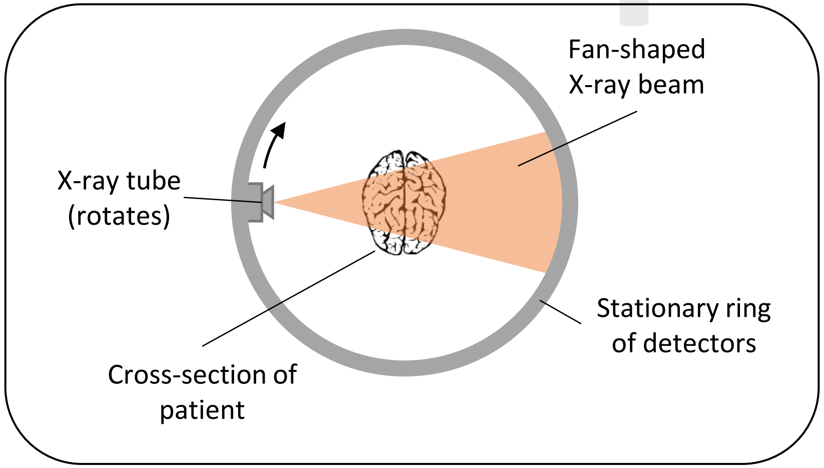
The patient is placed on a table that moves in and out of the gantry, which is the circular opening of the machine.

The ring inside the gantry contains a single X-ray tube and up to a thousand X-ray detectors making a ring of detectors.

The X-ray tube generates a thin, fan-shaped beam that rotates quickly around the patient, sending the beam through the patient at various angles.

The X-rays pass through the patient and are detected on the opposite side of the X-ray tube. These detectors monitor the amount of X-rays absorbed.

The detectors sends the signal to a computer. Then, the computer uses a software to calculate how much attenuation each part of the body has caused and provides a very high-quality image.



Computerised Axial Tomography (CAT)

Advantages of CAT scans:

- Creates 3D images.
- Show the precise position and shapes of tumours.
- Better contrast between soft tissue.
- Can tell the difference between tissues that have similar attenuation coefficients.

Disadvantages of CAT scans:

- Patients are exposed to ionising radiation which can harm cells and, in rare cases, cause cancer.
- Expensive.
- Time consuming.

Please see '21.1.2 Using X-rays worked examples' pack for exam style questions.

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