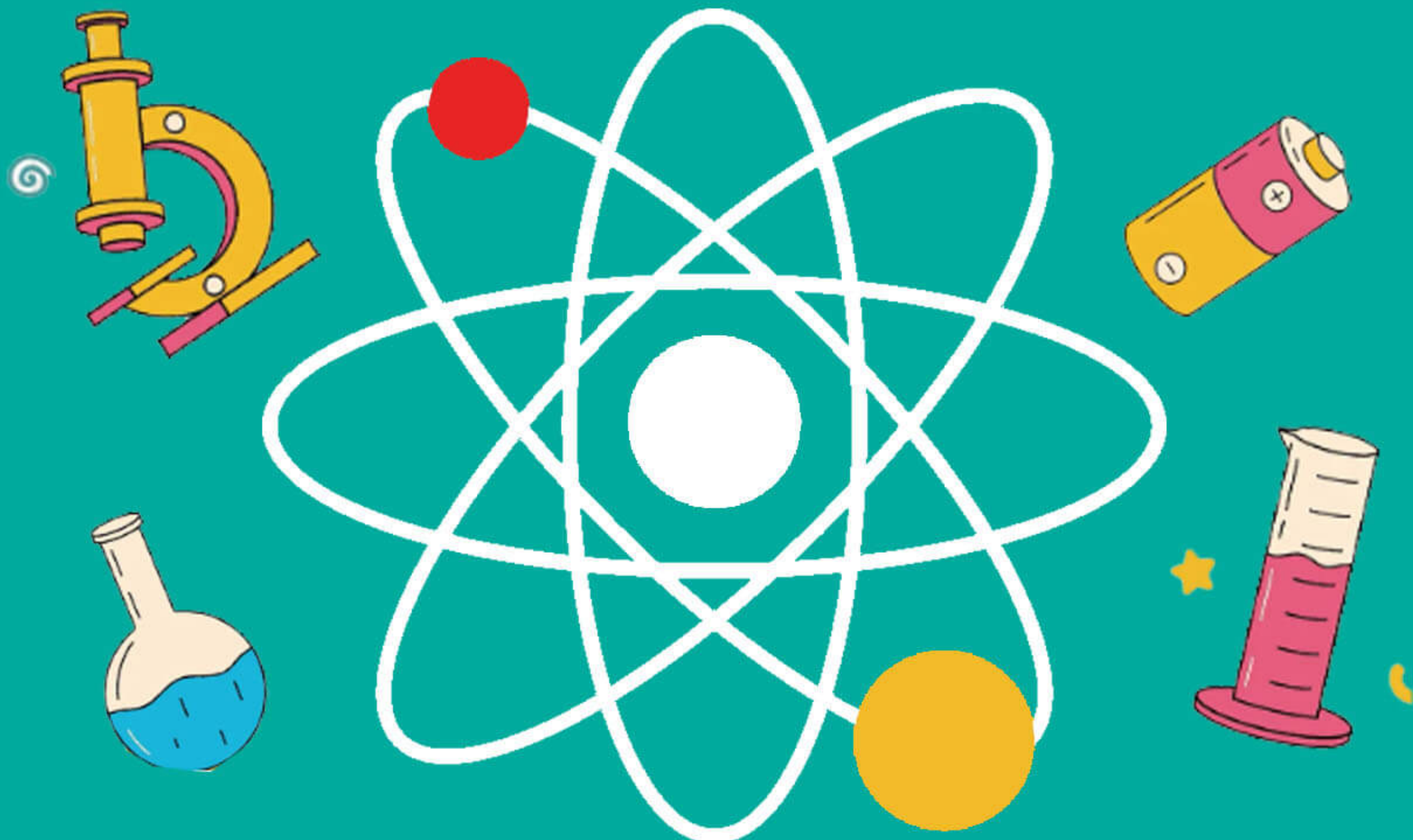
Exam Papers Practice

10.5 X-ray Imaging



AQA A Level Physics Revision Notes

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10.5.1 Production of X-rays

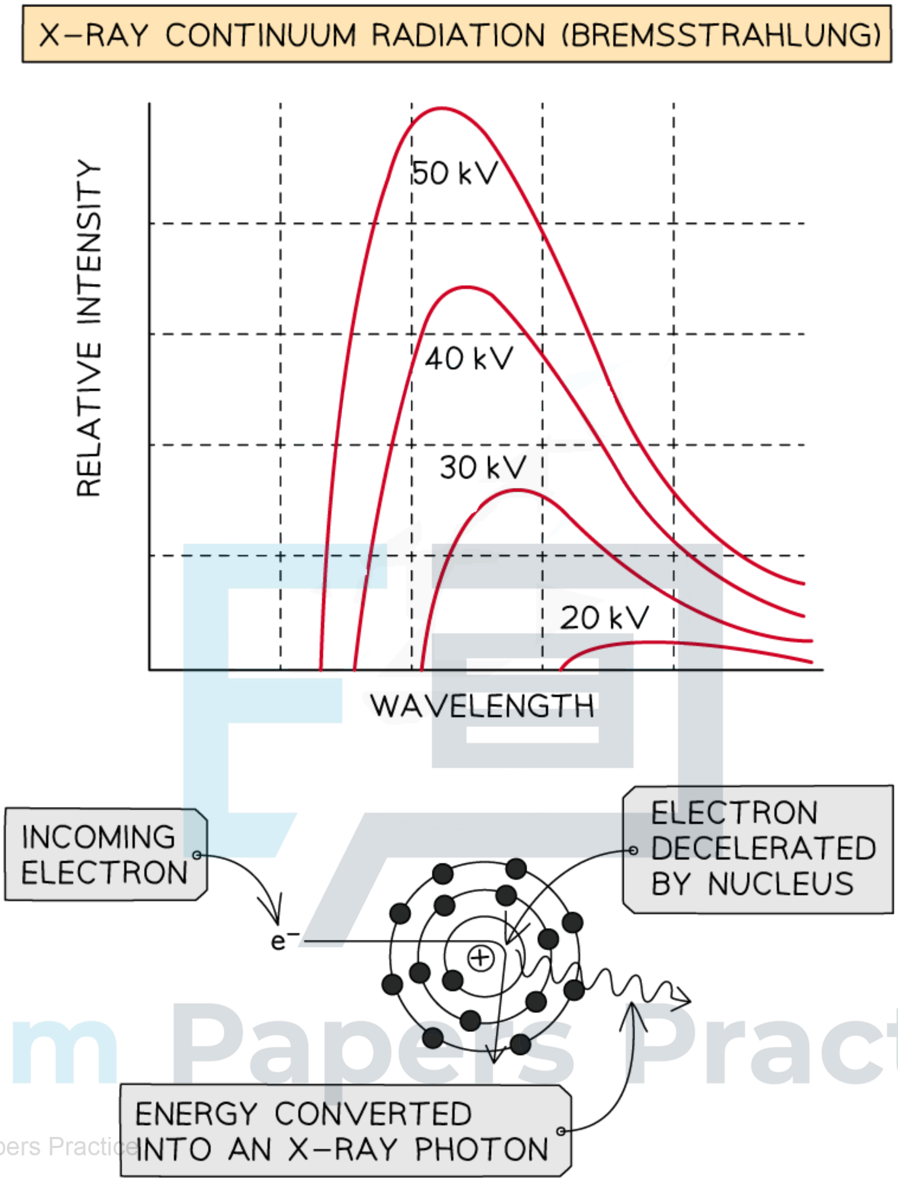
Production of X-rays

- When the fast-moving electrons collide with the target, X-rays are produced by one of two methods
  - Method 1: **Bremsstrahlung**
  - Method 2: **Characteristic Radiation**

Method 1: Bremsstrahlung

- When high-speed electrons collide with a metal target (often tungsten), they undergo a steep deceleration
  - When a charged particle decelerates quickly, some of the energy released is converted into a photon
- A small amount of the kinetic energy (~ 1%) from the incoming electrons is converted into X-rays as the electrons decelerate in the tungsten, due to conservation of energy
  - The rest of the energy heats up the anode, which usually requires some form of cooling
- The energy of the X-ray photon can be of any value, up to the original kinetic energy of the electron, giving a range of possible X-ray energies
  - These X-rays cause the continuous or 'smooth hump shaped' line on an intensity wavelength graph

Ranges of Wavelengths in Bremsstrahlung Radiation



The continuous spectra of Bremsstrahlung radiation at different acceleration potentials. As wavelength decreases, the energy of the X-rays photons increases.

- When an electron is accelerated, it gains energy equal to the product of its charge and the accelerating potential, V, this energy can be calculated using:

$$E_{max} = eV$$

- This is the **maximum energy** that an X-ray photon can have
- The smallest possible wavelength is equivalent to the highest possible frequency and therefore, the highest possible energy

- This is assuming all of the electron's kinetic energy has turned into electromagnetic energy

- Therefore, the maximum X-ray frequency f_{max}, or the minimum wavelength λ_{min}, that can be produced is calculated using the equation:

$$E_{max} = eV = hf_{max} = \frac{hc}{\lambda_{min}}$$

- The maximum **X-ray frequency**, f_{max}, is therefore equal to:

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

- The minimum **X-ray wavelength**, λ_{min}, is therefore equal to:

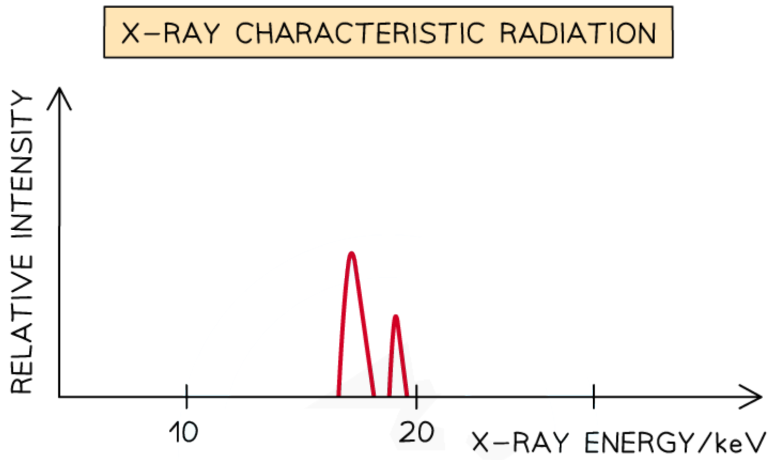
$$\lambda_{min} = \frac{hc}{eV}$$

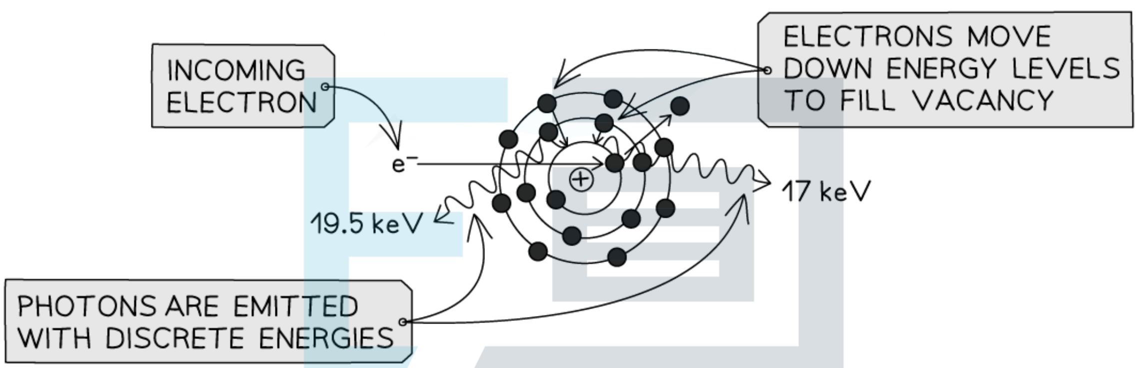
- Where:
  - e = elementary charge (C)
  - V = potential difference between the anode and cathode (V)
  - h = Planck's constant (J s)
  - c = the speed of light (m s^{-1})

Method 2: Characteristic Radiation

- Some of the incoming fast electrons cause inner shell electrons of the tungsten to be 'knocked out' of the atom, leaving a vacancy
  - This vacancy is filled by an outer electron moving down and releasing an X-ray photon as it does (equal in energy to the difference between the two energy levels)
  - Because these X-rays are caused by energy level transitions, they have only specific discrete energies
  - They cause sharp spikes on an intensity wavelength graph
  - The number of spikes depends on the element used for the target - there are two sets of spikes for a tungsten target, representing two sets of possible energy transitions

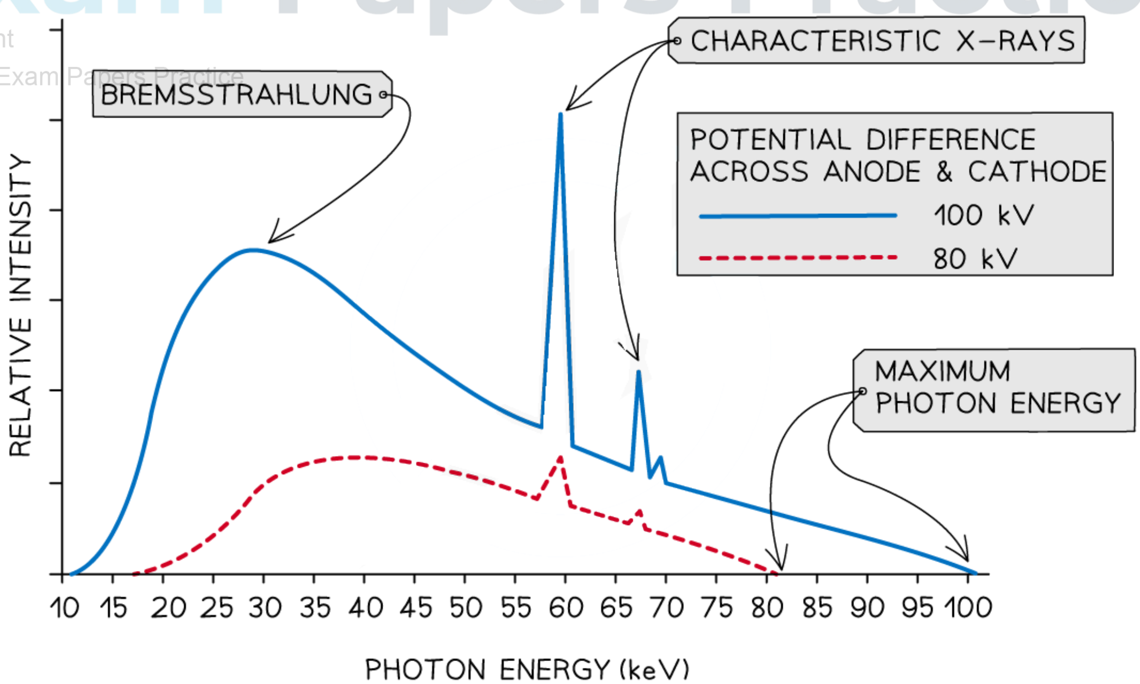
Characteristic Discrete X-Ray Wavelengths





Electron transitions emit photons with discrete energies. An incoming electron can cause these transitions, making tungsten emit characteristic photons.

Combined X-Ray Spectra of Bremsstrahlung and Characteristic Photons



Worked example

X-rays are a type of electromagnetic wave with wavelengths in the range 10^{-8} to 10^{-13} m

If the accelerating potential difference in an X-ray tube is 60 kV, determine if the photons emitted fall within this range.

Answer:

Step 1: Write out known quantities

- Charge on an electron, $e = 1.6 \times 10^{-19}$ C
- Accelerating potential difference, $V = 60\,000$ V
- Planck's constant, $h = 6.63 \times 10^{-34}$ J s
- Speed of light, $c = 3 \times 10^{8}$ m s^{-1}

Step 2: Determine the maximum possible energy of a photon

- The maximum possible energy of a photon corresponds to the maximum energy an electron could have:

$$E_{max} = eV$$

Step 3: Determine an expression for minimum wavelength

Planck relation: $E = hf$

Wave equation: $c = f\lambda$

- When energy is a maximum:

$$E_{max} = eV = hf_{max}$$

- Maximum energy corresponds to a minimum wavelength:

$$eV = \frac{hc}{\lambda_{min}}$$

- Rearrange for minimum wavelength, λ_{min}:

$$\lambda_{min} = \frac{hc}{eV}$$

Step 4: Calculate the minimum wavelength λ_{min}

$$\lambda_{min} = \frac{(6.63 \times 10^{-34})(3 \times 10^{8})}{(1.6 \times 10^{-19})(60\,000)}$$

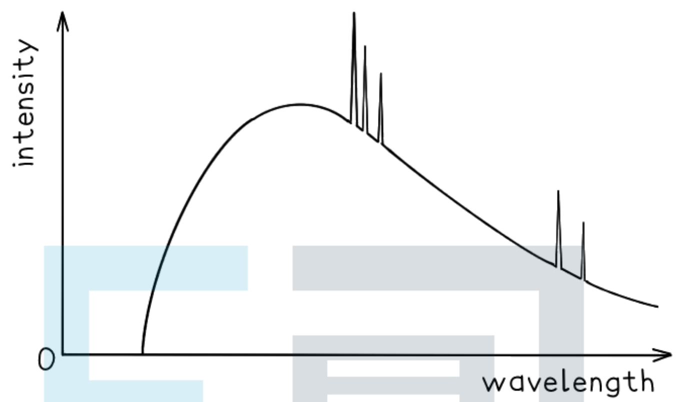
$$\lambda_{min} = 2.1 \times 10^{-11} \text{ m}$$

Step 5: Comment on whether this is within the range for the wavelength of an X-ray

- X-ray wavelengths are within 10^{-8} to 10^{-13} m
- The minimum wavelength for a 60 kV supply is 2.1×10^{-11} m, which means the photons produced will be X-rays

Worked example

A typical spectrum of the X-ray radiation produced by electron bombardment of a metal target is shown below.



Explain why:

(a) A continuous spectrum of wavelengths is produced.
(b) The gradient is steeper at shorter wavelengths.
(c) The spectrum has a sharp cut-off at short wavelengths.

Answer:

Part (a)

Step 1: Consider the path of the electrons from the cathode to the anode

- Photons are produced whenever a charged particle undergoes a large acceleration or deceleration
- X-ray tubes fire high-speed electrons at a metal target
- When an electron collides with the metal target, it loses energy in the form of an X-ray photon as it decelerates

Step 2: Consider the relationship between the energy of the electron and the wavelength of the photon

- The wavelength of a photon depends on the energy transferred by a decelerating electron
- The electrons don't all undergo the same deceleration when they strike the target
- This leads to a distribution of energies, hence, a range, or **continuous** spectrum, of wavelengths is observed

Part (b)

Step 1: Identify the significance of the intensity

- The intensity of the graph signifies the proportion of photons produced with a specific energy, or wavelength
- The higher the intensity, the more photons of a particular wavelength are produced
- In other words, the total intensity is the sum of all the photons with a particular wavelength

Step 2: Explain the shape of the graph

- When a single electron collides with the metal target, a single photon is produced
- Most electrons only give up part of their energy, and hence there are more X-rays produced at wavelengths higher than the minimum (or energies lower than the maximum)
- At short wavelengths, there is a steeper gradient because only a few electrons transfer all, or most of, their energy

Part (c)

Step 1: Identify the relationship between minimum wavelength and maximum energy

- The minimum wavelength of an X-ray is equal to

$$\lambda_{min} = \frac{hc}{E_{max}}$$

- The equation shows the maximum energy of the electron corresponds to the minimum wavelength, they are inversely proportional

$$\lambda_{min} \propto \frac{1}{E_{max}}$$

- Therefore, the higher the energy of the electron, the shorter the wavelength of the X-ray produced

Step 2: Explain the presence of the cut-off point

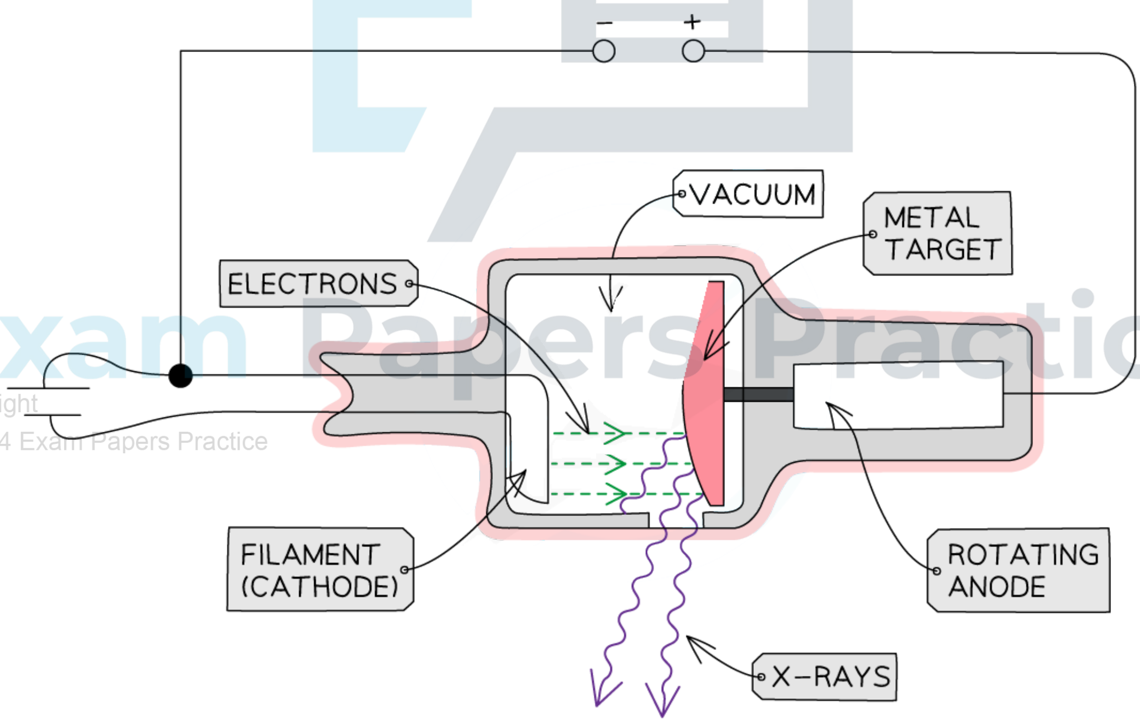
- The accelerating voltage determines the kinetic energy which the electrons have before striking the target
- The value of this accelerating voltage, therefore, determines the value of the maximum energy
- This corresponds to the minimum, or cut-off, wavelength

10.5.2 Rotating-Anode X-ray Tube

Rotating-Anode X-ray Tube

- An X-ray tube is a device that converts an electrical input into X-rays
- It is composed of four main components:
  - A heated cathode
  - An anode
  - A metal target
  - A high voltage power supply
- The production of X-rays has many practical uses, such as in:
  - Medical imaging (radiography)
  - Security
  - Industrial imaging

The Rotating-Anode X-ray Tube



The main components of an X-ray tube are the heated cathode, anode, metal target and a high voltage supply

Heated Cathode

- At one end of the tube is the cathode (negative terminal) which is **heated** by an electric **current**
  - The heat causes electrons to be **liberated** from the cathode, gathering in a cloud near its surface
  - This process of thermionic emission is the source of the electrons

Anode

- At the other end of the tube, an anode (positive terminal) is connected to the high-voltage supply
- This allows the electrons to be **accelerated** up to a voltage of 200 kV
  - When the electrons arrive at the anode, they gain a kinetic energy of 200 keV (by the definition of an electronvolt)
- Only about 1% of the kinetic energy is converted to X-rays
  - The rest is converted to heat energy
  - Therefore, to avoid overheating, the anode is spun at 3000 rpm and sometimes water-cooled

Metal Target

- When the electrons hit the target at **high speed**, they **lose** some of their kinetic energy
  - This energy is re-emitted as X-ray photons
- A heat-resistant block of metal, usually tungsten, is embedded at the end of the anode, facing the cathode
  - This is the material that the electrons **collide** with and X-rays are generated in

High Voltage Power Supply

- The high voltage supply creates a **large potential difference** (> 50 kV) between the cathode and the target
- This causes electrons in the cloud around the cathode to be accelerated to a high velocity towards the target, which they strike, creating X-rays

Other Components

- X-rays are produced in all directions, so the tube is surrounded by **lead shielding**
  - This is to ensure the safety of the operators and recipients of the X-rays
  - An adjustable window allows a concentrated beam of X-rays to escape and be controlled safely
- The anode and cathode are housed inside a **vacuum chamber**
  - This is to ensure that the electrons do not collide with any particles on their way to the metal target

10.5.3 Using X-rays in Medical Imaging

Using X-rays in Medical Imaging

- X-ray imaging has become a highly developed technique which enables physicians to produce detailed images of bones, soft tissues and even blood vessels
- When treating patients, the main aims of X-ray imaging are to:
  - Reduce the patient's **exposure** to radiation as much as possible
  - Improve the **contrast** of the image

Reducing Exposure

- X-rays are **ionising**, meaning they can cause damage to living tissue and can potentially lead to cancerous mutations
- Therefore, healthcare professionals must ensure patients receive the minimum radiation dosage possible
- The X-ray dose given to a patient depends on
  - The exposure time
  - The intensity of the beam
- X-ray equipment is designed to reduce exposure and minimise the risk to the patient by
  - Controlling the intensity of the X-ray beam
  - Using a beam definer
  - Using a metal filter
  - Using sensitive detection methods

Controlling the intensity of the X-ray beam

- The anode p.d. controls the **maximum energy** of the X-ray photons from an X-ray tube
  - The higher the anode p.d., the shorter the wavelength and hence, the higher the energy of the X-ray photons
  - Shorter wavelengths of X-ray (high energy photons) are more penetrating, therefore, they are less likely to be absorbed by the body
- The cathode current controls the **intensity** of the X-ray beam
  - The higher the cathode current, the more electrons that are emitted by thermionic emission
  - If more electrons reach the anode each second, then more X-ray photons are emitted per second
- To minimise the **exposure** to the patient, the beam intensity should be reduced by lowering the cathode current
- This minimises the **risk** to the patient by reducing the number of ionising photons passing through the patient each second

Beam definers

- A beam definer, or lead diaphragm plate, consists of two pairs of lead sheets with a narrow aperture in the centre which is placed close to the X-ray tube (where the X-rays are emitted)
- Lead diaphragm plates minimise the **exposure** to the patient by producing a focused (collimated) beam
- This is necessary because:
  - Photons are emitted by the X-ray tube in many directions
  - The lead plates absorb the scattered photons and the aperture allows X-rays travelling in a specific direction to pass through
- This minimises the **risk** to the patient because the narrow beam is used to investigate a specific area of the body only
- Therefore, the areas of the body not being scanned are not exposed to ionising photons

Metal filters

- A metal filter is a thin sheet of metal, usually aluminium, which is placed in the path of the beam between the X-ray tube and the patient
- Aluminium filters minimise the **exposure** to the patient by reducing the intensity of low-energy X-rays
- This is necessary because:
  - Many wavelengths of X-ray are emitted by the X-ray tube
  - Longer wavelengths of X-ray (low energy photons) are less penetrating, therefore, they are more likely to be absorbed by the body
- As a result, an aluminium filter minimises the **risk** to the patient because it reduces the amount of ionising photons which the body could absorb
- This happens because the aluminium sheet:
  - Absorbs a large percentage of the **low-energy** photons (which are not needed to produce an image)
  - Allows the **high-energy** photons to pass straight through

Sensitive detection methods

- The exposure time can be reduced by using a more sensitive X-ray detector, by
  - Using an electronic detector instead of photographic detection
  - Intensifying the image

Contrast & Sharpness

- Contrast is defined as:

The difference in degree of blackening between structures

- Contrast allows a clear difference between tissues to be seen
- Image contrast can be improved by:
  - Using the correct level of X-ray hardness: **hard X-rays** for bones, **soft X-rays** for tissue
  - Using a contrast media
- Sharpness is defined as:

How well-defined the edges of structures are

- Image sharpness can be improved by:
  - Using a narrower X-ray beam
  - Reducing X-ray scattering by using a collimator or lead grid
  - Smaller pixel size

Contrast Enhancement

- A contrast medium is defined as:

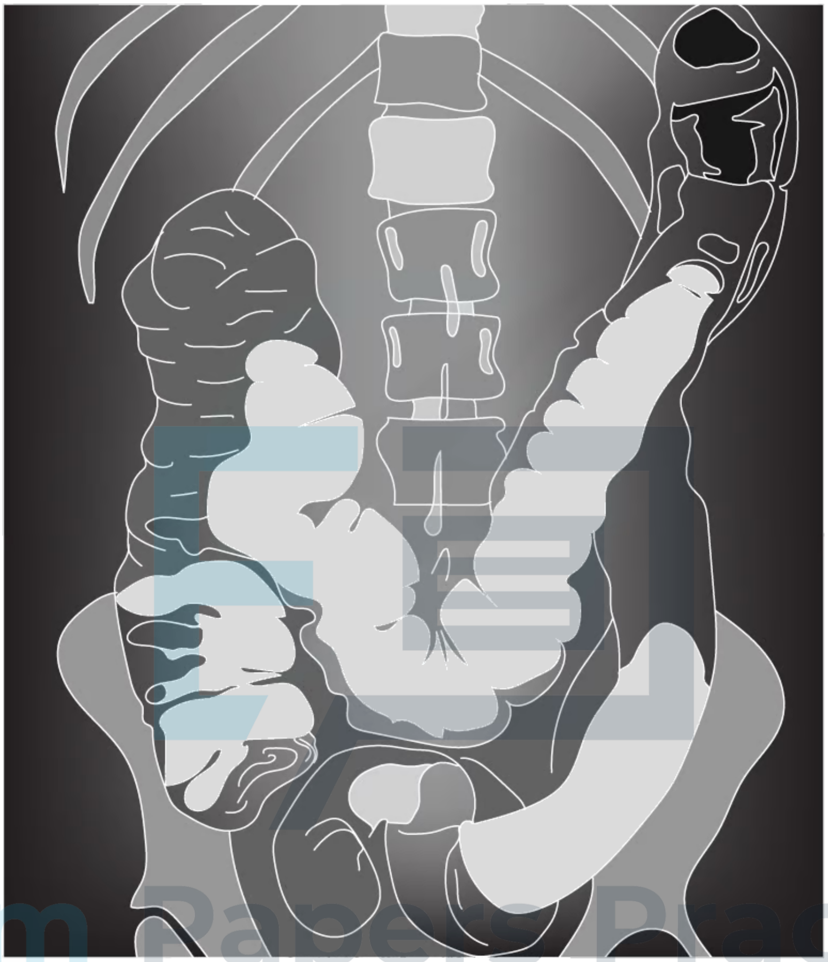
  A substance, such as barium or iodine, which is a good absorber of X-rays. A patient is given this so a bigger contrast can be obtained on an X-ray image

- The use of a contrast medium is sometimes required because:
  - Some soft tissue organs do not show up on X-rays when the organs have **similar** attenuation coefficients
  - Contrast media are good absorbers of X-rays as they have a **large** attenuation coefficient
  - Hence when contrast media enter an organ, the X-ray image is **enhanced** as the substance is **opaque** to X-rays
- Barium and iodine are used depending on the organ being imaged
  - Iodine is used as a contrast medium in **liquids** i.e. to observe blood flow - this is usually injected into the patient
  - Barium sulphate is used as a contrast medium in the **digestive system** - this is usually ingested by mouth and is known as a barium meal
- The large **attenuation coefficient** of contrast materials is due to the **large atomic number** of these elements
  - Barium has an atomic number of 56, while iodine has an atomic number of 53

Using iodine as a contrast medium

Iodine makes liquids, such as blood, opaque to X-rays and improves the contrast of the X-ray image

Using a barium meal as a contrast medium



Barium makes intestines opaque to X-rays and improves the contrast of the X-ray image

10.5.4 X-ray Detection

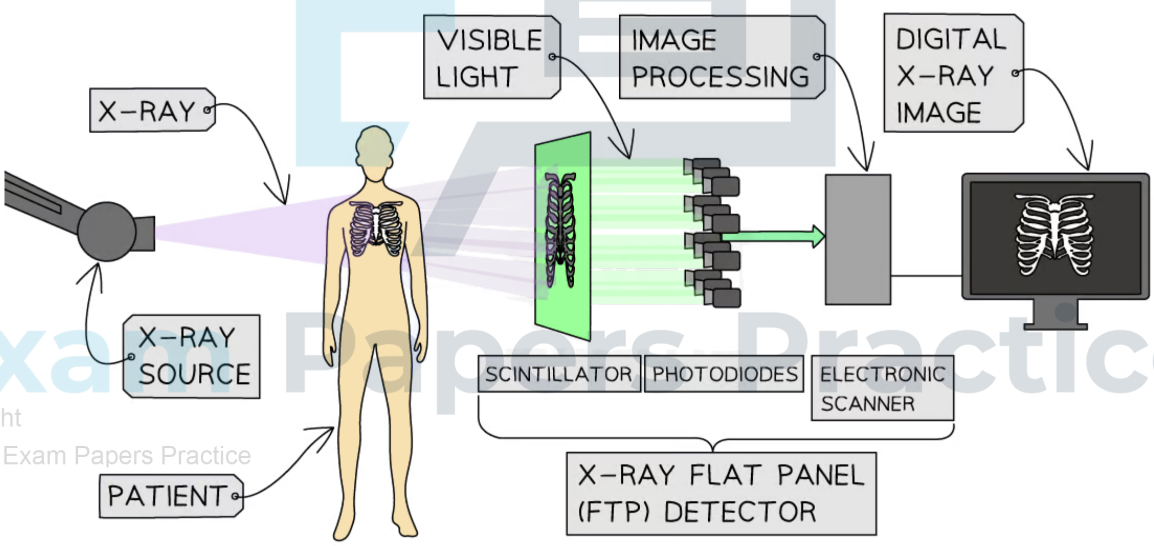
X-ray Detection

- X-rays can be detected and images can be produced from **three** main detection methods:
  - X-ray flat panel (FTP) detectors
  - Photographic film
  - Fluoroscopic image intensification

Flat-Panel Detectors

- X-ray flat panel (FTP) detectors are the most common type of detection method used in medical facilities today
- They are made up of three layers, or 'panels':
  - The **scintillator** layer
  - The **photodiode pixel** layer
  - The **electronic scanner** layer

X-ray Flat Panel Detector Structure



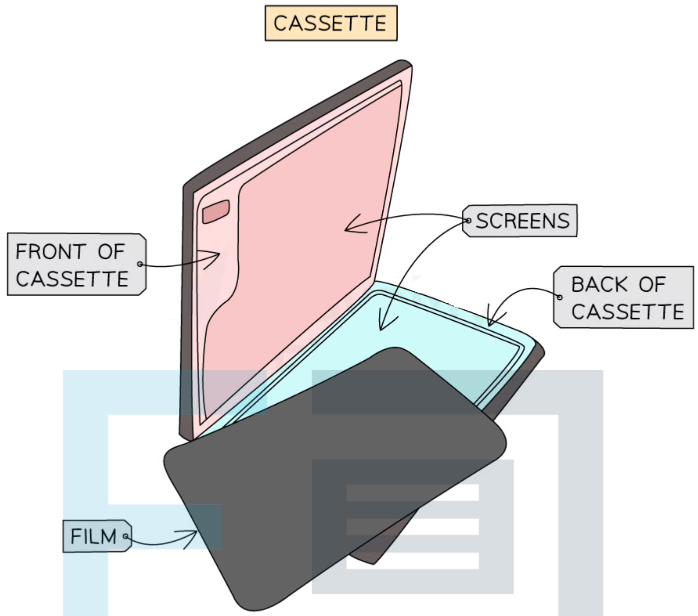
The process of forming a digital image using an X-ray flat panel detector

- Once the X-rays arrive at the FTP detector behind the patient:
  - The electrons in the scintillator layer absorb the high-energy X-rays and **emit visible photons**
  - The emitted visible photons are then absorbed by photodiode pixels and trigger the **release of electrons**
  - The release of electrons generates a p.d. (electrical signal) which is processed and transmitted as a **digital image** to be stored on a computer
- FTP detectors can produce high-quality images of most solid structures in the body, such as bones and joints
  - These types of detectors are also used in most commercial uses of X-rays, such as airport security

Photographic Film Detection

- Before digital methods, the original X-ray detectors used photographic film
  - In medicine today, however, photographic detection is rarely used
- An **intensifying screen** or 'cassette' is a device containing two fluorescent screens placed on either side of a double-sided X-ray film

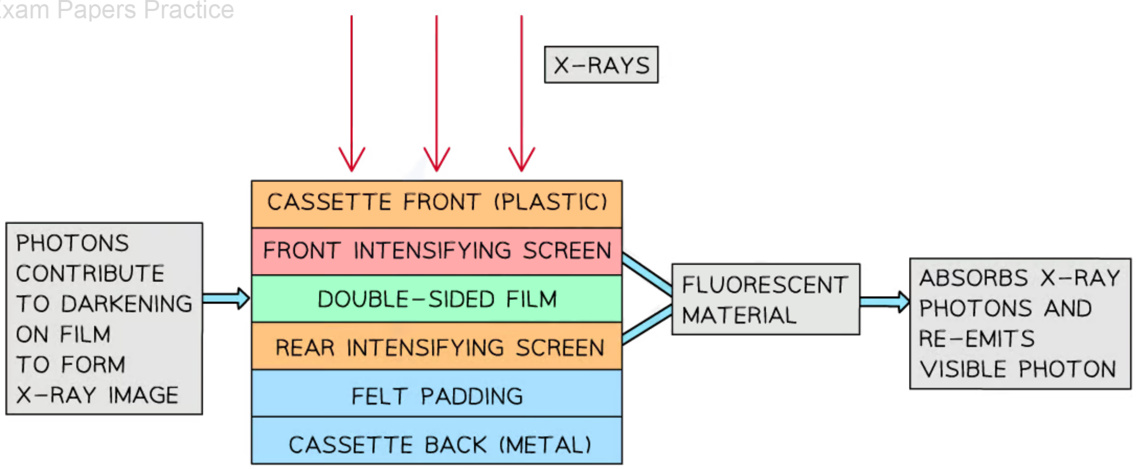
X-ray Intensifying Cassette



In an intensifying cassette, photographic film is sandwiched between two sheets of fluorescent material

- The X-rays expose the photographic film but the fluorescent screens emit light that exposes the film faster
- Each X-ray absorbed by the fluorescent material causes several visible light photons to be emitted
  - These visible photons contribute to the darkening of the film, allowing the image to form about 20 times faster than using X-rays alone

Structure of an Intensifying Screen



The fluorescent screens on both sides of the film significantly shorten the exposure time required to produce the X-ray image

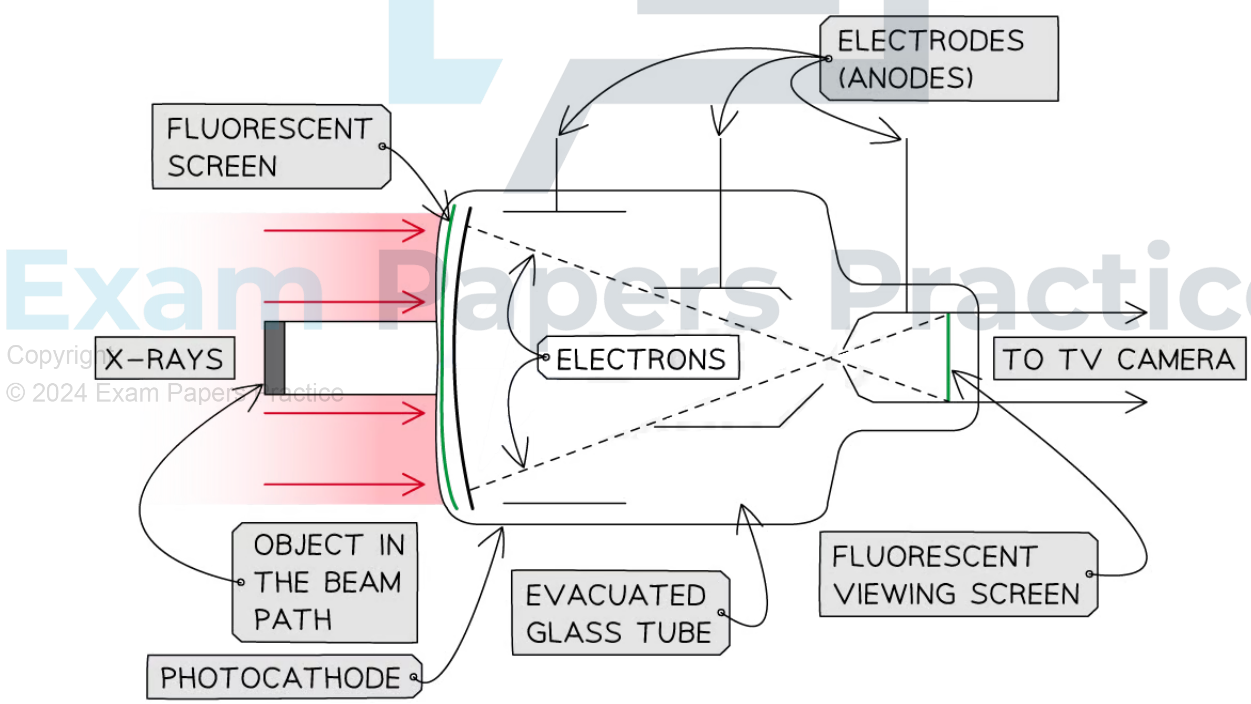
- Using an intensifying screen allows the overall exposure time of X-rays to be **shortened**

- This is beneficial to the patient because
  - Reducing the exposure time reduces the ionising dose of radiation received by a patient
  - The patient does not have to be stationary for so long

The Image Intensifier

- A fluoroscopic **image intensifier** is a device which consists of
  - An evacuated glass tube
  - A photocathode
  - Multiple anodes
  - Two fluorescent screens, one at each end of the evacuated tube
- The operation of an image intensifier is as follows:
  - An image forms on the first fluorescent screen as incident X-rays are absorbed and re-emitted as visible photons
  - Visible photons cause electrons to be emitted from the photocathode
  - The emitted electrons are accelerated through a large p.d. (about 25 kV) towards the anodes which focus them on an output window
  - The intensified image is formed on the fluorescent viewing screen at the end of the evacuated tube
- Often a camera is attached to the output window to allow the images to be viewed on a TV screen

Structure of a Fluoroscopic Image Intensifier



An image intensifier converts X-rays to photons using fluorescent screens and increases the brightness through the acceleration of electrons to show processes in real-time

- The final image on the fluorescent viewing screen is about 5000 times **brighter** compared to the initial image on the first fluorescent screen because the electrons are:
  - Focused onto a smaller area for a given power output, hence intensity increases $\left(I = \frac{P}{A}\right)$

  - Given a large amount of energy due to the acceleration by the anodes which means several photons are produced for every electron arriving at the fluorescent viewing screen
- This method of X-ray detection is used for **imaging movement**
  - This means real-time images can be observed and recorded
  - For example, dynamic processes such as swallowing or blood flow in and around organs
- This method involves a **higher radiation dose** to the patient than in X-ray imaging involving a single exposure
  - This is because a continuous beam of X-rays is required for the duration of the procedure
  - However, if the image intensifier is used with a TV camera, the radiation dose is **minimised** compared to taking several images of the same region

Worked example

For a fluoroscopic image intensifier, state the purpose(s) of

(a) the fluorescent screen at the photocathode
(b) the photocathode
(c) the anodes
(d) the fluorescent screen at the end of the evacuated tube
(d) the evacuated tube

Answer:

(a) The purpose of the fluorescent screen at the photocathode is...

- To absorb X-ray photons and emit visible light photons

(b) The purpose of the photocathode is...

- To absorb visible light photons and emit electrons from the surface of the cathode

(c) The purposes of the anodes are...

- To accelerate the electrons released at the cathode
- To focus the electron beams to produce an image

(d) The purpose of the fluorescent screen at the end of the evacuated tube is...

- To convert the energy of each electron into several visible light photons

(e) The purpose of the evacuated tube is...

- To prevent collisions between electrons and air molecules

Advantages of the FTP Detector

- Previously, X-ray images were predominantly produced using photographic film
  - Now, digital methods, such as flat panel detection (FTP), are preferred
- The key advantages of FTP detectors compared with photographic detection are:
  1. Flat-panel detectors are **faster** than film
     - This means X-ray images can be produced in real time, which allows for quicker diagnoses
     - Whereas photographic film requires time to be processed and developed
  2. Flat-panel detectors are more **sensitive** than film
     - This means a lower dose of radiation can be administered to the patient to produce an image of the same quality compared to one produced by film
  3. Flat-panel detectors produce **digital** images
     - Digital images can be processed quickly, as well as stored and transferred with ease

Worked example

For the following X-ray detection methods

- Photographic film
- Flat panel (FTP) detector
- Fluoroscopic image intensification

State and explain which one should be used in the following situations:

(a) to produce an image of a broken bone
(b) to observe the blood flow in an organ in real-time
(c) to perform a routine dental check

Answer:

(a)

Step 1: State the best technique to produce an image of a broken bone:

- Flat panel (FTP) detection

Step 2: Explain the advantage of FTP over image intensification:

- There is no movement so a real-time image is not required

Step 3: Explain the advantages of FTP over photographic film:

- FTP is more sensitive than film which means a more detailed image of the bone can be produced
- FTP is faster than film as it doesn't have to be developed, which means the diagnosis can be made quicker
- FTP produces a digital image which is easier to save, share or transfer unlike film
- FTP allows for a much lower dose of X-rays to be used than film which is safer for the patient

(b)

Step 1: State the best technique to observe the blood flow in an organ in real-time:

- Fluoroscopic image intensification

Step 2: Explain the advantages of image intensification:

- Blood flow is a dynamic process and only the fluoroscopic image intensifier can capture real-time movement
- The intensifying screen is more sensitive than film and does not need to be developed
- However, the intensifying screen does require a greater exposure time than film and FTP

(c)

Step 1: State the best technique to perform a routine dental check:

- Photographic film <u>OR</u> flat panel detection

Step 2: Explain the advantages of FTP or film over image intensification:

- There is no movement so a real-time image is not required
- Both film and FTP provide a lower dose of radiation than the intensifying screen

Step 3: Explain the advantage of FTP or photographic film over the other method:

- FTP is the best option as it is more sensitive than film, allows the shortest exposure time and produces a digital image
  OR
- Photographic film would be acceptable for a routine check if it was the only available technology

10.5.5 Attenuation of X-rays

Attenuation of X-rays in Matter

- When a collimated beam of X-rays passes through a patient's body, the X-ray photons are **absorbed** and **scattered**
- Different materials absorb X-rays by different amounts
  - For example, bones **absorb** a large proportion of X-ray photons which is why they appear bright white on an X-ray image
- As the X-rays pass through a material, the intensity of the beam is found to decay exponentially
  - This decrease in intensity is known as **attenuation**
- The attenuation of X-rays can be calculated using the equation:

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

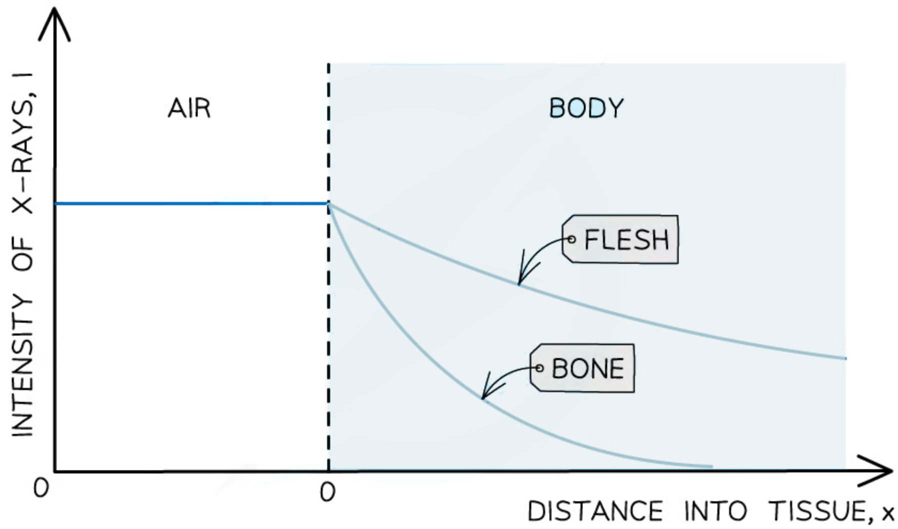
- Where:
  - I_0 = the intensity of the incident beam (W m^{-2})
  - I = the intensity of the transmitted beam (W m^{-2})
  - μ = the linear absorption coefficient (m^{-1})
  - x = distance travelled through the material (m)

- The linear attenuation coefficient μ is defined as

  The fraction of X-rays removed per unit thickness of the material for a specified energy of the X-rays

- The value of μ depends on the **density** of a substance and the **energy** of the X-ray photons
  - The greater the density of a material, the **greater** the value of μ
  - For example, **bone** absorbs a greater proportion of X-rays than **soft tissue** due to its higher density

Absorption of X-rays by flesh and bone



Bone is denser than soft tissues, such as flesh, so X-rays are absorbed more over a shorter distance

Half-value thickness

- Similar to half-life in radioactivity, a material's ability to absorb X-rays is known as its **half-value thickness**
- The half-value thickness of a material can be defined as:

  The thickness of the material which will reduce the intensity of X-rays to half its original level for a specified energy of the X-rays

- If the half-value thickness is $x = x_{1/2}$, then intensity has a value of $I = \frac{I_0}{2}$, so substituting this into the attenuation equation gives:

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

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

- Taking natural logarithms of both sides gives

$$\ln\frac{1}{2} = -\mu x_{1/2}$$

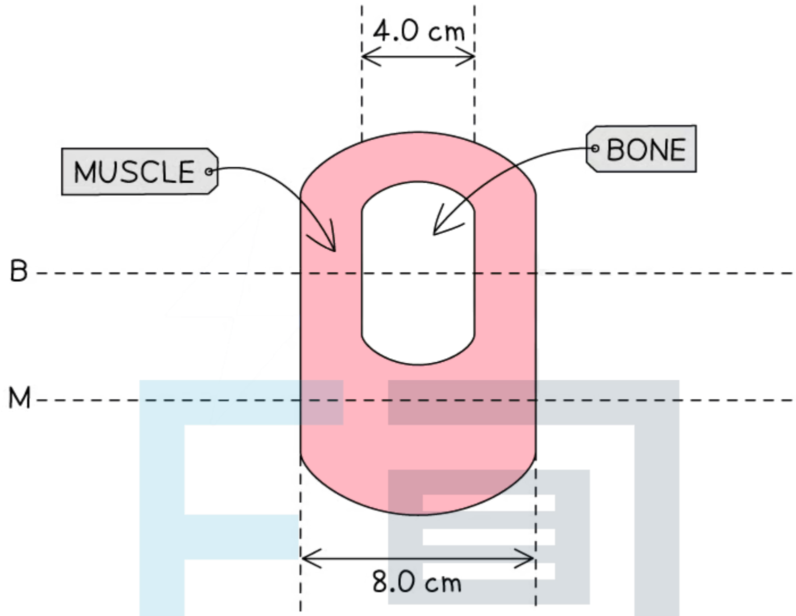
$$\ln 2 = \mu x_{1/2}$$

- Hence, the half-value thickness of a substance is given by:

$$x_{1/2} = \frac{\ln 2}{\mu}$$

Worked example

A student investigates the absorption of X-ray radiation in a model arm. A cross-section of the model arm is shown in the diagram.



Parallel X-ray beams are directed along line MM and line BB. The linear absorption coefficients of the muscle and the bone are 0.20 cm^{-1} and 12 cm^{-1} respectively.

Calculate the ratio:

$$\frac{intensity\ of\ incident\ X-ray\ beam\ from\ model}{intensity\ of\ incident\ X-ray\ beam\ on\ model}$$

for a parallel X-ray beam directed along

(a) line MM

(b) line BB

and state whether the X-ray images have good contrast.

Answer:

(a)

Step 1: Write out the known quantities

- Linear absorption coefficient for muscle, μ_m = 0.20 cm^{-1}
- Distance travelled through the muscle, x_m = 8.0 cm

Step 2: Write out the equation for attenuation and rearrange

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

- Where I = the intensity of the incident X-ray beam from the model
- And I_0 = the intensity of the incident X-ray beam on the model

$$\frac{intensity\ of\ incident\ X-ray\ beam\ from\ model}{intensity\ of\ incident\ X-ray\ beam\ on\ model} = \frac{I}{I_0} = e^{-\mu x}$$

Step 3: Substitute in values and calculate the ratio

$$\frac{I}{I_0} = e^{-(0.20 \times 8.0)} = 0.2$$

(b)

Step 1: Write out the known quantities

- Linear absorption coefficient for muscle, μ_m = 0.20 cm^{-1}
- Linear absorption coefficient for bone, μ_b = 12 cm^{-1}
- Distance travelled through the muscle, x_m = 4.0 cm
- Distance travelled through the bone, x_b = 4.0 cm

Step 2: Write out the equation for attenuation for two media and rearrange

$$\frac{I}{I_0} = e^{-\mu_m x_m} \times e^{-\mu_b x_b}$$

Step 3: Substitute in values and calculate the ratio

$$\frac{I}{I_0} = e^{-(0.20 \times 4.0)} \times e^{-(12 \times 4)} = 6.4 \times 10^{-22} \approx 0$$

Step 4: Write a concluding statement

- Each ratio gives a measure of the amount of transmission of the beam from the model
- A **good contrast** is when:
  - There is a large difference between the intensities
  - The ratio is much less than 1.0
- Therefore, **both images** have a good contrast

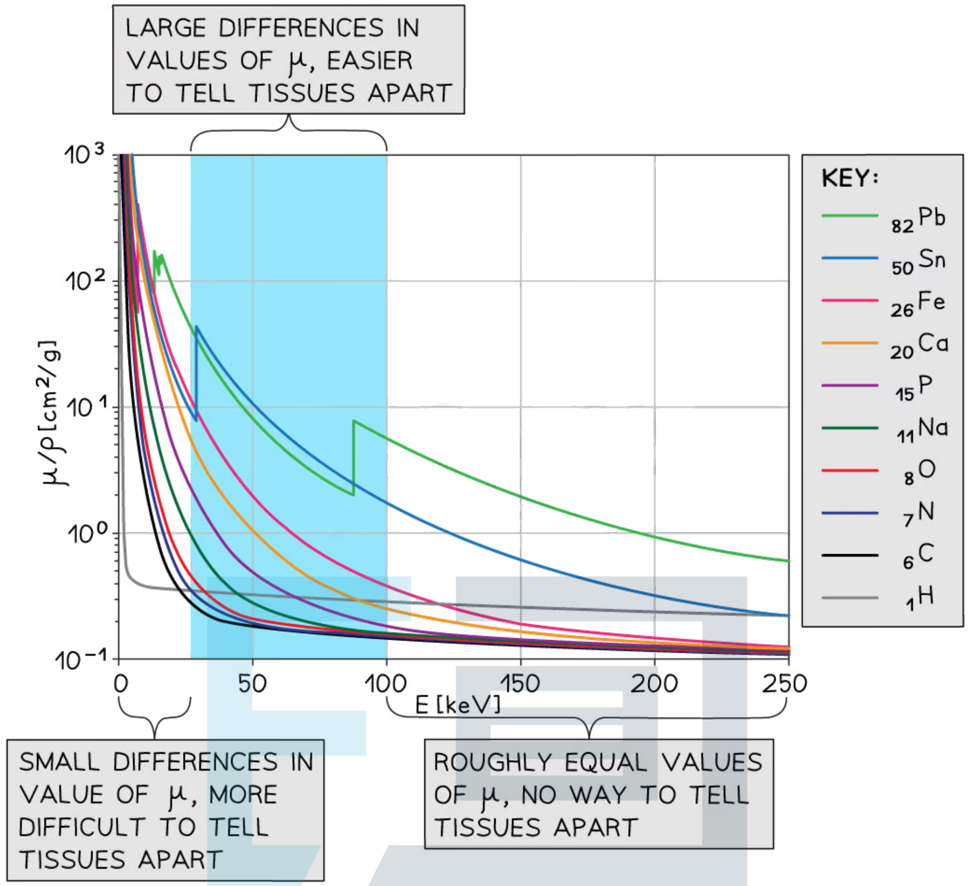
Differential Tissue Absorption

- The amount of attenuation of a beam of X-rays depends on
  - The **density** of the absorbing tissue
  - The **energy** of the X-ray photons
- The linear attenuation coefficient μ of an absorber is proportional to the density ρ of the absorbing substance
  - The higher the density of a material, the more X-ray energy that it absorbs
  - This is because the photons interact with **more** atoms, or a **larger mass** of atoms, in the same volume
- Therefore, dividing the value of μ of a material by its density gives a constant value for that particular substance
- This constant is known as the **mass attenuation coefficient**

$$\mu_m = \frac{\mu}{\rho}$$

- Where:
  - μ_m = mass attenuation coefficient ($m^2\ kg^{-1}$)
  - μ = linear attenuation coefficient (m^{-1})
  - ρ = density of the absorbing material ($kg\ m^{-3}$)
- The mass attenuation coefficient of a substance describes how easily a beam of X-rays of a certain energy can penetrate it
  - The greater the mass attenuation coefficient, the stronger the **absorption** of X-rays by the material
  - The lower the mass attenuation coefficient, the greater the **penetration** of X-rays through the material

Mass attenuation coefficients for common elements



At very high and very low X-ray energies, differences in attenuation are very small. The optimum range for distinguishing different tissues is 30 keV to 100 keV

Photons of energies less than 30 keV...

- Are absorbed by soft tissue **and** bone
- Therefore, these photons are **removed** from the X-ray beam by placing a suitable **metal filter** (e.g. lead or tin) in the path of the X-ray beam

Photons of energies between 30 keV and 100 keV...

- Are absorbed more readily by **bone** than by soft tissue
- This is because the elements in bone have **higher atomic numbers** than the elements in soft tissues so bone can absorb photons in this energy range **more readily**
- Therefore, these photons are used to distinguish between soft tissue and bone

Photons of energies greater than 100 keV...

- Are absorbed more equally in **all** types of tissue, including bone
- This means they produce **no distinction** between any tissues
- Therefore, these photons are **not** used in diagnostic X-ray imaging

Attenuation in different elements

- The graph of mass attenuation coefficient and X-ray photon energy for elements with different values of atomic number Z shows that
  - Elements with **lower Z values** tend to absorb a lower proportion of X-rays
  - Elements with **higher Z values** tend to absorb a greater proportion of X-rays

- The table below shows the composition of different substances and the effect of atomic number on attenuation

Substance	Elements	Effect on attenuation
soft tissue	hydrogen $\left({}_{1}\text{H}\right)$, carbon $\left({}_{6}\text{C}\right)$ and oxygen $\left({}_{8}\text{O}\right)$	lower Z values, less attenuation
bone	hydrogen $\left({}_{1}\text{H}\right)$, carbon $\left({}_{6}\text{C}\right)$, oxygen $\left({}_{8}\text{O}\right)$, calcium $\left({}_{20}\text{Ca}\right)$ and phosphorus $\left({}_{15}\text{P}\right)$	higher Z values, more attenuation
contrast media	iodine $\left({}_{53}\text{I}\right)$ and barium $\left({}_{56}\text{Ba}\right)$	very high Z values, very large attenuation ideal for improving contrast
heavy metals	lead $\left({}_{82}\text{Pb}\right)$ and tin $\left({}_{50}\text{Sn}\right)$	very high Z values, high attenuation at lower energies ideal for use as metal filters

Worked example

A monochromatic beam of X-rays passes through an aluminium sheet of thickness 2.5 mm. The intensity of the beam is reduced by 25%.

Calculate the mass attenuation coefficient for these X-rays.

The density of aluminium is 2700 kg m^{-3}

Answer:

Step 1: List the known quantities:

- Intensity of X-ray beam, $I = (1 - 0.25)I_0 = 0.75\ I_0$
- Thickness of aluminium sheet, x = 2.5 mm = 0.0025 m
- Density of aluminium, ρ = 2700 kg m^{-3}

Step 2: Determine the linear attenuation coefficient of the X-rays

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

$$0.75\ I_0 = I_0\ e^{-0.0025\mu}$$

$$0.75 = e^{-0.0025\mu}$$

- Take natural logs of both sides:

$$\ln 0.75 = -0.0025\mu$$

$$\mu = -\frac{\ln 0.75}{0.0025}$$

linear attenuation coefficient: μ = 115 m^{-1}

Step 3: Determine the mass attenuation coefficient of the X-rays

$$\mu_m = \frac{\mu}{\rho}$$

$$\mu_m = \frac{115}{2700}$$

mass attenuation coefficient: μ_m = 0.043 m^2 kg^{-1}

Worked example

The table shows the linear attenuation coefficients for bone and muscle at three different X-ray photon energies.

Photon energy / keV	Bone μ / cm^{-1}	Muscle μ / cm^{-1}
30	2.13	0.41
50	0.68	0.24
80	0.36	0.20
100	0.30	0.18

Determine the energy of X-ray photons that would produce an image of muscle next to bone with the best contrast.

Answer:

Step 1: Recall the factor that determines the quality of contrast

- Contrast depends on the **difference** in attenuation
  - The smaller the difference in attenuation, the poorer the contrast
  - The larger the difference in attenuation, the better the contrast

Step 2: Determine the difference between the values of attenuation at each energy

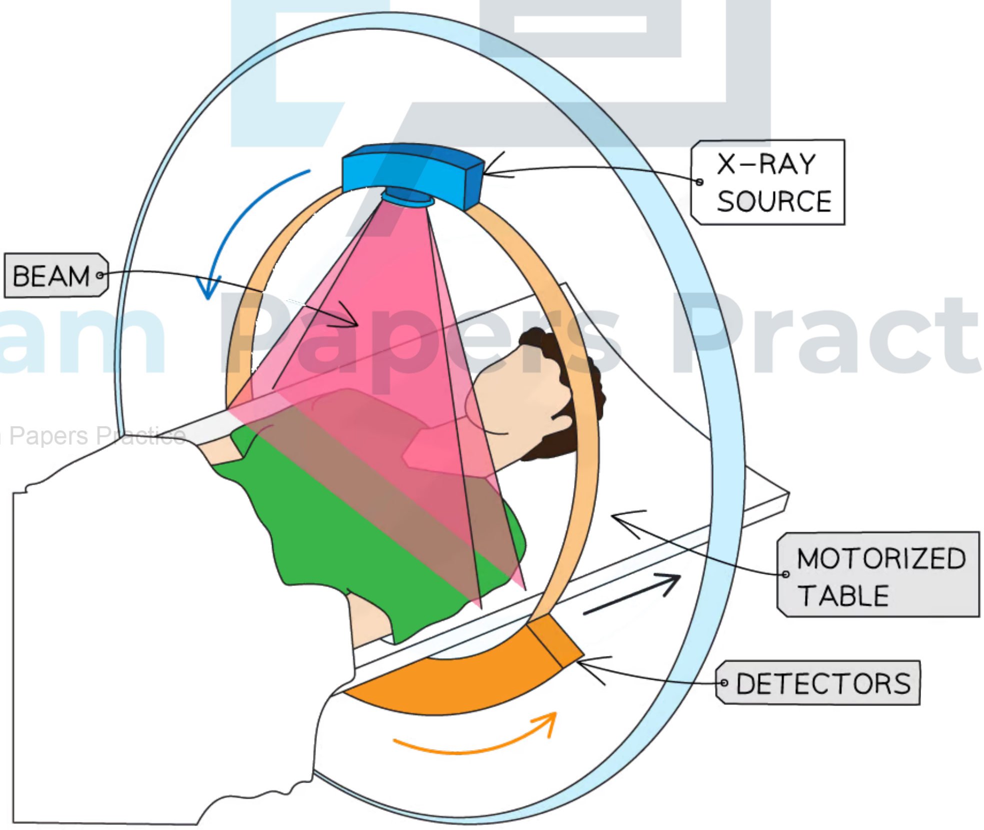
- At 30 keV, the difference in attenuation is 2.13 – 0.41 = 1.72 cm^{-1}
- At 50 keV, the difference in attenuation is 0.68 – 0.24 = 0.44 cm^{-1}
- At 80 keV, the difference in attenuation is 0.36 – 0.20 = 0.16 cm^{-1}
- At 100 keV, the difference in attenuation is 0.30 – 0.18 = 0.12 cm^{-1}
- The difference between μ of bone and muscle is greatest using **30 keV** X-rays hence this energy would produce an image with the best contrast

10.5.6 The CT Scanner

Computed Tomography Scanning

- Computerised axial tomography (**CT**) scanning is an imaging technique which uses X-rays to produce very **high-resolution** images of the internal structures of the body
- A CT scan can produce:
  - Sharp, focused **2D images** of thin slices of the body
  - Detailed **3D images** of sections of the body
- The main features of a CT scanner are
  - A **ring-shaped** structure which allows for rotation of the components
  - An **X-ray tube** mounted on one side of the ring
  - An **array of detectors** mounted on the other side of the ring (opposite the X-ray tube)
  - A **computer** which processes the images

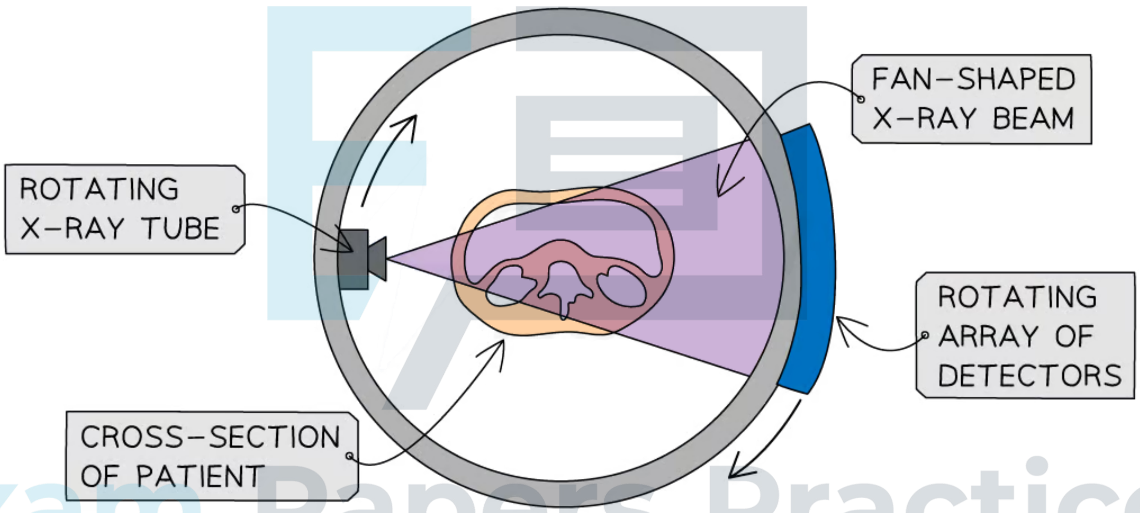
Features of a CT scanner



During a CT scan, the patient lies in the centre of a ring while the X-ray tube and detectors are rotated around the organ being examined

- The main principles of the operation of a CT scan are as follows:
  - The patient lies stationary at the centre of a ring while the X-ray tube and array of detectors are **rotated** around them in opposite directions
  - The X-ray tube produces a **narrow, monochromatic beam** of X-rays as short pulses
  - The X-ray beam passes through the patient and arrives at the array of detectors on the opposite side of the ring
  - The X-ray tube rotates and sends beams through the **same slice** of the body in different directions
  - Signals from the detectors are fed into a computer and are combined to generate a **2D image** of the slice
  - This process is **repeated** to build up images of successive slices
  - A computer combines the images to produce a **3D image** which can be rotated and viewed from different angles

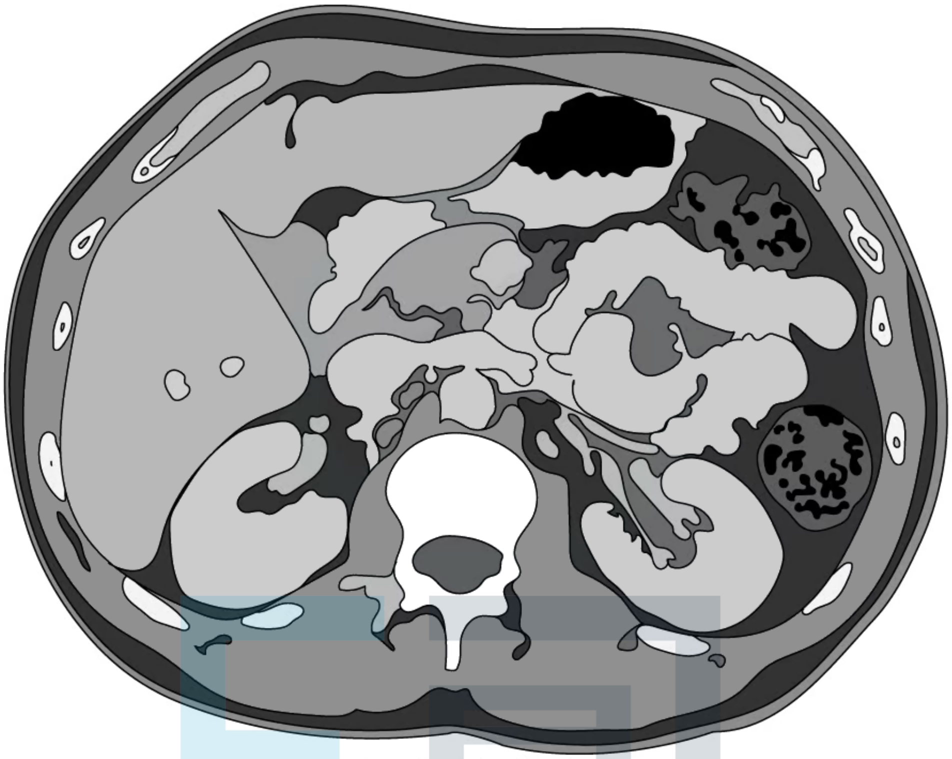
Building an image using CT scanning



CT scans take several 2D images from multiple positions to create a 3D image

- How the image is built up:
  - The detectors are arranged around the outside of the path of the X-rays
  - The X-rays pass through the patient and arrive at the detector on the opposite side
  - The detectors register a lower intensity than the initial intensity of the transmitted beam
  - The detectors relay this information to a computer which produces a cross sectional image over time

Image of a slice produced by a CT scan



A CT scan produces detailed images of slices of the body. This diagram shows a CT scan through a patient's abdomen, which can be combined with many slices to allow a comprehensive 3D image to be built up

Exam Tip

Don't confuse CAT scans with MRI scans. The machines both look like large doughnuts but MRI uses magnetic fields not X-rays!

Pros & Cons of CT Scanning

- A simple X-ray image can provide useful, but limited, information about internal structures in a 2D image
- When a more comprehensive image is needed, a **computerised axial tomography** (CT) scan is needed

Advantages of CT scans:

- Produces high **resolution** and high **contrast** images (software can add colour and sharpen images, and parts of the image can be edited out)
- Can distinguish between tissues with similar attenuation coefficients
- Soft tissue and bone can be imaged in a single process
- Produces a 3D image of the body by combining the images in each direction
- No overlapping images (e.g. bones obscuring organs)

Disadvantages of CT scans:

- The patient receives a much higher radiation dose compared to a normal X-ray
- CT scans are time-consuming and expensive
- Possible side effects from the contrast media

Worked example

An X-ray image is taken of the skull of a patient. Another patient has a CT scan of their entire head.

By reference to the formation of the image in each case:

- suggest which method is more suitable for assessing head injuries.
- explain why the exposure to radiation differs between the two imaging techniques.

Answer:

In X-ray imaging:

- The simple X-ray image involves taking a single exposure which produces a single 2D image
- A simple X-ray is suitable for identifying simple fractures to the skull, but cannot give further details about a head injury as it cannot image brain tissue
- This technique is quicker than CT scanning and less harmful to the patient as the radiation dose is much lower

In CT scanning:

- A CT scan involves taking several exposures of a slice of the head from many different directions
- This is repeated for several slices so signals can be combined to build a 3D image of the patient's head
- CT scanning is best for head injuries as it can provide a more detailed, high-resolution image of the tissue boundaries inside the skull than a simple X-ray
- However, CT scanning is more time-consuming, so the patient is exposed to a much greater radiation dose than the simple X-ray