# OCR A Level Physics

Your notes

## X-rays

### Contents

## X-Ray Tube

Your notes

# Structure of an 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

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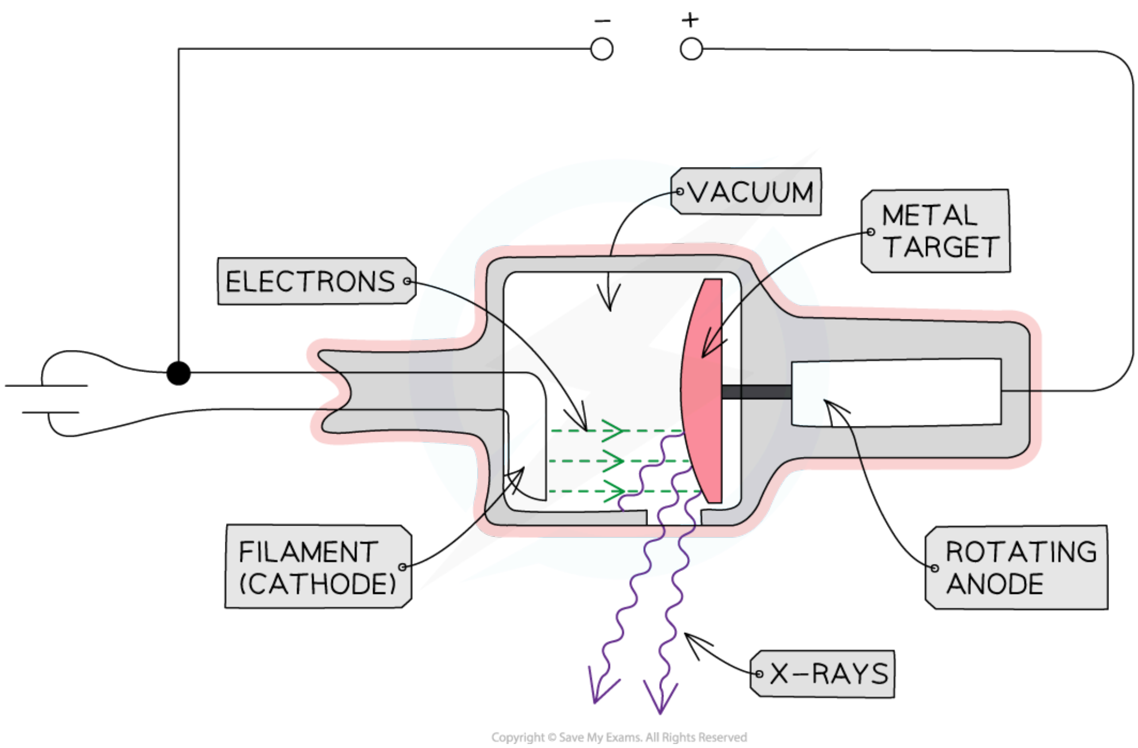


***The main components of an X-ray Tube are the heated cathode, anode, metal target and a high voltage supply***

## The Role of the Components

### 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 electron arrives at the anode, its kinetic energy is 200 keV (by the definition of an electronvolt)
- Only about 1% of the kinetic energy is converted to X-rays

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- 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 is 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

# Production of X-ray Photons

- 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 the high-speed electrons collide with the metal target, 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

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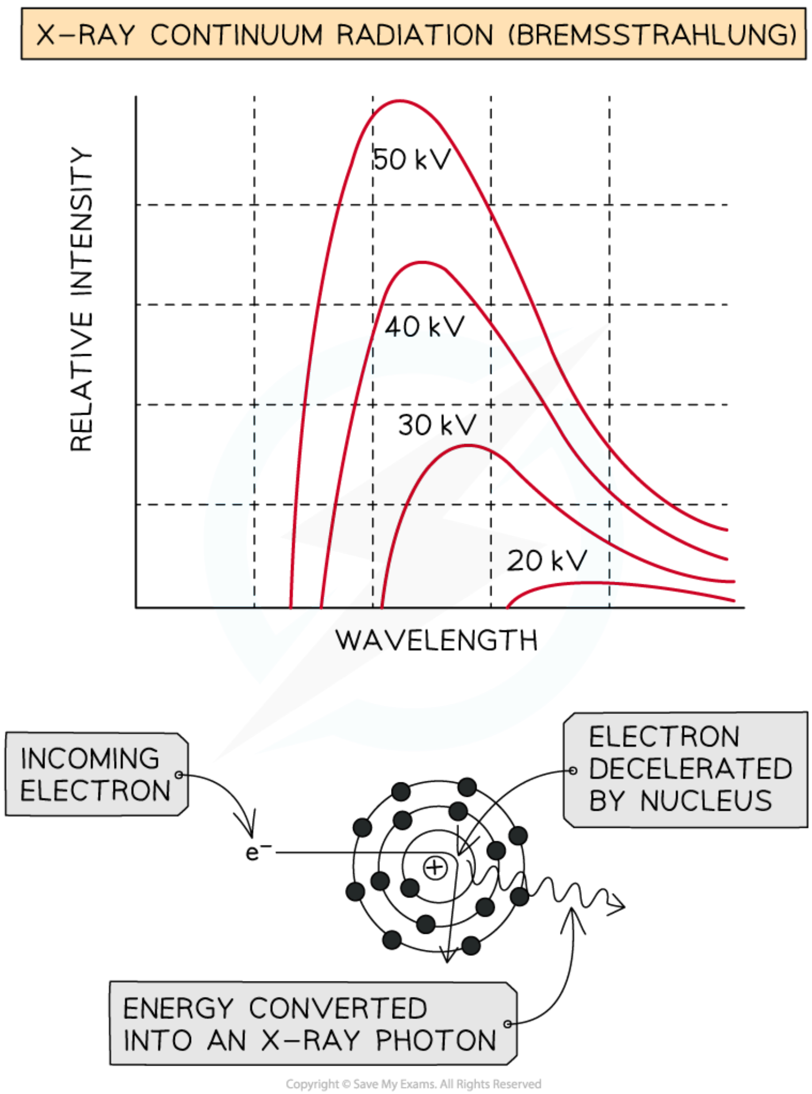
- The rest of the energy heats up the anode, which usually requires some form of cooling
- The energy of the X-ray photon can be of any value, up to the original kinetic energy of the electron, giving a spread of possible X-ray energies
  - These X-rays cause the continuous or 'smooth hump shaped' line on an intensity wavelength graph




- When an electron is accelerated, it gains energy equal to the electronvolt, this energy can be calculated using:

$$E_{max} = eV$$

- This is the **maximum energy** that an X-ray photon can have

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- 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 $\lambda_{min}$, 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**, $\lambda_{min}$, 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

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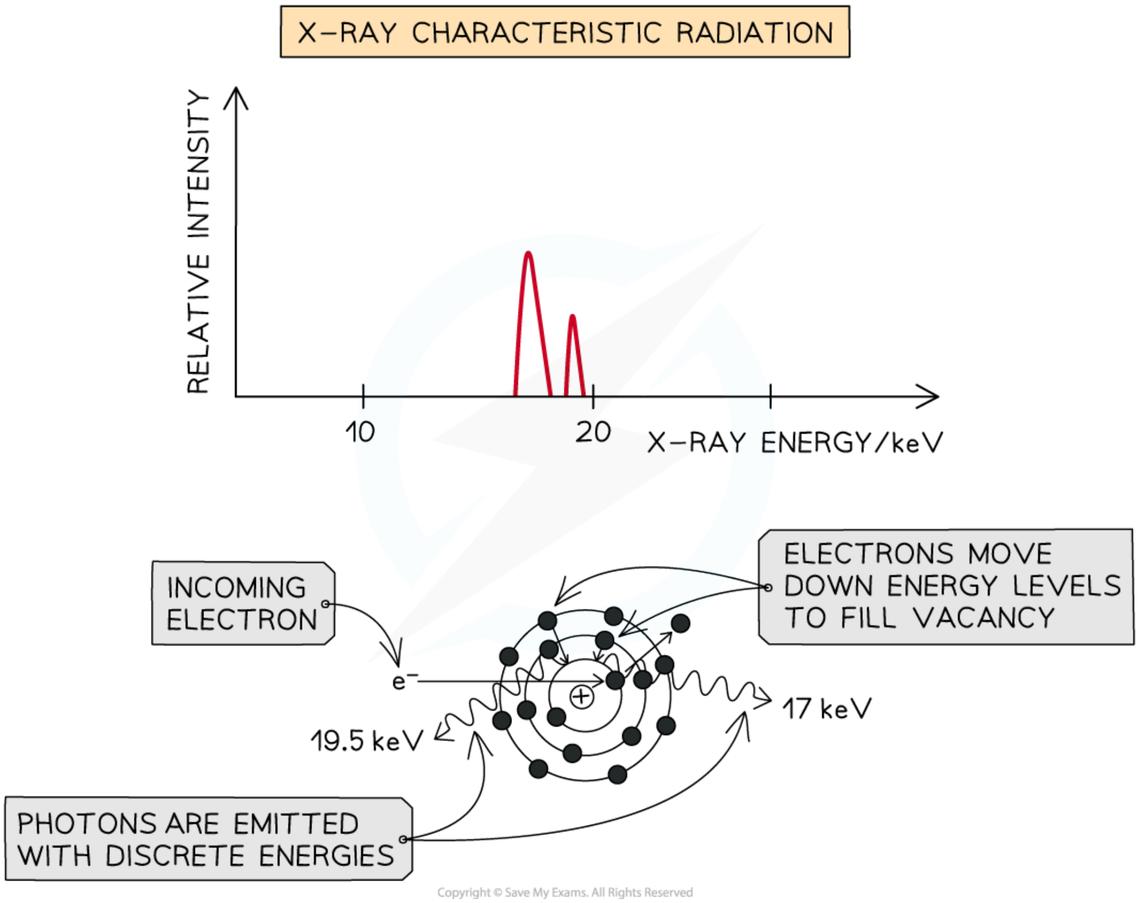
X-RAY CHARACTERISTIC RADIATION
RELATIVE INTENSITY
10
20
X-RAY ENERGY/keV
INCOMING ELECTRON
e⁻
ELECTRONS MOVE DOWN ENERGY LEVELS TO FILL VACANCY
19.5 keV
17 keV
PHOTONS ARE EMITTED WITH DISCRETE ENERGIES
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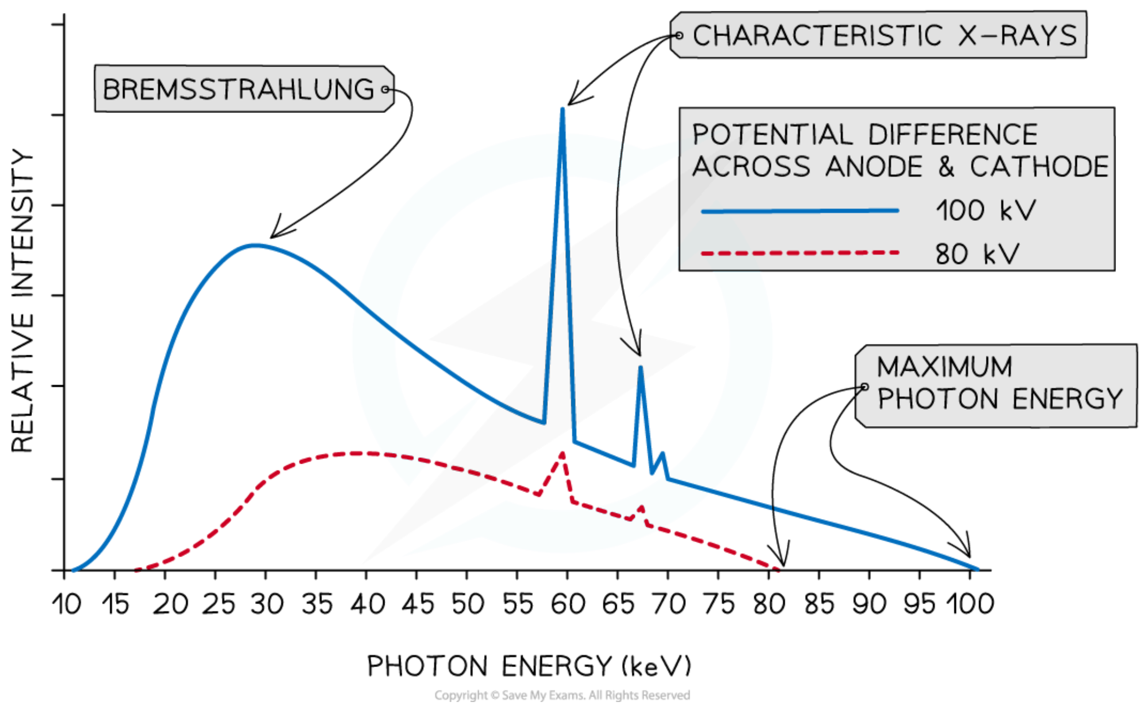


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## Worked Example

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, $\lambda_{min}$:

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

**Step 4: Calculate the minimum wavelength $\lambda_{min}$**

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

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

**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 $2.1 \times 10^{-11}$ 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.

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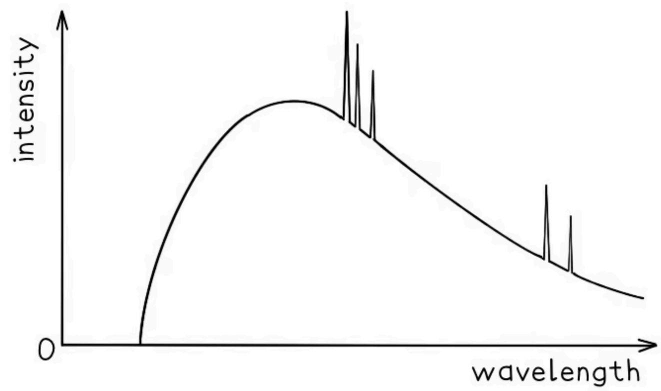


Explain why:

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

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**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

## X-ray Attenuation Mechanisms

Your notes

# X-ray Attenuation Mechanisms

- X-ray attenuation is defined as:

  **The reduction in energy, or intensity, of a beam of X-rays due to their interaction with matter**

- There are four main methods in which X-rays can be attenuated:
  - Simple scattering
  - Photoelectric effect
  - Compton scattering
  - Pair production
- These mechanisms occur within the material the X-rays are travelling in

## Simple Scattering

- Simple scattering occurs when:

  **A low-energy X-ray photon encounters an electron in an atom causing it to be scattered without a change in energy**

- Simple scattering occurs with lower-energy X-ray photons
  - In this scenario, 'low-energy' means the energy of the X-ray photon is not sufficient to cause ionisation
- During simple scattering, photons are deflected from their initial path by interaction with the atoms of the material. However, there are:
  - No change in energy of the X-ray photon
  - No absorption of the X-ray photon
- This mechanism causes **blurring** or 'noise' in X-ray imaging
  - This is because scattered X-rays arrive at the detector from several angles as well as from the main beam

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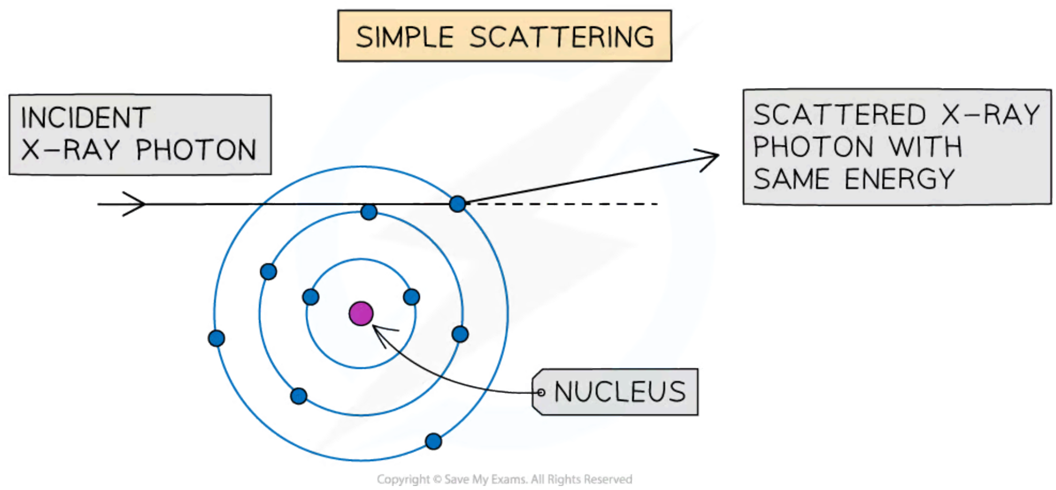



## Photoelectric Effect

- The photoelectric effect occurs when:

  **An X-ray photon is absorbed by an inner shell electron causing it to be ejected from the atom as a photoelectron**

- As a result of the photoelectric effect, the X-ray photon is completely absorbed and all its energy is imparted to the photoelectron
- Since energy is always conserved, the energy of an incident X-ray photon is equal to:

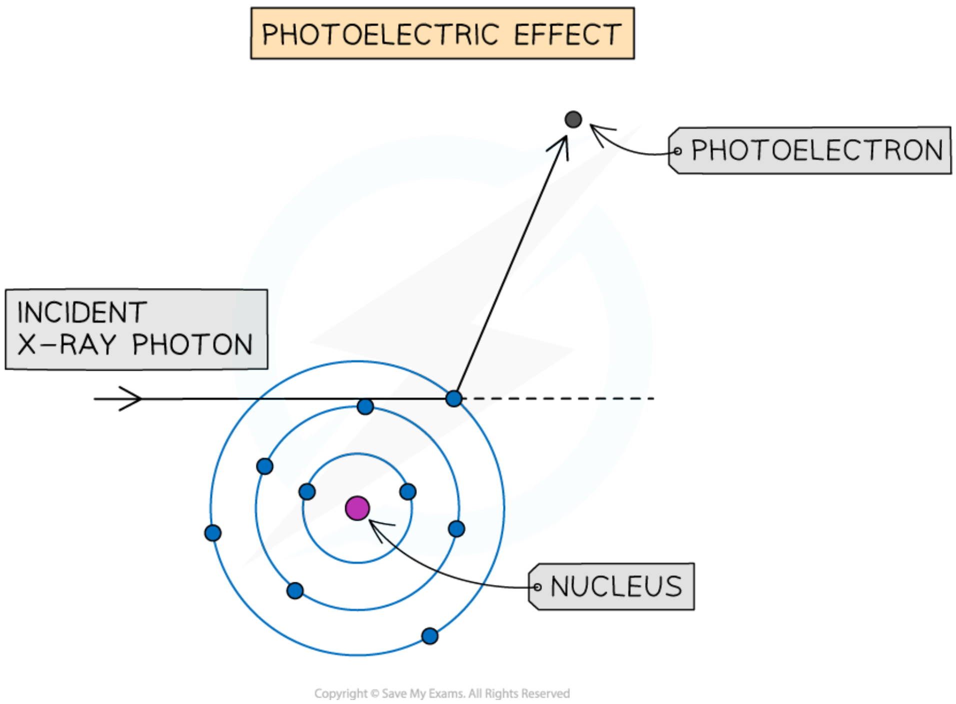
  **The work function + the maximum kinetic energy of the photoelectron**

- The energy within a photon is equal to ***hf***
  - This energy is transferred to the electron to release it from a material (the work function) and the remaining amount is given as kinetic energy to the emitted photoelectron
- This equation is known as the **photoelectric equation**:

$$E = hf = \phi + \frac{1}{2}mv^2{}_{max}$$

- Where:
  - $h$ = Planck's constant (J s)
  - $f$ = the frequency of the incident radiation (Hz)
  - Φ = the work function of the material (J)

- $\frac{1}{2} mv^2_{max} = E_{k(max)}$ = the maximum kinetic energy of the photoelectrons (J)




## Compton Scattering

- The Compton Effect is when:

  **An X-ray photon is deflected by an interaction with an orbital electron causing the wavelength of the photon to increase and the ejection of the electron from the atom at a high speed**

- This process is similar to simple scattering, except the X-ray photon imparts some of its energy to the orbital electron
- Because of this exchange of energy:
  - The X-ray is **deflected** from its initial path
  - The X-ray's **wavelength** increases, as its energy decreases
  - The electron involved is **ejected** from the atom involved in the interaction
- The electron and X-ray are deflected in different directions due to **conservation of momentum**

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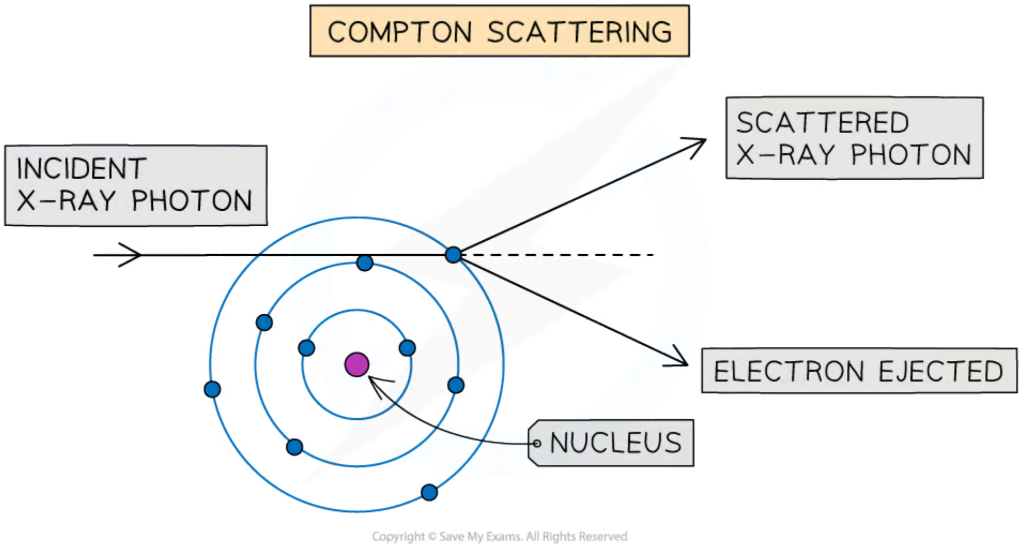


## Pair Production

- Pair production occurs when:

  **A high energy X-ray photon passes close to the nucleus of an atom causing the production of an electron-positron pair**

- This arises as a consequence of Einstein's mass-energy equivalence principle:

$$E = mc^2$$

- Where:
  - $E$ = the energy of the X-ray photon (J)
  - $m$ = the mass of the electron and position = $2m_e$ (kg)
  - c = the speed of light (m $s^{-1}$)
- Pair production can, therefore, only occur with high energy X-rays
  - This is because the energy of the X-ray photon must be above a certain value to provide the total rest mass energy of the electron-positron pair
- The minimum energy, $E_{min}$, for a photon to undergo pair production is the total rest mass energy of the particles produced:

$$E_{min} = hf_{min} = 2m_ec^2$$

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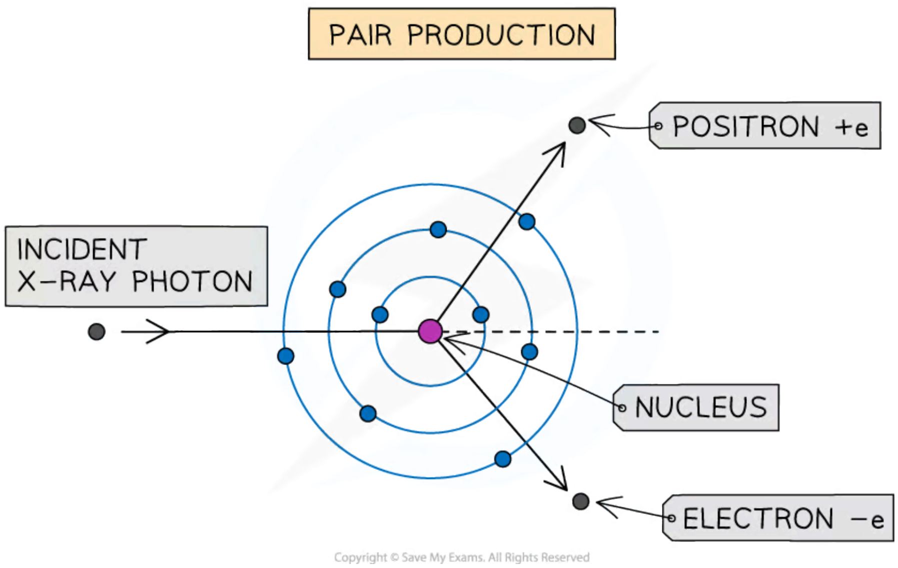
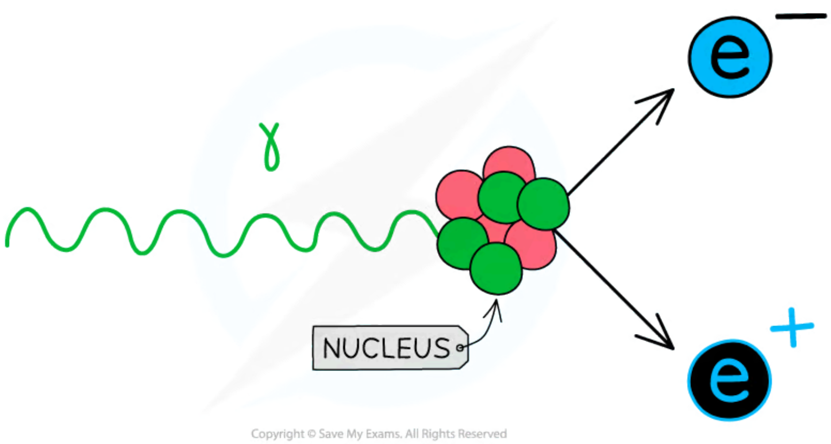
- As a result of pair production, the X-ray photon is completely absorbed and all its energy is imparted to the electron-positron pair




***When a photon with enough energy interacts with a nucleus it can produce an electron-positron pair***

## Calculating X-ray Attenuation

Your notes

# Attenuation of X-rays in Matter

- Bones **absorb** X-ray radiation
  - This is why they appear white on the X-ray photograph
- When the collimated beam of X-rays passes through the patient's body, they are **absorbed** and **scattered**
- 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$^{-2}$)
  - $\mu$ = the linear absorption coefficient (m$^{-1}$)
  - $x$ = distance travelled through the material (m)
- The attenuation coefficient also depends on the energy of the X-ray photons
- The intensity of the X-ray decays exponentially
- The thickness of the material that will reduce the X-ray beam or a particular frequency to half its original value is known as the **half thickness**

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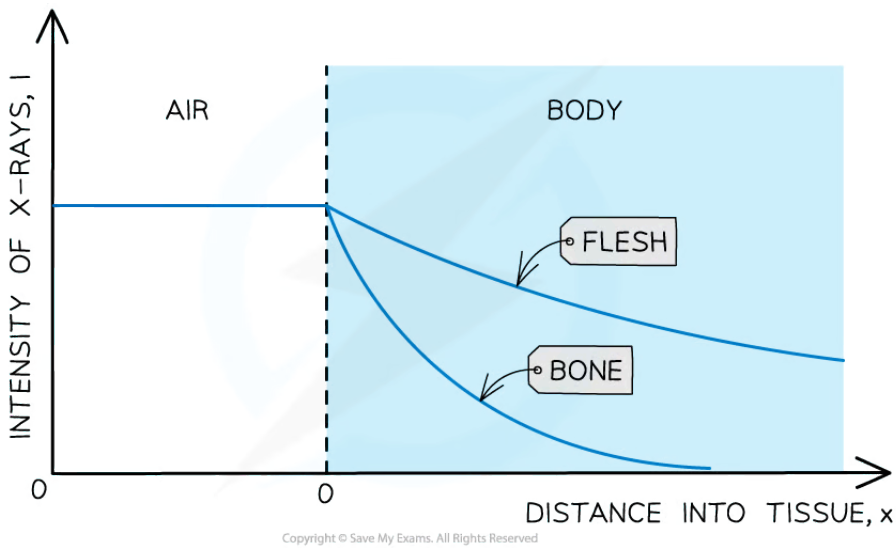
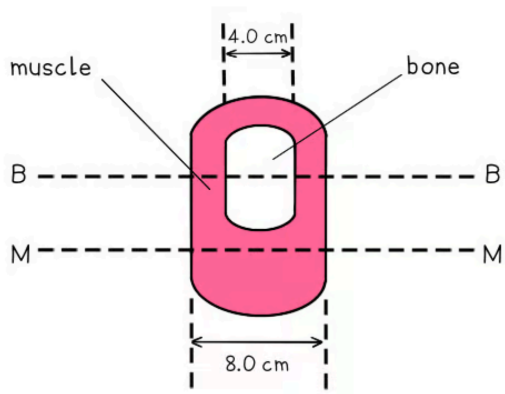



*Absorption of X-rays by different materials*

## 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 the line MM and along the line BB. The linear absorption coefficients of the muscle and the bone are 0.20 $cm^{-1}$ and 12 $cm^{-1}$ respectively.

Your notes

Calculate the ratio:

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

for a parallel X-ray beam directed along the line

a) MM

b) BB

and state whether the X-ray images are sharp, or have good contrast.

**Answer:**

**Part (a)**

**Step 1: Write out the known quantities**

- Linear absorption coefficient for muscle, $\mu = 0.20\ cm^{-1}$
- Distance travelled through the muscle, $x = 8.0\ cm$

**Step 2: Write out the equation for attenuation and rearrange**

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

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

**Step 3: Substitute in values and calculate the ratio**

$$\frac{I}{I_0} = e^{-(0.20 \times 8)} = 0.2$$

**Part (b)**

**Step 1: Write out the known quantities**

- Linear absorption coefficient for muscle, $\mu_m$ = **$0.20\ cm^{-1}$**
- Linear absorption coefficient for bone, $\mu_b$ = **$12\ cm^{-1}$**
- 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**

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

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**Step 3: Substitute in values and calculate the ratio**

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

**Step 4: Write a concluding statement**

- Each ratio gives a measure of the amount of transmission of the beam
  - **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

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## X-ray Imaging

# Using X-rays in Medical Imaging

- X-rays have been highly developed to provide detailed images of soft tissue and even blood vessels
- When treating patients, the aims are to:
  - Reduce the 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 dosage possible
- In order to do this, **aluminium filters** are used
  - This is because many wavelengths of X-ray are emitted
  - Longer wavelengths of X-ray are less penetrating, therefore, they are more likely to be absorbed by the body
  - This means they do not contribute to the image and pose more of a health hazard
  - The aluminium sheet **absorbs** these long wavelength X-rays making them safer

## 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 Media

- Contrast media is defined as:

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

- These are sometimes used because:
  - Some soft tissue organs do not show up on X-rays when the organ has a **similar** attenuation coefficient to other tissues in the same area
  - Contrast media are good absorbers of X-rays as they have a **large** attenuation coefficient
  - Hence when contrast media enter an organ, the **image** of the organ is **enhanced** when imaged using 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

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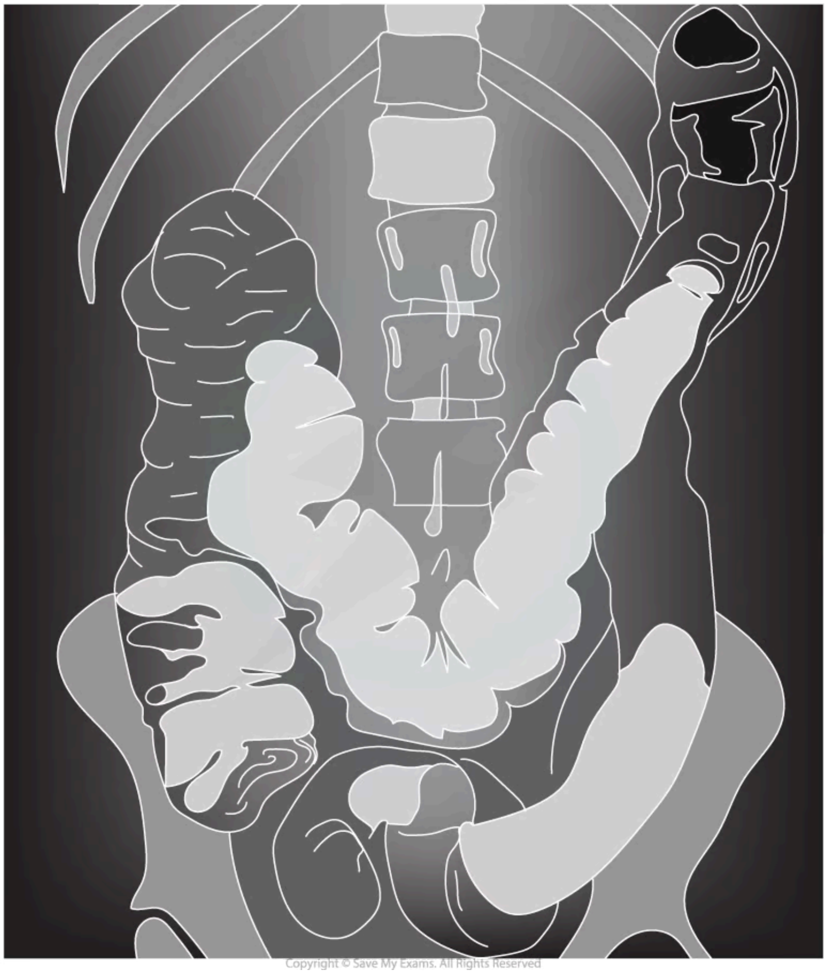


Your notes

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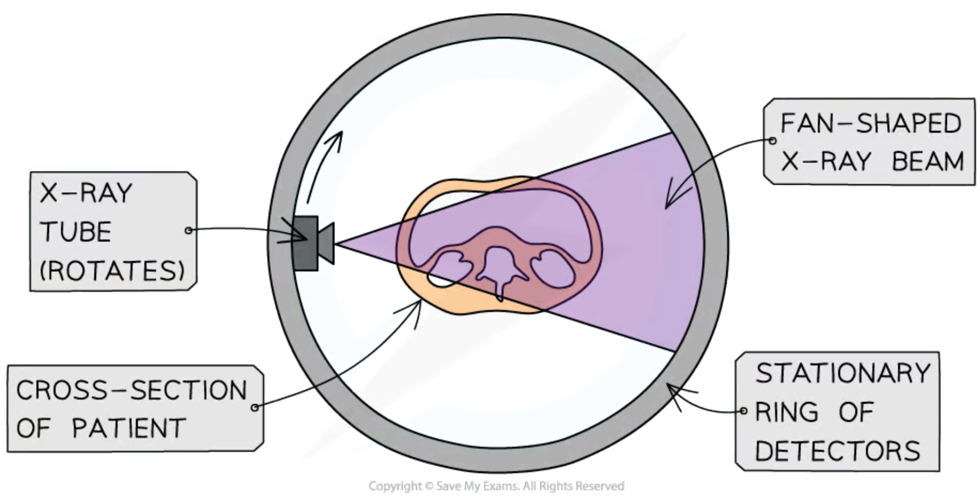
## CAT Scans

# Computed Tomography 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** (CAT or CT) scan is used
- The main features of the operation of a CT scan are as follows:
  - An X-ray tube rotates around the stationary patient
  - A CT scanner takes X-ray images of the **same slice**, at many different angles
  - This process is **repeated**, then images of successive slices are combined together
  - A computer pieces the images together to build a **3D image**
  - This 3D image can be **rotated** and viewed from different angles




*CAT scans take 2D images from multiple positions to create a 3D image*


Your notes

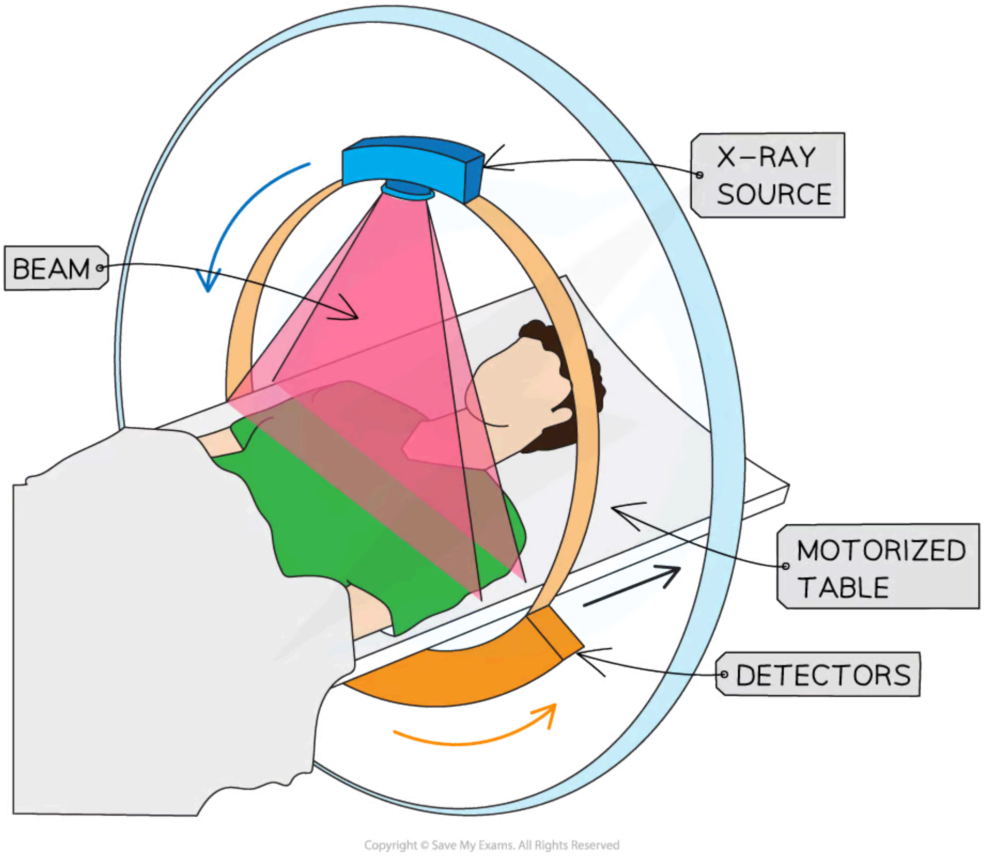
#### Examiner Tips and Tricks

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

## CAT Scan vs X-ray Image

- Advantages of CAT scans:
  - Produces much more detailed 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 giving a higher resolution image
  - Soft tissue and bone can be imaged in a single process
  - Produces a 3D image of the body by combining the images at each direction

- No overlapping images (for example bones obscuring organs)




- Disadvantages of CAT scans:
  - The patient receives a much higher dose than a normal X-ray
  - Possible side effects from the contrast media

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## Worked Example

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

By reference to the formation of the image in each case, suggest why the exposure to radiation differs between the two imaging techniques.

**Answer:**

Your notes

**X-ray**

- The simple X-ray image involves taking a single exposure
- This produces a single 2D image

**CT scan**

- The CT scan requires taking several exposures of a slice from many different angles
- This is then repeated for different slices before being combined together to build a 3D image
- This involves taking a much greater exposure than the simple X-ray