A2 Level Physics

Chapter 21 – Medical Imaging

21.1.2 Using X-rays

Worked Examples

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X-rays

Exam Style Question 1

Fig. 1 shows data for the intensity of a parallel beam of X-rays after penetration through varying thicknesses of a material.

intensity / MW m^{-2}	thickness / mm
0.91	0.40
0.69	0.80
0.52	1.20
0.40	1.60
0.30	2.00
0.23	2.40
0.17	2.80

Fig. 1

(a) On Fig. 2 plot a graph of transmitted X-ray intensity against thickness of absorber.

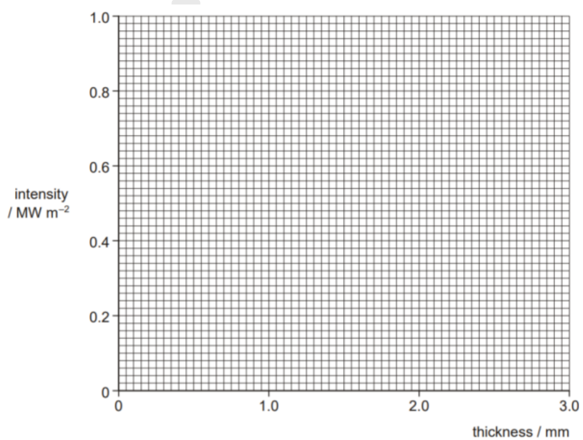

Fig. 2

(b) (i) Find the thickness that reduces the intensity of the incident beam by one half.

(ii) Use your answer to (b)(i) to calculate the linear attenuation coefficient μ. Give the unit for your answer.

X-rays

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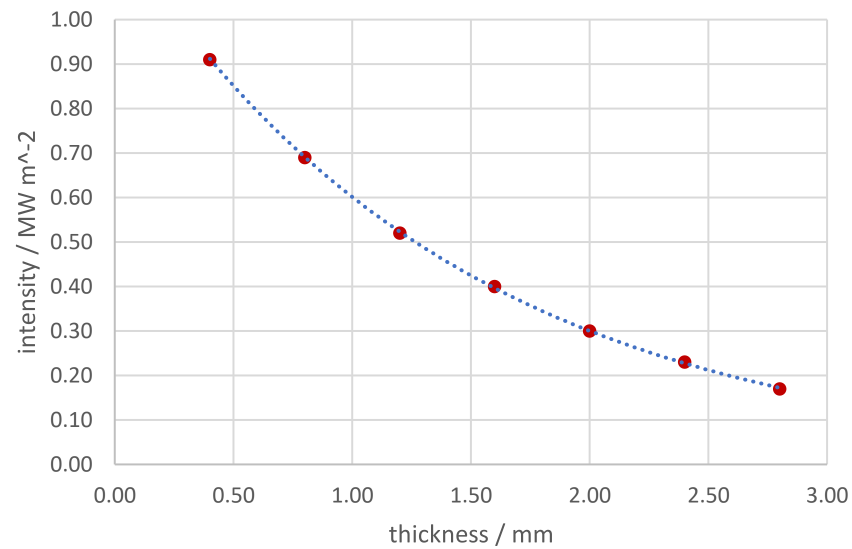

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X-rays

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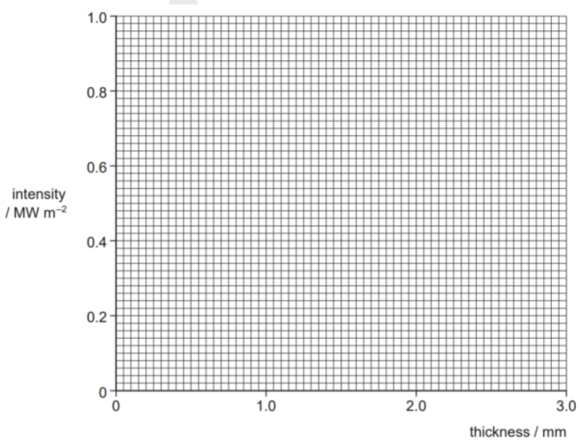

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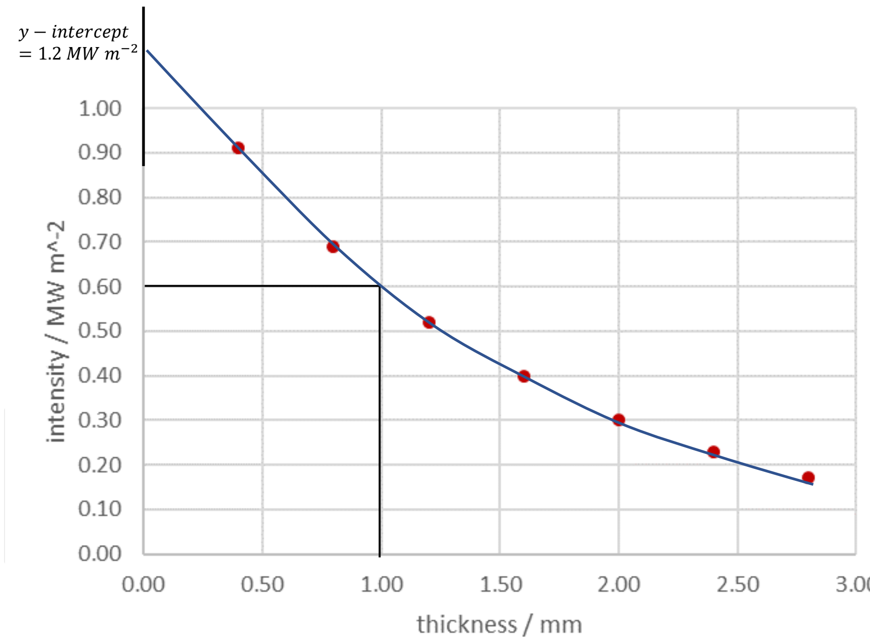
X-rays

Exam Style Question 1



(b) (i) Find the thickness that reduces the intensity of the incident beam by one half.
You will need to extend the line of best fit until it crosses the y-axis. Take your best guess for where it would cross and divide that number by 2.
My guess = $1.2\ MW\ m^{-2}$
Therefore:

$$\frac{1.2\ MW\ m^{-2}}{2} = 0.6\ MW\ m^{-2}$$

Now extend the line from $0.6\ MW\ m^{-2}$ until it hits the line of best fit and then draw a line vertically and read off the x-axis which is 0.95 mm. Therefore the thickness that reduces the intensity of the incident beam by one half is:

$$thickness = 0.95\ mm$$

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X-rays

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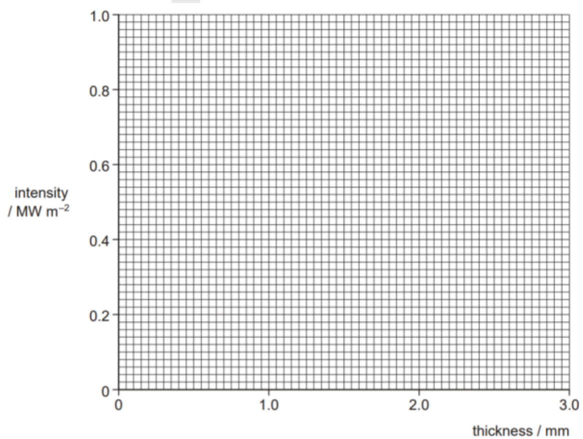

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(b) (i) Find the thickness that reduces the intensity of the incident beam by one half.

(ii) Use your answer to (b)(i) to calculate the linear attenuation coefficient μ. Give the unit for your answer.

X-rays

Exam Style Question 1

(ii) Use your answer to (b)(i) to calculate the linear attenuation coefficient μ. Give the unit for your answer.

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

We already know at one half the original intensity the thickness is $0.95\ mm$ therefore:

$$0.5\ I_0 = I_0 e^{-\mu(0.95\times10^{-3}\ m)}$$

Simplify by cancelling the I_0:

$$0.5 = e^{-\mu(0.95\times10^{-3}\ m)}$$

Therefore:

$$In(0.5) = -\mu(0.95 \times 10^{-3}\ m)$$

$$\mu = \frac{In(0.5)}{(-0.95 \times 10^{-3}\ m)}$$

$$\mu = 730\ m^{-1}\ (3\ s.f.)$$

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X-rays

Exam Style Question 2

An average person in the UK will have at least 30 X-ray photographs taken in their lifetime.

In order to take an X-ray photograph, the X-ray beam is passed through an aluminium filter to safely remove low energy X-ray photons before reaching the patient.

(a) Suggest why it is necessary to remove these low energy X-rays.

(b) The average linear attenuation coefficient for X-rays that penetrate the aluminium is $250\ m^{-1}$.

The intensity of an X-ray beam after travelling through $2.5\ cm$ of aluminium is $347\ W\ m^{-2}$.

Show that the intensity incident on the aluminium is about $2\ \times\ 10^5\ W\ m^{-2}$.

(c) The X-ray beam at the filter has a circular cross-section of diameter $0.20\ cm$. Calculate the power of the X-ray beam from the aluminium filter. Assume that the beam penetrates the aluminium filter as a parallel beam.

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X-rays

Exam Style Question 2

(a) Suggest why it is necessary to remove these low energy X-rays.

Low energy X-rays are absorbed by the skin which is undesirable as it can cause greater ionising.

(b) Show that the intensity incident on the aluminium is about 2 $\times$ $\mathbf{10^5\ W\ m^{-2}}$.

Use $I = I_0 e^{-\mu x}$ and rearrange for I_0

$$I_0 = \frac{I}{e^{-\mu x}} = \frac{347\ W\ m^{-2}}{e^{-(250\ m^{-1})(0.025\ m)}}$$

$$I_0 = 179750.4502$$

$$\therefore I_0 \approx 2 \times 10^5\ W\ m^{-2}\ (1\ s.f.)$$

(c) Calculate the power of the X-ray beam from the aluminium filter. Assume that the beam penetrates the aluminium filter as a parallel beam.

Use $I = \frac{P}{A}$ and rearrange for P:

Area of a circle is $= \pi r^2$

$r = radius = \dfrac{diameter}{2}$

$$P = IA = (347\ W\ m^{-2})(\pi)(0.10 \times 10^{-2}\ m)^2$$

$$P = 1.09 \times 10^{-3}\ W$$

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X-rays

Exam Style Question 3

(a) State two main properties of X-ray photons.

(b) Fig. 7.1 shows an X-ray photon interacting with an atom to produce an electron-positron pair in a process known as pair production.

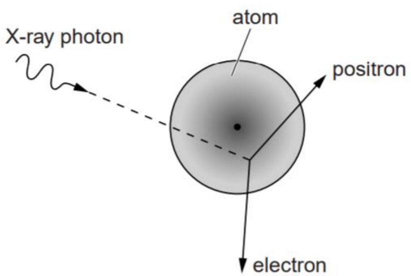

Fig. 7.1

Calculate the maximum wavelength of X-rays that can produce an electron-positron pair.

(c) Name an element used as a contrast material in X-ray imaging. Explain why contrast materials are used in the diagnosis of stomach problems.

X-rays

Exam Style Question 3

(a) State two main properties of X-ray photons.

- Can travel in a vacuum.
- Travel at the speed of light.
- No charge.
- Highly ionising.

(b) Calculate the maximum wavelength of X-rays that can produce an electron-positron pair.

Use $E = \frac{hc}{\lambda}$ and $E = mc^2$

$$\frac{hc}{\lambda} = mc^2$$

$$\frac{(6.63 \times 10^{-34}\, J\, s)(3.0 \times 10^{8}\, m\, s^{-1})}{\lambda} = 2(9.11 \times 10^{-31}\, kg)(3.0 \times 10^{8}\, m\, s^{-1})^2$$

$$\lambda = \frac{(6.63 \times 10^{-34}\, J\, s)(3.0 \times 10^{8}\, m\, s^{-1})}{2(9.11 \times 10^{-31}\, kg)(3.0 \times 10^{8}\, m\, s^{-1})^2}$$

$$\lambda = 1.2 \times 10^{-12}\, m\ (2\, s.f.)$$

(c) Name an element used as a contrast material in X-ray imaging. Explain why contrast materials are used in the diagnosis of stomach problems.

Element: Barium/iodine.

The patient swallows a liquid rich in barium (known as a barium meal) and since it has a large attenuation coefficient it will readily absorb X-rays. If a patient swallows the contrast medium and an X-ray of the intestines is needed, the barium meal will coat the walls of the tract, enabling for the imaging of the outline to be seen.

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X-rays

Exam Style Question 4

(a) State two properties of X-rays.

(b) Explain what is meant by the Compton effect.

(c) The intensity I of a collimated beam of X-rays decreases exponentially with thickness x of the material through which the beam passes according to the equation $I = I_0 \, e^{-\mu x}$. The attenuation (absorption) coefficient μ depends on the material.

(i) State what I_0 represents in this equation.

(ii) Bone has an attenuation coefficient of 3.3 cm^{-1}. Calculate the thickness in cm of bone that will reduce the X-ray intensity by half.

(d) Explain the purpose of using a contrast medium such as barium when taking X-ray images of the body.

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X-rays

Exam Style Question 4

(a) State two properties of X-rays.

- X-rays are EM waves
- Travel at speed of light
- Travel in a vacuum
- Transverse waves
- Can cause ionisation
- X-rays are high energy photons
- Have wavelength of about $10^{-10}\ m$

(b) Explain what is meant by the Compton effect.

The X-ray photon interacts with an orbital electron. The incident photon is scattered by an orbital electron. Some of the photon's energy is given to the electron, which is ejected from the atom at high speed and goes off in a different direction from that of the scattered photon.

(c) (i) State what I_0 represents in this equation.

Initial intensity.

(c) (ii) Bone has an attenuation coefficient of $3.3\ cm^{-1}$. Calculate the thickness in cm of bone that will reduce the X-ray intensity by half.

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

We already know that the X-ray intensity is halved therefore:

$$0.5\ I_0 = I_0 e^{-(3.3\ cm^{-1})x}$$

Simplify by cancelling the I_0:

$$0.5 = e^{-(3.3\ cm^{-1})x}$$

Therefore:

$$In(0.5) = -(3.3\ cm^{-1})x$$

$$x = \frac{In(0.5)}{(-3.3\ cm^{-1})}$$

$$x = 0.21\ cm\ (2\ s.f.)$$

(d) Explain the purpose of using a contrast medium such as barium when taking X-ray images of the body.

A contrast material has large attenuation coefficient and hence can easily absorb X-rays. Using a contrast medium will allow for the imaging of the outline of soft tissues.

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X-rays

Exam Style Question 5

(a) State and describe one way in which X-ray photons interact with matter.

(b) The intensity of a collimated beam of X-rays is reduced to 10% of its initial value after passing through $3.0\ mm$ of soft tissue. Calculate the thickness of soft tissue that reduces the intensity to 50% of its initial value.

X-rays

Exam Style Question 5

(a) State and describe one way in which X-ray photons interact with matter.

Pick one:

1) The photoelectric effect – where an orbital electron is ejected from the atom or the atom is ionised.
2) Compton scattering – where X-ray scattered by the interaction with an orbital electron.
3) Pair production – where X-ray photon interacts with the nucleus and an electron and positron are produced.

(b) The intensity of a collimated beam of X-rays is reduced to 10% of its initial value after passing through $3.0\ mm$ of soft tissue. Calculate the thickness of soft tissue that reduces the intensity to 50% of its initial value.

Use $I = I_0 e^{-\mu x}$ and solve it simultaneously.

At 10%: $0.1\ I_0 = I_0 e^{-\mu 3}$

$$\therefore 0.1 = e^{-\mu 3}$$

$$In(0.1) = -\mu 3 \ \dots\dots\dots (1)$$

At 50%: $0.5\ I_0 = I_0 e^{-\mu x}$

$$\therefore 0.5 = e^{-\mu x}$$

$$In(0.5) = -\mu x \ \dots\dots\dots (2)$$

Now divide (2) by (1):

$$\frac{In(0.5)}{In(0.1)} = \frac{-\mu x}{-\mu 3}$$

$$\frac{In(0.5)}{In(0.1)} = \frac{x}{3}$$

$$\therefore x = 0.903\ mm\ (3\ s.f.)$$

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X-rays

Exam Style Question 6

(i) Explain what is meant by the half-value thickness of lead for X-rays.

(ii) Calculate the linear attenuation coefficient of lead for 90 keV X-ray photons.

half value thickness of lead for 90 keV X-ray photons = $12mm$.

(iii) Calculate the thickness of lead needed to reduce the intensity of a beam of 90 keV X-ray photons to 5.0 % of the intensity incident on the lead.

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X-rays

Exam Style Question 6

(i) Explain what is meant by the half-value thickness of lead for X-rays.

Thickness needed to reduce intensity by half for X-rays of specific energy.

(ii) Calculate the linear attenuation coefficient of lead for 90 keV X-ray photons. half value thickness of lead for 90 keV X-ray photons = $12mm$.

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

$$\mu = \frac{In(2)}{(12 \times 10^{-3}\ m)}$$

$$\mu = 57.762 \ldots = 58\ m^{-1}\ (2\ s.f.)$$

(iii) Calculate the thickness of lead needed to reduce the intensity of a beam of 90 keV X-ray photons to 5.0 % of the intensity incident on the lead.

Use $I = I_0 e^{-\mu x}$ and rearrange for x

$$0.05\ I_0 = I_0 e^{-(57.762\ldots\ m^{-1})x}$$

Simplify by cancelling the I_0:

$$0.05 = e^{-(57.762\ldots\ m^{-1})x}$$

Therefore:

$$In(0.05) = -(57.762 \ldots\ m^{-1})x$$

$$x = \frac{In(0.05)}{(-57.762 \ldots\ m^{-1})}$$

$$x = 0.05186 \ldots = 0.52\ m\ (2\ s.f.)$$

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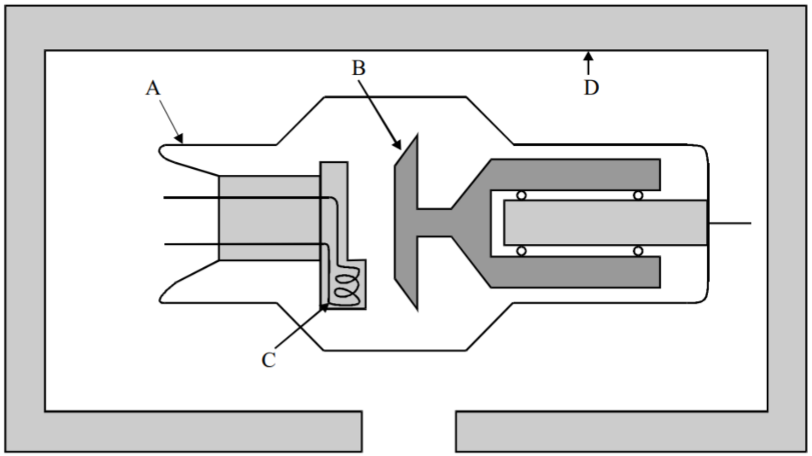
X-rays

Exam Style Question 7

The simplified diagram shows a modern X-ray tube.



(a) For each of the labelled parts, state what it is and explain its purpose.

(b) On the diagram draw and label

(i) the direction of the electron beam,

(ii) the direction of the useful X-ray beam.

X-rays

Exam Style Question 7

(a)For each of the labelled parts, state what it is and explain its purpose.
A: Glass tube which is sealed and evacuated to allow electrons to travel unimpeded.

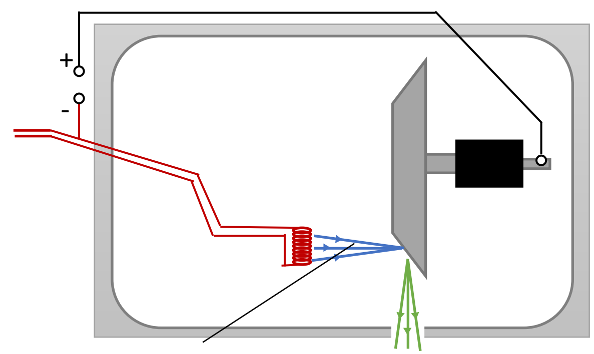
B: Rotating anode (or target).
The rotation of anode spreads the heat over a greater area and this is where X-rays are emitted when hit by energetic electrons.

C: Filament (or cathode).
Heat source to release electrons from surface of cathode by thermionic emission.

D: Lead housing.
To prevent X-rays from escaping in unwanted directions.

(b) On the diagram draw and label
(i) the direction of the electron beam,
(ii) the direction of the useful X-ray beam.

path of electrons shown from filament (C) to anode (B) (1)
path of X-rays shown starting at anode (B)
and emerging through window in lead housing (D) (1)



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Please see '21.1.1 Using X-rays notes' pack for revision notes.

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