Week 53

A-Level Physics

Homework bundle for this week

本周作业合集

exercises.lol

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A-Level Physics Name: ____________ Score: ______

1. A piezo-electric crystal:
   - ☐ changes shape with a p.d., and makes an e.m.f. when squeezed
   - ☐ only emits light
   - ☐ stores charge like a battery
   - ☐ conducts current in one direction only
2. X-rays are produced when fast electrons:
   - ☐ hit a metal target and slow down sharply
   - ☐ pass through a magnet
   - ☐ are heated gently
   - ☐ travel through glass
3. A PET tracer is:
   - ☐ a positron (β^+) emitter taken up by active tissue
   - ☐ a strong magnet
   - ☐ an X-ray source
   - ☐ an ultrasound gel
4. An echo returns after 2.0×10^{-4} s; the speed of sound is $1500\ \frac{\mathrm{m}}{\mathrm{s}}$. How deep is the boundary?

   ______________ m
5. Most of the electrons' kinetic energy in an X-ray tube becomes heat, not X-rays.

   ☐ True ☐ False
6. When the emitted positron meets an electron, they:
   - ☐ annihilate into two photons
   - ☐ bounce off each other
   - ☐ form a stable atom
   - ☐ do nothing
7. The coupling gel between the probe and the skin:
   - ☐ pushes out air so the ultrasound can enter the body
   - ☐ cools the skin

☐ blocks the ultrasound

☐ is only for comfort

8. Each photon from electron–positron annihilation has an energy of (in keV):

_________________ keV

9. Acoustic impedance Z = density × ______.

____

10. A higher accelerating voltage gives a ______ minimum wavelength.

____

A-Level Physics

1. **changes shape with a p.d., and makes an e.m.f. when squeezed**

   Both effects let one crystal send ultrasound (apply p.d.) and detect it (read the e.m.f.).

2. **hit a metal target and slow down sharply**

   The sudden deceleration on the target gives out X-ray photons (Bremsstrahlung).

3. **a positron (β^+) emitter taken up by active tissue**

   It is a β^+ emitter on a molecule (like glucose) that active tissue absorbs more of.

4. **0.15 m**

   $d = \frac{ct}{2} = \frac{1500 \times 2.0 \times 10^{-4}}{2} = 0.15$ m (the pulse travels there and back).

5. **True**

   Only a small fraction becomes X-rays — which is why the target must be cooled.

6. **annihilate into two photons**

   Matter and antimatter annihilate: their mass turns into two photons.

7. **pushes out air so the ultrasound can enter the body**

   Without it, the huge skin–air impedance difference would reflect almost all the ultrasound at the surface.

8. **511 keV**

   Each carries $m_e c^2 \approx 0.511$ MeV $= 511$ keV.

9. **speed**

   $Z = \rho c$ — density times the speed of sound in the medium.

10. **shorter**

    $\lambda_{\min} = \frac{hc}{eV}$, so a larger V gives a smaller $\lambda_{\min}$ (more energetic X-rays).

A-LEVEL PHYSICS • EXERCISE SHEET

24.1 Production and use of ultrasound

Name: ______________ Class: __________ Date: ____________ **Total: 25 marks**

KEY WORDS ultrasound 超声波 • specific acoustic impedance 声阻抗 • transducer 换能器 • intensity reflection coe
• piezo-electric 压电

Objective

Build the skills to answer exam questions on **ultrasound** in medicine.

You must be able to:

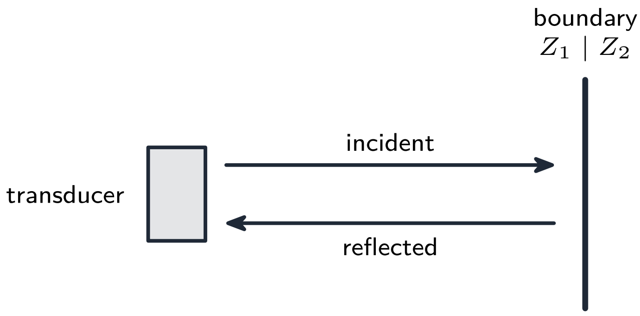
- explain the **piezo-electric** transducer (send and detect)
- use **acoustic impedance** $Z = \rho c$ and the **reflection coefficient**
- use the attenuation $I = I_0 e^{-\mu x}$

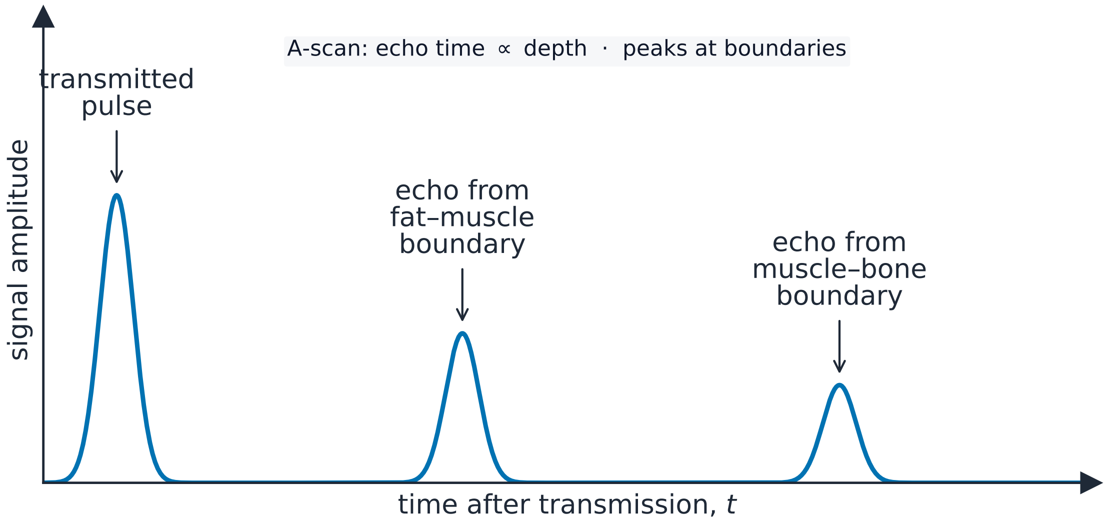
1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Transducer and pulse-echo

A **piezo-electric** crystal changes shape when a p.d. is applied (to **emit** ultrasound) and produces an e.m.f. when squeezed (to **detect** it) — so one transducer both sends and receives. A pulse partly **reflects** at a boundary between tissues:





An ultrasound A-scan trace

$$Z = \rho c, \qquad \frac{I_R}{I_0} = \frac{(Z_1 - Z_2)^2}{(Z_1 + Z_2)^2}, \qquad I = I_0 e^{-\mu x}.$$

A large impedance **mismatch** reflects strongly — which is why a **coupling gel** removes the air gap (air's Z is very different).

2 Practice

Now apply the methods above.

2.1 Describe the **piezo-electric effect**. [2]

2.2 Define the **specific acoustic impedance** of a medium. [1]

2.3 Explain how **one** transducer can both send and detect ultrasound. [2]

2.4 Write the equation for the **attenuation** of ultrasound. [1]

3 Exam-style questions

3.1 For a **strong** reflection at a tissue boundary, the two acoustic impedances must be: [1]

- **A** equal
- **B** very different
- **C** both zero
- **D** both very large

3.2 Calculate the intensity reflection coefficient for a boundary where $Z_1 = 1.6 \times 10^6$ and $Z_2 = 1.7 \times 10^6$ (SI units). [3]

3.3 Explain why a **coupling gel** is used between the transducer and the skin. [2]

3.4 Ultrasound of intensity I_0 passes through 5.0 cm of tissue with $\mu = 23\ \mathrm{m^{-1}}$. Calculate I/I_0. [2]

3.5 An ultrasound scanner sends a pulse into a patient. The specific acoustic impedance of soft tissue is $1.63 \times 10^6\ \mathrm{kg\,m^{-2}\,s^{-1}}$, of bone $6.40 \times 10^6\ \mathrm{kg\,m^{-2}\,s^{-1}}$ and of air $4.29 \times 10^2\ \mathrm{kg\,m^{-2}\,s^{-1}}$.

(a) **Define specific acoustic impedance**. [1]

(b) **Explain** how a piezoelectric crystal **detects** the reflected ultrasound. [2]

(c) **Determine** the intensity reflection coefficient at a soft tissue-bone boundary. [3]

(d) **Determine** the intensity reflection coefficient at a soft tissue-air boundary, and **explain** why a gel is smeared on the skin before a scan. [3]

(e) The pulse returns from a boundary 9.6 cm deep after 1.2×10^{-4} s. **Determine** the speed of ultrasound in the tissue. [2]

Solutions

2.1 Applying a p.d. across the crystal makes it **change shape**; changing its shape makes it produce an **e.m.f.**.

2.2 $Z = \rho c$, the product of the medium's density and the speed of sound in it.

2.3 An alternating p.d. makes the crystal **vibrate**, emitting ultrasound; a returning pulse makes it vibrate and produce an **e.m.f.**, which is detected.

2.4 $I = I_0 e^{-\mu x}$.

3.1 **B** — very different.

3.2 $\dfrac{I_R}{I_0} = \dfrac{(1.6 - 1.7)^2}{(1.6 + 1.7)^2} = \dfrac{(0.1)^2}{(3.3)^2} = 9.2 \times 10^{-4}$.

3.3 Without gel there is an **air gap**, whose acoustic impedance is very different from skin, so almost all the ultrasound would be reflected; the gel removes the air gap so the ultrasound enters the body.

3.4 $I/I_0 = e^{-\mu x} = e^{-(23)(0.050)} = e^{-1.15} = 0.32$.

3.5 (a) The product of the **density** of the medium and the **speed of sound** in it, $Z = \rho c$.
(b) The reflected wave's pressure variation makes the crystal **change shape**, and a piezoelectric crystal produces a **potential difference** across its faces when it is deformed, giving an electrical signal that varies with the received wave.
(c) $\dfrac{I_R}{I_0} = \dfrac{(Z_2 - Z_1)^2}{(Z_2 + Z_1)^2} = \dfrac{(6.40 - 1.63)^2}{(6.40 + 1.63)^2} = \dfrac{22.8}{64.5} = 0.35$.
(d) With air, $\dfrac{(1.63 \times 10^6 - 429)^2}{(1.63 \times 10^6 + 429)^2} \approx 0.999$ — essentially **all** the ultrasound is reflected at a skin-air boundary. Gel excludes the air layer and has an impedance close to that of skin, so the pulse actually enters the body.
(e) The pulse travels **there and back**, a distance of $2 \times 0.096 = 0.192$ m; $c = \dfrac{0.192}{1.2 \times 10^{-4}} = 1.6 \times 10^3$ m s^{-1}.

10 **(a)** Define specific acoustic impedance.

....

....

.... [2]

(b) Explain how ultrasound waves are detected by a piezoelectric crystal.

....

....

.... [2]

(c) Table 10.1 shows the specific acoustic impedance Z for body tissue, water and steel.

Table 10.1

material	$Z\,/\,\mathrm{kg\,m^{-2}\,s^{-1}}$
body tissue	1.38×10^{6}
water	1.48×10^{6}
steel	4.04×10^{7}

(i) Calculate the intensity reflection coefficient for ultrasound incident on a water–steel boundary.

intensity reflection coefficient = ... [2]

(ii) Explain, without calculation, what is likely to happen when ultrasound is incident on a body tissue–water boundary.

....

....

.... [2]

[Total: 8]

10 (a) Describe how the piezoelectric crystal in a transducer generates ultrasound waves for use in medical diagnosis.

....

....

....

....

.... [3]

(b) A parallel ultrasound beam is incident on the boundary between two media, as illustrated in Fig. 10.1.

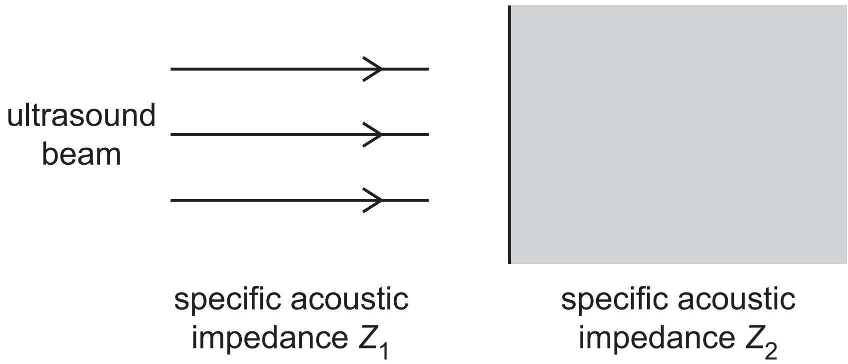


Fig. 10.1

The media have specific acoustic impedances Z_1 and Z_2.

At the boundary, a fraction α of the incident intensity of the ultrasound beam is reflected. The remainder is transmitted.

(i) State what is meant by specific acoustic impedance.

....

....

.... [2]

(ii) Describe how α depends on the relative values of Z_1 and Z_2.

....

....

....

.... [2]

(c) A parallel ultrasound beam of intensity I_0 enters a region of soft tissue. After passing a distance of 2.1 cm through this tissue, the intensity of the ultrasound is $0.62\,I_0$.

Calculate the linear attenuation coefficient μ of ultrasound in the soft tissue. Give a unit with your answer.

μ = ... unit .... [2]

[Total: 9]

24.2 Production and use of X-rays

Name: ____________ Class: ________ Date: __________ **Total: 25 marks**

KEY WORDS contrast 对比度 • x-ray tube X 射线管 • electron 电子 • target 靶 • cathode 阴极

Objective

Build the skills to answer exam questions on **X-rays** in medicine.

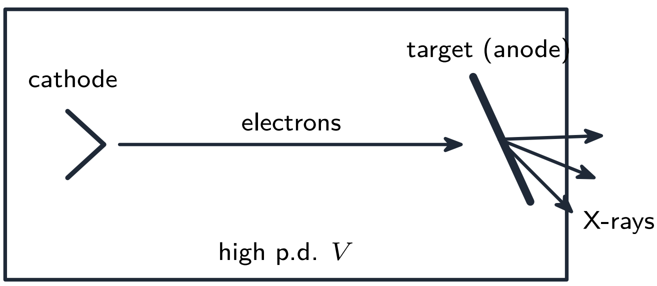
You must be able to:

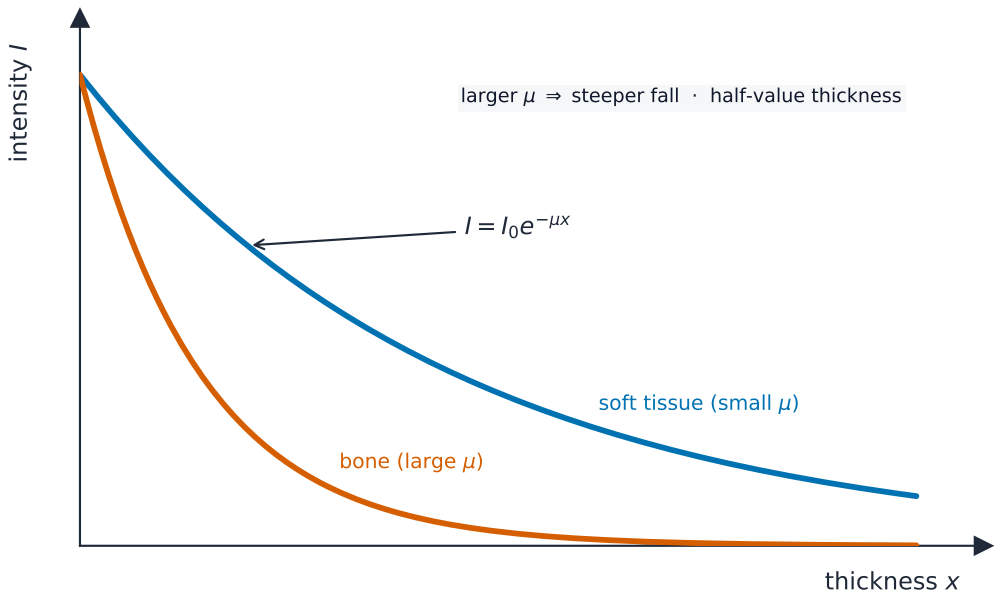
- explain X-ray production and find the **minimum wavelength**
- use the attenuation $I = I_0 e^{-\mu x}$ and **contrast**
- describe **CT scanning**

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Production





X-ray attenuation through tissue

Electrons from a heated **cathode** are accelerated by a high p.d. V onto a metal **target**. The most energetic photon has the full electron KE:

$$hf_{\text{max}} = eV, \qquad \lambda_{\text{min}} = \frac{hc}{eV}.$$

■ Imaging

X-rays are **attenuated** as $I = I_0 e^{-\mu x}$; bone (high μ) absorbs more than soft tissue, giving **contrast**. **CT scanning** combines many X-ray images from different angles into a 2D slice, then stacks slices into a **3D** image.

2 Practice

Now apply the methods above.

2.1 Describe how **X-rays** are produced in an X-ray tube. [2]

2.2 Write the equation for the **minimum wavelength** of X-rays. [1]

2.3 Write the equation for the **attenuation** of X-rays. [1]

2.4 State what is meant by **contrast** in an X-ray image. [1]

3 Exam-style questions

3.1 The **minimum wavelength** of the X-rays from a tube depends on: [1]

- **A** the target metal
- **B** the accelerating p.d.
- **C** the tube current
- **D** the tube length

3.2 An X-ray tube uses an accelerating p.d. of 50 kV. Calculate the **minimum wavelength** of the X-rays. [3]

3.3 Describe how a **CT scan** produces a 3D image of the body. [3]

3.4 An X-ray tube accelerates electrons through a potential difference of 5.80 kV onto a metal target. Take $h = 6.63 \times 10^{-34}$ J s, $c = 3.00 \times 10^{8}$ m s^{-1} and $e = 1.60 \times 10^{-19}$ C.

(a) **Name** the two processes by which X-rays are produced at the target, and **state** which gives the continuous part of the spectrum. [3]

(b) **Explain** why the spectrum has a sharp **minimum** wavelength. [2]

(c) **Determine** that minimum wavelength. [3]

(d) The X-rays pass through a medium of attenuation coefficient 1.4 cm^{-1}. **Determine** the percentage of the X-ray energy **absorbed** by a thickness of 2.8 cm. [3]

(e) **Explain** why a contrast medium such as barium is given to a patient before imaging soft tissue. [2]

Solutions

2.1 A heated **cathode** emits electrons (thermionic emission); a high p.d. accelerates them onto a metal **target**, where they decelerate and emit X-rays.

2.2 $\lambda_{\min} = \dfrac{hc}{eV}$.

2.3 $I = I_0 e^{-\mu x}$.

2.4 The **difference in brightness** between structures (e.g. bone vs soft tissue) caused by their different absorption of X-rays.

3.1 **B** — the accelerating p.d.

3.2 $\lambda_{\min} = \dfrac{hc}{eV} = \dfrac{(6.63 \times 10^{-34})(3.0 \times 10^{8})}{(1.6 \times 10^{-19})(50\,000)} = 2.5 \times 10^{-11}$ m.

3.3 Take many X-ray images of one **slice** from **different angles** and combine them into a 2D image of that slice; repeat for many slices **along the body**; stack the slices to build a **3D** image.

3.4 (a) **Bremsstrahlung** (braking radiation), where an electron is decelerated by a target nucleus, and **characteristic** X-ray emission, where an inner-shell electron is knocked out and an outer electron falls in to replace it. Bremsstrahlung gives the **continuous** spectrum; the characteristic process gives the sharp spikes on top of it.
(b) The most energetic photon possible is produced when an electron gives up **all** of its kinetic energy in a single interaction; no photon can carry more energy than that, and a maximum energy means a **minimum** wavelength.
(c) $eV = \dfrac{hc}{\lambda_{\min}}$, so $\lambda_{\min} = \dfrac{(6.63 \times 10^{-34})(3.00 \times 10^{8})}{(1.60 \times 10^{-19})(5800)} = 2.1 \times 10^{-10}$ m.
(d) $\dfrac{I}{I_0} = e^{-\mu x}$ with $\mu x = 1.4 \times 2.8 = 3.92$; $\dfrac{I}{I_0} = e^{-3.92} = 0.0198$, so the fraction **absorbed** is $1 - 0.0198$, i.e. 98%. (Answering 2% gives the transmitted share instead.)
(e) Soft tissues have very similar attenuation coefficients, so they absorb almost equally and the image shows little contrast between them. Barium has a much higher atomic number and absorbs far more strongly, so an organ filled with it stands out sharply against the tissue around it.

8 **(a)** State what is meant by a photon.

....

....

.... [2]

(b) Fig. 8.1 shows a tube in which X-rays are produced at a metal target.

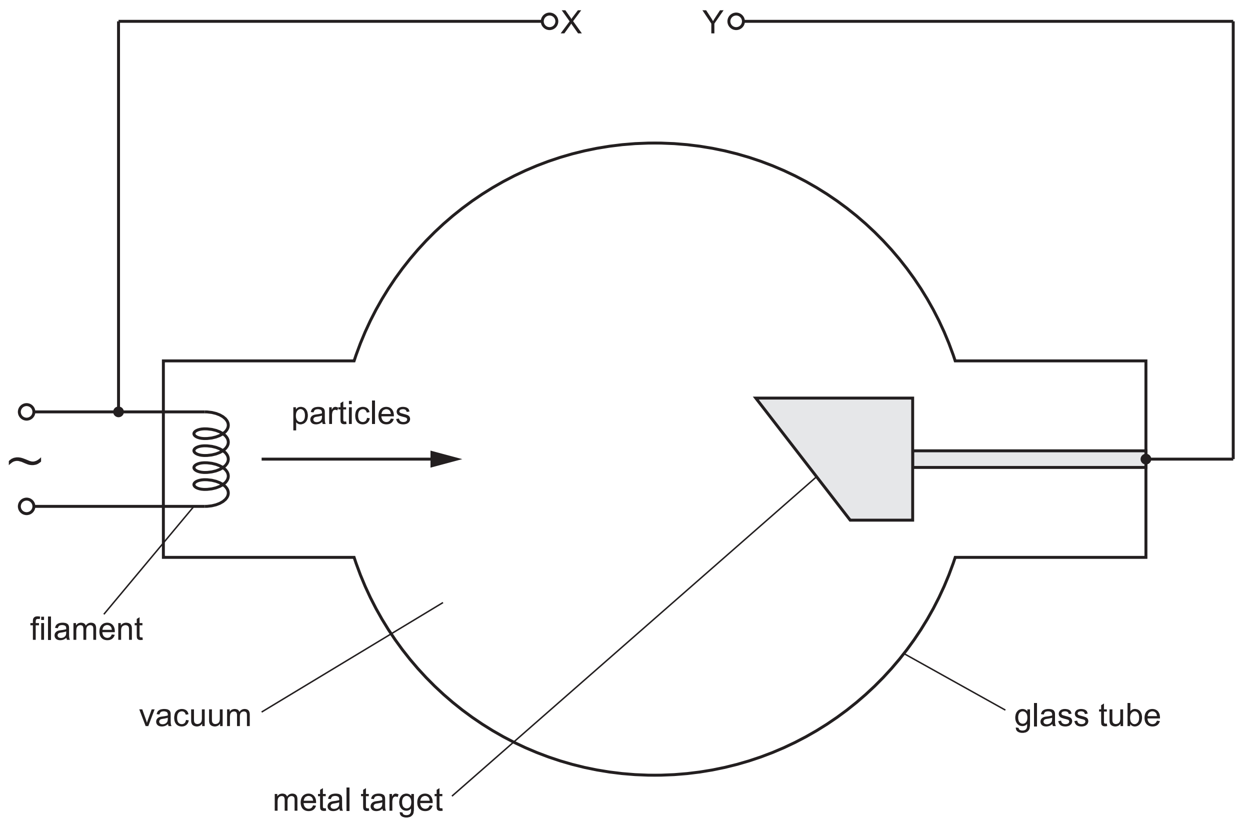


Fig. 8.1

Particles are accelerated from the filament to the target by a constant high voltage applied across the terminals X and Y.

(i) State the name of the particles.

.... [1]

(ii) On Fig. 8.1, use + and – signs to label terminals X and Y to indicate the polarity of the high voltage. [1]

(c) For an accelerating voltage of 32 kV in Fig. 8.1, determine:

(i) the maximum energy, in MeV, of an X-ray photon produced at the target

maximum photon energy = ... MeV [1]

(ii) the maximum momentum of an X-ray photon produced at the target

maximum photon momentum = ... N s [2]

(iii) the minimum wavelength of X-rays produced at the target.

minimum wavelength = ... m [3]

(d) Explain why X-rays can be used to produce images of internal body structures that have good contrast.

....

....

....

....

.... [3]

[Total: 13]

10 **(a)** X-rays for use in medical diagnosis are produced in an X-ray tube. In the X-ray tube, charged particles are accelerated towards a metal target by an applied potential difference (p.d.).

(i) State the name of the charged particles that are accelerated by the applied p.d.

.... [1]

(ii) Explain how X-rays are produced at the metal target.

....

....

....

.... [2]

(iii) Calculate the minimum wavelength of X-rays produced when the applied p.d. is 5.80 kV.

wavelength = ... m [3]

(b) X-rays pass through a medium that has an attenuation coefficient of $1.4\,\text{cm}^{-1}$.

Calculate the percentage of the X-ray energy that is **absorbed** by a 2.8 cm thickness of this medium.

percentage absorbed = ... % [3]

[Total: 9]

24.3 PET scanning

Name: ____________ Class: ________ Date: __________ **Total: 13 marks**

KEY WORDS positron 正电子 • tracer 示踪剂 • antiparticle 反粒子 • photon 光子 • momentum 动量

Objective

Build the skills to answer exam questions on **PET scanning**.

You must be able to:

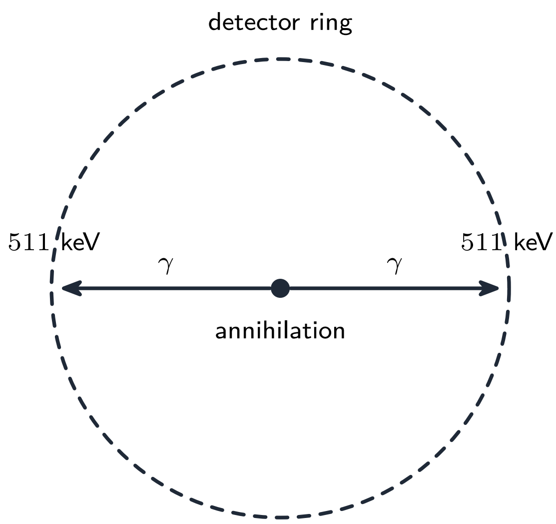
- explain the **tracer** and **annihilation**
- calculate the **annihilation photon energy**
- explain how the photons locate the event

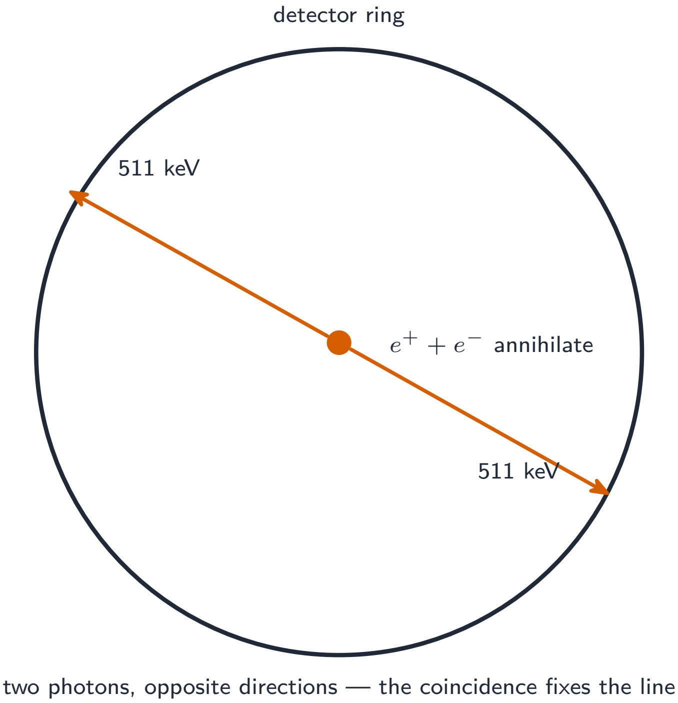
1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Tracer and annihilation

A **tracer** is a radioactive substance put into the body and taken up by the tissue studied. In **PET** it is a β^+ **(positron) emitter**. The positron meets an **electron** and they **annihilate**:





PET detects annihilation photons

Mass-energy and **momentum** are conserved. Since the total momentum is ~zero, **two** γ photons go in **opposite directions**, each of energy $m_e c^2 = 511$ keV.

Detecting **both** photons (and their arrival times) lets the scanner work out the **line** they came from, building an image of tracer concentration.

2 Practice

Now apply the methods above.

2.1 State what a **tracer** is. [1]

2.2 State the type of **decay** a PET tracer undergoes. [1]

2.3 Explain what **annihilation** is. [2]

2.4 State the **energy** of each annihilation photon. [1]

3 Exam-style questions

3.1 In PET, the two γ photons from an annihilation travel: [1]

- **A** in the same direction
- **B** in opposite directions
- **C** at right angles
- **D** in random directions

3.2 Calculate the **energy** of each γ photon produced when an electron and positron annihilate. ($m_e = 9.11 \times 10^{-31}$ kg.) [3]

3.3 Explain why **two** photons are produced (not one), travelling in opposite directions. [2]

3.4 Explain how detecting the two photons helps locate the **annihilation** event. [2]

Solutions

2.1 A substance containing **radioactive nuclei** introduced into the body and **taken up** by the tissue being studied.

2.2 β^+ **(positron)** decay.

2.3 When a particle meets its **antiparticle**, they are destroyed and their **mass becomes energy** (electromagnetic radiation).

2.4 511 keV ($= m_e c^2$).

3.1 **B** — in opposite directions.

3.2 Total rest energy $= 2m_e c^2$, shared by two photons, so each $E = m_e c^2 = (9.11 \times 10^{-31})(3.0 \times 10^8)^2 = 8.2 \times 10^{-14}$ J (= 511 keV).

3.3 Momentum must be **conserved**; the pair's total momentum is ~zero, so the photons must go in **opposite directions** with equal momentum (a single photon could not conserve momentum).

3.4 Both photons are detected (almost simultaneously) on **opposite sides** of the ring; the annihilation lies on the **straight line** joining the two detectors — combining many such lines builds the image.

8 Oxygen-15 ($^{15}_{8}O$) is radioactive and has a half-life of 2.04 minutes.

The decay of oxygen-15 produces positrons. For this reason, oxygen-15 is sometimes used as a tracer in positron emission tomography (PET scanning).

(a) State what is meant by a tracer.

....

....

.... [2]

(b) The equation for the decay of oxygen-15 is

$$^{15}_{8}O \rightarrow {}^{P}_{Q}X + {}^{R}_{S}\beta^{+} + Z$$

where X is the nucleus formed during the decay and Z is another particle.

(i) State the values of the integers *P*, *Q*, *R* and *S*.

P = ... *R* = ...

Q = ... *S* = ...

[2]

(ii) State the name of particle Z.

.... [1]

(c) **(i)** Define the activity of a sample.

....

.... [1]

(ii) Calculate the decay constant of oxygen-15. Give a unit with your answer.

decay constant = ... unit .... [2]

(iii) Determine the rate at which positrons are produced in a sample of oxygen-15 that has a mass of 2.85×10^{-6} kg.

rate = ... s^{-1} [4]

(d) The particles that are emitted from the body and detected outside it during PET scanning are not positrons but another type of particle.

(i) State the name of the particles that are detected.

.... [1]

(ii) Explain how these particles are formed inside the body.

....

....

....

.... [2]

[Total: 15]