



OCR A Level Physics



Your notes

Diagnostic Methods in Medicine

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Your notes

Medical Tracers

Medical Tracers

- A **radioactive tracer** is defined as:

A radioactive substance that can be absorbed by tissue in order to study the structure and function of organs in the body

- Radioactive **isotopes**, such as **technetium-99m** or **fluorine-18**, are suitable for this purpose because:
 - They both bind to organic molecules, such as glucose or water, which are readily available in the body
 - They both emit gamma (γ) radiation and decay into stable isotopes
 - **Technetium-99m** has a short half-life of 6 hours (it is a short-lived form of Technetium-99)
 - **Fluorine-18** has an even shorter half-life of 110 minutes, so the patient is exposed to radiation for a shorter time
- A common tracer used in PET scanning is a glucose molecule with radioactive fluorine attached called **fluorodeoxyglucose**
 - The fluorine nuclei undergoes **β^+ decay** – emitting a **positron** (β^+ particle)
- The radioactive tracer is injected or swallowed into the patient and flows around the body
- Once the tissues and organs have absorbed the tracer, then they appear on the screen as a bright area for a diagnosis
 - This allows doctors to determine the progress of a disease and how effective any treatments have been
- Tracers are used not only for the diagnosis of cancer but also for the heart and detecting areas of decreased blood flow and brain injuries, including Alzheimer's and dementia



Worked Example

Write a nuclear decay equation for the decay of fluorine-18 (${}^{18}_{9}\text{F}$) into an isotope of oxygen by β^+ emission.

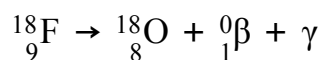
Answer:



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Step 1: Work out the reactants and products

- Reactant:
 - Fluorine ${}^{18}_{9}\text{F}$
- Products:
 - Beta-plus particle (positron) ${}^0_1\beta$
 - Oxygen ${}^{18}_8\text{O}$
 - Gamma-ray γ

Step 2: Write the nuclear decay equation**Worked Example**

Discuss the advantages of using a gamma-emitting tracer in a patient rather than a beta-emitting tracer.

Answer:

Step 1: Consider the properties of gamma and beta particles

- Gamma particles are not (very) ionising and have a long range
- Beta particles are very ionising and have a short range

Step 2: Compare the effects of the gamma and beta particles in relation to detection

- Gamma radiation will pass through the patient and hence can be easily detected
- Beta particles will be absorbed by the patient and hence cannot be detected

Step 3: Compare the effects of the gamma and beta particles in relation to patient safety

- Gamma radiation is not very ionising, hence, it does little damage to cells
- Beta particles is highly ionising, hence, it can cause a lot of damage to cells



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Gamma Camera

Gamma Camera Components

- A medical tracer's progress around the body can be detected using a gamma camera
- A gamma camera is comprised of four major components:
 - Collimator
 - Scintillator
 - Photomultiplier tubes
 - Computer and display

Collimator

- Images of slices of the body can be taken to show the position of the gamma-emitting **radioactive tracers**
- Once injected with a tracer, the patient lays stationary in a tube surrounded by a ring of detectors
- When gamma rays are emitted, they are absorbed by thin lead tubes known as **collimators**
- Collimators are the key to producing the **sharpest** and **highest resolution** images
 - Only photons moving **parallel** to the collimator will be absorbed, this improves the sharpness of the image as scattered photons are excluded
 - The **narrower** and **longer** the collimators, the more gamma rays that will be absorbed and hence, the more electrons that will be produced, this improves the image quality as more electrons contributing to the electrical pulse output will increase the **resolution** of the image

Scintillator

- When the gamma-ray (γ -ray) photon is incident on a crystal scintillator, an electron in the crystal is excited to a higher energy state
 - As the excited electron travels through the crystal, it excites more electrons
 - When the excited electrons move back down to their original state, the lost energy is transmitted as visible light photons

Photomultiplier Tubes

- The photons produced by the scintillator are very faint
- Hence, they need to be amplified and converted to an electrical signal by a photomultiplier tube



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Image Formation on a Computer

- The signals produced by the photomultiplier tubes are used to produce an **image** using the electrical signals from the detectors
- The tracers will emit lots of γ rays simultaneously, and the computers will use this information to create an image
- The more photons from a particular point, the more tracer that is present in the tissue being studied, and this will appear as a bright point on the image
- An image of the **tracer concentration** in the tissue can be created by **processing the arrival times** of the gamma-ray photons

Diagnosis Using a Gamma Camera

- Gamma camera imaging can be used for diagnosing issues in multiple organs
- When imaging a patient using a gamma camera, a gamma emitter, usually **technetium-99m**, is used as the radioactive tracer
 - The 'm' stands for **metastable** which means its nucleus stays in a high-energy state for extended periods
- Tc-99m loses energy by the emission of a gamma photon with an energy of exactly 140 keV
- When Tc-99m decays through gamma emission (with a half-life of approximately 6 hours), it becomes Tc-99, which is stable and has a half-life of 210,000 years
- Technetium-99m is used because:
 - Its **short half-life** means it stays around long enough to be imaged but reduces harm to the patient.
 - Its chemical properties enable a small quantity to be incorporated into several tissues, so it can be used to **image several organs** at once



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PET Scans

Positron Emission Tomography (PET) Scanning

- Positron Emission Tomography (PET) is defined as:
A type of nuclear medical procedure that images tissues and organs by measuring the metabolic activity of the cells of body tissues
- In PET scanning, a beta-plus emitting radioactive tracer is used in order to stimulate positron-electron annihilation to produce gamma photons
 - These are then detected using a ring of gamma cameras

Principles of PET Scanning

Before the scan

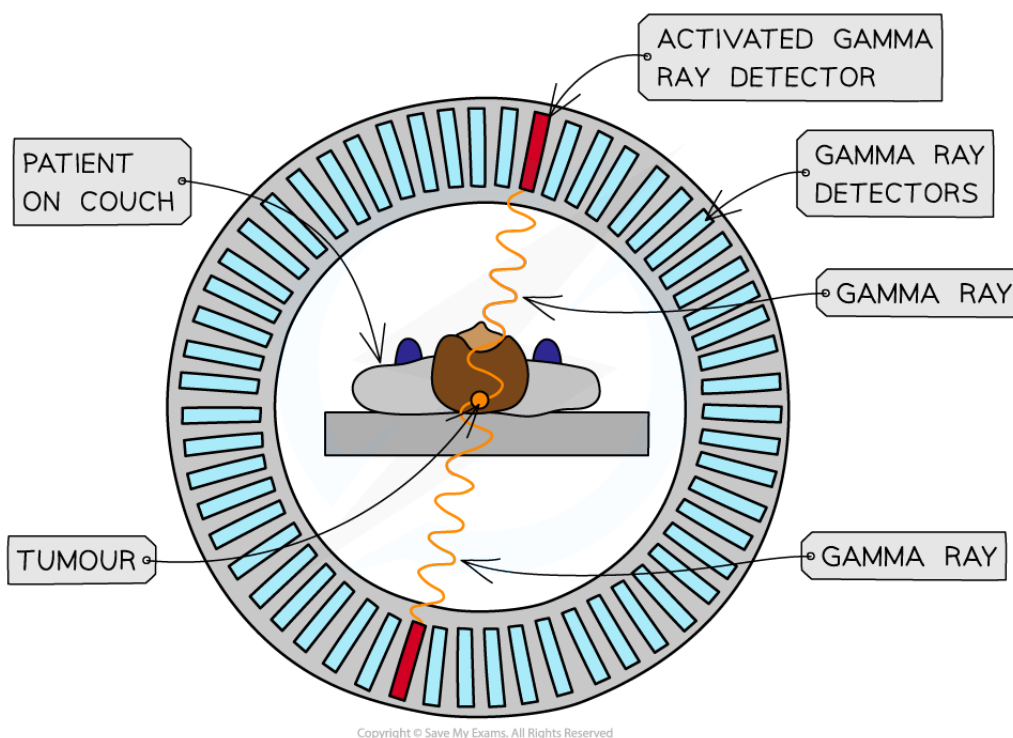
- The patient is injected with a beta-plus emitting isotope, usually fluorine-18 (F-18)

During the scan

- The part of the body being studied is surrounded by a ring of gamma cameras
- The positrons from the F-18 nuclei annihilate with electrons in the patient
- The annihilation of a positron and an electron produces two identical gamma photons travelling in opposite directions
- The delay time between these two gamma ray photons is used to determine the location of the annihilation due to the F-18 tracer
 - Photons that do not arrive within a nanosecond of each other are ignored, since they cannot have come from the same point

After the scan

- Computer connected to the gamma cameras detect the signal and an image is formed by the computer



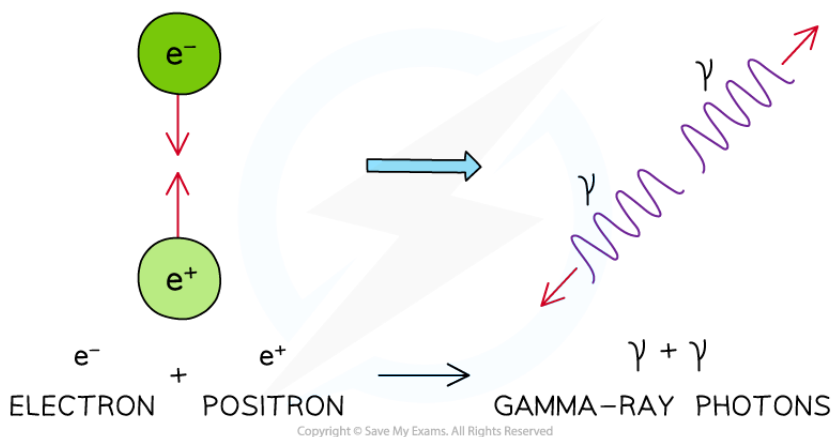
Detecting gamma rays with a PET scanner

Annihilation

- When a positron is emitted from a tracer in the body, it travels less than a millimetre before it collides with an electron
- The positron and the electron will **annihilate**, and their mass becomes pure energy in the form of two gamma rays which move apart in opposite directions
- Annihilation doesn't just happen with electrons and positrons, annihilation is defined as:

When a particle meets its equivalent antiparticle they are both destroyed and their mass is converted into energy

- As with all collisions, the mass, energy and momentum are conserved



Annihilation of a positron and electron to form two gamma-ray photons

- The gamma-ray photons produced have an energy and frequency that is determined solely by the mass-energy of the positron-electron pair
- The energy E of the photon is given by

$$E = hf = m_e c^2$$

- The momentum p of the photon is given by

$$p = \frac{E}{c}$$

- Where:
 - m_e = mass of the electron or positron (kg)
 - h = Planck's constant (J s)
 - f = frequency of the photon (Hz)
 - c = the speed of light in a vacuum (m s^{-1})



Worked Example

Fluorine-18 decays by β^+ emission. The positron emitted collides with an electron and annihilates producing two γ -rays.



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(a) Calculate the energy released when a positron and an electron annihilate.

(b) Calculate the frequency of the γ -rays emitted.

(c) Calculate the momentum of one of the γ -rays.

Answer:

Part (a)

Step 1: Write down the known quantities

- Mass of an electron = mass of a positron, $m_e = 9.11 \times 10^{-31} \text{ kg}$
- Total mass is equal to the mass of the electron and positron = $2m_e$

Step 2: Write out the equation for mass-energy equivalence

$$E = m_e c^2$$

Step 3: Substitute in values and calculate energy E

$$E = 2 \times (9.11 \times 10^{-31}) \times (3.0 \times 10^8)^2 = 1.6 \times 10^{-13} \text{ J}$$

Part (b)

Step 1: Determine the energy of one photon

- Planck's constant, $h = 6.63 \times 10^{-34} \text{ J s}$
- Two photons are produced, so, the energy of one photon is equal to half of the total energy from part (a):

$$E = \frac{1.6 \times 10^{-13}}{2} = 0.8 \times 10^{-13} \text{ J}$$

Step 2: Write out the equation for the energy of a photon

$$E = hf$$

Step 3: Rearrange for frequency f , and calculate

$$f = \frac{E}{h} = \frac{0.8 \times 10^{-13}}{6.63 \times 10^{-34}} = 1.2 \times 10^{20} \text{ Hz}$$

Part (c)

Step 1: Write out the equation for the momentum of a photon



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$$p = \frac{E}{c}$$

Step 2: Substitute in values and calculate momentum, p

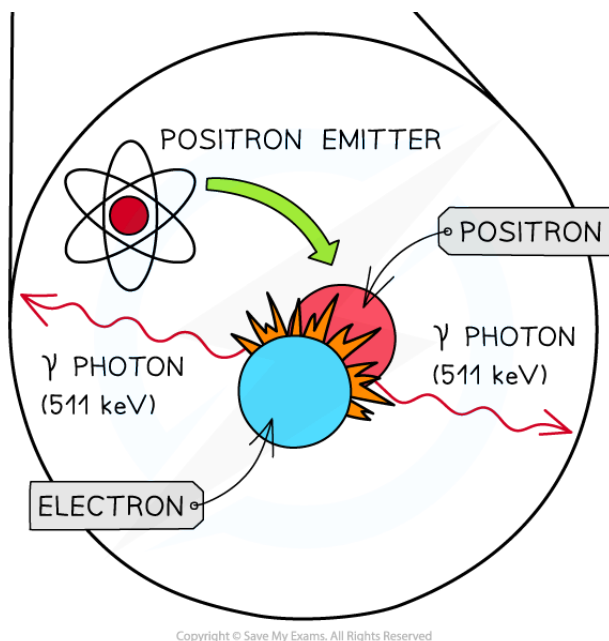
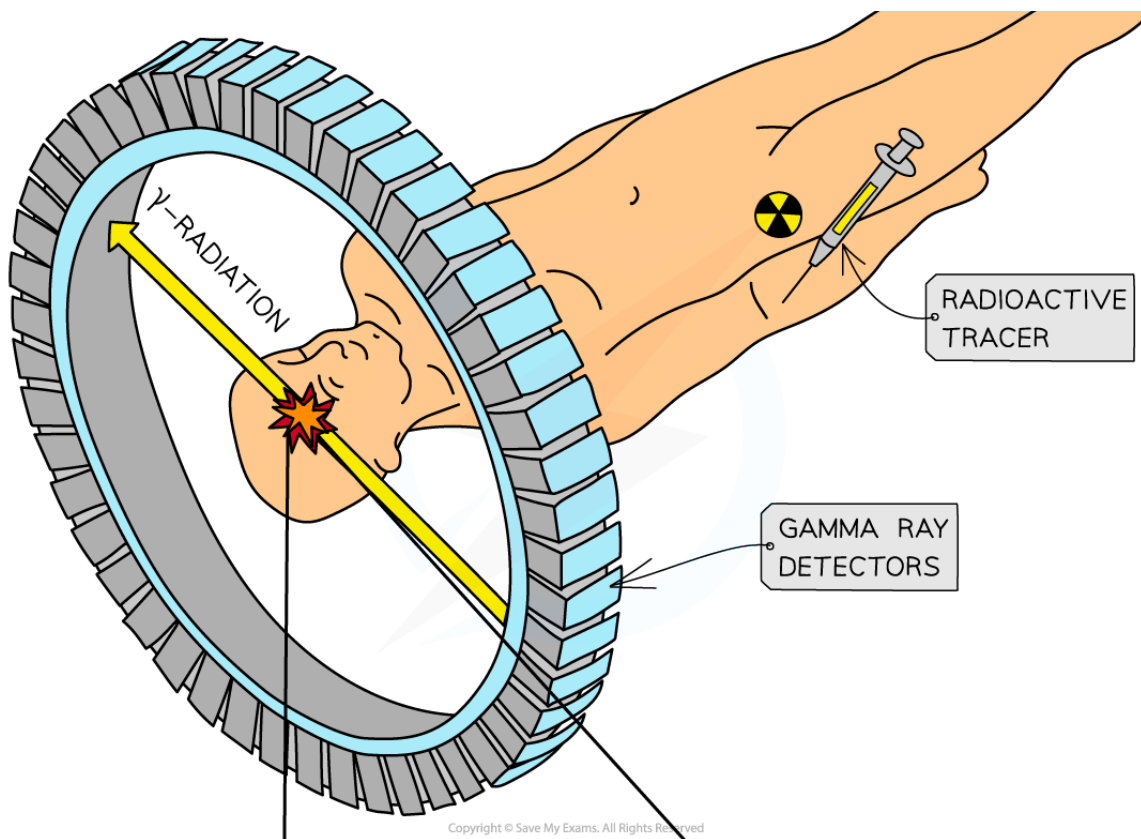
$$p = \frac{E}{c} = \frac{0.8 \times 10^{-13}}{3.0 \times 10^8} = 2.7 \times 10^{-22} \text{ N s}$$

Diagnosis Using PET Scanning

- Once the tracer is introduced to the body it has a **short half-life**, so, it begins emitting positrons (β^+) immediately
 - This allows for a short exposure time to the radiation
 - A short half-life does mean the patient needs to be scanned quickly and not all hospitals have access to expensive PET scanners
- In PET scanning:
 - Positrons are emitted by the decay of the tracer
 - They travel a small distance and annihilate when they interact with electrons in the tissue
 - This annihilation produces a pair of gamma-ray photons which travel in opposite directions



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Annihilation of a positron and an electron is the basis of PET Scanning

Image Formation on a Computer

- The signals produced by the photomultiplier tubes are used to produce an **image**
- The γ rays travel in straight lines in opposite directions when formed from a positron-electron annihilation
 - This happens in order to **conserve momentum**
- They hit the detectors in a line – known as the **line of response**
- The tracers will emit lots of γ rays simultaneously, and the computers will use this information to create an image
- The more photons from a particular point, the more tracer that is present in the tissue being studied, and this will appear as a bright point on the image
- An image of the **tracer concentration** in the tissue can be created by **processing the arrival times** of the gamma-ray photons



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