# OCR A Level Physics

Your notes

## Diagnostic Methods in Medicine

### Contents

# 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 ($\gamma$) 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 **$\beta^+$ decay** – emitting a **positron** ($\beta^+$ 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 $\left({}^{18}_{9}\text{F}\right)$ into an isotope of oxygen by $\beta^+$ emission.

**Answer:**

**Step 1: Work out the reactants and products**

- Reactant:

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- Fluorine $^{18}_{9}F$
- Products:
  - Beta-plus particle (positron) $^{0}_{1}\beta$
  - Oxygen $^{18}_{8}O$
  - Gamma-ray $\gamma$

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

$$^{18}_{9}F \rightarrow ^{18}_{8}O + ^{0}_{1}\beta + \gamma$$

## 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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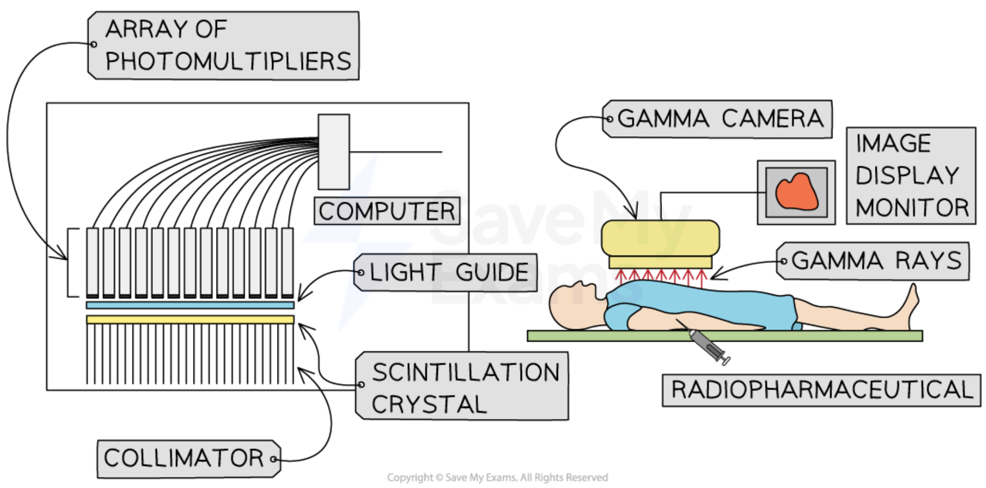
# Gamma Camera Components

- The progress of a medical tracer around the body can be detected using a **gamma camera**
- Images obtained by a gamma camera can be used for diagnosing issues in specific organs
- A gamma camera is comprised of **four** major components:
  - Collimator
  - Scintillator
  - Photomultiplier tubes
  - Computer and display

## Structure of the Gamma Camera



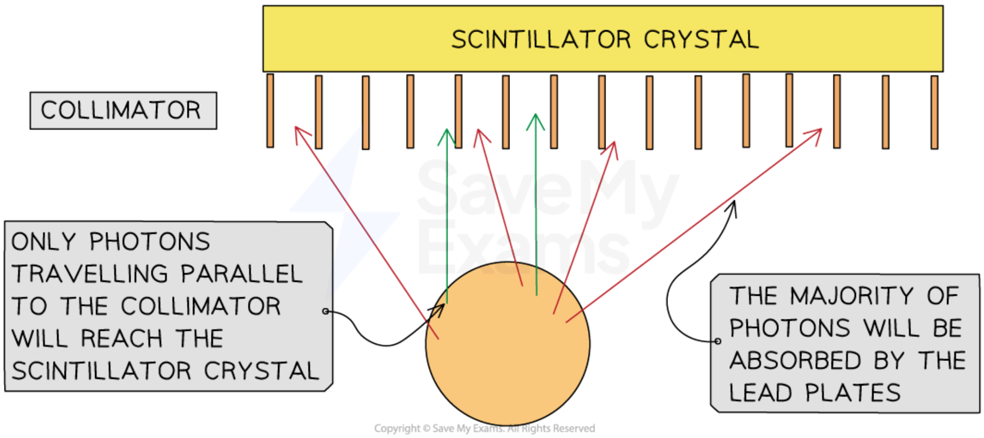

***A gamma camera detects the gamma rays emitted by a radioactive tracer in the body using a large scintillator crystal connected to an array of photomultipliers***

# 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 lies stationary in a tube surrounded by a ring of detectors
- When gamma rays are emitted, they may be absorbed by thin lead tubes known as **collimators**
- Collimators are the key to producing the **sharpest** and **highest resolution** images

- Photons moving **parallel** to the collimator will not be absorbed, which means only these photons reach the scintillator crystal
- Photons moving in any other direction will be **absorbed**
- The **narrower** and **longer** the collimators, the more effectively they filter out scattered gamma rays
- This improves the image **resolution** as excluding scattered photons allows for sharper images to be produced

## The Collimator




***The collimator ensures high resolution images are produced by only allowing photons travelling parallel to the lead plates to pass through***

# Scintillator

- When the gamma-ray ($\gamma$-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
- These visible light photons then travel through the light guide into photomultiplier tubes

## The Scintillator

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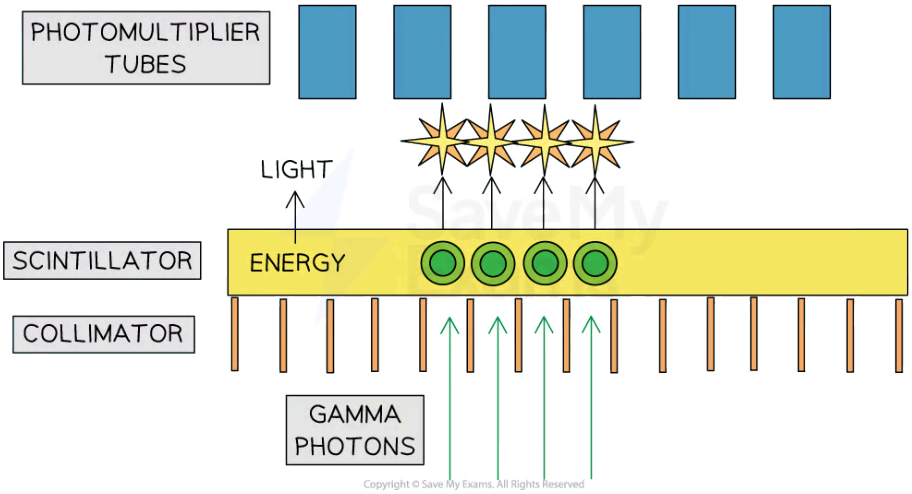
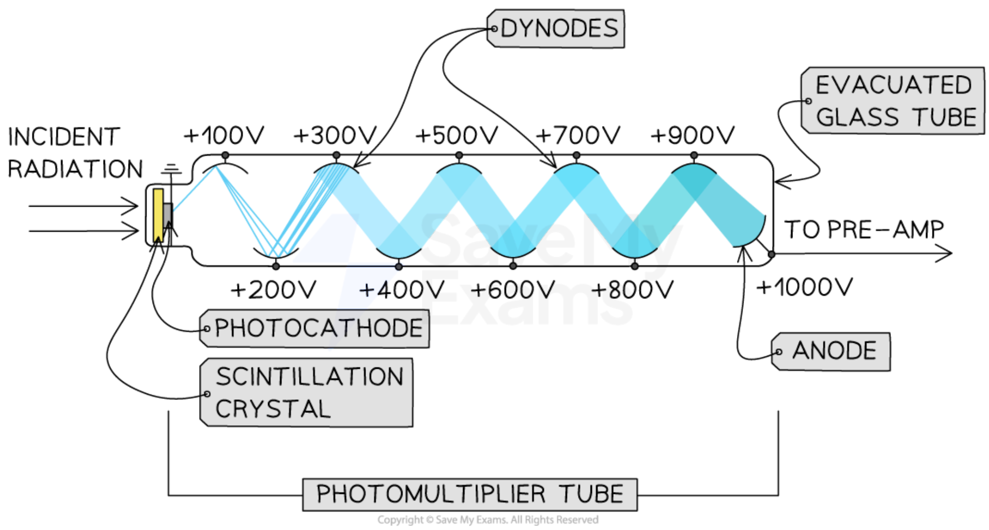



***The scintillator crystal converts the energy from gamma photons into visible light photons***

## Photomultiplier Tubes

- The photons produced by the scintillator are very faint
- Hence, they need to be converted to an electrical signal and **amplified** by a photomultiplier tube
- When photons from the scintillator reach the photomultiplier, electrons are released from a **photocathode**
- The liberated electrons **accelerate** through a series of dynodes, each at a progressively higher potential difference, before reaching an **anode** at the end of the tube
- Energy gained by the acceleration of the electrons triggers the release of **more electrons** at each dynode, resulting in a stronger electrical signal

### A photomultiplier tube



*A photomultiplier detects the faint flashes of light from the scintillator, converts them into voltage pulses, and amplifies the signals*

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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, with a half-life of approximately 6 hours
- Technetium-99m is an ideal medical tracer because:
  - it has a **short half-life**, meaning it remains active long enough to be imaged while reducing 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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# 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**

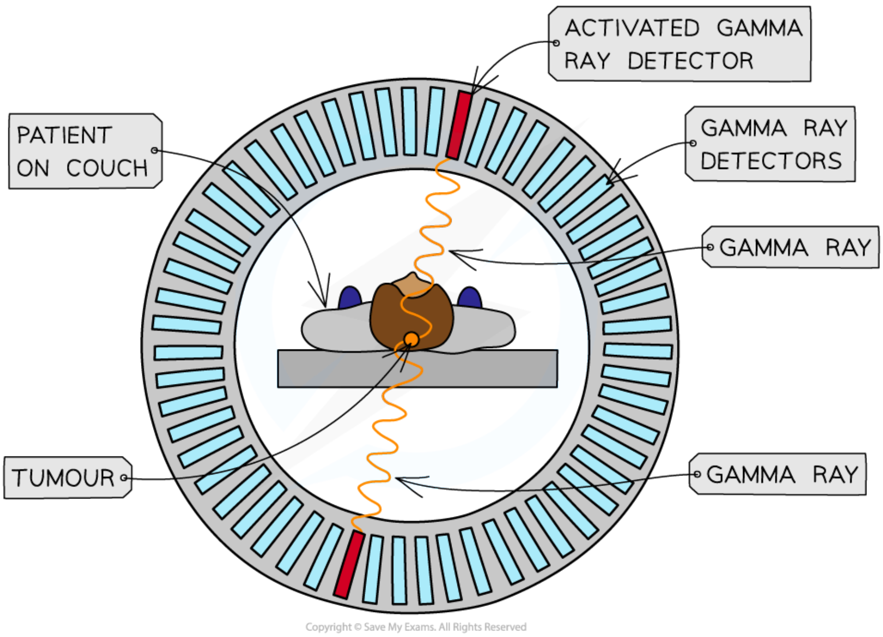
- The patient is injected with a beta-plus emitting isotope, usually fluorine-18 (F-18)

**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



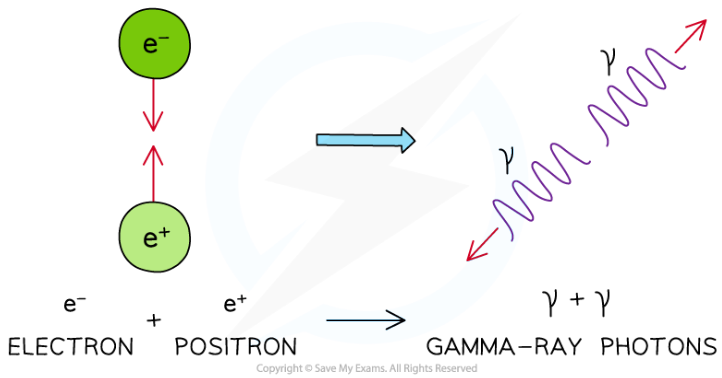

***Detecting gamma rays with a PET scanner***

## 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***

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- 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.

(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, $m_e = 9.11 \times 10^{-31}$ 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, $h = 6.63 \times 10^{-34}$ J s

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- 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**

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

**Part (c)**

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

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

**Step 2: Substitute in values and calculate momentum, *p***

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

# Diagnosis Using PET Scanning

- Once the tracer is introduced to the body it has a **short half-life**, so, it begins emitting positrons ($\beta^+$) 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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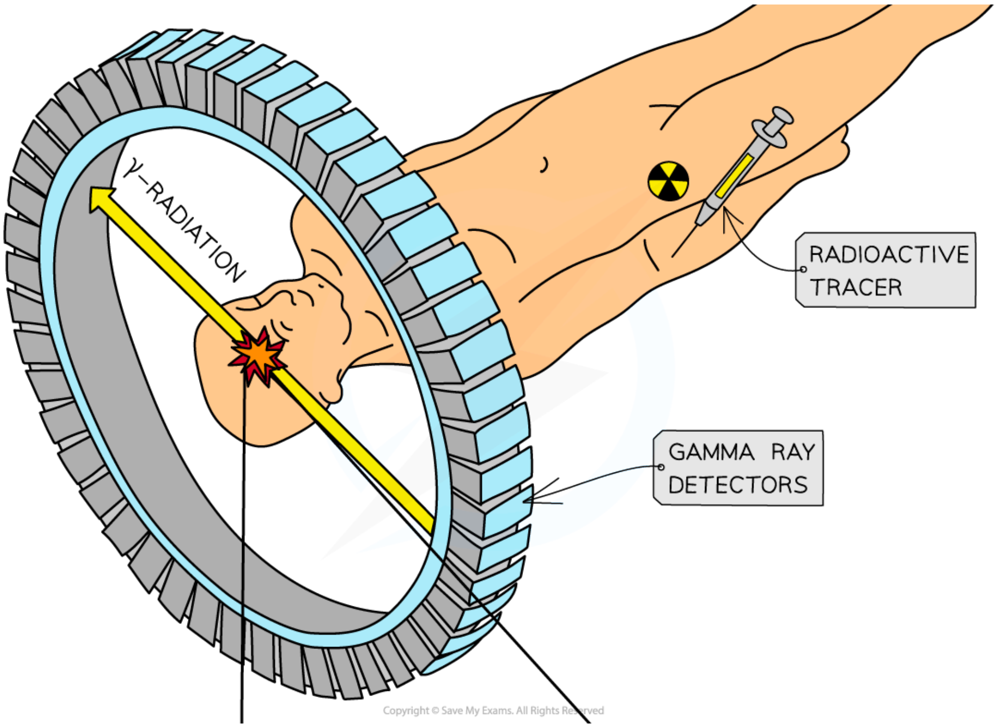


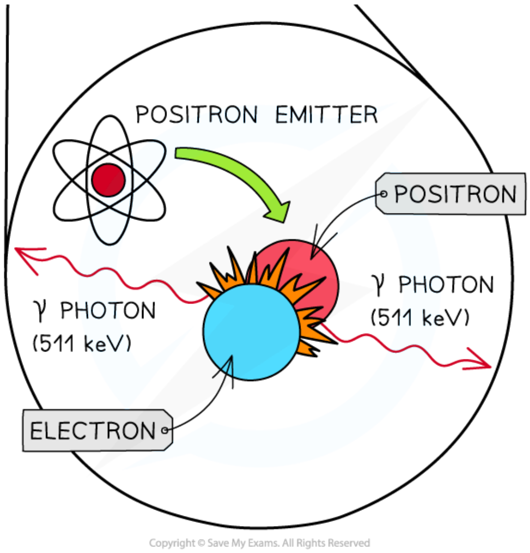


***Annihilation of a positron and an electron is the basis of PET Scanning***

## Image Formation on a Computer

- The signals produced by the photomultiplier tubes are used to produce an **image**
- The $\gamma$ 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**

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- The tracers will emit lots of $\gamma$ 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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