# Cambridge (CIE) IGCSE Physics

Your notes

## Radioactivity

### Contents


- Background Radiation
- Types of Radiation
- Ionising Power & Deflection
- Radioactive Decay
- Half-Life
- Uses of Radiation
- Dangers of Radiation

# Background radiation

- Background radiation is defined as:

**The radiation that exists around us all the time**

- There are two types of background radiation:
  - **Natural sources** from radioactive elements that have always existed on Earth and in outer space
  - **Man-made sources** from human activity that adds to the amount of radiation humans are exposed to on Earth
- The count rate of detected levels of background radiation can vary significantly from place to place

# Sources of background radiation

- The sources that make a significant contribution to background radiation include:
  - radon gas (in the air)
  - rocks and buildings
  - food and drink
  - cosmic rays

## Sources of background radiation

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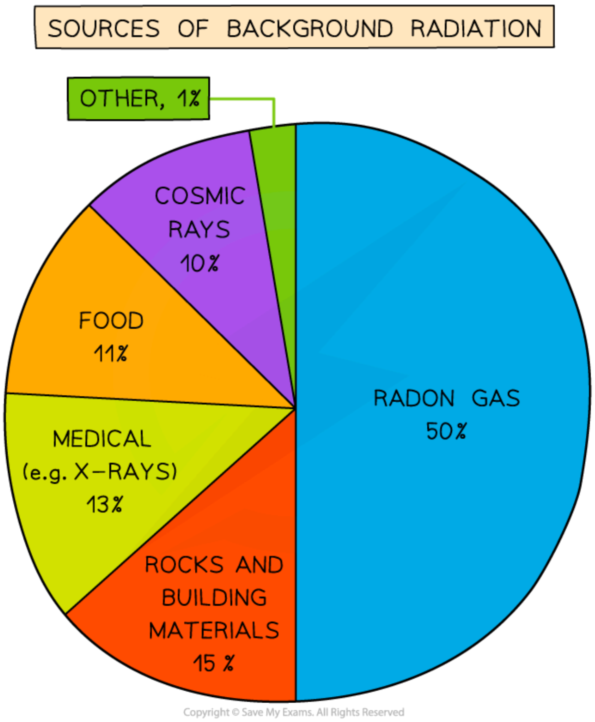


***Background radiation is the radiation that is present all around in the environment. Radon gas is given off from some types of rock***

## Natural sources

- **Rocks and buildings**
  - Natural radioactivity can be found in building materials, including decorative rocks, stone and brick
  - Heavy radioactive elements, such as uranium and thorium, occur naturally in rocks in the ground
  - Uranium decays into radon gas
- **Radon gas (in the air)**
  - Radon gas is an alpha emitter
  - Radon gas is particularly dangerous if it is inhaled into the lungs in large quantities
  - The gas is tasteless, colourless and odourless, but it is not generally a health issue unless levels are significantly high
- **Radioactive material in food and drink**
  - Naturally occurring radioactive elements can get into food and water since they are in contact with rocks and soil containing these elements
  - Some foods contain higher amounts such as potassium-40 in bananas

- However, the amount of radioactive material is minuscule and is not a cause for concern
- **Cosmic rays from space**
  - The sun emits an enormous number of protons every second
  - Some of these enter the Earth's atmosphere at high speeds
  - When they collide with molecules in the air, this leads to the production of gamma radiation
  - Other sources of cosmic rays are supernovae and other high-energy cosmic events
- **Carbon-14 in biological material**
  - All organic matter contains a tiny amount of carbon-14
  - Living plants and animals constantly replace the supply of carbon in their systems hence the amount of carbon-14 in the system stays almost constant

## Man-made sources

- **Medical sources**
  - In medicine, radiation is used frequently
  - Uses include X-rays, CT scans, radioactive tracers, and radiation therapy
- **Nuclear waste**
  - While nuclear waste itself does not contribute much to background radiation, it can be dangerous for the people handling it
- **Nuclear fallout from nuclear weapons**
  - Fallout is the residue radioactive material that is thrown into the air after a nuclear explosion, such as the bomb that exploded at Hiroshima
  - While the amount of fallout in the environment is presently very low, it increases significantly in areas where nuclear weapons are tested
- **Nuclear accidents**
  - Accidents such as that in Chernobyl contributed a large dose of radiation into the environment
  - While these accidents are now extremely rare, they can be catastrophic and render areas devastated for centuries

### Examiner Tips and Tricks

The sources that make the most significant contribution are the natural sources:

- Radon gas
- Rocks and buildings

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- Food and drink
- Cosmic rays

Make sure you remember these for your exam!

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# Detecting radiation

- Ionising nuclear radiation can be measured using a **detector** connected to a counter

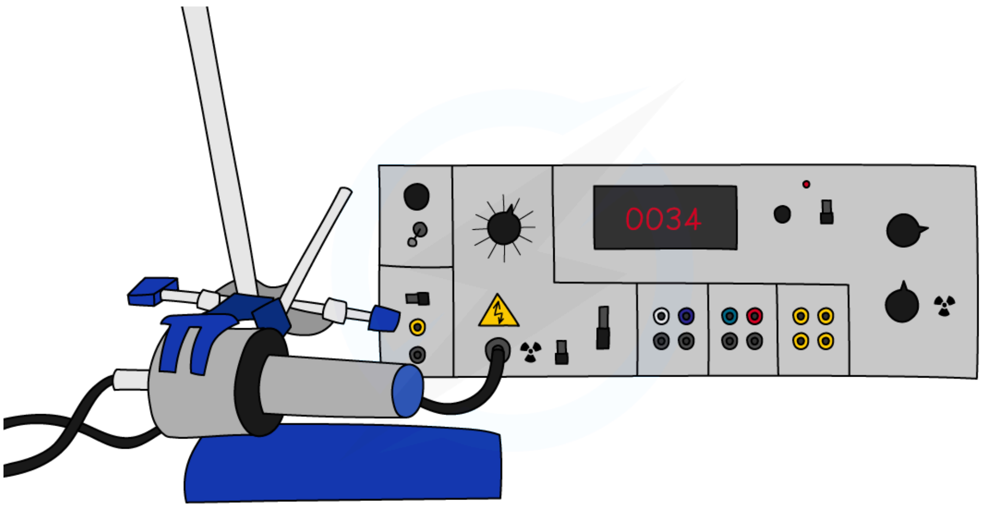
## Count rate

- The detector uses **count rate** measured in **counts/s** or **counts/minute**
  - The count rate is the **number** of decays per second
- The count rate decreases the further the detector is from the source
  - This is because the radiation becomes more spread out the further away it is from the source

## Geiger–Müller tube detects count rate

- The Geiger-Müller tube is the most common device used to measure and detect the count rate of radiation
- Each time it absorbs radiation, it transmits an electrical pulse to a counting machine
  - This makes a clicking sound and it displays the **count rate** on a screen
- The greater the frequency of clicks, or the higher the count rate, the more radiation the Geiger-Müller tube is absorbing
  - Therefore, it matters how close the tube is to the radiation source
  - The further away from the source, the lower the count rate detected

### Geiger–Müller tube detects count rate



*A Geiger-Müller tube (or Geiger counter) is a common type of radiation detector detecting count rate*

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Examples of other radiation detectors include:

- **Photographic film** (often used in badges)
- **Ionisation chambers**
- **Scintillation counters**
- **Spark counters**

## Worked Example

A Geiger-Müller tube is used to detect radiation in a particular location. What is the count rate if it counts 16,000 decays in 1 hour?

**Answer:**

**Step 1: Identify the different variables**

- The number of decays is 16 000
- The time is 1 hour

**Step 2: Determine the time period in seconds**

- 1 hour is equal to 60 minutes, and 1 minute is equal to 60 seconds

$$\text{time period} = 1 \times 60 \times 60 = 3600 \text{ s}$$

**Step 3: Divide the total counts by the time period in seconds**

$$\text{decays} = \frac{\text{counts}}{\text{time period}}$$

$$\text{decays} = \frac{16\,000}{3600}$$

$$\text{decays} = 4.5$$

- Therefore, there are **4.5 decays per second**

## Examiner Tips and Tricks

If asked to name a device for detecting radiation, the Geiger-Müller tube is a good example to give. You can also refer to it as a GM tube, a GM detector, GM counter, Geiger counter etc. (The examiners will allow some level of misspelling, providing it is readable). Don't, however, refer to it as a 'radiation detector' as this is too vague and may simply restate what was asked for in the question.

It is important to regulate the exposure of humans to radiation. The amount of radiation received by a person is called the **dose.**

# Accounting for background radiation

**Extended tier only**

- Measurements of background radiation are used to determine a **corrected count rate**
- This can be done by taking readings with **no radioactive source** present and then subtracting this from readings with the source present

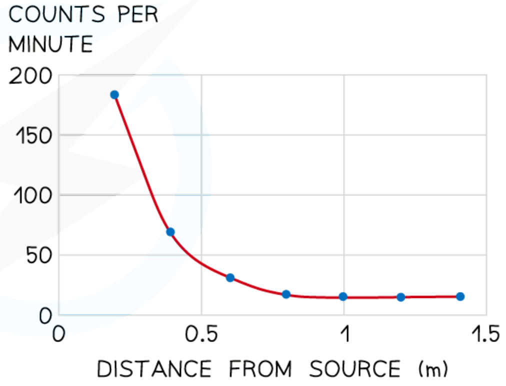
### Worked Example

A student is using a Geiger-counter to measure the counts per minute at different distances from a source of radiation. Their results and a graph of the results are shown here.

RESULTS TABLE

| Distance from source (m) | Counts per minute |
|---|---|
| 0.2 | 180 |
| 0.4 | 67 |
| 0.6 | 29 |
| 0.8 | 17 |
| 1.0 | 15 |
| 1.2 | 15 |
| 1.4 | 15 |

GRAPH






Determine the background radiation count.

**Answer:**

**Step 1: Determine the point at which the source radiation stops being detected**

- The background radiation is the amount of radiation received all the time

- When the source is moved back far enough it is all absorbed by the air before reaching the Geiger-counter
- Results after 1 metre do not change
- Therefore, the amount after 1 metre is only due to background radiation

**Step 2: State the background radiation count**

- The background radiation count is **15 counts per minute**

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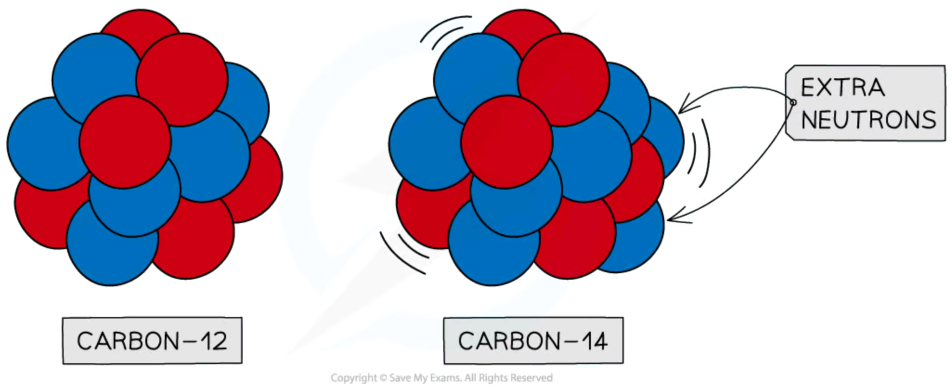
# Radioactive decay

- The emission of radiation from a nucleus is **spontaneous** and **random** in direction
- This random process of radioactive decay means:
  - There is an **equal probability** of any nucleus decaying
  - It cannot be known **which particular nucleus will decay next**
  - It cannot be known **at what time a particular nucleus will decay**
  - The rate of decay is **unaffected** by the surrounding conditions
  - It is only possible to estimate the **probability** of a nuclei decaying in a given time period

## Unstable nuclei

- Some atomic nuclei are **unstable**
- This is because of an imbalance in the forces within the nucleus
  - Forces exist between the particles in the nucleus
- Instability is commonly due to:
  - The nucleus having **too many** protons or neutrons
  - The nucleus being **very large**
- An example of an **unstable** nucleus is carbon-14
  - This is an **isotope** of carbon
    - It has two extra neutrons compared to stable carbon-12

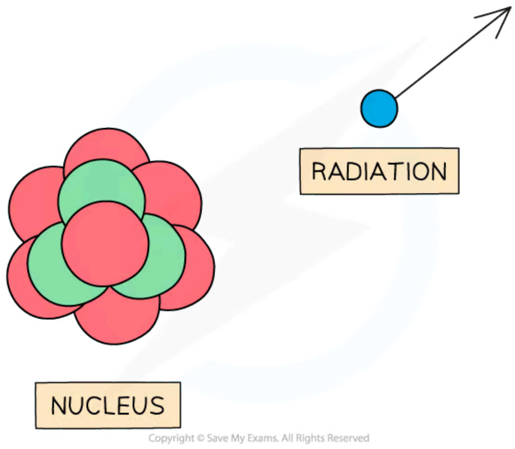
### Isotopes of carbon



*Carbon-12 is stable, whereas carbon-14 is unstable. This is because carbon-14 has two extra neutrons*

- Unstable nuclei can **emit radiation** to become more stable
  - Radiation can be in the form of a **high-energy** particle or wave

## Unstable nuclei emit radiation




*Unstable nuclei decay by emitting high-energy particles or waves*

- As the radiation moves away from the nucleus, it takes some energy with it
  - This reduces the overall energy of the nucleus
  - This makes the nucleus more **stable**

### Worked Example

Which of the following statements is **not** true?

**A** Isotopes can be unstable because they have too many or too few neutrons

**B** The process of emitting particles or waves of energy from an unstable nucleus is called radioactive decay

**C** Scientists can predict when a nucleus will decay

**D** Radiation refers to the particles or waves emitted from a decaying nucleus

**Answer: C**

- Consider what you know about the statements above:

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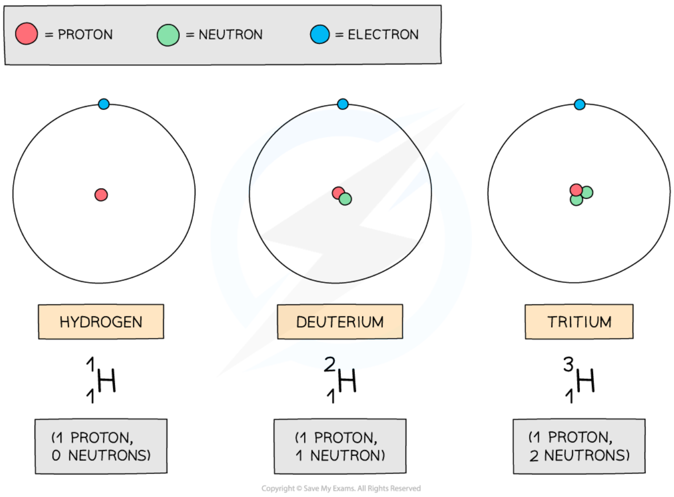
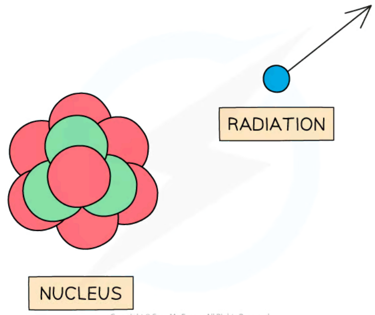
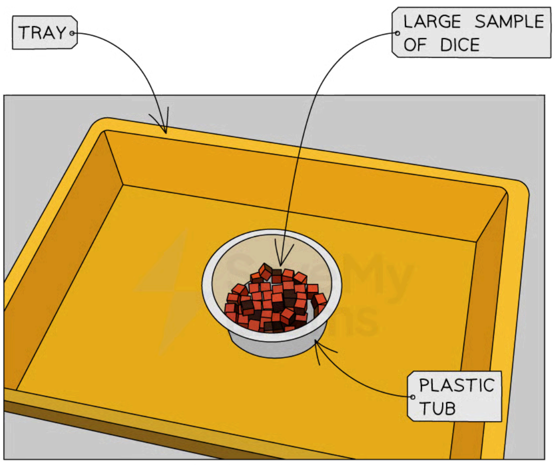
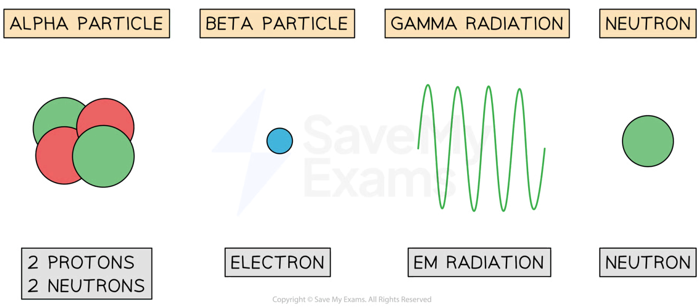
| | |
|---|---|
| **Isotopes** |  |
| **Radioactive decay** |  |
| **Nuclei decay prediction** |  |
| **Radiation** |  |

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- Answer A is **true.** The number of neutrons in a nucleus determines the stability
- Answer B is **true.** This is a suitable description of radioactive decay
- Answer D is **true.** Radiation is about emissions. It is different to radioactive particles
- Answer C is **not true**
- Radioactive decay is a random process
- It is not possible to predict precisely when a particular nucleus will decay

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### Examiner Tips and Tricks

The terms **unstable**, **random** and **decay** have very particular meanings in this topic. Remember to use them correctly when answering questions!

# Types of radioactive decay

- Radioactive decay is a change in an unstable nucleus that can result in the emission of one of the following types of radiation:
  - **Alpha (α)** particles
  - **Beta ($\beta^-$)** particles
  - **Gamma (γ)** radiation
- Remember that these changes are **spontaneous** and **random**

## Alpha particles

- The radiation symbol for alpha is **α**
- An alpha particle is the same as a helium nucleus
  - This is because they consist of two neutrons and two protons
- Alpha particles have a charge of +2
  - This means they can be affected by an electric field

## Beta particles

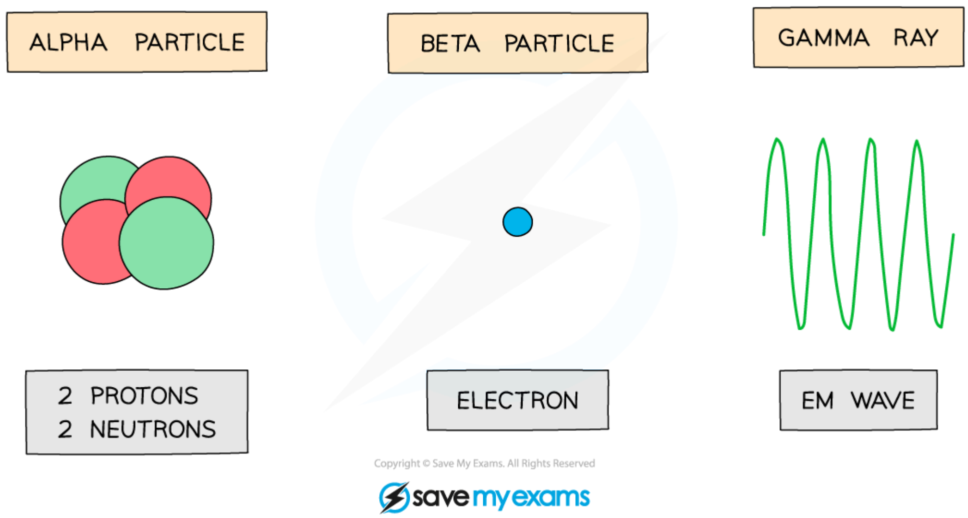
- The radiation symbol for beta is $\boldsymbol{\beta^-}$
- Beta particles are fast-moving electrons
- They are produced in nuclei when a neutron changes into a proton and an electron
- Beta particles have a charge of -1
  - This means they can be affected by an electric field

## Gamma rays

- The radiation symbol for gamma is **γ**

- Gamma rays are electromagnetic waves
- They have the highest energy of the different types of electromagnetic waves
- Gamma rays have no charge

## Types of radioactive decay




*Alpha particles, beta particles and gamma waves can be emitted from unstable nuclei*

# Alpha, beta & gamma emission

- α, β and γ radiation can be identified by the emission from a nucleus by recalling their:
  - Nature (what type of particle or radiation they are)
  - Their relative ionising effects (how easily they **ionise** other atoms)
  - Their relative penetrating abilities (how far can they travel before they are stopped completely)
- The properties of alpha, beta and gamma are given in the table which shows the following trends down the table:
  - The range increases
  - Penetrating power increases
  - Ionisation decreases

### Summary of the properties of nuclear radiation

| Particle | Nature | Range in air | Penetrating power | Ionising ability |
|---|---|---|---|---|

| | | | | |
|---|---|---|---|---|
| Alpha (α) | helium nucleus (2 protons, 2 neutrons) | a few cm | low; stopped by a thin sheet of paper | high |
| Beta (β) | high-energy electron | a few 10s of cm | moderate; stopped by a few mm of aluminium foil or Perspex | moderate |
| Gamma (γ) | electromagnetic wave | infinite | high; reduced by a few cm of lead | low |

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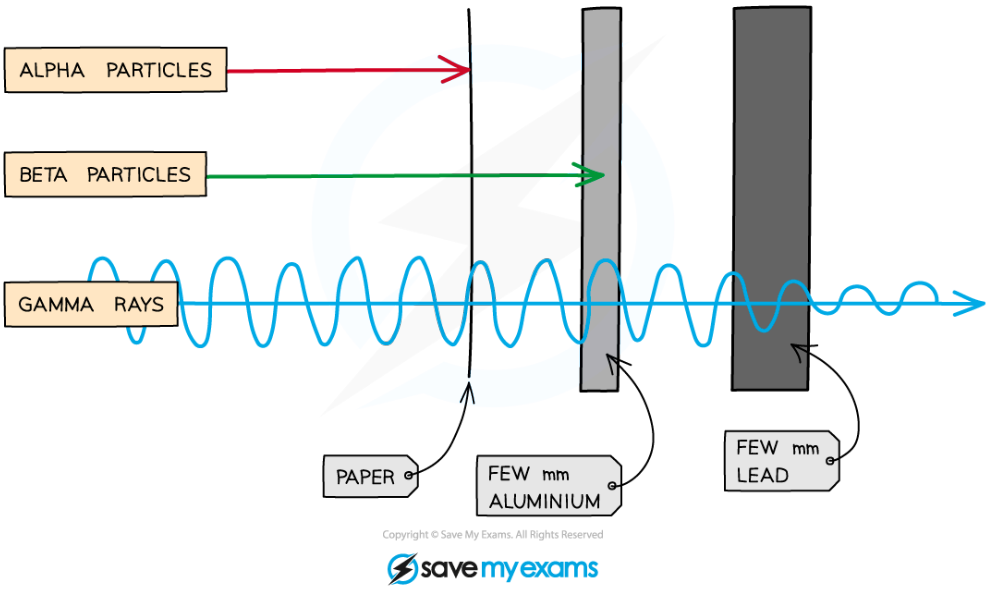
## Penetrating power

- Alpha, beta and gamma radiation have different properties
- So they **penetrate** materials in different ways
  - This means they are each **stopped** by different materials

### Penetrating power of alpha, beta and gamma radiation




***Alpha, beta and gamma are different in how they penetrate materials. Alpha is the least penetrating, and gamma is the most penetrating***

- Alpha is stopped by **paper**, whereas beta and gamma pass through it
- Beta is stopped by a few millimetres of aluminium
  - Gamma can pass through **aluminium**
- Gamma rays are only partially stopped by thick **lead**

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## Examiner Tips and Tricks

It is important to note that **beta particles** are only **stopped** by **aluminium** if it is a **few mm** thick. They **can** pass though aluminium which is **thinner** than this. This concept often comes up in exam questions.

## Worked Example

A student has an unknown radioactive source and is trying to determine which type of radiation it emits. Using a Geiger-Muller tube, they measure the count rate when the source is placed behind different materials.

Their results are shown in the table below:

| | **No material between source and detector** | **Paper between source and detector** | **5 mm aluminium between source and detector** | **5 mm lead between source and detector** |
|---|---|---|---|---|
| **Count rate** | 4320 | 4218 | 256 | 34 |

Which type of radiation is being given off by the source?

**A** Alpha particles

**B** Beta particles

**C** Gamma rays

**D** Neutrons

**Answer: B**

- Consider the diagram showing penetrating power from above
- The answer is **not A** because the radiation passed through the paper almost unchanged
  - This means it is **not** alpha
- The answer is **not C or D** because the aluminium decreased the count rate significantly
  - This means it is **not** gamma (gamma penetrates aluminium)
  - This also means it is **not** neutrons (neutrons penetrate aluminium, however, you do not need to know this for your exam)
- Therefore, the source must be **beta** particles

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## Examiner Tips and Tricks

Remembering the type of particle, penetration and ionising power for alpha, beta and gamma radiation is very important for your exam! Often the exam question will give some clues and you will have to choose which type of radiation it could be based on these.

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# Ionising effect of radiation

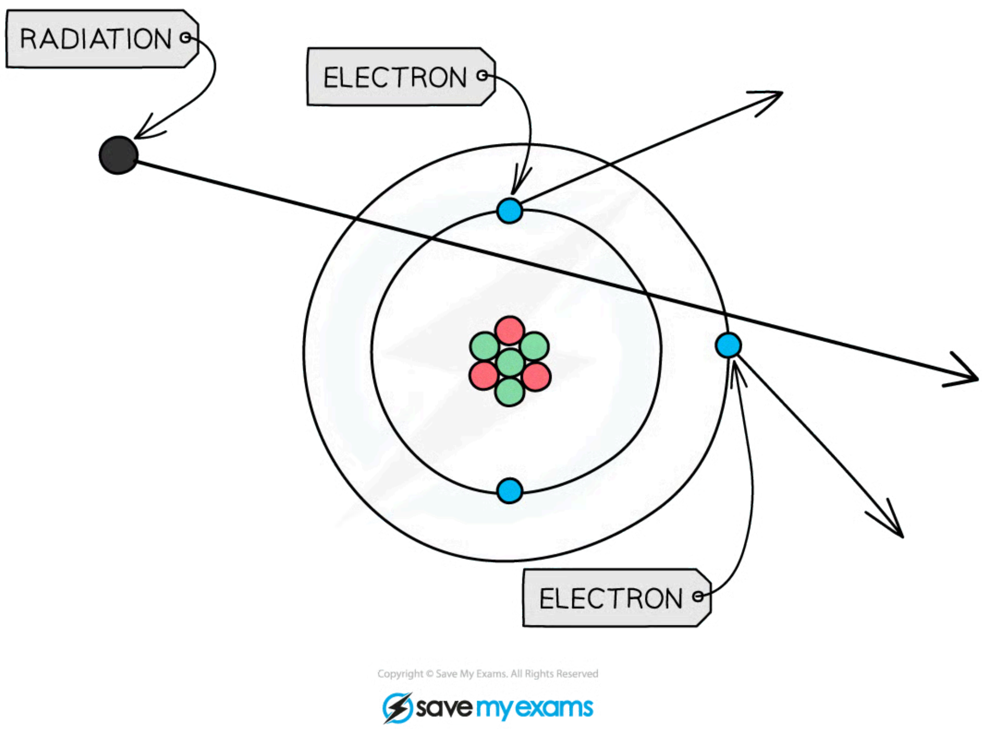
**Extended tier only**

- The relative ionising effects of nuclear radiation depend upon their:
  - **kinetic energy**
  - **electric charge**

## Ionisation

- Ionisation is when an atom becomes negatively or positively charged by gaining or losing electrons
- Nuclear radiation can **ionise** the atoms that it hits
  - This is mostly done by removing an electron so the atom loses a negative charge and is left with an overall **positive** charge

### Nuclear radiation ionising an atom




***When radiation passes close to atoms it can knock out electrons, ionising the atom***

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## Effects of kinetic energy and charge on ionising power

- The **greater** the **charge** of the radiation, the **more** ionising it is
  - This means alpha radiation is the most ionising as it has a charge of +2
  - A beta particle has a charge of –1 so it is moderately ionising
  - This means gamma radiation is the least ionising as it has a charge of 0 (no charge)
- The **higher** the **kinetic energy** of the radiation, the **more** ionising it is
  - This means the alpha particle is still the most ionising because it has the greatest mass
  - However, a beta particle is very light (it is an electron) but travels at high speeds, therefore, it has a lot of kinetic energy and is still moderately ionising
  - Gamma radiation has virtually no mass so it is weakly ionising

### Examiner Tips and Tricks

Remembering the properties of alpha, beta and gamma radiation helps to deduce how much ionising power they have. E.g. An alpha particle is a helium nucleus which contains two protons and two neutrons. It therefore has a charge of +2 since each proton has a charge of +1 and a neutron has no charge.

Kinetic energy is defined by the equation $\frac{1}{2}mv^2$ therefore it depends on the mass *m* of the particle and its velocity *v*.

# Deflection in electric & magnetic fields

**Extended tier only**

- α-particles, β-particles and γ-radiation are deflected differently in electric and magnetic fields
- A particle is deflected in an electric field if it has **charge**
- A particle is deflected in a magnetic field if it has **charge** and is **moving** perpendicular to it
  - Therefore, since gamma (γ) particles have no charge, they are **not** deflected by either electric or magnetic fields
  - Only alpha (α) and beta (β) particles are deflected

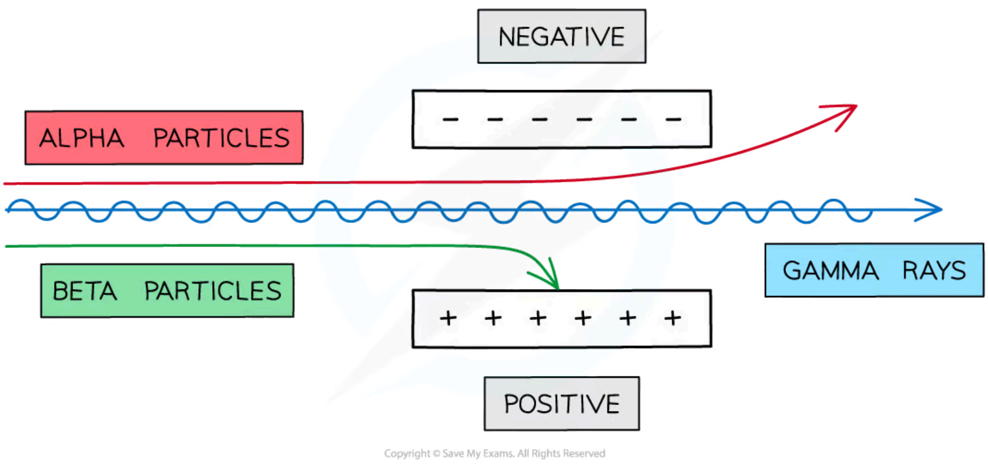
## Electric fields

- Alpha particles have a **charge of +2** (the charge of a helium nucleus)

Your notes

- Beta particles have a **charge of –1** (the charge of an electron)
- Therefore, in an electric field created between negatively and positively charged plates
  - Alpha particles are deflected towards the **negative** plate
  - Beta particles are deflected towards the **positive** plate
  - Gamma radiation is not deflected and travels straight through between the plates

## Deflection in electric fields



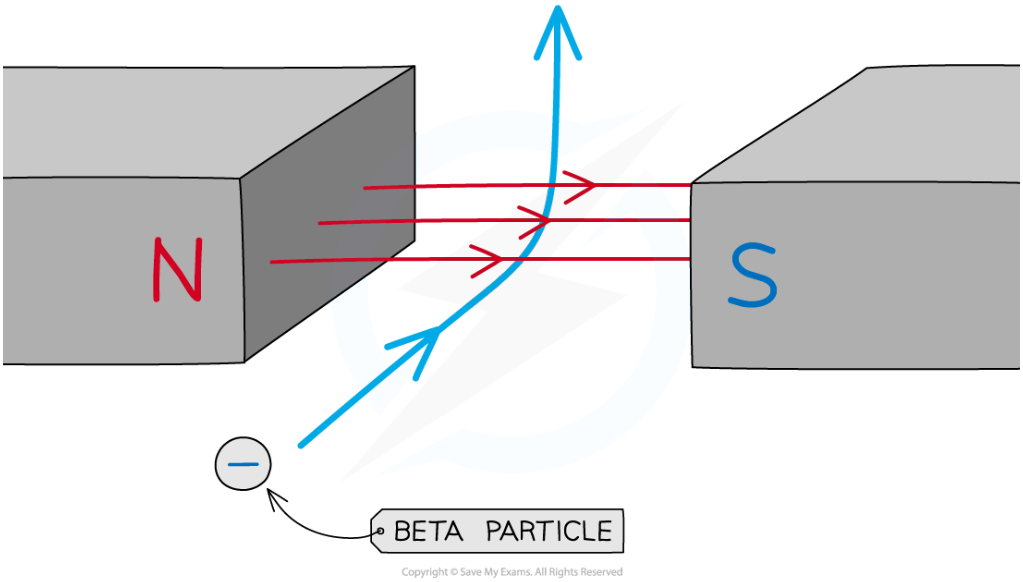

***Alpha and Beta particles can be deflected by electric fields***

- Alpha particles are **heavier** than beta particles
  - Therefore, **beta** particles are deflected **more** in the electric field

# Magnetic fields

- Similarly, alpha and beta particles are deflected by magnetic fields whilst they are moving
- They are deflected in **opposite** directions due to their opposite charges

## Deflection of a beta particle in a magnetic field




*Alpha and beta particles can also be deflected by magnetic fields*

## Examiner Tips and Tricks

It is important to note that because of their opposite charges, alpha and beta particles will deflect in **opposite** directions. You need to know in which direction alpha and beta particles are deflected in an electric field and a magnetic field.

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# Effect of nuclear size on decay

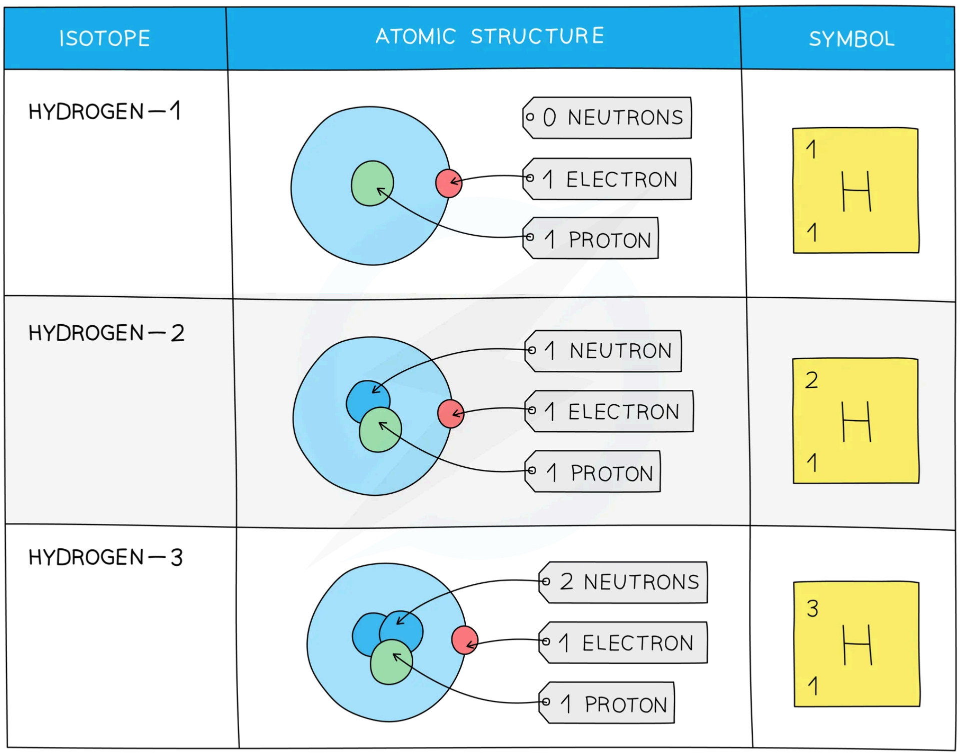
**Extended tier only**

- **Isotopes** of an element may be **radioactive** due to an **excess of neutrons** in the nucleus and/or the nucleus being too **heavy**

## Excess of protons or neutrons

- The most **stable** nuclei have roughly the **same number** of protons as neutrons, especially among light elements
- In **heavier** nuclei, stability requires more **neutrons** than protons because neutrons help reduce the **electrostatic repulsion** between positively charged protons by contributing to the strong nuclear force
- If a **nucleus** has too many or too few **neutrons** relative to **protons**, it becomes unstable and may decay into a more stable nucleus by releasing **radiation**
- An example of this is the isotope of hydrogen-1
  - H-1 is the stable nucleus of hydrogen with 0 neutrons and 1 proton
  - H-2 (deuterium) has one more neutron in the nucleus
  - H-3 (tritium) has 2 neutrons to 1 proton. This is much more unstable than H-1 or H-2

### Hydrogen isotopes

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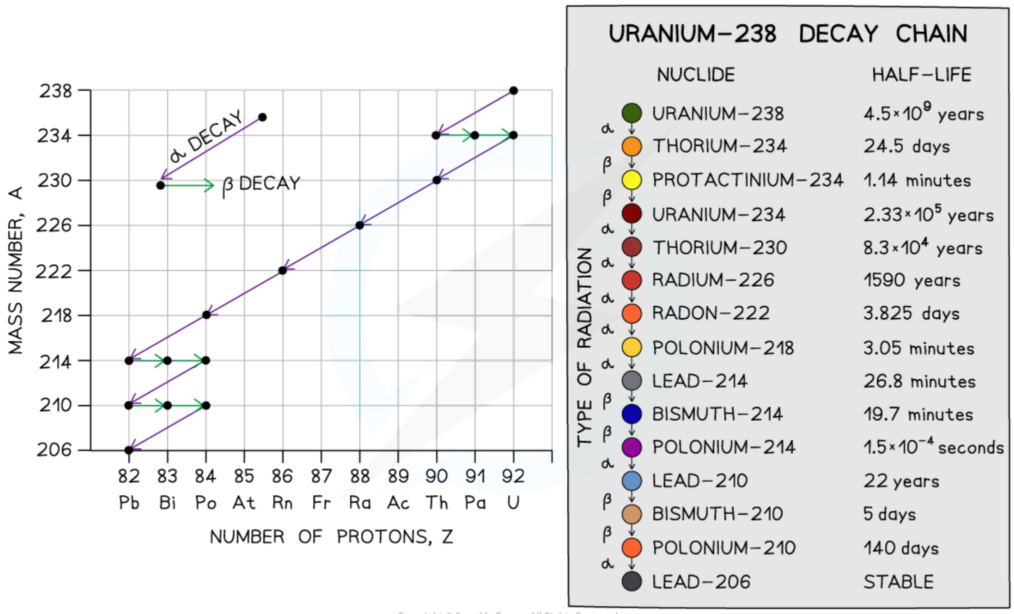
## Heavy nucleus

- If a nucleus is too **heavy**, this means it has too many protons and neutrons
  - The forces keeping the protons and neutrons together in the nucleus will be **weaker**
- An example of this is uranium-238
  - It has a nucleus with 238 protons and neutrons
- During nuclear decay, the **mass number** of the element which it decays into is gradually **reduced**
  - This is done through alpha (α) or beta (β) decay

## Uranium-238 decay chain





*The graph shows the decay chain of uranium-238 through alpha and beta emission*

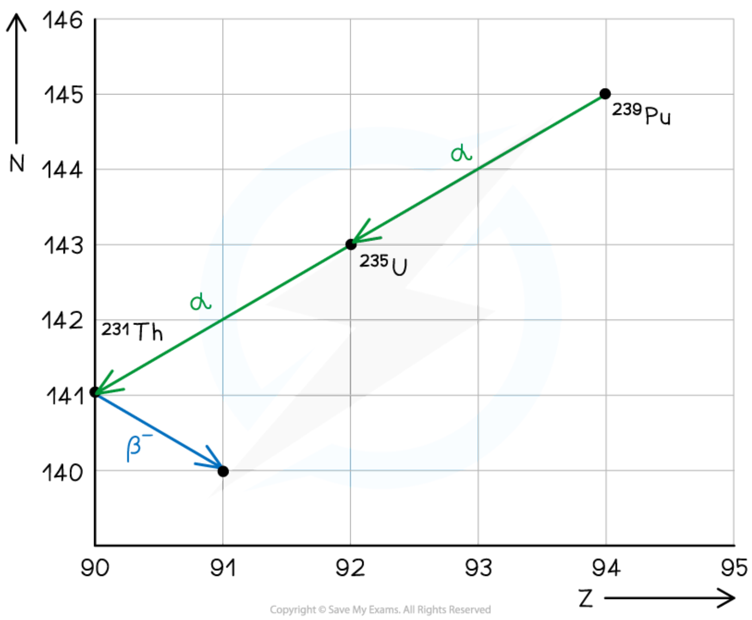
### Examiner Tips and Tricks

The notation of C-12 for example, means the element 'carbon' with the **mass** (or nucleon) number of 12.

# Change to a new element

- A nucleus changes to a **different element**, during α-decay or β-decay
  - The initial nucleus is often called the **parent nucleus**
  - The nucleus of the new element produced is often called the **daughter** nucleus
- The daughter nucleus is a new element because it has a **different** proton and/or nucleon number than the original parent nucleus
- This can be seen on a graph of N (neutron number) against Z (proton number)
  - For example; when Pu-239 decays by alpha to U-235, it loses 2 protons and 2 neutrons
  - U (uranium) is a completely different element from Pu (plutonium)

## Graph of neutron number against proton number




*Graph of N against Z for the decay of Pu-239*

# Reducing neutron number

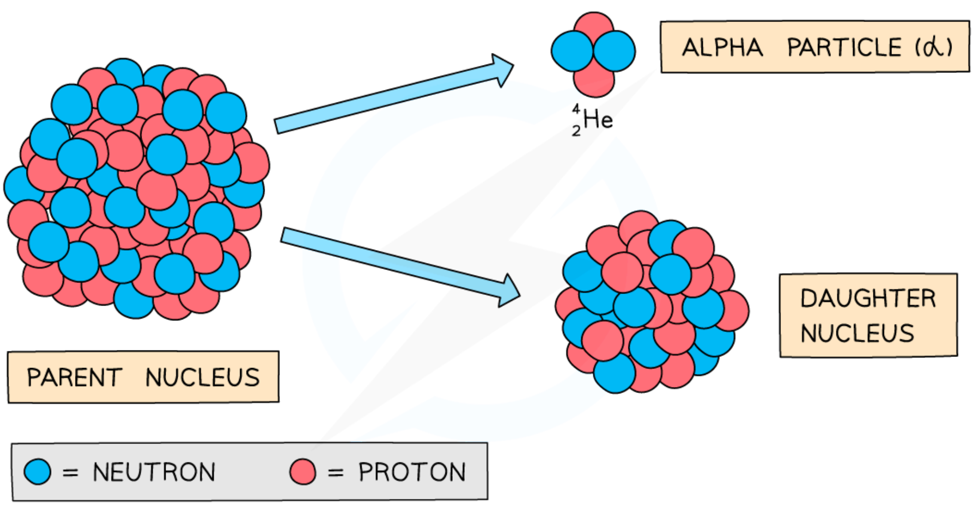
**Extended tier only**

- α and β-decay affect the nucleus by
  - **increasing** its **stability**
  - **reducing** the number of **excess neutrons**

## Alpha decay

- During alpha decay an alpha particle is emitted from an unstable nucleus
- A completely **new element** is formed in the process

### Alpha decay



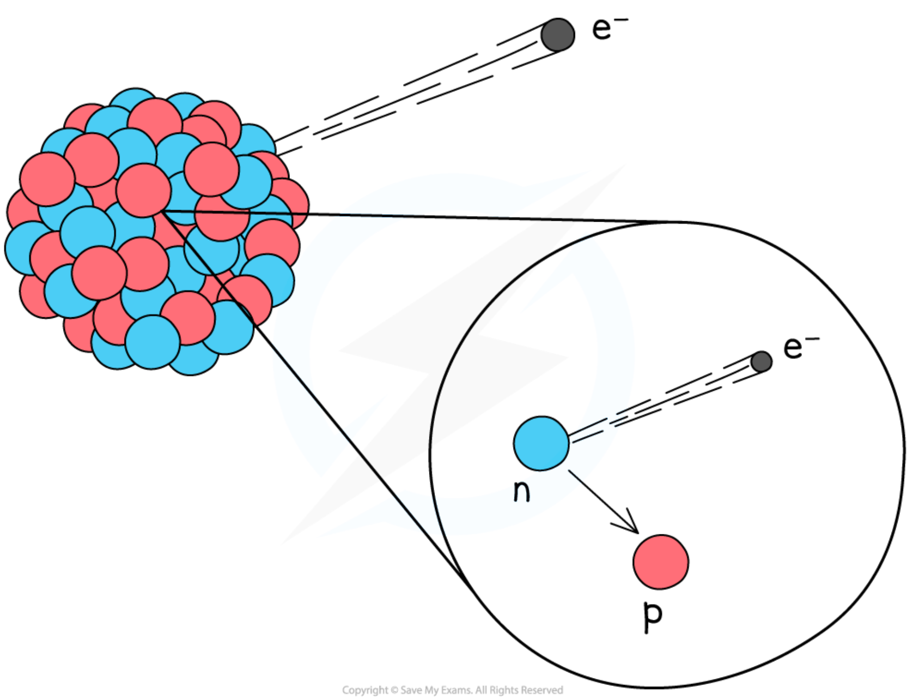

***Alpha decay usually happens in large unstable nuclei, causing the overall mass and charge of the nucleus to decrease***

- An alpha particle is a **helium nucleus**
  - It is made of 2 protons and 2 neutrons
- When the alpha particle is emitted from the unstable nucleus, the mass number and atomic number of the nucleus changes
  - The mass number **decreases** by 4
  - The atomic number **decreases** by 2
- The charge on the nucleus also decreases by 2
  - This is because protons have a charge of +1 each

## Beta decay

- During **beta** decay, a **neutron** changes into a **proton** and an **electron**
  - The electron is **emitted** and the proton **remains** in the nucleus
- A completely new element is formed because the **atomic number** changes

### Beta decay



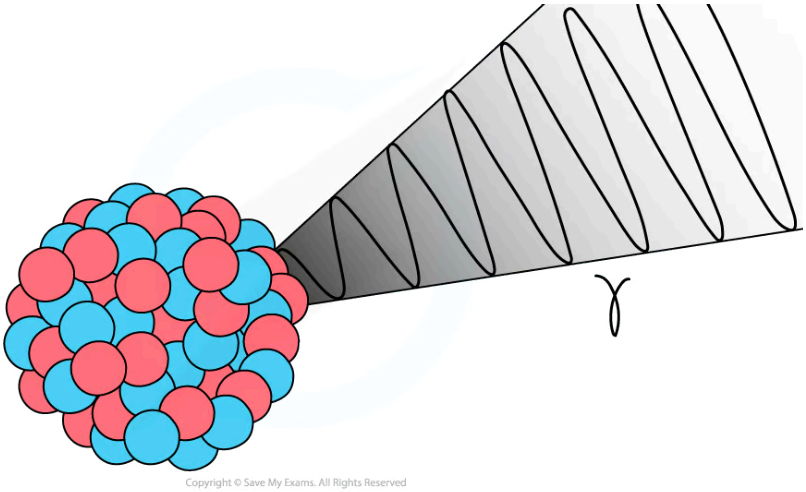

***Beta decay often happens in unstable nuclei that have too many neutrons. The mass number stays the same, but the atomic number increases by one***

- A beta particle is a high-speed **electron**
- It has a mass number of 0
  - This is because the electron has a negligible mass, compared to neutrons and protons
- Therefore, the **mass number** of the decaying nucleus **remains the same**
- Electrons have an atomic number of -1
  - This means that the new nuclei will **increase their atomic number by 1** so atomic number is conserved before and after the decay

# Gamma decay

- During gamma decay, a gamma ray is emitted from an unstable nucleus
  - This process makes the nucleus less energetic but does not change its structure because gamma radiation has no mass or charge

## Gamma decay




***Gamma decay does not affect the mass number or the atomic number of the radioactive nucleus, but it does reduce the energy of the nucleus***

### Examiner Tips and Tricks

There is a second form of beta decay during which a proton changes into a neutron. This is called beta-plus decay - you might come across it while revising, but you don't need to know about it for your exam. Only use the information here for your iGCSE.

It is easy to forget that an alpha particle **is** a helium nucleus, or that a beta particle is an electron. Look out for either wording!

# Decay equations

**Extended tier only**

- Decay equations, use **nuclide notation**, to show the emission of α-particles, β-particles and γ-radiation
- A decay equation is similar to a chemical reaction equation
  - The particles present before the decay are shown **before** the arrow
  - The particles produced in the decay are shown **after** the arrow
- During decay equations, the sum of the mass and atomic numbers **before** the reaction must be the same as the sum of the mass and atomic numbers **after** the reaction

## Alpha decay equation

- All alpha decay equations have the following form for isotopes X and Y:

$$ {}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha $$

Your notes

- The following decay equation shows polonium-212 undergoing alpha decay
  - It forms lead-208 and an alpha particle
  - An alpha particle can also be written as a helium (He) nucleus

$$^{212}_{84}\text{Po} \rightarrow {}^{208}_{82}\text{Pb} + {}^{4}_{2}\alpha$$

## Beta decay equation

- All beta decay equations have the following form for isotopes X and Y:

$$^{A}_{Z}\text{X} \rightarrow {}_{Z+1}^{A}\text{Y} + {}^{0}_{-1}\beta$$

## Gamma decay equation

- All gamma decay equations have the following form for isotope X

$$^{A}_{Z}\text{X} \rightarrow {}^{A}_{Z}\text{X} + {}^{0}_{0}\gamma$$

### Worked Example

A nucleus with 84 protons and 126 neutrons undergoes alpha decay. It forms lead, which has the element symbol Pb.

A $^{206}_{82}\text{Pb}$

B $^{208}_{82}\text{Pb}$

C $^{210}_{84}\text{Pb}$

D $^{214}_{86}\text{Pb}$

Which isotope of lead pictured is the correct one formed during the decay?

**Answer: A**

**Step 1: Calculate the mass number of the original nucleus**

- The mass number is equal to the number of protons plus the number of neutrons
- The original nucleus has 84 protons and 126 neutrons

$$84 + 126 = 210$$

- The mass number of the original nucleus is 210

**Step 2: Calculate the new atomic number**

- The alpha particle emitted is made of two protons and two neutrons
- Protons have an atomic number of 1, and neutrons have an atomic number of 0

Your notes

- Removing two protons and two neutrons will reduce the atomic number by 2

$$84 - 2 = 82$$

- The new nucleus has an atomic number of **82**

**Step 3: Calculate the new mass number**

- Protons and neutrons both have a mass number of 1
- Removing two protons and two neutrons will reduce the mass number by 4

$$210 - 4 = 206$$

- The new nucleus has a mass number of **206**

Your notes

## Worked Example

A nucleus with 11 protons and 13 neutrons undergoes beta decay. It forms magnesium, which has the element symbol Mg.

**A** $^{20}_{9}\text{Mg}$

**B** $^{24}_{10}\text{Mg}$

**C** $^{23}_{11}\text{Mg}$

**D** $^{24}_{12}\text{Mg}$

Which is the correct isotope of magnesium formed during the decay?

**Answer: D**

**Step 1: Calculate the mass number of the original nucleus**

- The mass number is equal to the number of protons plus the number of neutrons
- The original nucleus has 11 protons and 13 neutrons

$$11 + 13 = 24$$

- The mass number of the original nucleus is 24

**Step 2: Calculate the new atomic number**

- During beta decay a neutron changes into a proton and an electron
- The electron is emitted as a beta particle
- The neutron has an atomic number of 0 and the proton has an atomic number of 1
- So the atomic number increases by 1

$$11 + 1 = 12$$

- The new nucleus has an atomic number of 12

**Step 3: Calculate the new mass number**

- Protons and neutrons both have a mass number of 1

- Changing a neutron to a proton will not affect the mass number
- The new nucleus has a mass number of 24 (the same as before)

Your notes

### Examiner Tips and Tricks

You are not expected to know the names of the elements produced during radioactive decays, but you do need to be able to calculate the mass and atomic numbers by making sure they are balanced on either side of the reaction.

Your notes

# Half-life basics

- The **half-life** of a particular **isotope** is defined as:

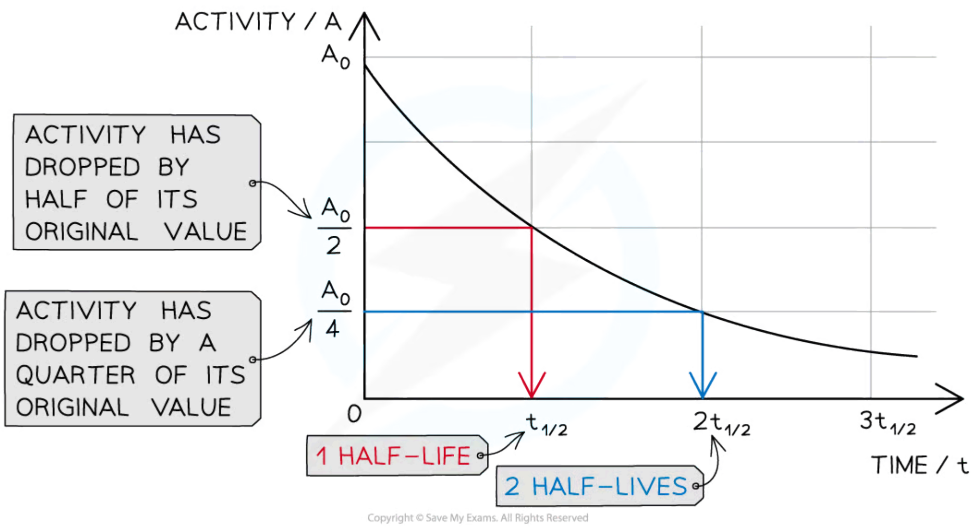
**The time taken for half the nuclei of that isotope in any sample to decay**

- The **rate** at which the activity of a sample decreases is measured in terms of **half-life**
  - This is the time it takes for the activity of a sample to fall to half its original level
- This is the time it takes for the activity of the sample to decrease from 100 % to 50 %
  - It is the same length of time as it would take to decrease from 50 % activity to 25 % activity
- Different isotopes have different half-lives and half-lives can vary from a fraction of a second to billions of years in length
  - The half-life is **constant** for a particular isotope

## Representing half life

- Half-life can be determined from an activity-time graph

### A half-life graph




***The graph shows how the activity of a radioactive sample changes over time. Each time the original activity halves, another half-life has passed***

- Half-life can also be represented on a table
  - As the number of the half-life increases, the proportion of the isotope remaining **halves**

## Table showing the number of half-lives to the proportion of isotope remaining

Your notes

| Number of half-lives | Proportion of isotope remaining |
|---|---|
| 0 | 1 |
| 1 | $\frac{1}{2}$ |
| 2 | $\frac{1}{4}$ |
| 3 | $\frac{1}{8}$ |
| 4 | $\frac{1}{16}$ |
| ... | ... |

### Worked Example

An isotope of protactinium-234 has a half-life of 1.17 minutes.

Calculate the amount of time it takes for a sample to decay from a mass of 10 mg to 2.5 mg.

**Answer:**

**Step 1: Calculate the fraction of the sample remaining**

- Initial mass of sample = 10 mg
- Final mass of sample = 2.5 mg

$$\frac{2.5}{10} = \frac{1}{4}$$

- The fraction of the sample remaining is $\frac{1}{4}$

**Step 2: Calculate the number of half-lives that have passed**

- Using the table above we can see that **two** half-lives have passed

**Step 3: Calculate the time for the sample to decay**

- Two half lives have passed
- So the time for the sample to decay is twice the half-life

$$2 \times 1.17 = 2.34 \text{ minutes}$$

- The time for the sample to decay to a mass of 2.5 mg is **2.34 minutes**

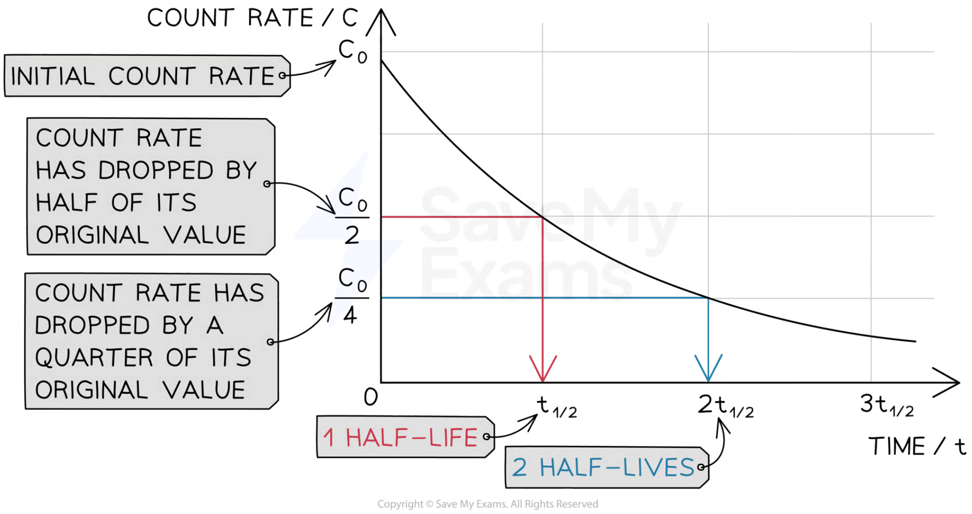
Your notes

# Half-life graphs

**Extended tier only**

- The half-life of an isotope should be calculated by **removing** the **background radiation** from data or decay curves
- To calculate the half-life of a sample from a graph:
  - Check the original activity or count rate (where the line crosses the y-axis), $C_0$
  - Halve this value and look for this activity
  - Go across from the halved value (on the y-axis) to the best-fit curve, and then straight down to the x-axis
  - The point where you reach the x-axis should be the half-life

## Obtaining half-life from a half-life graph

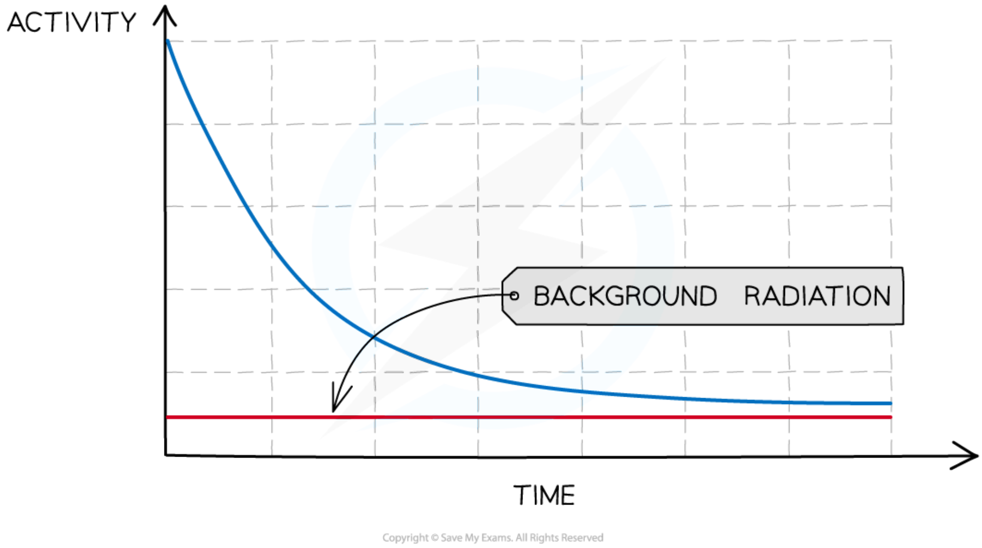



***To find the time for the half-life find half of the activity first***

- To **remove background radiation** from the decay curve:
  - Start by measuring the background radiation (with no sources present) – this is called the **background count**
  - Then carry out the experiment
  - Subtract the background count from each reading, to provide a **corrected count**

- The corrected count is your best estimate of the radiation emitted from the source and should be used to measure its half-life

## A half-life graph that removes background radiation

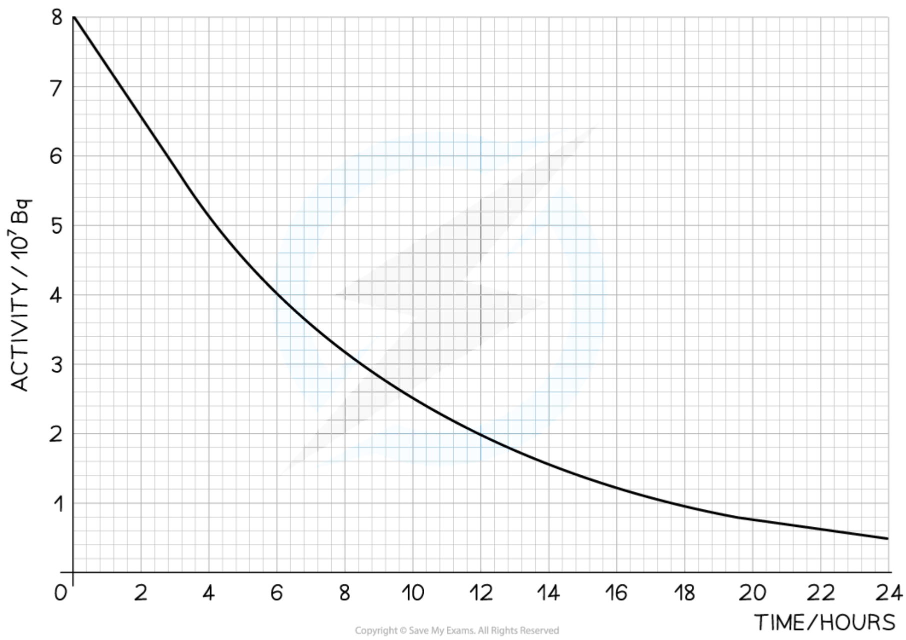



***When measuring radioactive emissions, some of the detected radiation will be background***

### Worked Example

The radioisotope technetium is used extensively in medicine. The graph below shows how the activity of a sample varies with time.

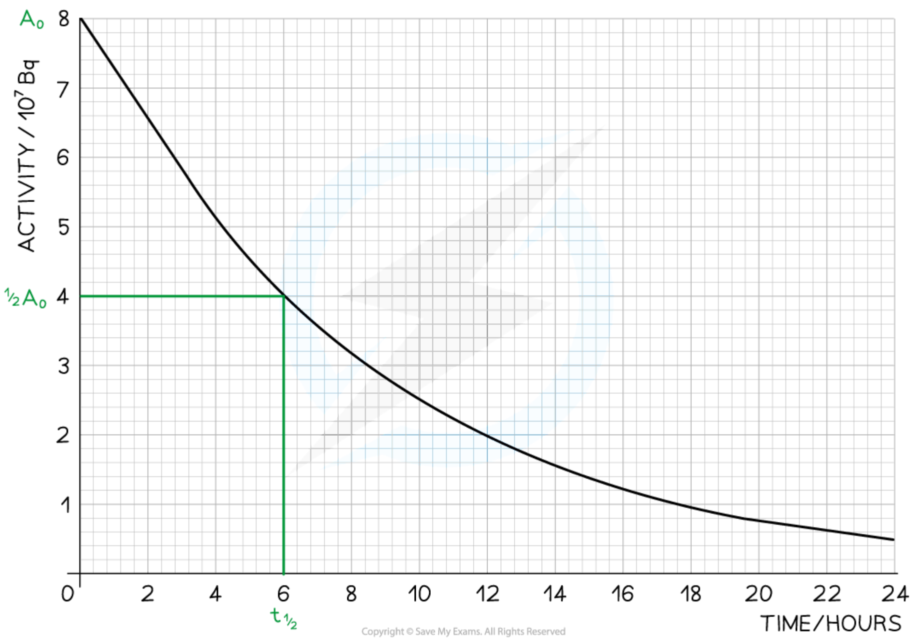
Your notes




Determine the half-life of this material.

**Answer:**

**Step 1: Draw lines on the graph to determine the time it takes for technetium to drop to half of its original activity**




## Worked Example

Your notes

Your notes

A particular radioactive sample contains 2 million un-decayed atoms. After a year, there are only 500 000 atoms left un-decayed. What is the half-life of this material?

**Answer:**

**Step 1: Calculate how many times the number of un-decayed atoms has halved**

- There were 2 000 000 atoms to start with
- **1 000 000** atoms would remain after **1 half-life**
- **500 000** atoms would remain after **2 half-lives**
- Therefore, the sample has undergone 2 half-lives

**Step 2: Divide the time period by the number of half-lives**

- The time period is a year
- The number of half-lives is 2

$$2\ 000\ 000 \xrightarrow[\text{6 months}]{\text{1 half life}} 1\ 000\ 000 \xrightarrow[\text{1 year}]{\text{2 half lives}} 500\ 000$$

- So two half-lives is 1 year, and one half-life is 6 months
- Therefore, the half-life of the sample is **6 months**

## Examiner Tips and Tricks

When looking for the corresponding time for the activity, it is good practice to draw a line on the graph with your ruler, as in the mark scheme of the worked example. This ensures you're reading the most accurate value possible.

# Uses of radiation

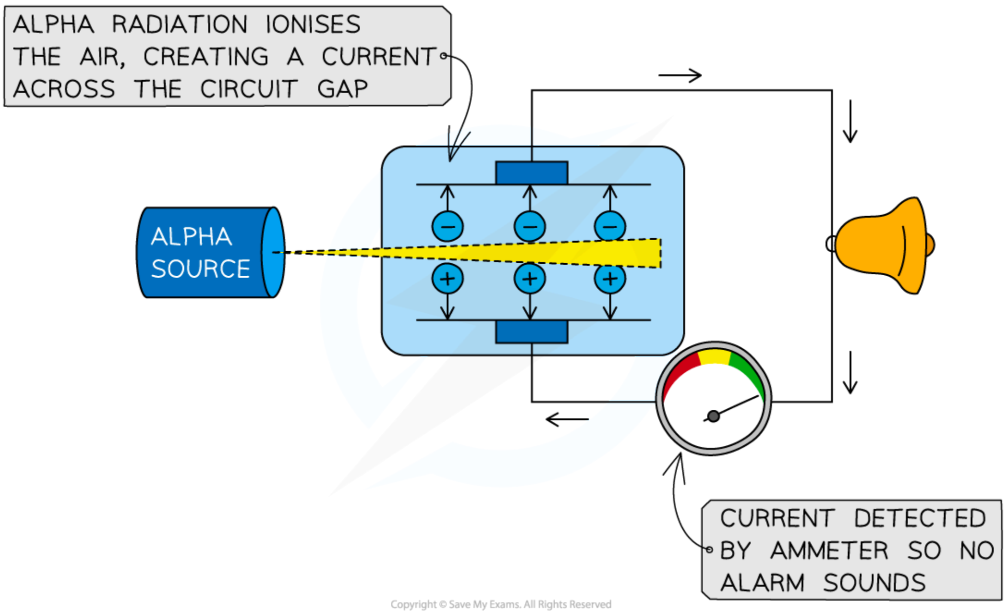
**Extended tier only**

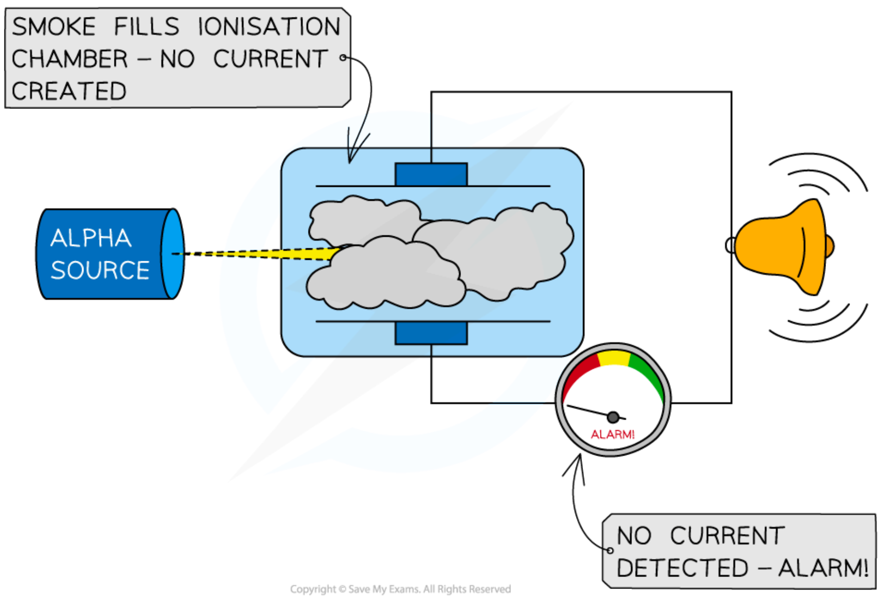
- The **type of radiation** emitted and the **half-life** of an isotope determine which isotope is used for the following applications:
  - household fire (smoke) alarms
  - irradiating food to kill bacteria
  - sterilisation of equipment using gamma rays
  - measuring and controlling thicknesses of materials with the choice of radiations used linked to penetration and absorption
  - diagnosis and treatment of cancer using gamma rays

## Household fire alarms are a use of alpha radiation

- Alpha particles are used in smoke detectors
- The alpha radiation **ionises** the air within the detector, creating a current
- The alpha emitter is blocked when smoke enters the detector
- The alarm is triggered by a microchip when the sensor no longer detects the alpha particles
- An isotope of alpha radiation with a long half-life is used for smoke detectors so they don't need replacing often

### Uses of alpha radiation: household fire alarms






***In the diagram at the bottom, alpha particles are stopped by the smoke, preventing the flow of current and triggering the alarm***

## Sterilisation of equipment using gamma rays

- Gamma radiation is widely used to **sterilise** medical equipment
- Gamma is most suited to this because:
  - It is the most **penetrating** out of all the types of radiation
  - It is penetrating enough to irradiate **all sides** of the instruments
  - Instruments can be sterilised without removing the **packaging**
- The source of gamma radiation used for sterilisation has a half-life of around **5 years**
  - This means the **sterilisation equipment** does not need to be replaced often

## Irradiating food to kill bacteria using gamma rays

- Food can be irradiated to **kill any microorganisms** that are present on it
- This makes the food last longer and reduces the risk of food-borne infections

### Uses of gamma radiation: killing bacteria

Your notes



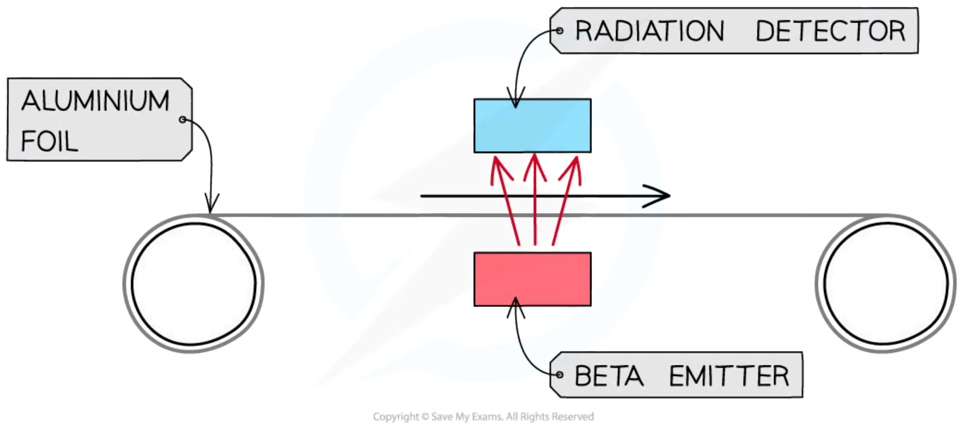
***Food that has been irradiated carries this symbol, called the Radura. Different countries allow different foods to be irradiated***

Your notes

## Measuring the thickness of materials using different radiation

- Beta radiation is most commonly used to measure the thickness of materials because it will be **partially absorbed** by most materials
  - **Alpha** particles are used for thinner materials because they have a lower penetrating power and are absorbed by a thin sheet of aluminium
  - **Gamma** radiation can be used for very thick materials because they have a higher penetrating power and are mostly absorbed by thick pieces of lead.
- A material moves across a **radiation** source
  - The particles that penetrate it are monitored using a detector above
- The thickness of the material is monitored
  - If the material gets **thicker, more** particles will be absorbed by the material, meaning that **less** will get through and be detected by the detector
  - If the material gets **thinner** the **opposite** happens
- The machine makes **adjustments** to keep the thickness of the material **constant**
- Radiation used to measure the thickness of materials has a half-life of **many years** (10–20 years) so that the count rate remains relatively **constant** each day

### Uses of radiation: monitoring material thickness




***Beta particles can be used to measure the thickness of thin materials such as paper, cardboard or aluminium foil***

### Examiner Tips and Tricks

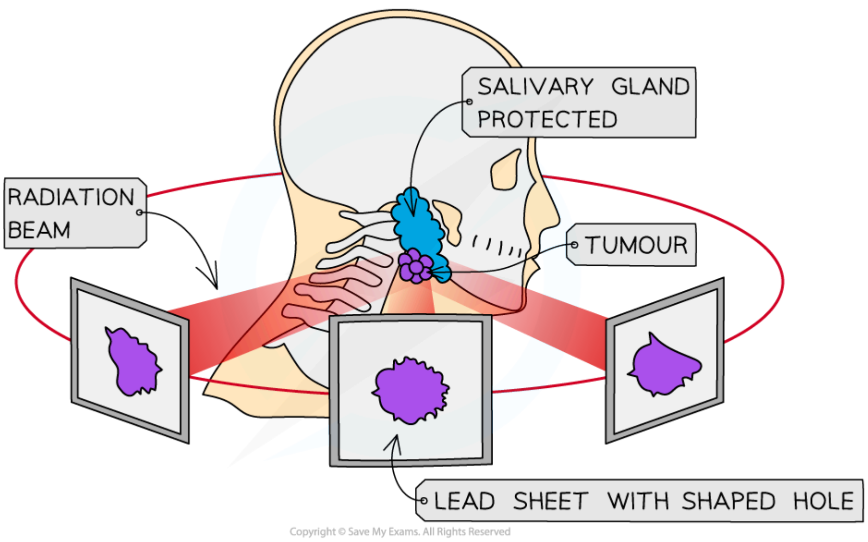
Students often get confused about whether **beta particles** can pass though **aluminium foil**. Beta particles **can be stopped** by aluminium foil if it is thick enough (**a few mm** thick); if the foil is thin enough, they can pass through. This is the basis of using beta radiation to measure the thickness of aluminium foil (a common exam question!). The thicker the foil, the fewer beta particles pass through and are measured by a detector on the other side of the foil.

## Diagnosis and treatment of cancer using gamma rays

- **Radiotherapy** is the name given to the treatment of cancer using radiation
  - Chemotherapy is treatment using chemicals
- Radiation can kill living cells
  - Some cells, such as bacteria and cancer cells, are more susceptible to radiation than others
- Beams of gamma rays are directed at the cancerous tumour
  - Gamma rays are used because they can **penetrate the body**, reaching the tumour
  - The beams are moved around to minimise harm to healthy tissue whilst still being aimed at the tumour
- Gamma radiation used in radiotherapy has a half-life of around **5 years**
  - This means that it does not need to be replaced often within the machine that uses it

### Uses of gamma radiation: treatment of cancer

Your notes



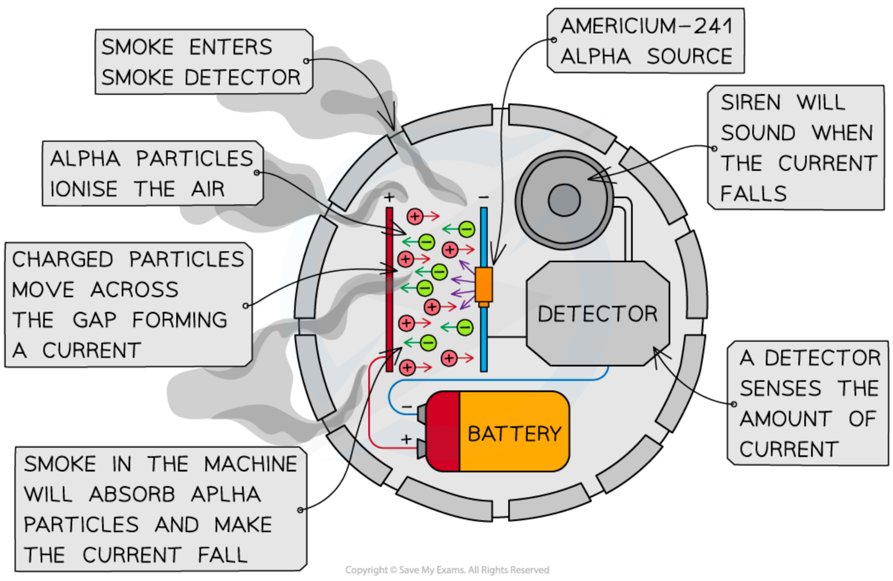

***Radiation therapy to remove a tumour***

- A **tracer** is a radioactive isotope that can be used to track the movement of substances, like blood, around the body
  - A PET scan can detect the emissions from a tracer to diagnose cancer and determine the location of a tumour
- The half-life of a tracer is **several hours**
  - This provides time for a **scan** to be conducted and then the radiation to **leave the body** quickly

## Worked Example

Use the diagram to explain why alpha radiation is used in smoke detectors, and beta or gamma radiation is not.

Your notes




**Answer:**

- Consider the different properties of alpha, beta and gamma:
  - **Alpha** is the most **weakly** penetrating and **strongest** ioniser
  - **Beta** and **gamma** have **stronger** penetrating power and **weaker** ionising power
- If beta or gamma radiation were used in this situation then they would pass straight through the smoke and the alarm would not go off
- Therefore, since alpha is **absorbed** by smoke, and beta and gamma are not, this makes it **most suitable** for use in a smoke detector

## Examiner Tips and Tricks

If you are presented with an unfamiliar situation in your exam don't panic! Just apply your understanding of the properties of alpha, beta and gamma radiation. Mainly think about the range (how far it can travel) and ionising power of the radiation to help understand which radiation is used in which situation.

Your notes

Your notes

# Dangers of radioactivity

- Ionising nuclear radiation can **damage living things** such as human cells and tissues at high doses:
- This can include:
  - Cell death
  - Mutations
  - Cancer
- If the atoms that make up a DNA strand are **ionised,** then the DNA strand can be **damaged**
- If the DNA is damaged, then the cell may die, or the DNA may be **mutated** when it is replicated
- If a mutated cell replicates itself then a **tumour** may develop
  - This is an example of **cancer**, which is a significant danger of radiation exposure

## Ionising DNA is a danger of radioactivity

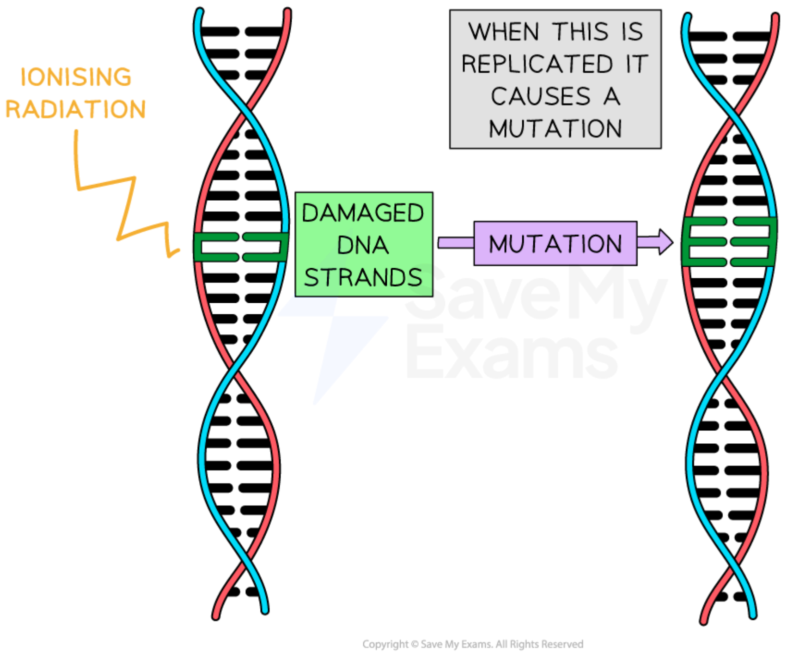



***Diagram showing the damage caused to DNA by ionising radiation. Sometimes the cell is able to repair the DNA during replication successfully, but incorrect repairs can cause a mutation***

- Acute radiation exposure can have other serious symptoms:
  - It can cause skin **burns**, similar to severe sunburn
  - Radiation can **reduce** the amount of **white blood cells** in the body, making a person more susceptible to infections by lowering their immune system
- Because of this, it is very important to handle radioactive sources carefully

# Safe storage

- Radioactive materials are moved, used and stored in a safe way

## Safe handling to minimise the dangers of radioactivity

- The risks associated with handling radioactive sources can be minimised by following a few simple procedures:
  - Store the sources in **lead-lined boxes** and keep them at a distance from people
  - **Minimise** the amount of **time** you handle sources and return them to their boxes as soon as you have finished using them
  - During use, keep yourself (and others) as **far** from the sources as possible.
  - When handling the sources do so at **arm's length**, using a pair of tongs

### A sign indicating the dangers of radioactivity


Your notes

*Radioactivity warning sign*

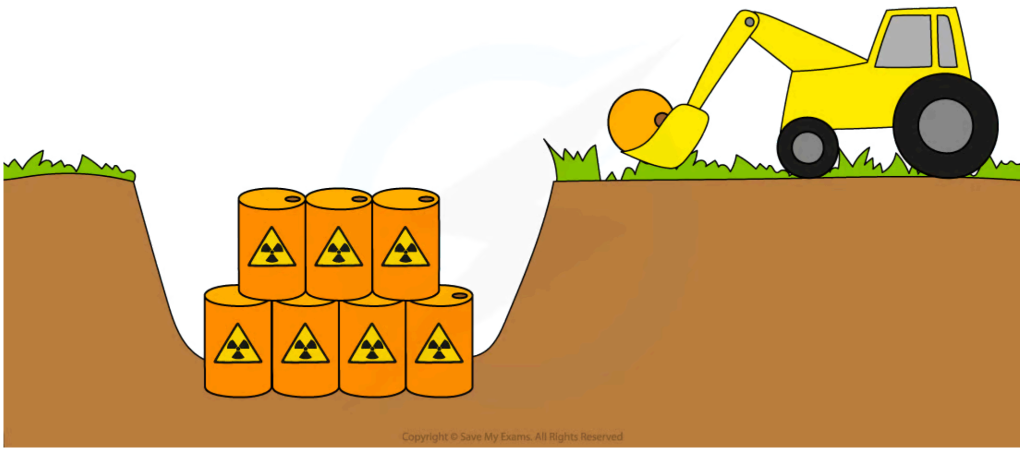
## Safe transportation to minimise the dangers of radioactivity

- Radioactive materials such as used nuclear fuel are transported in special containers called casks
- These casks can withstand extreme conditions such as fire, cold and being submerged in water

## Disposing of radioactive waste to minimise the dangers of radioactivity

- If an isotope has a long half-life then a sample of it will decay slowly
  - Although it may not emit a lot of radiation, it will **remain radioactive for a very long time**
- Sources with long half-life values present a risk of **contamination** for a much longer time
- Radioactive waste with a long half-life is **buried** underground to prevent it from being released into the environment

### Correct disposal of radioactive waste reduces the dangers of radioactivity




*Radioactive waste with long half-lives is buried deep underground*

#### Worked Example

A student plans to use a gamma source to conduct an experiment. List four things that the student should do in order to minimise the risk to themselves when using the source.

Your notes

**Answer:**

**Any four from:**

- Keep the source in a lead-lined container until the time it is needed
- Use tongs to move the source, rather than handling it directly
- The source should be kept at as far a distance from the student as possible during the experiment
- The time that the source is being used should be minimised
- After the experiment, the student should wash their hands
- The date and the time that the radiation has been used should be recorded

# Safety precautions

**Extended tier only**

- Safety precautions for all ionising radiation include:
  - reducing **exposure time**
  - increasing the **distance** between the source and living tissue
  - using **shielding** to absorb radiation

## Reducing exposure time reduces the dangers of radioactivity

- Limiting the amount of time spent near a radioactive source reduces the amount of radiation dose received
- The amount of radiation received by a person is called the dose and is measured in **sieverts** (Sv)
- One sievert is a very big dose of radiation
  - It would cause acute **radiation poisoning**

## Increasing the distance reduces the dangers of radioactivity

- **Increasing** the **distance** the radiation is away greatly **reduces** the size of the **dose** received
  - Using tongs instead of your hand when handling a radioactive source can help with this
- Constructing nuclear power plants in **remote areas** increases their distance from people if there is a problem
- Burying nuclear waste far from places where people live also increases **the distance** to people

## Shielding reduces the dangers of radioactivity

- Radiation shielding is a **barrier** placed between a radiation source and a person or area to protect them
    - The purpose of shielding is to **limit exposure** to radiation at a certain location or time
- Barriers **absorb the energy** from radioactive sources
- Barriers are normally made of lead, water or concrete
    - People handling radioactive sources should wear a **lead apron** to reduce their exposure
- When X-rays are taken:
    - the area around where the image is needed is shielded
    - the radiologist stands behind a barrier or leaves the room

## Reducing the dangers of radiation for a radiologist

***A radiologist can stand behind a lead barrier to reduce the amount of radiation they are exposed to***

Your notes