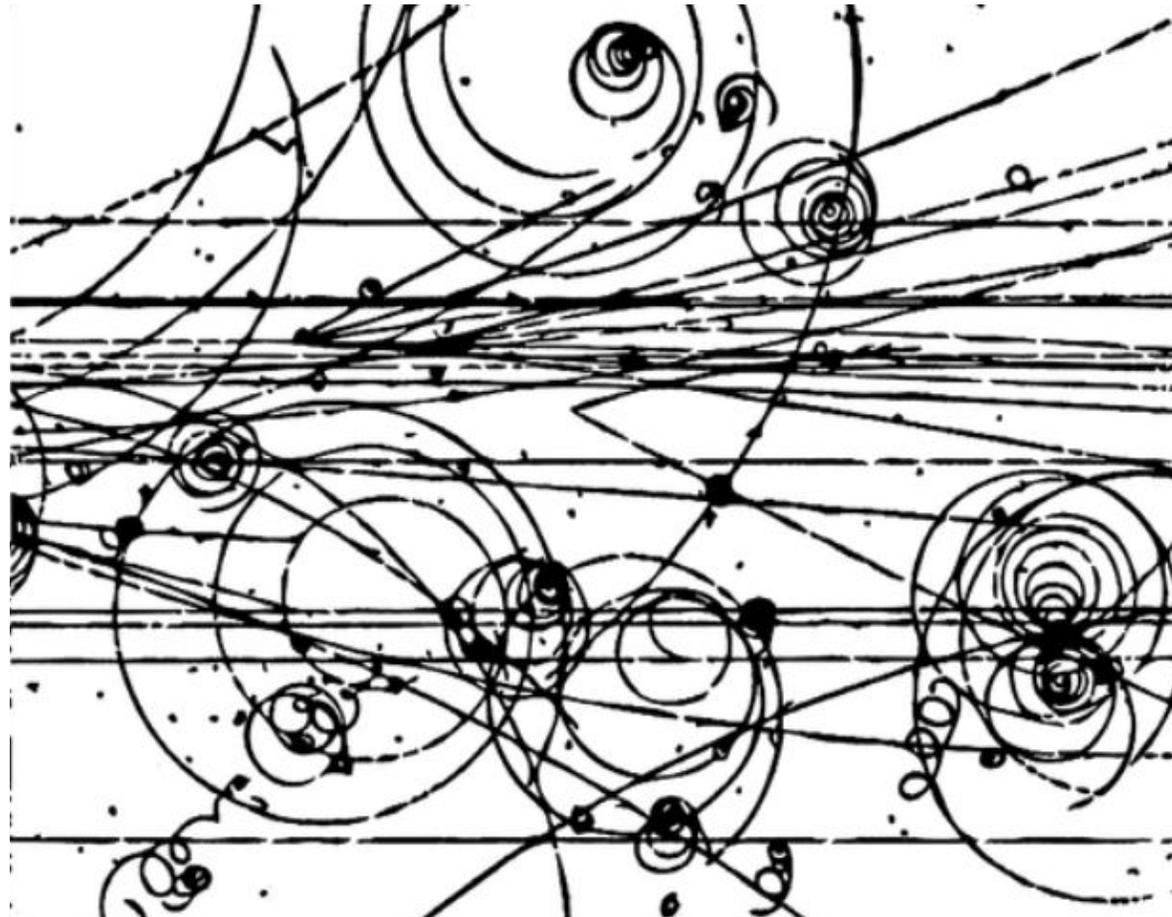# Particles, Nuclear Physics & Radioactivity

Material Covered

Particle Physics
1. The Nucleus.
2. Types of Particles.

Radioactive Decay
1. Nuclear Radiation.
2. Radioactivity.

Nuclear Physics
1. Mass-Energy Equivalence.
2. Fusion and Fission.

Particle Physics

Specification Points - AQA

3.8.1.1 Rutherford scattering (A-level only)

Content

Qualitative study of Rutherford scattering.

3.2.1.3 Particles, antiparticles and photons

Content

For every type of particle, there is a corresponding antiparticle.

Comparison of particle and antiparticle masses, charge and rest energy in MeV.

Students should know that the positron, antiproton, antineutron and antineutrino are the antiparticles of the electron, proton, neutron and neutrino respectively.

3.2.1.5 Classification of particles

Content

Hadrons are subject to the strong interaction.

The two classes of hadrons:

- baryons (proton, neutron) and antibaryons (antiproton and antineutron)
- mesons (pion, kaon).

Baryon number as a quantum number.

Conservation of baryon number.

3.2.1.6 Quarks and antiquarks

Content

Properties of quarks and antiquarks: charge, baryon number and strangeness.

Combinations of quarks and antiquarks required for baryons (proton and neutron only), antibaryons (antiproton and antineutron only) and mesons (pion and kaon only).

Only knowledge of up (u), down (d) and strange (s) quarks and their antiquarks will be tested.

Specification Points – OCR A

6.4.1 The nuclear atom

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) alpha-particle scattering experiment; evidence of a small charged nucleus

(b) simple nuclear model of the atom; protons, neutrons and electrons

(c) relative sizes of atom and nucleus

(d) proton number; nucleon number; isotopes; notation $^{A}_{Z}X$ for the representation of nuclei

6.4.2 Fundamental particles

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) particles and antiparticles; electron–positron, proton-antiproton, neutron-antineutron and neutrino-antineutrino

(b) particle and its corresponding antiparticle have same mass; electron and positron have opposite charge; proton and antiproton have opposite charge

(c) classification of hadrons; proton and neutron as examples of hadrons; all hadrons are subject to both the strong nuclear force and the weak nuclear force

(d) classification of leptons; electron and neutrino as examples of leptons; all leptons are subject to the weak nuclear force but not the strong nuclear force

(e) simple quark model of hadrons in terms of up (u), down (d) and strange (s) quarks and their respective anti-quarks

(f) quark model of the proton (uud) and the neutron (udd)

(g) charges of the up (u), down (d), strange (s), anti-up ($\bar{u}$), anti-down ($\bar{d}$) and the anti-strange ($\bar{s}$) quarks as fractions of the elementary charge e

Specification Points – OCR B

6.2.1 Probing deep into matter

Learning outcomes

(a) *Describe and explain:*

(i) use of particle accelerators to generate high-energy beams of particles for scattering

(ii) evidence from scattering for a small massive nucleus within the atom

(iii) evidence of discrete energy levels in atoms

(iv) a simple model of the atom as the quantum behaviour of electrons in a confined space

(v) simple picture of the quark structure of protons and neutrons

(vi) application of conservation of mass/energy, charge and lepton number in balanced nuclear equations

(vii) relativistic calculations for particles travelling at very high speed, for example in particle accelerators or cosmic rays.

(b) *Make appropriate use of:*

(i) the terms: energy level, scattering, nucleus, proton, neutron, nucleon, electron, positron, quark, gluon, neutrino, hadron, lepton, antiparticle, lepton number

by sketching and interpreting:

(ii) paths of scattered particles

(iii) electron standing waves in simple models of an atom.

Specification Points - Edexcel

130. understand what is meant by *nucleon number (mass number)* and *proton number (atomic number)*

131. understand how large-angle alpha particle scattering gives evidence for a nuclear model of the atom and how our understanding of atomic structure has changed over time

140. know that in the standard quark-lepton model particles can be classified as:

  - baryons (e.g. neutrons and protons) which are made from three quarks

  - mesons (e.g. pions) which are made from a quark and an antiquark

  - leptons (e.g. electrons and neutrinos) which are fundamental particles

  - photons

  and that the symmetry of the model predicted the top quark

141. know that every particle has a corresponding antiparticle and be able to use the properties of a particle to deduce the properties of its antiparticle and vice versa

142. understand how to use laws of conservation of charge, baryon number and lepton number to determine whether a particle interaction is possible

143. be able to write and interpret particle equations given the relevant particle symbols.

The Nucleus

The **Nuclear Model** of the **atom** we are familiar with arises from **observations** made during **Ernst Rutherford's** historic **alpha-particle experiment**.

Experimental Setup:

- **Scintillating zinc sulphide** screen **detector**.

- **Gold foil** which is a **few atoms** thick.

- **α-particle source** inside **lead box**.
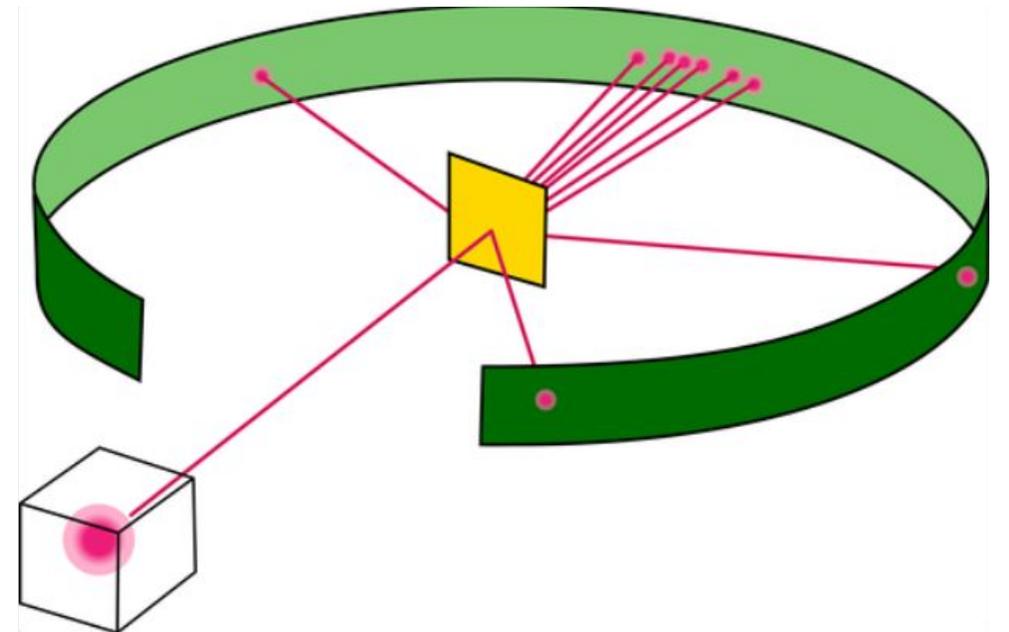
The following **observations** and **conclusions** were made from the **experiment**:

- Most **α-particles** passed straight through the **gold foil** without being **deflected**.

  ⇒ **Most** of the **atom** is **empty space** with its **mass concentrated** at its **centre**.

- Some **α-particles** (**1** in **10, 000**) were **deflected** by **angles** more than **90°**.

  ⇒ This **centre** (the **nucleus**) is **positively charged**.
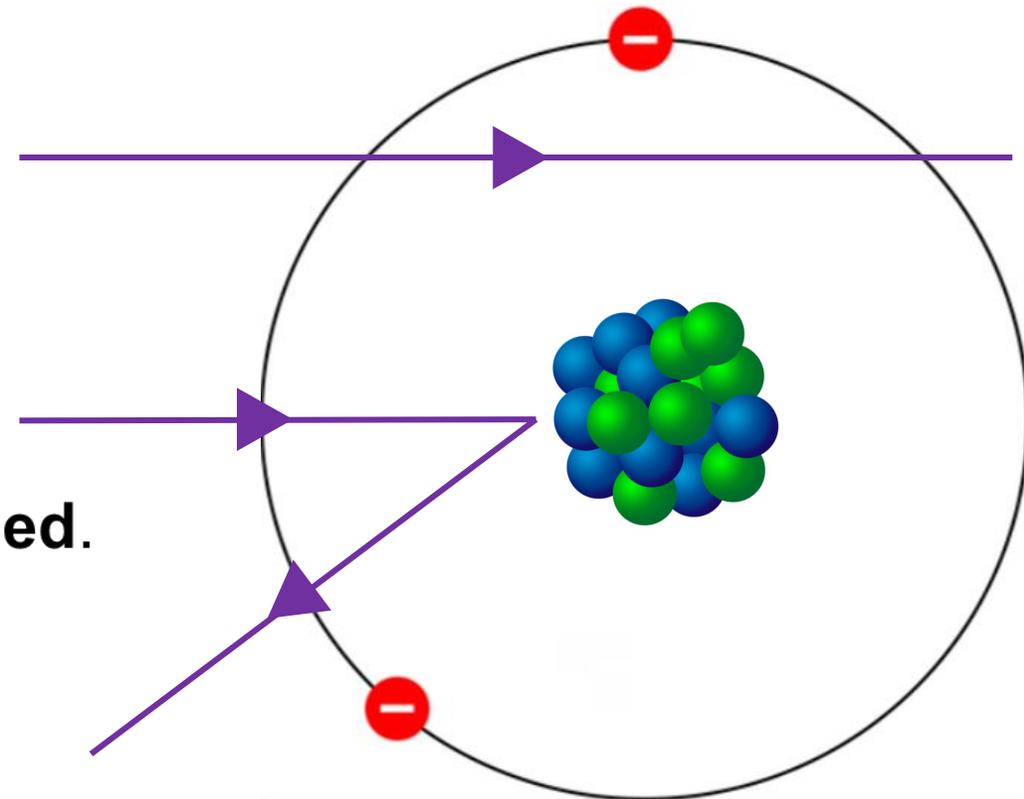
The **nucleus** is usually made of **2 types** of **nucleons** – **protons** and **neutrons**.

- **Protons** are **positively charged** with **mass** $\approx 1u$

Nuclei with **different numbers** of **protons** (Z) are **different elements**.

- **Neutrons** are **uncharged** with **mass** $\approx 1u$

Nuclei with **different numbers** of **neutrons** (N) but the **same number** of **protons** are **different isotopes** of the **same element**.

$$^{A}_{Z}X$$

How would this **affect** an **alpha particle?**

Exemplar Explanation Exam Question

**Context: Model of the atom** and **Rutherford Scattering.**

1) In 1904, J.J.Thompson proposed the "Plum Pudding" model as a way of explaining the structure of the atom. It stated that electrons occupied a region, or "soup", of positive charge, as shown in the diagram. This was the generally accepted model for the atom before Rutherford's alpha-particle experiment.
Describe, with reasons, the results that Rutherford would have expected from his experiment, and explain how his actual results showed that the Plum Pudding model was incorrect.

[4 marks]

2 part question, give **detailed reasoning** for both.

4 mark question, about **4 key points** to make.

Thompson's Plum Pudding Model
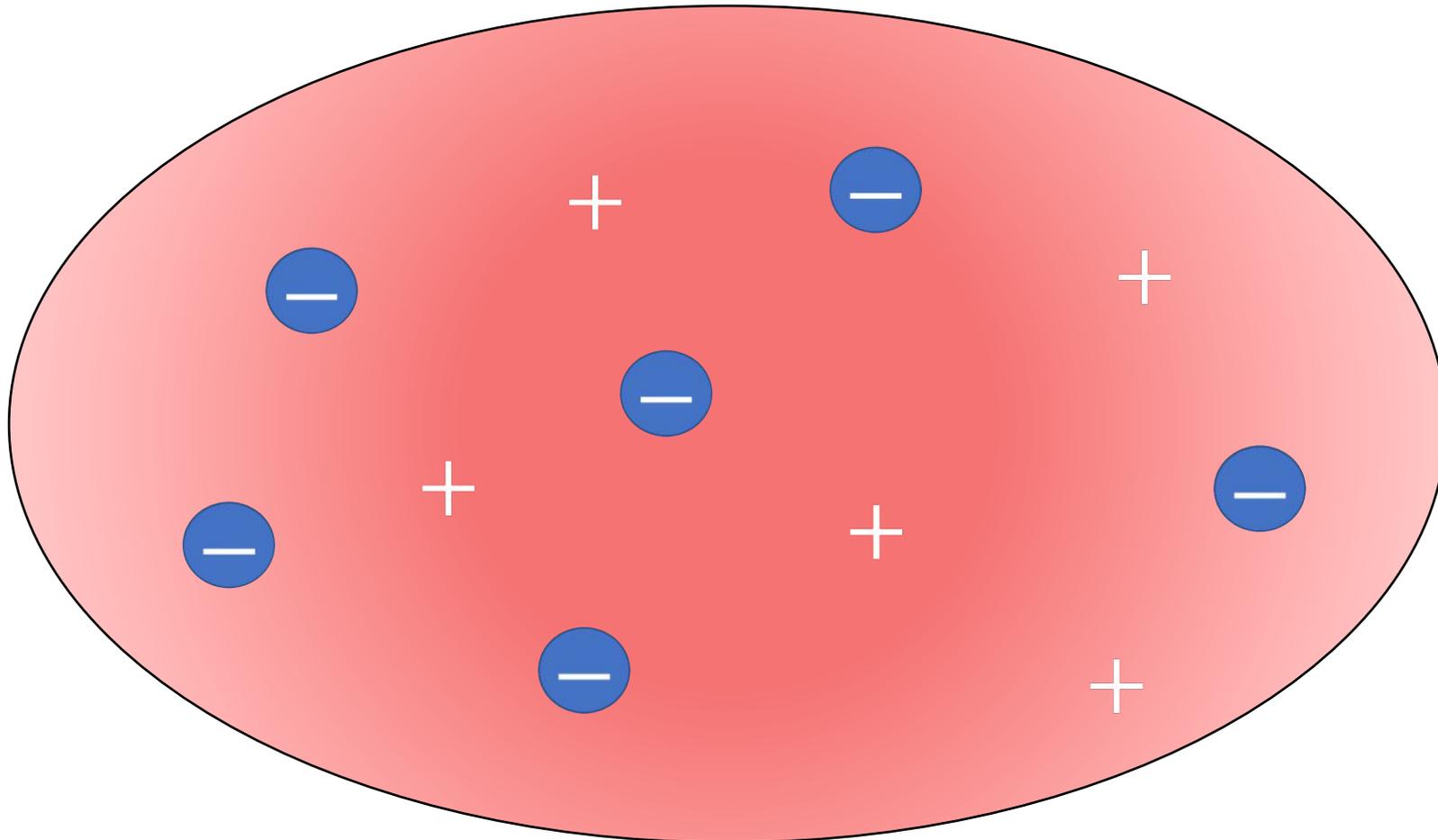
EXPECTED RESULTS

- Most particles would shoot through the foil with only a minimal amount of deflection.

[1 Mark]

- This is because the foil is thin, and so the positive charge and mass wouldn't be concentrated enough to affect the alpha particles.

[1 Mark]

HOW THOMPSON'S MODEL IS INCORRECT

- Found almost all atoms passed through unaffected, with a minority being completely deflected.

- This means almost of the particle's mass is concentrated at a small point in the atom, most of the atom is actually empty space.

[1 Mark]

- Also means this small point contains all of the atom's charge, it is not even spread across the atom.

[1 Mark]

Types of Particles

There are **3 types** of **fundamental particles** in the **Standard Model**:

- **Quarks** – There are **6 types** of **quarks**. **Up quarks** and **down quarks** make up **nucleons**.

- **Leptons** – These include **electrons** and **neutrinos**.

- **Bosons** – These include **photons** and **gluons**.

Up u	Charm c	Top t	Gluon g
Down d	Strange s	Bottom b	Photon γ
Electron e	Muon μ	Tau τ	Z boson Z^0
e neutrino ν_e	μ neutrino ν_μ	τ neutrino ν_τ	W boson $W^\pm$

Hadrons are **particles** which contain **quarks**.
**Hadrons** feel the **strong nuclear force**.

Quarks can **never** be **found** on **their own** but in **groups** with other **quarks**.

- **Mesons** are **particles** formed of a **pair** of a **quark** and an **antiquark**.

- **Baryons** are **particles** formed of **3 quarks**.

Quark	$Q\ (e)$	Antiquark	$Q\ (e)$
u	$+\frac{2}{3}$	$\bar{u}$	$-\frac{2}{3}$
d	$-\frac{1}{3}$	$\bar{d}$	$+\frac{1}{3}$
c	$+\frac{2}{3}$	$\bar{c}$	$-\frac{2}{3}$
s	$-\frac{1}{3}$	$\bar{s}$	$+\frac{1}{3}$
t	$+\frac{2}{3}$	$\bar{t}$	$-\frac{2}{3}$
b	$-\frac{1}{3}$	$\bar{b}$	$+\frac{1}{3}$

Every **quark** and **lepton** in the **Standard Model** has a **corresponding antiparticle**.

- **Antiparticles** have the **same mass** but **equal** and **opposite charge** to their **corresponding particle**.

- When **antiparticles** meet their **corresponding particles** they **annihilate** into **photons**.
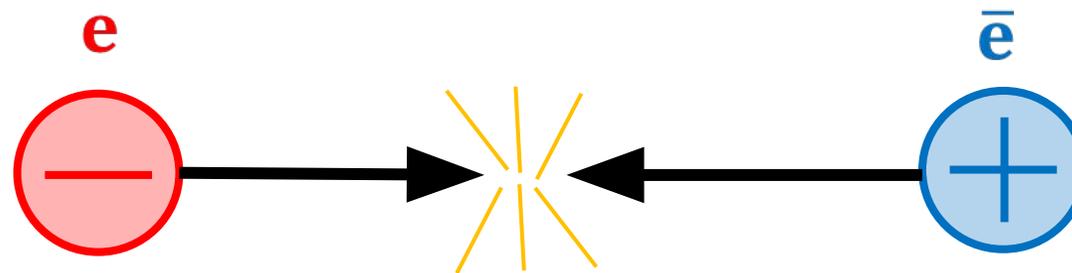
- **Antiparticles** are indicated by their **corresponding particle's symbol overlined**.

Exemplar Statement Exam Question

Context: Quark and **antiquark** combinations.

Write question: Little to **no working** required.

1) For each of the following quark combinations, write the charge of the respective particle, and if it is a baryon, anti-baryon or meson.

(i) $\bar{u}d$
(ii) uus
(iii) $\bar{s}\bar{b}\bar{b}$

Recall the **definitions** of these **particles**.

[3 marks]

Use table of **quark properties**.

3 mark question, 3 quick parts.

Exemplar Statement Question Answer

(i) Identify type of particle

$$\bar{u}d$$

Quark-antiquark pair, so particle is a meson.

Determine charge of particle

Charge for $\bar{u}$ is $-\frac{2}{3}e$

Charge for d is $-\frac{1}{3}e$

So charge of $\bar{u}d$ is $-e$

[1 Mark]

Exemplar Statement Question Answer

(ii) Identify type of particle

uus

3 quarks, so particle is a baryon.

Determine charge of particle

Charge for **u** is $\frac{2}{3}e$

Charge for **s** is $-\frac{1}{3}e$

So charge of **uus** is e

[1 Mark]

Exemplar Statement Question Answer

(iii) Identify type of particle

$\bar{s}\bar{b}\bar{b}$

3 antiquarks, so particle is an anti-baryon.
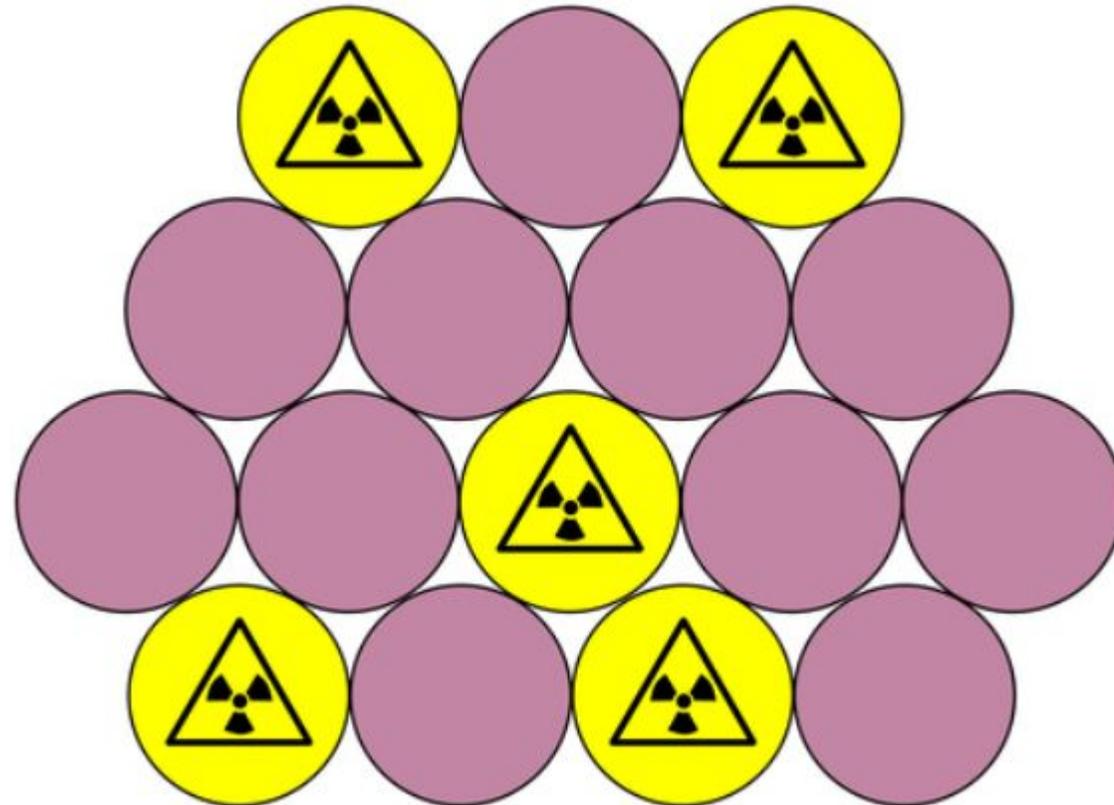
Determine charge of particle

Charge for $\bar{s}$ is $\frac{1}{3}e$

Charge for $\bar{b}$ is $\frac{1}{3}e$

So charge of $\bar{s}\bar{b}\bar{b}$ is e

[1 Mark]

Radioactive Decay

Specification Points - AQA

3.2.1.2 Stable and unstable nuclei

Content

The strong nuclear force; its role in keeping the nucleus stable; short-range attraction up to approximately 3 fm, very-short range repulsion closer than approximately 0.5 fm.

Unstable nuclei; alpha and beta decay.

Equations for alpha decay, β⁻ decay including the need for the neutrino.

The existence of the neutrino was hypothesised to account for conservation of energy in beta decay.

3.2.1.7 Applications of conservation laws

Content

Change of quark character in β⁻ and in β⁺ decay.

Application of the conservation laws for charge, baryon number, lepton number and strangeness to particle interactions. The necessary data will be provided in questions for particles outside those specified.

Students should recognise that energy and momentum are conserved in interactions.

3.8.1.3 Radioactive decay (A–level only)

Content

Random nature of radioactive decay; constant decay probability of a given nucleus;

$$\frac{\Delta N}{\Delta t} = -\lambda N$$

$$N = N_0 e^{-\lambda t}$$

Use of activity, $A = \lambda N$

Modelling with constant decay probability.

Questions may be set which require students to use

$$A = A_0 e^{-\lambda t}$$

Questions may also involve use of molar mass or the Avogadro constant.

Half-life equation: $T_{\frac{1}{2}} = \frac{\ln 2}{\lambda}$

Determination of half-life from graphical decay data including decay curves and log graphs.

Applications eg relevance to storage of radioactive waste, radioactive dating etc.

Specification Points – OCR A

6.4.3 Radioactivity

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) radioactive decay; spontaneous and random nature of decay

(b) (i) α-particles, β-particles and γ-rays; nature, penetration and range of these radiations

    (ii) techniques and procedures used to investigate the absorption of α-particles, β-particles and γ-rays by appropriate materials

(c) nuclear decay equations for alpha, beta-minus and beta-plus decays; balancing nuclear transformation equations

(e) (i) half-life of an isotope; $\lambda t_{1/2} = \ln(2)$

    (ii) techniques and procedures used to determine the half-life of an isotope such as protactinium

(f) (i) the equations $A = A_0 e^{-\lambda t}$ and $N = N_0 e^{-\lambda t}$, where A is the activity and N is the number of undecayed nuclei

    (ii) simulation of radioactive decay using dice

(g) graphical methods and spreadsheet modelling of the equation $\dfrac{\Delta N}{\Delta t} = -\lambda N$ for radioactive decay

(h) radioactive dating, e.g. carbon-dating.

(e) simple quark model of hadrons in terms of up (u), down (d) and strange (s) quarks and their respective anti-quarks

(f) quark model of the proton (uud) and the neutron (udd)

(g) charges of the up (u), down (d), strange (s), anti-up ($\overline{u}$), anti-down ($\overline{d}$) and the anti-strange ($\overline{s}$) quarks as fractions of the elementary charge e

(h) beta-minus (β^-) decay; beta-plus (β^+) decay

(i) β^- decay in terms of a quark model; $d \rightarrow u + {}_{-1}^{0}e + \overline{\nu}$

(j) β^+ decay in terms of a quark model; $u \rightarrow d + {}_{+1}^{0}e + \nu$

(k) balancing of quark transformation equations in terms of charge

(l) decay of particles in terms of the quark model.

Specification Points – OCR B

6.2.2 Ionising radiation and risk

Learning outcomes

(a) *Describe and explain:*

   (i) the nature and effects of ionising radiations: differences in ionising and penetrating power, effects on living tissue

(b) *Make appropriate use of:*

   (i) the terms: nucleon number, proton number, isotope, binding energy, atomic mass unit, absorbed and effective dose, risk

(c) *Make calculations and estimates involving:*

   (i) activity of a sample of radioactive material (related to half-life or decay constant)

(d) *Demonstrate and apply knowledge and understanding of the following practical activities (HSW4):*

   (i) studying the absorption of α-particles, β-particles and γ-rays by appropriate materials

   (ii) determining the half-life of an isotope such as protactinium.

Specification Points - Edexcel

169. understand the relationships between the nature, penetration, ionising ability and range in different materials of nuclear radiations (alpha, beta and gamma)

170. be able to write and interpret nuclear equations given the relevant particle symbols

172. understand the spontaneous and random nature of nuclear decay

173. be able to determine the half-lives of radioactive isotopes graphically and be able to use the equations for radioactive decay:

activity $A = \lambda N$, $\dfrac{dN}{dt} = -\lambda N$, $\lambda = \dfrac{\ln 2}{t_{\frac{1}{2}}}$, $N = N_0\, e^{-\lambda t}$ and $A = A_0\, e^{-\lambda t}$ and

derive and use the corresponding log equations.

Nuclear Radiation

Nuclear radiation can occur in **several types**. In each case, a different **type of particle** is **emitted** which has **different properties**.

- **Alpha (α) decay:**   **α particles** are made of **2 protons** and **2 neutrons** (equivalent to a $_{2}^{4}\text{He}$ **nucleus**).

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

Decay equations must be **balanced**, with A, Z and **charge** being **conserved**.

- **Gamma (γ) decay:**   **γ particles** are **high energy gamma-ray photons**.

  γ decay occurs after α or β **decay** to remove **energy** from an **excited nucleus**.

- **Beta + (β^+) decay:** β^+ **particles** are **positrons** ($\bar{e}$) which are **produced** when a **proton** (p) **decays** into a **neutron** (n).

$$^1_1p^+ \longrightarrow {}^1_0n + {}^0_{+1}\bar{e}^+ + {}^0_0\nu \qquad\qquad u \longrightarrow d + {}^0_{+1}\bar{e} + \nu$$

Neutrinos (ν) are **uncharged particles** which carry away **energy** in the **decay**.

- **Beta - (β^-) decay:** β^- **particles** are **electrons** (e) which are **produced** when a **neutron** (n) **decays** into a **proton** (p).

$$^1_0n \longrightarrow {}^1_1p^+ + {}^0_{-1}e^- + {}^0_0\bar{\nu} \qquad\qquad d \longrightarrow u + {}^0_{-1}e + \bar{\nu}$$

Context: Alpha and **Beta decay equations**

Exemplar Statement Exam Question

No gamma decay, only α or β taking place.

Complete equation: Determine **other particles created** in decay.

1) Particle **X** decays to particle **Y** through a combination of multiple alpha and beta decays. Complete the combined decay equation to show all by-products produced in the decay, assuming that any particles have cancelled with their respective anti-particle if present. You do not need to include photons in your equation.

3 mark question, likely **3 things** to add to **equation.**
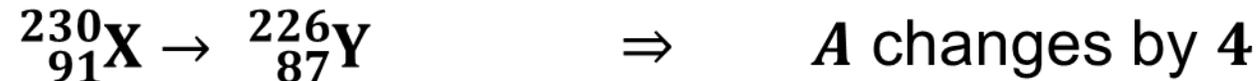
$$^{230}_{91}X \rightarrow \ ^{226}_{87}Y + \cdots$$
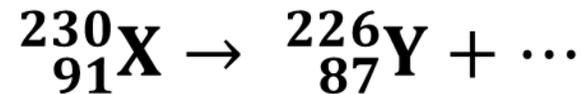
Only information given is A and Z **values,** how can we use this?

[3 marks]

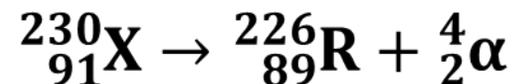# Exemplar Statement Question Answer

Calculate number of alpha decays

Beta decays do not affect A value for a particle, so change in A must only be due to alpha decays

$$^{230}_{91}X \rightarrow {}^{226}_{87}Y \qquad \Rightarrow \qquad A \text{ changes by } 4$$

So there is **1** alpha decay, giving intermittent particle $^{226}_{89}R$
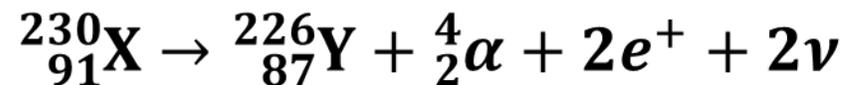
$$^{230}_{91}X \rightarrow {}^{226}_{89}R + {}^{4}_{2}\alpha$$

[1 Mark]

Exemplar Statement Question Answer

Calculate number of beta decays

Remaining change in Z must be due to beta decays

$$^{226}_{89}R \rightarrow {}^{226}_{87}Y \qquad \Rightarrow \qquad Z \text{ decreases by } 2$$

So there are **2** beta+ decays, meaning full equation is

$$^{230}_{91}X \rightarrow {}^{226}_{87}Y + {}^{4}_{2}\alpha + 2e^+ + 2\nu$$

[2 Marks]

Radioactivity

Radioactive decay is both **spontaneous** (not affected by **external factors**) and **random** (cannot be **predicted**).

- Although **radioactive decay** is **random** it can be **modelled probabilistically**.

The **decay constant** λ is the **probability** that a **nucleus** will **decay** in **1 second**.

- We **measure radioactivity** as **activity** (A) in **decays per second** (**Becquerels**, **Bq**).

$$A = \lambda N$$

$$\frac{dN}{dt} = -A = -\lambda N$$

$$A = A_0 e^{-\lambda t}$$
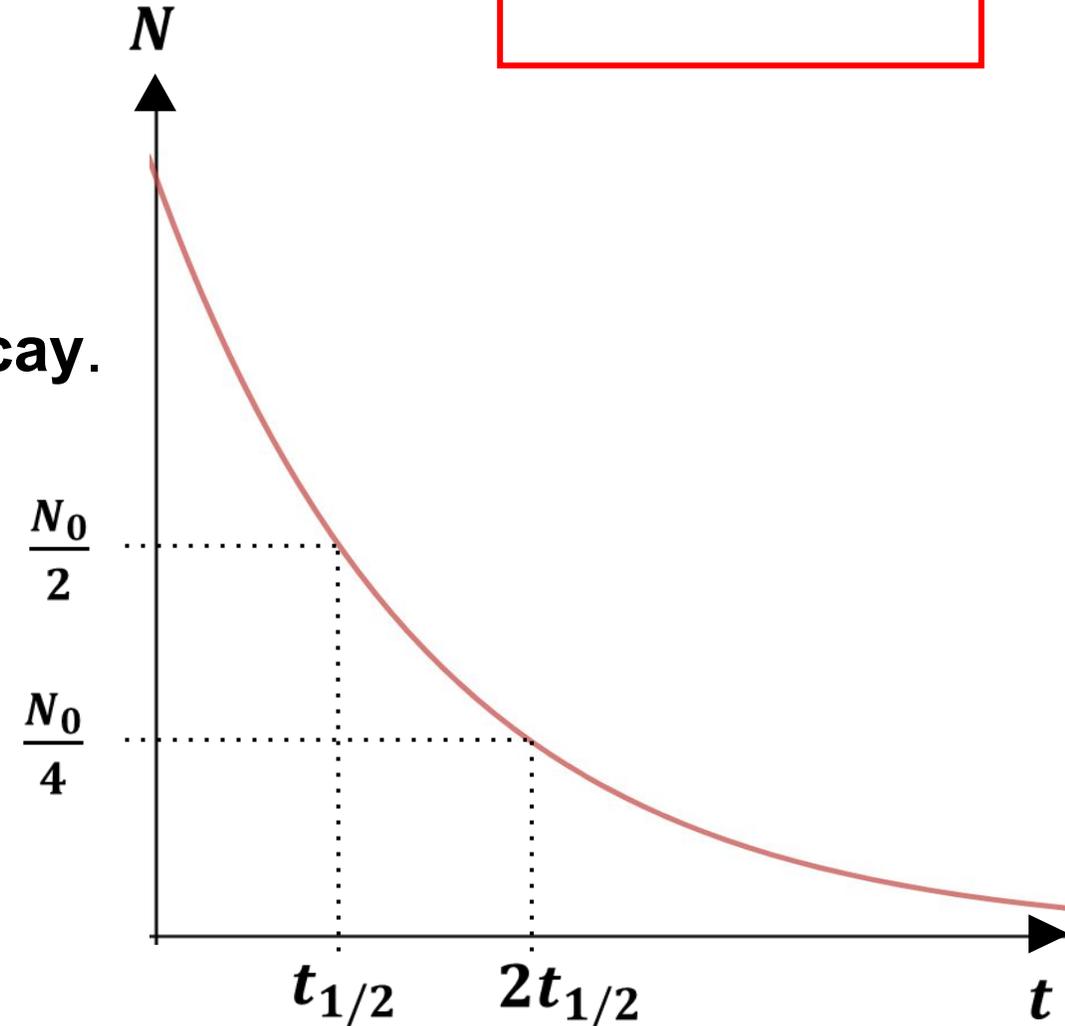
$$\frac{dN}{dt} = -\lambda N \longrightarrow N = N_0 e^{-\lambda t}$$

The **solution** of this **equation** is **exponential decay**.

- The **time** for **number** of **remaining nuclei** N to **half** is a **constant** called the **half-life** $(t_{1/2})$ which depends on the **radioactivity** of the **sample**.

$$t_{1/2} = \frac{\ln 2}{\lambda}$$

SNAPREVISE

What does **initial sample** and **half life mean** for graph?

Exemplar Plot/Sketch Exam Question

Context: decay of atoms and **half lives**

1) A sample of **800** atoms of **X** decay over time into atoms of **Y**, with a half life of **3** years. On the axes provided, plot a graph of **N**, the number of atoms of **X** in the sample, against *t*, the time in years. You should provide a suitable scale for the *y*-axis.

Plot question: calculate key points for accuracy

Need to **provide a scale,** what would the **highest value** be?

[3 marks]

3 marks, 3 key requirements for our graph
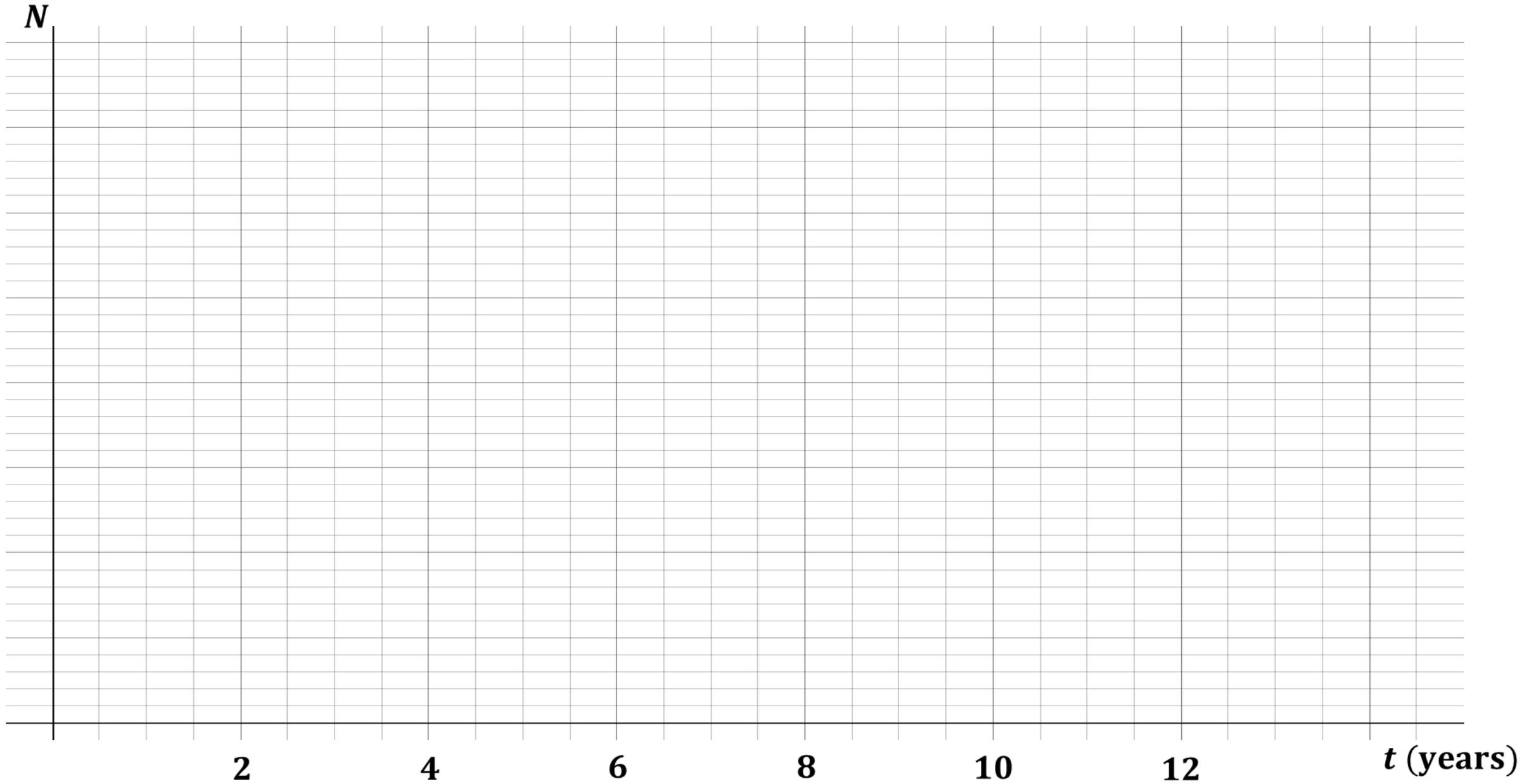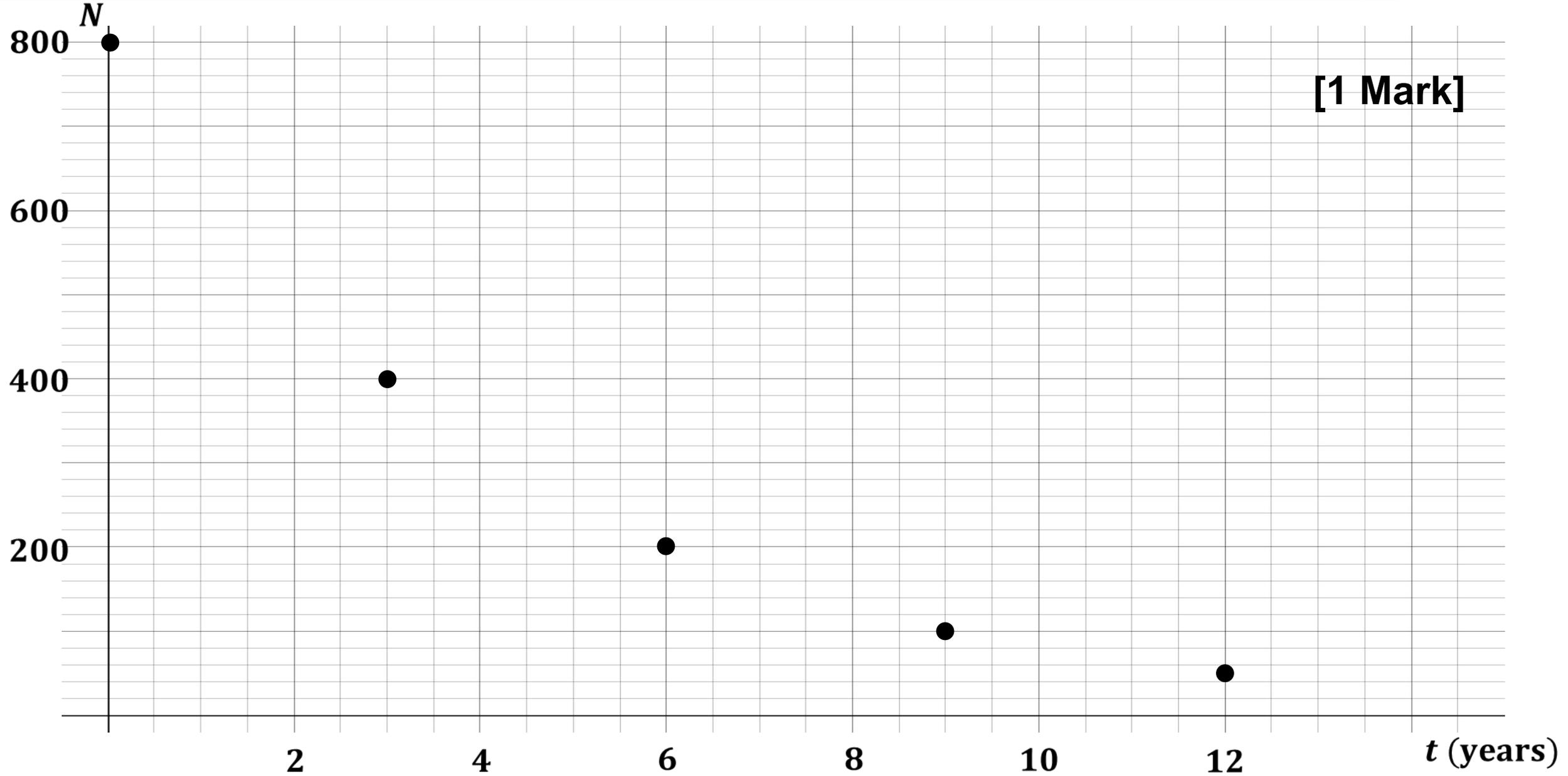
Exemplar Sketch/Plot Question Answer
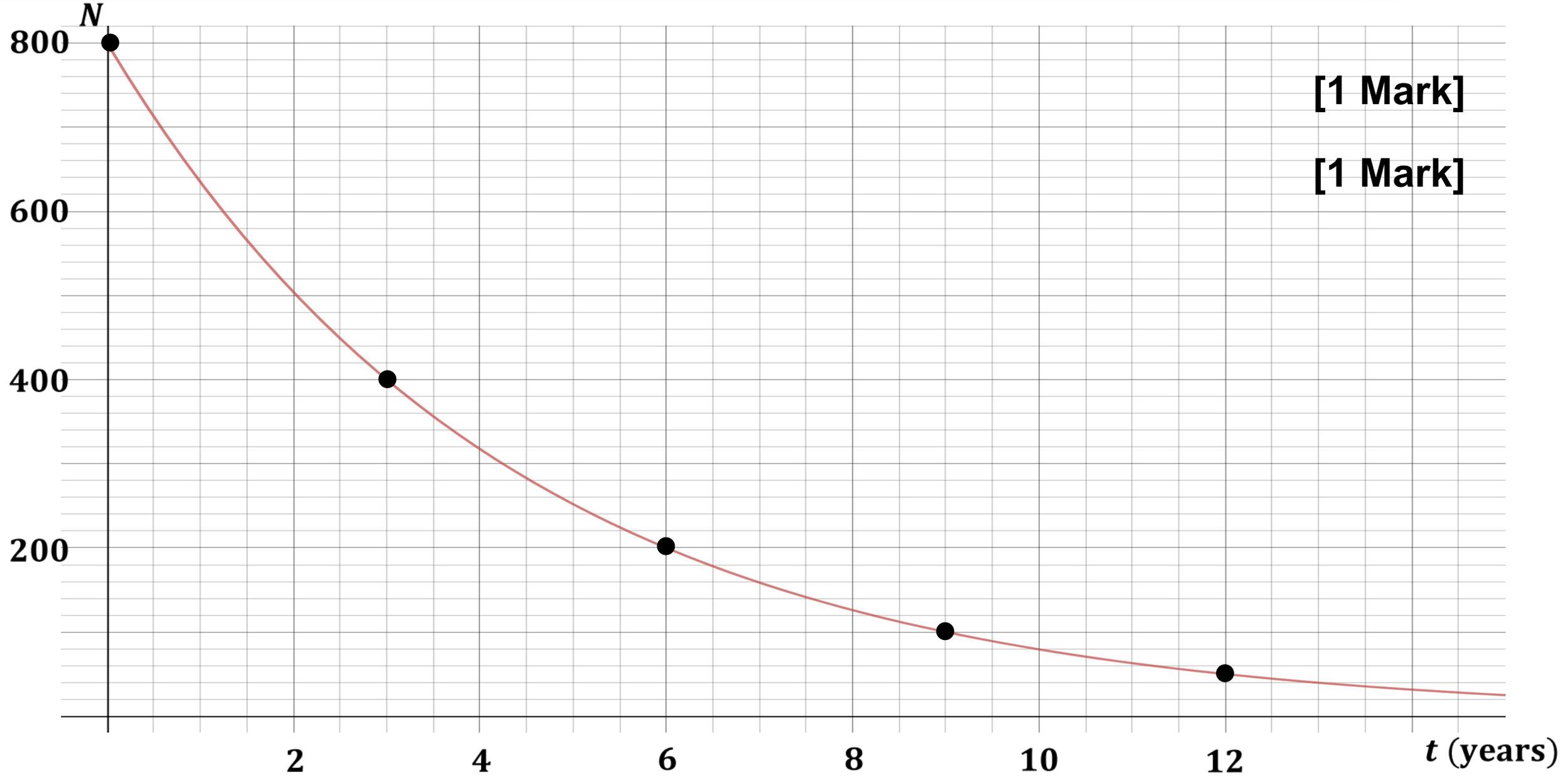
Determine key points and plot graph
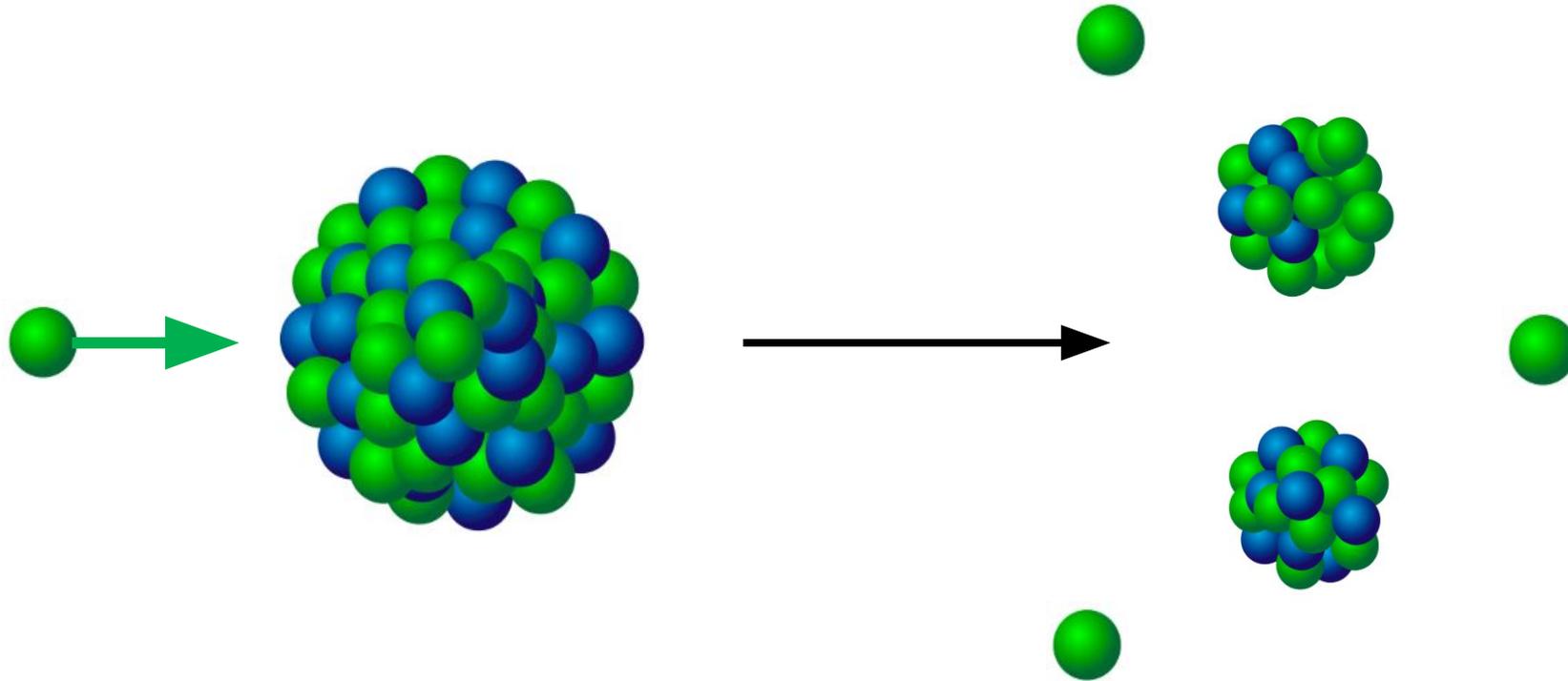
[1 Mark]

N at $t = 0$ will be initial value, **800**.

This value will then half every **3** years

Plot these points on the axes with a suitable scale, then draw a curve through them

[1 Mark]

[1 Mark]

[1 Mark]

Nuclear Physics

Specification Points - AQA

3.8.1.4 Nuclear instability (A-level only)

Content
Graph of N against Z for stable nuclei.
Possible decay modes of unstable nuclei including α, β^+, β^- and electron capture.
Changes in N and Z caused by radioactive decay and representation in simple decay equations.
Questions may use nuclear energy level diagrams.
Existence of nuclear excited states; γ ray emission; application eg use of technetium-99m as a γ source in medical diagnosis.

3.8.1.6 Mass and energy (A-level only)

Content
Appreciation that $E = mc^2$ applies to all energy changes,
Simple calculations involving mass difference and binding energy.
Atomic mass unit, u.
Conversion of units; $1\ u = 931.5\ MeV$.
Fission and fusion processes.
Simple calculations from nuclear masses of energy released in fission and fusion reactions.
Graph of average binding energy per nucleon against nucleon number.
Students may be expected to identify, on the plot, the regions where nuclei will release energy when undergoing fission/fusion.
Appreciation that knowledge of the physics of nuclear energy allows society to use science to inform decision making.

3.8.1.7 Induced fission (A-level only)

Content
Fission induced by thermal neutrons; possibility of a chain reaction; critical mass.
The functions of the moderator, control rods, and coolant in a thermal nuclear reactor.
Details of particular reactors are not required.

Specification Points – OCR A

6.4.4 Nuclear fission and fusion

Learning outcomes

Learners should be able to demonstrate and apply their knowledge and understanding of:

(a) Einstein's mass–energy equation; $\Delta E = \Delta mc^2$

(b) energy released (or absorbed) in simple nuclear reactions

(c) creation and annihilation of particle–antiparticle pairs

(d) mass defect; binding energy; binding energy per nucleon

(e) binding energy per nucleon against nucleon number curve; energy changes in reactions

(f) binding energy of nuclei using $\Delta E = \Delta mc^2$ and masses of nuclei

(g) induced nuclear fission; chain reaction

(h) basic structure of a fission reactor; components – fuel rods, control rods and moderator

(i) environmental impact of nuclear waste

(j) nuclear fusion; fusion reactions and temperature

(k) balancing nuclear transformation equations.

Specification Points – OCR B

6.2.2 Ionising radiation and risk

Learning outcomes

(a) *Describe and explain:*

  (ii) the stability and decay of nuclei in terms of binding energy; transformation of nucleus on emission of radiation; qualitative variation of binding energy with proton and neutron number ("Nuclear Valley")

  (iii) nuclear fission; chain reaction; nuclear fusion; nuclear power generation.

(b) *Make appropriate use of:*

  (i) the terms: nucleon number, proton number, isotope, binding energy, atomic mass unit, absorbed and effective dose, risk

  by sketching and interpreting:

  (ii) plots of binding energy per nucleon of nuclei against nucleon number.

(c) *Make calculations and estimates involving:*

  (iv) energy changes from nuclear transformations: $E_{rest} = mc^2$.

Specification Points - Edexcel

164.	understand the concept of *nuclear binding* energy and be able to use the equation $\Delta E = c^2 \Delta m$ in calculations of nuclear mass (including mass deficit) and energy
165.	use the *atomic mass unit (u)* to express small masses and convert between this and SI units
166.	understand the processes of nuclear fusion and fission with reference to the binding energy per nucleon curve
167.	understand the mechanism of nuclear fusion and the need for very high densities of matter and very high temperatures to bring about and maintain nuclear fusion

|	
170.	be able to write and interpret nuclear equations given the relevant particle symbols

Mass-Energy Equivalence

$$E = mc^2$$

Mass and **energy** are related by **Einstein's** famous **equation**:

- This **implies** that any **change in** the **mass** of a **system** is **accompanied** by a **release of energy**.

- **Consider** an **electron** and **positron** (both of **mass** $m_e = 9.11 \times 10^{-31}$ **kg**) **annihilating** to **2 photons**.
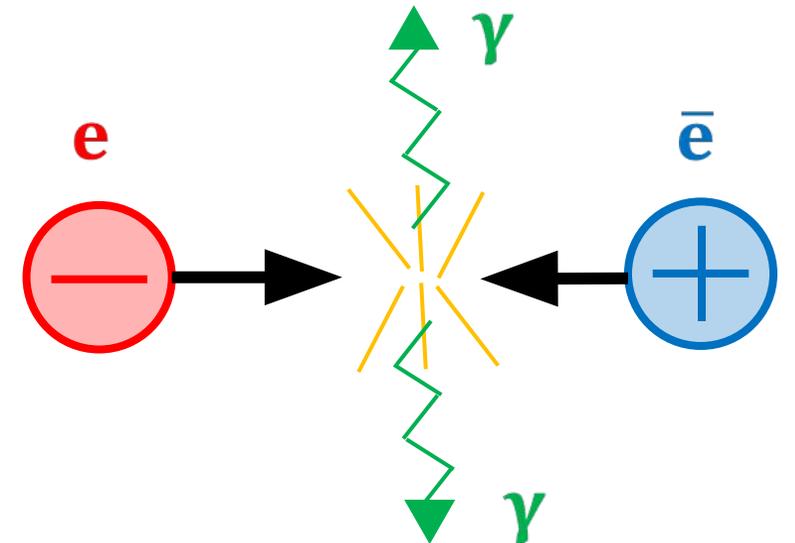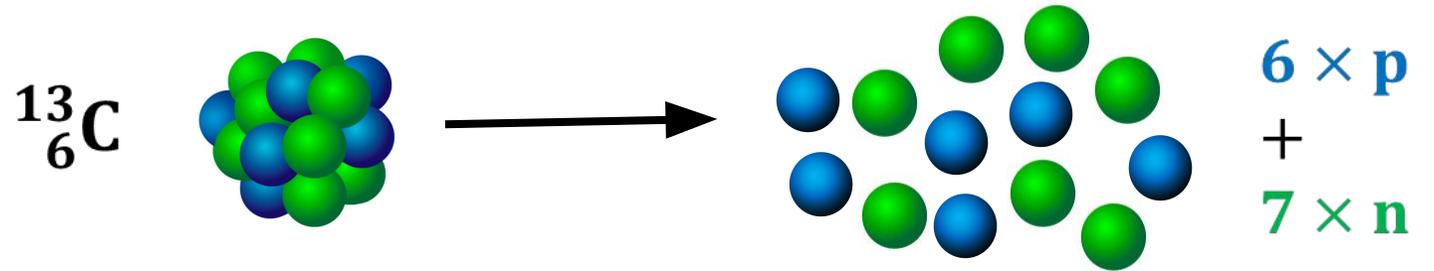
The **binding energy** of a **nucleus** is the **total work** that must be **done** to **separate** a **nucleus** into its **constituent nucleons**.
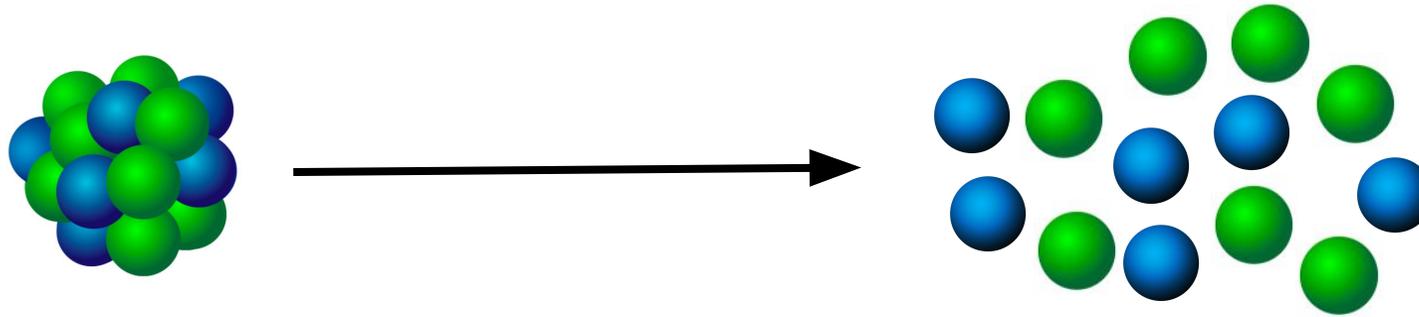
The **mass defect** is the **difference** in **mass** between a **nucleus** and the **sum** of its **constituent nucleons**.

The **mass defect** is **associated** with a **release** of **energy** according to $E = mc^2$.

Particle	Mass (u)
p	1.00728
n	1.00867
$^{13}_{6}C$	13.00336

$^{13}_{6}C$

$6 \times p$
$+$
$7 \times n$

Calculation question: Recall **relevant formulas** and **substitute key values**.

Exemplar Calculation Exam Question

Context: Mass-Energy equivalence.

1) Calculate the difference between the energy required to break a sulfur-32 nucleus into 8 alpha particles and into its individual nucleons. Give your answer in Joules to **3 s.f.**

- Mass of Sulfur-32 Nucleus = 31.9720 u
- Mass of Alpha particle = 4.0015 u
- Mass of Proton = 1.0073 u
- Mass of Neutron = 1.0087 u
- Atomic mass unit $1 \text{ u} = 1.661 \times 10^{-27} \text{ kg}$
- Speed of light $c = 3.00 \times 10^8 \text{ ms}^{-1}$

Remember to **convert units**!

3 marks, **3 key stages** to **calculation**.

[3 marks]

Normally you'd need to find **values** in the **formula booklet**.

Exemplar Calculation Question Answer

Calculate mass change in alpha decay

$$\Delta m = 8m_\alpha - m_S$$

$$\Delta m = 8 \times 4.0015 - 31.9720$$

$$\Delta m = 0.04 \text{ u}$$

Calculate energy required

$$\Delta E_\alpha = \Delta mc^2$$

$$\Delta E_\alpha = 0.04 \times 1.661 \times 10^{-27} \times \left(3.00 \times 10^8\right)^2$$

$$\Delta E_\alpha = 5.9796 \times 10^{-12} \text{ J}$$

[1 Mark]

Exemplar Calculation Question Answer

Deduce number of protons and neutrons in Sulfur-32

Sulfur-32 breaks down completely into 8 alpha particles.

So it must consist of 16 protons and 16 neutrons.

Calculate mass change in nucleon separation

$$\Delta m = 16m_p + 16m_n - m_S$$

$$\Delta m = 16 \times 1.0073 + 16 \times 1.0087 - 31.9720$$

$$\Delta m = 0.284 \text{ u}$$

[1 Mark]

Exemplar Calculation Question Answer

Calculate energy required

$$\Delta E_i = \Delta m c^2$$

$$\Delta E_i = 0.284 \times 1.661 \times 10^{-27} \times \left(3.00 \times 10^8\right)^2$$

$$\Delta E_i = 4.245516 \times 10^{-11} \text{ J}$$

Find difference in energies

$$\Delta E = \Delta E_i - \Delta E_n$$

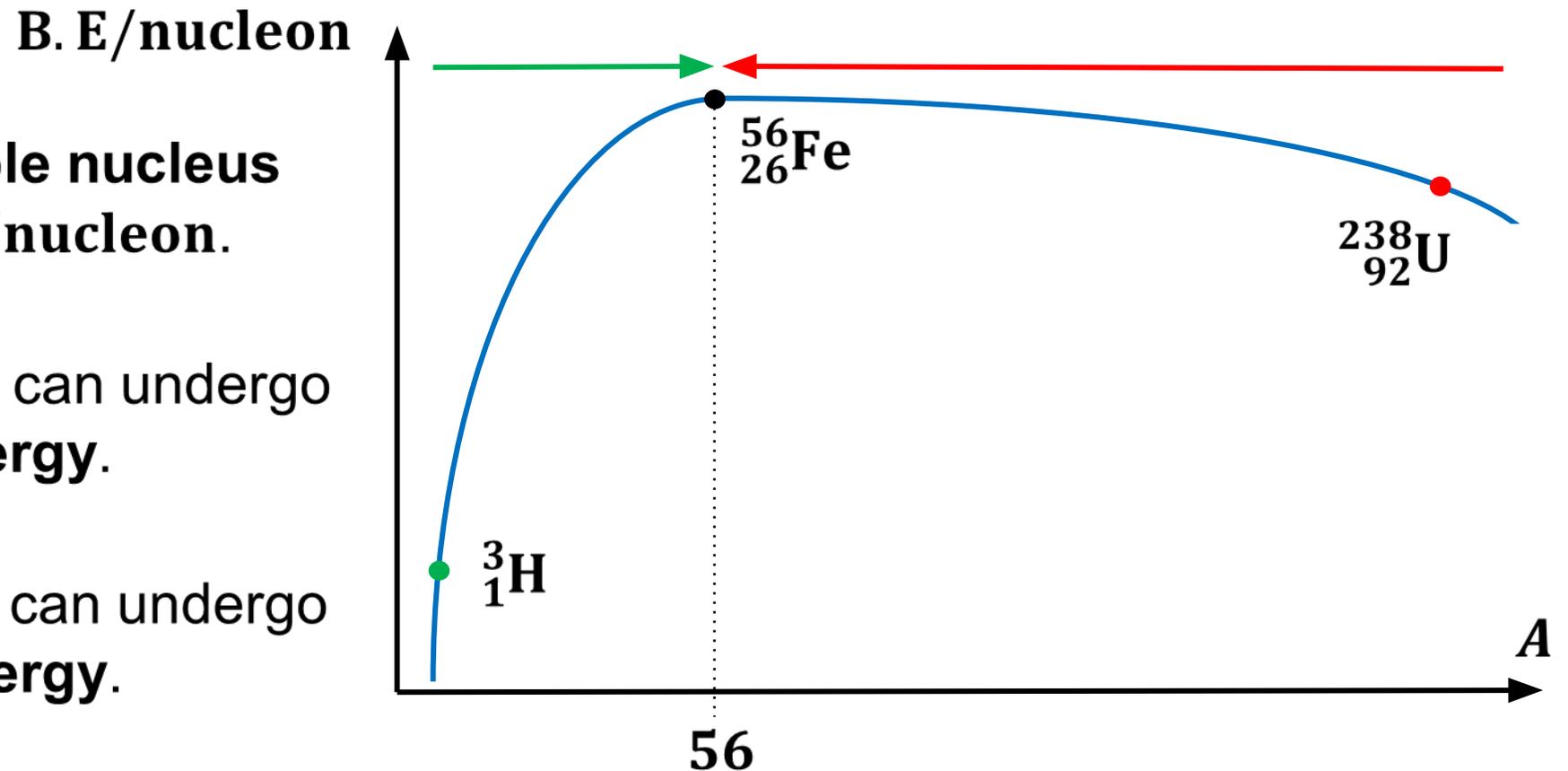$$\Delta E = 4.245516 \times 10^{-11} - 5.9796 \times 10^{-12}$$

$$\Delta E = 3.647556 \times 10^{-11} \text{ J}$$

[1 Mark]

Fusion and Fission

The **binding energy per nucleon** is a **measure** of the **stability** of a **nucleus.**

- $^{56}_{26}Fe$ is the **most stable nucleus** with the **highest B. E/nucleon**.

- **Isotopes** with $A < 56$ can undergo **fusion** to **release energy**.

- **Isotopes** with $A > 56$ can undergo **fission** to **release energy**.
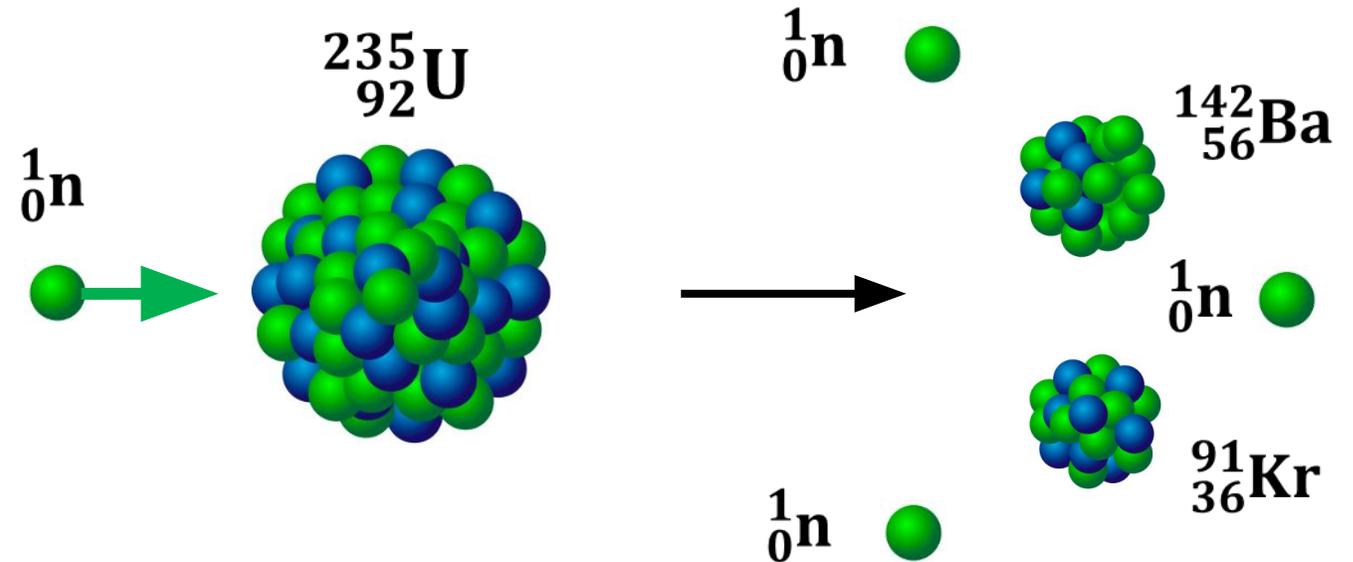
Nuclear Fission

Heavy radioactive nuclei can undergo **fission**, **splitting** into smaller **daughter nuclei** and some **individual neutrons**.

- The **energy released** by **fission** of **uranium-235** is **equal** to the **change** in **binding energy**.

- **Fission** is **induced** by a ^{235}U **nucleus absorbing** a **neutron**.

$^{1}_{0}n$ $^{235}_{92}U$ $^{1}_{0}n$ $^{142}_{56}Ba$ $^{1}_{0}n$ $^{91}_{36}Kr$ $^{1}_{0}n$

- The **neutrons** released by **fission** can go on to **induce** more **fission** in a **chain reaction**.
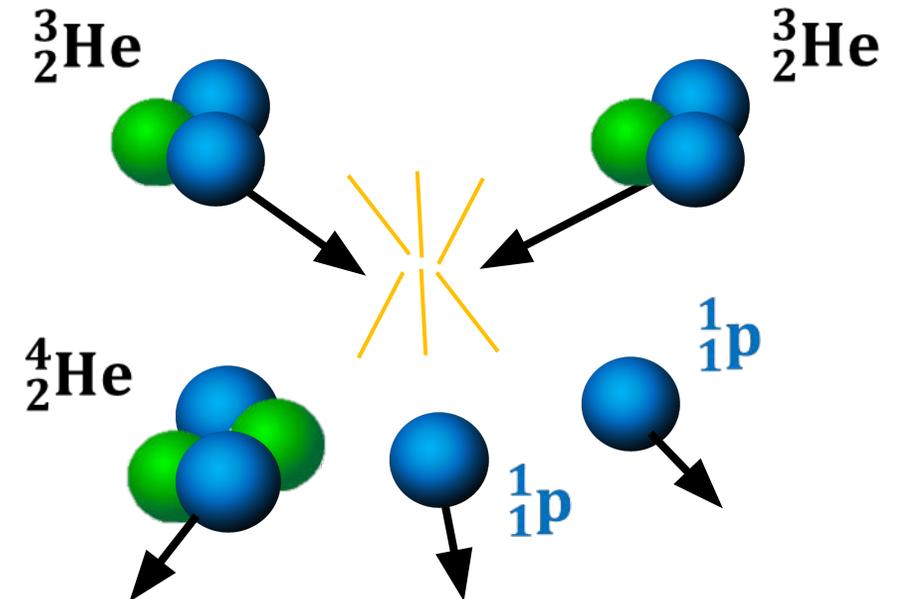
Nuclear Fusion

Some **light nuclei** can undergo **fusion**, **combining together** into a **larger nucleus**.

- For **fusion** to occur, **2 nuclei** must be brought **close enough** for the **attractive strong nuclear force** to overcome the **electrostatic repulsion** between them.

An **example** of a **fusion cycle** is:

- $^1_1p + {}^1_1p \longrightarrow {}^2_1H + {}^{\ 0}_{+1}\bar{e} + \nu$

- $^2_1H + {}^1_1p \longrightarrow {}^3_2He$

- $^3_2He + {}^3_2He \longrightarrow {}^4_2He + {}^1_1p + {}^1_1p$

^3_2He ^3_2He

^4_2He ^1_1p

^1_1p

Exemplar Explanation Exam Question

Context: Energy produced by a star

Protons collide, how does this **produce energy?**

1) Stars are formed when protons are brought together under intense pressure, so that they can overcome electrostatic repulsion and collide.
Explain how these collisions cause the star to produce energy and atoms with larger nuclei.

[3 marks]

Explanation question: use **bullet points** and break down **key points**

3 mark question, about **3 key points** to make

- **2** protons are brought close enough together by intense gravity so that the attractive strong nuclear force overcomes electrostatic repulsion, causing nuclear fusion.

[1 Mark]

- The fusion reaction turns the two protons into a single, larger nucleus.

[1 Mark]

- This nucleus has more binding energy per nucleon, meaning energy must be released during the fusion.

[1 Mark]

MINI MOCK PAPER

1. A scientist tracks the number of ^{185}Os isotopes in a sample of osmium. He takes two readings on the same day, one at 9am and one at 5pm. The first reading determines that 100% of the sample is ^{185}Os. Given that the half life of ^{185}Os is 93.6 days, calculate the percentage of the sample that the scientist would expect to be ^{185}Os in the second reading. You may assume that the total number of atoms in the sample is constant.

    [3 marks]

Exam Question Answer

Determine equation for percentage of ^{185}Os

Let P be percentage of ^{185}Os remaining, and N be number of ^{185}Os remaining

$$\Rightarrow P = \frac{N}{N_0} \times 100 = \frac{N_0 e^{-\lambda t}}{N_0} \times 100 = 100 e^{-\lambda t}$$

[1 Mark]

Determine decay constant of ^{185}Os

$$\lambda = \frac{\ln 2}{T_{\frac{1}{2}}} = \frac{\ln 2}{93.6 \times 24} = 3.08559\ldots \times 10^{-4}\,\text{hr}^{-1}$$
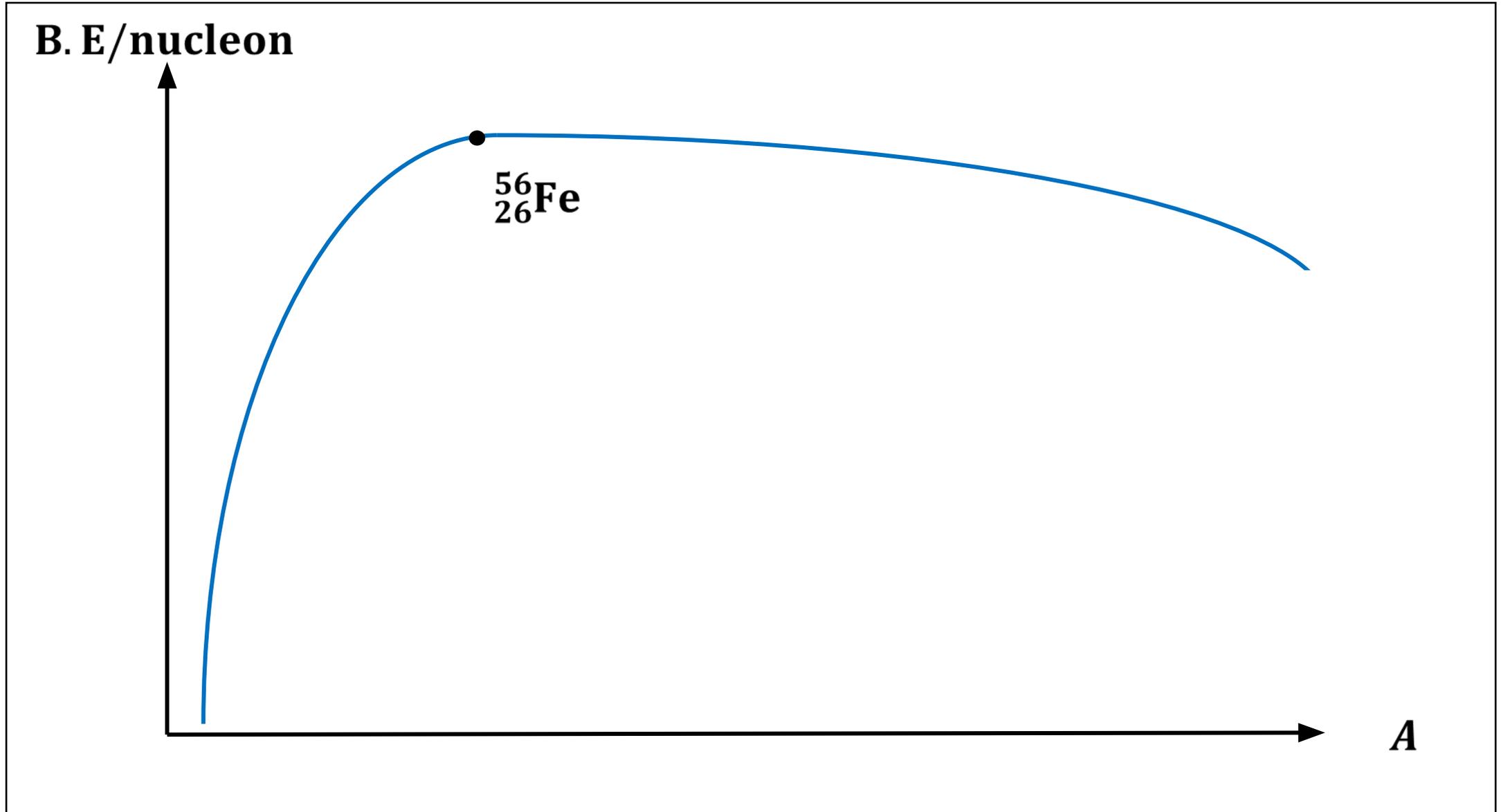
[1 Mark]

Exam Question Answer

Determine percentage of ^{185}Os remaining

Time from 9am to 5pm is 8 hours

$$\Rightarrow P = 100e^{-3.08559\ldots\times10^{-4}\times8} = 99.7534\ldots\%$$

$$= 99.8\%\,(\text{to 3 s.f.})$$

[1 Mark]

2. Explain, with reference to a relevant graph, why iron is an unsuitable reactant to use in generating energy through nuclear fission or nuclear fusion.

[4 marks]

- Fusion generates energy by merging small nuclei together into larger nuclei, increasing the binding energy per nucleon.   **[1 Mark]**

- Fission generates energy by splitting apart large nuclei into smaller nuclei, increasing the binding energy per nucleon.   **[1 Mark]**

- As iron has the largest binding energy per nucleon of all elements, fusion or fission wouldn't be able to increase this so no energy would be released   **[1 Mark]**

3. Below is a nuclear equation for a possible way that plutonium-239 can undergo fission.

$$... + {}^{239}_{94}\text{Pu} \rightarrow {}^{134}_{54}\text{Xe} + {}^{103}_{...}\text{Y} + ...$$
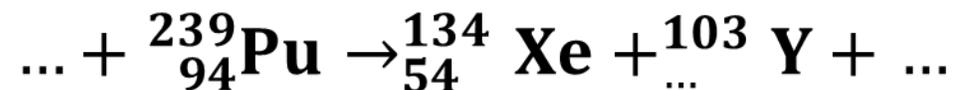
(i) Complete the equation to show all reactants and products in the fission. You do not need to name the element **Y**.

(ii) State how, in a reactor containing only ${}^{239}_{94}\text{Pu}$, this initial fission can cause a chain reaction.

[5 marks]

- Fission reaction starts with a neutron

- Neutrons are also produced in the reaction, the number of neutrons must balance the nucleon numbers: $n = (239 + 1) - (134 + 103) = 3$ **[1 Mark]**
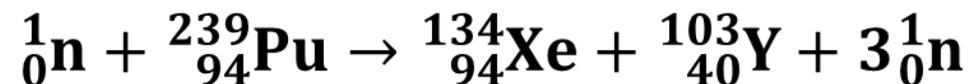
- Proton number must also be conserved, so missing element has proton number $94 - 54 = 40$ **[1 Mark]**

$$^{1}_{0}n + {}^{239}_{94}Pu \rightarrow {}^{134}_{94}Xe + {}^{103}_{40}Y + 3{}^{1}_{0}n$$

[1 Mark]

- Each reaction is started by 1 slow moving neutron but produces 3 fast moving neutrons

[1 Mark]

- If these 3 neutrons are slowed down, then they can be used to start further reactions

[1 Mark]