

NUCLEAR PHYSICS

AQA A-Level Physics | Topic 3.8

STUDENT EDITION

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Name: _____ Teacher: _____

Lesson 1: Rutherford Scattering

DO NOW — Lesson 1

1. Draw and label a simple diagram of an atom showing the nucleus, protons, neutrons, and electrons. State the relative charge of each particle. (3 marks)
2. An alpha particle has charge $+2e$ and a gold nucleus has charge $+79e$. State whether the electrostatic force between them is attractive or repulsive. Name this type of force. (2 marks)
3. A particle has mass 6.64×10^{-27} kg and speed 2.0×10^7 m s⁻¹. Calculate its kinetic energy using $E_K = \frac{1}{2}mv^2$. (2 marks)
4. State which type of radiation (α , β , or γ) has the shortest range in air and explain why in one sentence. (2 marks)

Part 1 of 3 | The Geiger-Marsden Experiment

In 1909, Hans Geiger and Ernest Marsden worked with Ernest Rutherford in Manchester. They fired **alpha particles** (positively charged, a few MeV) at a thin piece of **gold foil** inside an **evacuated chamber**. A zinc sulphide screen emitted light whenever an alpha particle struck it, detected via a moving microscope in a dark room.

At the time, the accepted atomic model was the **plum pudding model**: a diffuse positive charge with electrons embedded throughout (like plums in a pudding).

Results

- Almost all alpha particles passed straight through with little or no deflection.
- About 1 in 8000 was 'reflected' back, scattered through an angle greater than 90°.

Rutherford famously said this was like firing bullets at tissue paper and having them bounce back!

Why vacuum? Alpha particles have a range of only ~5 cm in air — they would be absorbed before reaching the foil.

Why thin gold foil? To avoid multiple scattering events, so each deflection comes from a single nucleus.

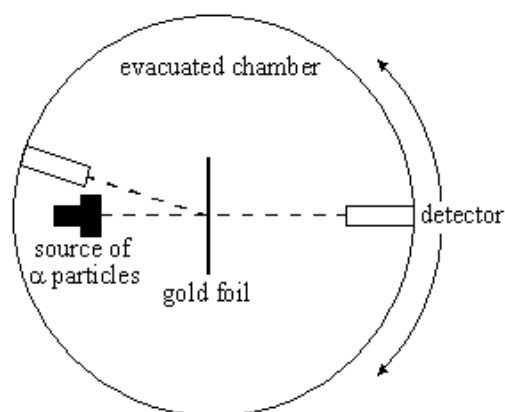


Fig 1.1 — Rutherford scattering apparatus

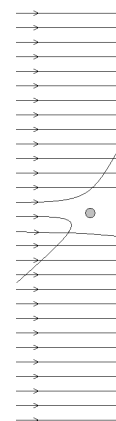


Fig 1.2 — Alpha particle scattering paths

Questions

1. State what may be concluded about the structure of the atom from the observation that *most* alpha particles passed straight through the gold foil with little or no deflection.

(2 marks)

2. State what may be concluded from the observation that *about 1 in 8000* alpha particles were scattered through angles greater than 90° .

(2 marks)

3. Explain why the gold foil and alpha source were placed in a vacuum.

(2 marks)

4. Explain why the gold foil had to be very thin.

(2 marks)

Part 2 of 3 | The Nuclear Model

Rutherford used the scattering results to propose the **nuclear model**:

- **Most mass is in a tiny nucleus.** The nucleus can repel a fast-moving alpha particle — consistent with 1 in 8000 being scattered back.
- **The nucleus is positively charged.** It repels positive alpha particles via electrostatic (Coulomb) repulsion.
- **Most of the atom is empty space.** Only 1 in 8000 alpha particles approaches close enough to the nucleus to scatter at large angles.
- **Negative electrons orbit the nucleus** at a relatively large distance, keeping the atom electrically neutral.

Upper limit on nuclear size: The distance of closest approach gives an upper limit on the nuclear radius. When all kinetic energy converts to electric potential energy:

$$r = \frac{qQ}{4\pi\epsilon_0 E_K}$$

Typical nuclear diameter: $\sim 10^{-14}$ m (atom diameter $\sim 10^{-10}$ m, so the nucleus is $\sim 10,000$ times smaller).

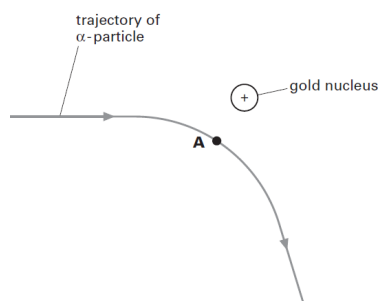


Fig 1.3 — Alpha particle trajectory past a gold nucleus

Questions

5. A very small percentage of alpha particles were scattered through angles greater than 90° . State two properties of the nucleus that can be deduced from this.

(2 marks)

6. An alpha particle travelling at 1.5×10^7 m s $^{-1}$ approaches a gold nucleus ($Z = 79$) head-on. Calculate the distance of closest approach. (mass of alpha = 6.64×10^{-27} kg, $e = 1.6 \times 10^{-19}$ C, $\epsilon_0 = 8.85 \times 10^{-12}$ C 2 J $^{-1}$ m $^{-1}$)

(4 marks)

7. The diagram shows an alpha particle passing near a gold nucleus. Name the force responsible for the deflection.

(1 mark)

8. State a typical value for the diameter of an atomic nucleus.

(1 mark)

Part 3 of 3 | Particle Scattering Techniques

Different particles are used for different scattering investigations. Two key considerations are the **type of particle** and its **energy**.

Alpha Scattering: Energies ~4 MeV. Higher energies bring the alpha particle close enough to experience the strong nuclear force, complicating results.

Electron Scattering: Accelerated to ~6 GeV. High enough energy to probe inside protons and neutrons, leading to the discovery of quarks. The de Broglie wavelength is ~1000 × smaller than visible light, giving much finer resolution.

X-ray Scattering: Short wavelengths scatter off atomic electrons. Elastic (coherent) scattering occurs when the photon energy is insufficient to ionise. At higher energies the photon ionises the electron and loses energy.

Neutron Scattering: Uncharged — not affected by the electromagnetic force. Penetrates deeply. Wavelengths similar to atomic spacing so diffraction occurs at crystal lattices. Cannot be accelerated easily by electric fields.

For diffraction to reveal structure, the wavelength must be **comparable to or smaller than** the object being studied.

de Broglie wavelength for high-energy electrons (relativistic approximation):

$$\lambda = \frac{hc}{E}$$

where $h = 6.63 \times 10^{-34}$ J s, $c = 3.0 \times 10^8$ m s⁻¹, E is energy in joules.

Diffraction minimum (nuclear radius):

$$\sin \theta = \frac{1.22 \lambda}{d} \quad (d = \text{nuclear diameter})$$

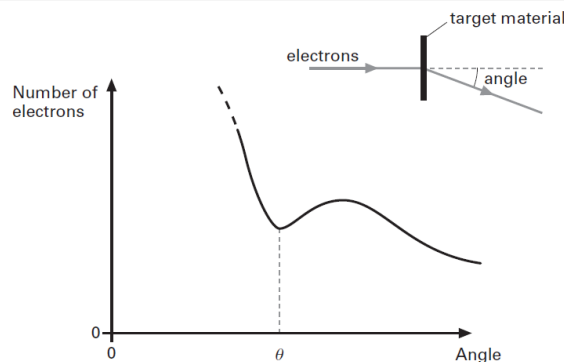


Fig 1.4 — Electron diffraction pattern showing first minimum at θ

Questions

9. Name three techniques used to investigate the crystalline structure of matter.

(3 marks)

10. High-speed electrons are diffracted by atomic nuclei.

(a) What does electron diffraction demonstrate about the nature of high-speed electrons?

(b) Suggest a typical wavelength for electrons used to investigate nuclear size.

(2 marks)

11. For a wavelength of 2.0×10^{-10} m, calculate:

(a) The frequency of X-rays of this wavelength.

(b) The speed of electrons with this de Broglie wavelength. ($m_e = 9.11 \times 10^{-31}$ kg, $h = 6.63 \times 10^{-34}$ J s)

(c) The speed of neutrons with this de Broglie wavelength. ($m_n = 1.67 \times 10^{-27} \text{ kg}$)

(5 marks)

12. In an electron-diffraction experiment, 420 MeV electrons fired at carbon nuclei give a first diffraction minimum at $\theta = 52^\circ$. Calculate the diameter of a carbon nucleus. ($1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$)

(4 marks)

Additional Questions — Lesson 1

Questions

- A1. The spacing between atoms in a solid is typically $2.0 \times 10^{-10} \text{ m}$. For diffraction the incident wavelength must be comparable to or less than this spacing. For a wavelength of $2.0 \times 10^{-10} \text{ m}$, calculate:

(a) The frequency of the X-rays. ($c = 3.0 \times 10^8 \text{ m s}^{-1}$)

(b) The speed of electrons with this de Broglie wavelength. ($m_e = 9.11 \times 10^{-31} \text{ kg}$, $h = 6.63 \times 10^{-34} \text{ J s}$)

(c) The speed of neutrons with this de Broglie wavelength. ($m_n = 1.67 \times 10^{-27} \text{ kg}$)

(5 marks)

- A2. The density of ordinary matter is about 10^3 kg m^{-3} . What does the nuclear density suggest about the structure of atoms?

(2 marks)

- A3. List three key conclusions about the nature of the atom from the α -scattering experiment.

(3 marks)

- A4. X-rays of wavelength $2.5 \times 10^{-11} \text{ m}$ are diffracted by a thin copper sample.

(a) What causes the diffraction of the X-rays?

(b) State the approximate diameter of a copper atom in metres.

(c) Estimate the speed of an electron with the same de Broglie wavelength. ($m_e = 9.11 \times 10^{-31} \text{ kg}$)

(d) Explain why this diffraction pattern cannot be due to atomic nuclei of copper.

(5 marks)

Exam-Style Questions — Lesson 1

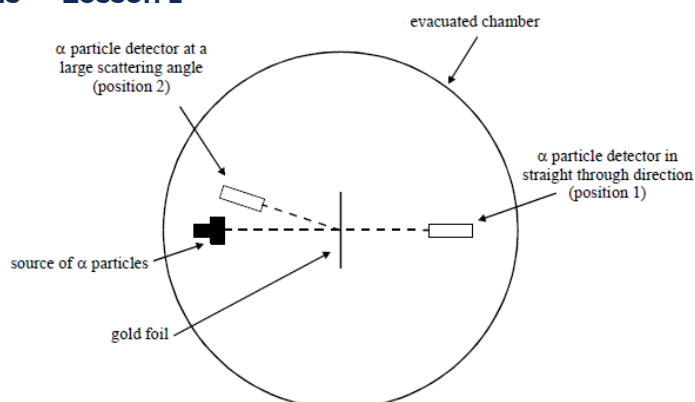


Fig 1.5 — Rutherford scattering apparatus (exam diagram)

EXAM QUESTION – Q1: Rutherford Scattering Apparatus (9 marks)

- (a) Why is it necessary to remove the air from the apparatus?

(2)

- (b) Explain why the gold foil should be very thin.

(2)

- (c) The count rate at position 1 (straight through) is much greater than at position 2 (large scattering angle). Explain this and state what can be deduced about the structure of the atom and the properties of the gold nucleus.

(5)

EXAM QUESTION – Q2: Rutherford Scattering Setup (6 marks)

- (a) Why is it necessary to remove the air from the Rutherford scattering apparatus?

(2)

- (b) Explain why the gold foil should be very thin.

(2)

- (c) Explain why the count rate at position 1 (straight through) is much greater than at position 2 (large scattering angle). What can be deduced about the structure of the atom?

(5)

EXAM QUESTION – Q2: Alpha Scattering Analysis (7 marks)

- (a(i)) In which direction will the number of alpha particles per second be a maximum?

(1)

- (a(ii)) What does this suggest about the structure of the atoms in the metal?

(1)

- (b) A small number of alpha particles are scattered through 180° . Explain what this suggests about the structure of atoms.

(2)

- (c(i)) Name the force responsible for the deflection of the alpha particle.

(1)

- (c(ii)) The nucleus is replaced with one having a larger mass number but smaller proton number. Describe how the path of the alpha particle changes.

(2)

Lesson 2: Ionising Radiation

DO NOW — Lesson 2

1. Name the three main types of ionising radiation and state the composition of each. (3 marks)
2. State whether each radiation type (α , β , γ) is deflected by an electric field, giving the direction of deflection for each. (3 marks)
3. Which type of radiation has the greatest penetrating power? What thickness of what material is typically needed to reduce its intensity significantly? (2 marks)
4. State what is meant by ionisation and give one reason why ionising radiation is harmful to living tissue. (2 marks)

Part 1 of 3 | Alpha and Beta Radiation

Ionisation is the removal of one or more electrons from an atom. Radiation entering a GM tube ionises the gas inside; electrons are attracted to a positive wire, producing a detectable current.

Alpha (α) — Helium nucleus ($2p + 2n$)

Property	Alpha (α)
Relative mass	4
Relative charge	+2
Deflection by E/M field	Yes
Ionising power	High
Penetrating power	Low
Range in air	~5 cm
Stopped by	Skin / paper
Uses	Smoke detectors; targeted radiotherapy
Danger outside body	Low
Danger inside body	High — cell death, mutation, cancer

Beta-minus (β^-) — Fast-moving electron (from neutron \rightarrow proton conversion)

Property	Beta-minus (β^-)
Relative mass	1/2000
Relative charge	-1
Deflection by E/M field	Yes
Ionising power	Medium
Penetrating power	Medium
Range in air	2-3 m
Stopped by	~3 mm aluminium
Uses	Thickness control in paper/foil production
Danger outside body	Skin damage
Danger inside body	Similar to alpha but less damaging

Questions

1. Complete the table of radiation properties.

Use the information above to summarise alpha and beta-minus properties.

For each: state the composition, relative mass, charge, ionising power, and what stops it.

(4 marks)

2. Which ionising radiation produces the greatest number of ion pairs per mm in air?

(1 mark)

2b(i). Complete the table showing the typical maximum range in air:

Alpha particles: typical range = _____ m

Beta particles: typical range = _____ m

(2 marks)

2b(ii). Gamma rays have a range of at least 1 km in air. However, a gamma detector placed 0.5 m from a gamma source detects a noticeably smaller count-rate when moved a few centimetres further away. Explain this.

(2 marks)

2c. Following an accident, a room is contaminated with dust containing americium (an alpha emitter). Explain the most hazardous aspect to an unprotected person entering.

(3 marks)

3. State the typical maximum range in air for: (a) alpha particles (b) beta particles

(2 marks)

Part 2 of 3 | Gamma Radiation and the Inverse Square Law

Gamma (γ) – High-frequency electromagnetic wave

Property	Gamma (γ)
Relative mass	0
Relative charge	0
Deflection by E/M field	No
Ionising power	Low
Penetrating power	High
Range in air	~15 m (significant)
Slowed by	Lead / thick concrete
Uses	Medical/industrial tracers; sterilising surgical equipment
Danger outside body	Cell death, mutation, cancer
Danger inside body	Low (mostly passes through)

Inverse Square Law for Gamma Radiation

Gamma radiation from a point source spreads out equally in all directions (**isotropic**). The same energy is distributed over an ever-increasing spherical surface as distance increases.

$$I = \frac{kI_0}{x^2}$$

where I = intensity at distance x , I_0 = source intensity, k = constant.

For two points A and B:

$$I_A (x_A)^2 = I_B (x_B)^2$$

Background radiation must always be subtracted from measured readings to obtain the true (corrected) count rate due to the source.

Sources of background radiation (approximate UK percentages):

Radon/Thoron gas 51% • Ground/rocks/buildings 14% • Food/drink 12% • Medical 12% • Cosmic rays 10%
• Air travel 0.4% • Nuclear weapons testing 0.3% • Occupational 0.2% • Nuclear power 0.1%

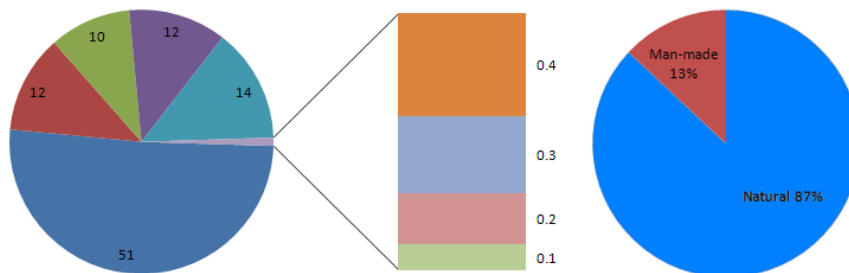


Fig 2.1 — Sources of background radiation in the UK

Questions

- A gamma source is 0.15 m from a detector giving a corrected count rate of 2010 counts min^{-1} . Calculate the expected corrected count rate at 0.90 m from the source.
(3 marks)
- A gamma detector gives a count rate of 2050 counts min^{-1} at 0.15 m (background = 40 counts min^{-1}). Calculate the corrected count rate at 0.90 m.
(3 marks)
- Explain why a student recording a count rate at 0.90 m from a source might choose to record for longer than 5 minutes.
(1 mark)
- State one source of background radiation that has increased in the past 100 years.
(1 mark)

Part 3 of 3 | Radiation Hazards and Safety

The danger from radiation depends on **type, dose, and whether the source is inside or outside the body.**

- **Alpha outside body:** Low risk — stopped by skin. **Alpha inside body (ingested/inhaled):** Very high risk — high ionising power causes severe localised cell damage.
- **Beta outside body:** Can penetrate skin and damage surface tissue. **Beta inside body:** Less damaging than alpha but still hazardous.
- **Gamma outside body:** Penetrates deep into body — can damage internal organs. **Gamma inside body:** Lower danger as it mostly passes through without ionising.

Gamma sterilisation of surgical instruments: Gamma rays penetrate packaging and kill micro-organisms. Gamma radiation does not make instruments radioactive (the gamma photons are absorbed and do not leave residual radioactivity).

Checking for beta emission: Place a sheet of aluminium (~3 mm) between source and detector. If count rate drops significantly beyond that expected from gamma alone, beta particles are also present.

Questions

8. Following an accident, a room is contaminated with dust containing americium (an alpha emitter). Explain the most hazardous aspect of this contamination to an unprotected person entering the room. (2 marks)
9. Explain why the public need not worry that gamma-sterilised surgical instruments become radioactive. (1 mark)
10. A student measures count rates at three distances from a gamma source (corrected for background). Explain with calculations why these data are NOT consistent with an inverse square law: $d = 0.20 \text{ m} \rightarrow 9013$; $d = 0.50 \text{ m} \rightarrow 1395$; $d = 1.00 \text{ m} \rightarrow 242$. (3 marks)
11. Suggest two reasons why the count rate data in Q10 might not follow the inverse square law. (2 marks)

Exam-Style Questions — Lesson 2

EXAM QUESTION – Q1: Radioactive Decay & Gamma Intensity (5 marks)

- (a) Describe the changes that occur in the proton number and nucleon number of a nucleus that decays by alpha emission followed by gamma emission. (2)
- (b) Comment on the relative penetrating powers of alpha and gamma radiation. (1)
- (c) Gamma rays travel from a point source to a detector. The distance is changed from 1.0 m to 3.0 m. Calculate the ratio: intensity at 3.0 m / intensity at 1.0 m. (2)

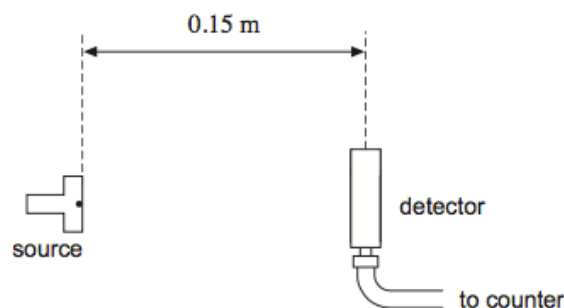


Fig 2.2 – Gamma source and detector arrangement

EXAM QUESTION – Q2: Gamma Source Investigation (6 marks)

- (a(i)) Calculate the corrected count rate expected when the gamma source is placed 0.90 m from the detector (corrected count rate at 0.15 m = 2010 min^{-1}). (3)
- (a(ii)) Explain why the student should record for longer than 5 minutes at 0.90 m. (1)
- (a(iii)) The count rate at 0.90 m is lower than expected. It is suggested the source also emits beta particles. Explain how this can be checked. (2)

EXAM QUESTION – Q3: Radiation Investigation (5 marks)

- (a) Suggest, with a reason, which type of radiation is most appropriate for sterilising metallic surgical instruments.

(1)

(b(i)) A student has a source emitting alpha, beta, and gamma. Explain how they can ensure only gamma radiation is detected during an inverse-square-law investigation.

(2)

(b(ii)) The corrected count rate due to gamma is 64 counts s^{-1} at 50 mm. Calculate the expected corrected count rate at 80 mm from the source.

(2)

EXAM QUESTION – Q4: Inverse-Square Law Data Analysis (5 marks)

(c) A student records these corrected count rates from a gamma source: $d = 0.20 \text{ m}$ 9013 min^{-1} | $d = 0.50 \text{ m}$ 1395 min^{-1} | $d = 1.00 \text{ m}$ 242 min^{-1} Show with calculations why these data are NOT consistent with an inverse-square law.

(3)

(d) State two possible reasons why the results do not follow the expected inverse-square law.

(2)

Lesson 3: Radioactive Decay

DO NOW — Lesson 3

1. A sample starts at $800 \text{ counts min}^{-1}$. Each 5 minutes the count rate halves. What is the count rate after: (a) 5 min, (b) 10 min, (c) 20 min? (3 marks)
2. State two reasons why radioactive decay is described as both random and spontaneous. (2 marks)
3. Calculate: (a) $\ln(2)$, (b) $e^{-1.386}$, (c) the value of λ if $T_{1/2} = 3600 \text{ s}$, using $T_{1/2} = \ln 2 / \lambda$. (3 marks)
4. Convert 4.5×10^9 years into seconds. (1 year = $3.15 \times 10^7 \text{ s}$) (2 marks)

Part 1 of 3 | Decay Constant and Activity

Radioactive decay is **random** and **spontaneous**: it cannot be predicted when any individual nucleus will decay, and external conditions (temperature, pressure, chemical state) have no effect.

Decay Constant λ

The decay constant λ is the **probability** that a given nucleus decays per unit time. It is unique to each radioactive isotope.

Units: s^{-1} (per second)

Activity A

Activity is the number of nuclear decays per second. 1 Becquerel (Bq) = 1 decay per second.

$$A = \lambda N$$

where N is the number of undecayed nuclei present. The minus sign indicates N is decreasing:

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

The activity of a sample continuously decreases as the number of undecayed nuclei falls.

Questions

1. What is meant by the term 'decay constant'? Give its units.

(2 marks)

2. What is meant by 'activity' of a radioactive source? State the unit.

(2 marks)

Part 2 of 3 | Half-Life and Exponential Decay

Half-Life $T_{1/2}$: The time taken for the number of undecayed nuclei (or the activity) to fall to **half** of its initial value.

$$T_{1/2} = \frac{\ln 2}{\lambda} = \frac{0.693}{\lambda}$$

• Large $\lambda \rightarrow$ short half-life (decays quickly) • Small $\lambda \rightarrow$ long half-life (decays slowly)

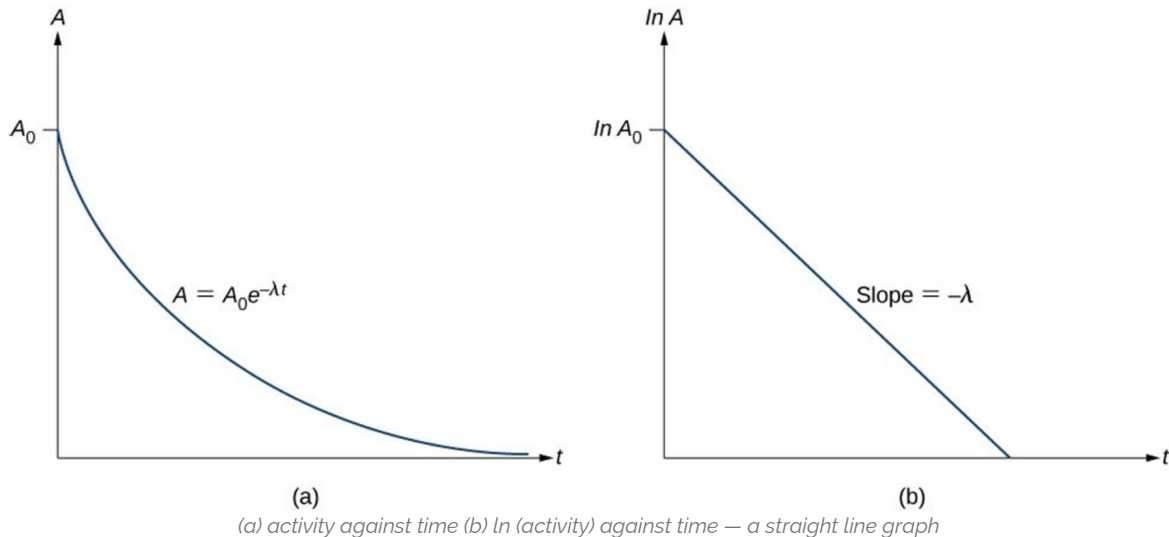
Exponential Decay Equations

$$N = N_0 e^{-\lambda t} \quad A = A_0 e^{-\lambda t}$$

where N_0 and A_0 are the initial values at $t = 0$.

Reading half-life from a graph: Choose any starting value, find the time for it to fall to half — this is $T_{1/2}$. Repeat from a different starting point for reliability.

Linearising: Taking \ln of both sides: $\ln A = \ln A_0 - \lambda t$. A graph of $\ln A$ vs t gives a straight line with gradient $-\lambda$.



Questions

3. A sample contains one mole of sodium (half-life = 2.6 years). Calculate: (a) the decay constant in s^{-1} , (b) the initial activity.

(4 marks)

4. What type of decay curve describes radioactive decay?

(1 mark)

5. How are the decay constant and half-life related? State the equation.

(2 marks)

6. Iodine-124 has a half-life of 4.2 days. Estimate the fraction of the original sample remaining after 10 days.

(3 marks)

7. In an experiment to find the half-life of Zn-63, the following background-corrected count rates (counts min^{-1}) were measured: $t=0$: 229; $t=0.5\text{h}$: 128; $t=1.0\text{h}$: 71; $t=1.5\text{h}$: 46; $t=2.0\text{h}$: 26; $t=2.5\text{h}$: 19; $t=3.0\text{h}$: 7.

(a) Describe how you would find the half-life from a graph of count rate vs time.

(b) Describe how plotting $\ln(\text{count rate})$ vs time would give a more reliable value.

(4 marks)

8. Explain how you would find the half-life of a substance if it is known to be more than 10,000 years, given that a sample can be isolated.

(3 marks)

Part 3 of 3 | Radioactive Dating and Medical Applications

Carbon Dating

Living wood continuously exchanges carbon with the atmosphere, maintaining a constant ratio of radioactive ^{14}C to stable ^{12}C (1 in 10^{12}). Once wood is cut, the ^{14}C decays without replacement.

By comparing the ^{14}C activity of ancient wood with that of living wood, the age can be calculated using: $A = A_0 e^{-\lambda t}$

$$t = \frac{1}{\lambda} \ln\left(\frac{A_0}{A}\right)$$

Medical applications of radioactive tracers

Gamma emitters (e.g. Tc-99m) are injected and detected externally by scanners. Requirements: short half-life (limits dose), gamma emitter (penetrates body for detection), not alpha/beta (would damage tissue). Gamma rays can cause some cell damage.

Limitations of carbon dating: Assumes constant atmospheric ^{14}C ratio (may not hold over long timescales); very low activity gives large statistical uncertainty; contamination affects results.

Questions

3. A scientist makes these measurements on a rock sample: • Decay rate of potassium = 0.16 Bq • Mass of potassium = 0.6×10^{-6} g • Mass of argon = 4.2×10^{-6} g (molar mass of K = 40 g mol^{-1}) Show that the decay constant of potassium is $1.8 \times 10^{-17} \text{ s}^{-1}$ and its half-life is 1.2×10^9 years.

(4 marks)

4. Calculate the age of the rock (originally no argon). = $1.77 \times 10^{-17} \text{ s}^{-1}$

(4 marks)

5. Identify and explain a difficulty involved in measuring the decay rate of 0.16 Bq.

(2 marks)

6. Iodine-124 (half-life 4.2 days) is used in medical diagnosis. Estimate the fraction remaining after 10 days.

(3 marks)

7. Explain how you would find the half-life of a substance known to be more than 10,000 years, given a sample can be isolated.

(3 marks)

8. In an experiment to find the half-life of Zn-63, the following count rates were recorded (background = 30 min^{-1}): t = 0: 259 | t = 0.5 h: 158 | t = 1.0 h: 101 | t = 1.5 h: 76 | t = 2.0 h: 56 | t = 2.5 h: 49 | t = 3.0 h: 37

(a) Plot corrected count rate vs time and find the half-life graphically.

(b) Plot $\ln(\text{corrected count rate})$ vs time; find half-life from the gradient.

(c) Which method gives a more reliable value, and why?

(5 marks)

9. In living wood, 1 in 10^{12} carbon atoms is radioactive ^{14}C with a decay constant of $3.84 \times 10^{-12} \text{ s}^{-1}$. A sample of 3.00×10^{23} carbon atoms is taken from living wood.

(a) Calculate the half-life of ^{14}C in years. (1 year = 3.15×10^7 s)

(b) Show that the activity of ^{14}C in this living wood sample is approximately 1.15 Bq.

(5 marks)

10. A 3.00×10^{23} carbon sample from an ancient boat has a ^{14}C activity of 0.65 Bq. Calculate the age of the ancient boat in years. ($\lambda = 3.84 \times 10^{-12} \text{ s}^{-1}$, 1 year = $3.15 \times 10^7 \text{ s}$)
- (3 marks)
11. Give two reasons why it is difficult to obtain a reliable age for the ancient boat from carbon dating.
- (2 marks)
12. Explain why a gamma emitter such as Tc-99m is suitable for use as a medical tracer, while an alpha emitter would not be suitable.
- (3 marks)

Exam-Style Questions — Lesson 3

EXAM QUESTION – Q1: Carbon Dating (11 marks)

- (a) What is meant by the decay constant?
- (1)
- (b) Calculate the half-life of ^{14}C in years, given $\lambda = 3.84 \times 10^{-12} \text{ s}^{-1}$ and 1 year = $3.15 \times 10^7 \text{ s}$. Give your answer to an appropriate number of significant figures.
- (3)
- (c) Show that the rate of decay of ^{14}C atoms in a living wood sample ($N_0(^{14}\text{C}) = 3.00 \times 10^{11}$) is 1.15 Bq.
- (2)
- (d) A sample from an ancient boat has an activity of 0.65 Bq. Calculate the age of the boat in years.
- (3)
- (e) Give two reasons why it is difficult to obtain a reliable age from this carbon dating.
- (2)

Lesson 4: Modes of Decay

DO NOW — Lesson 4

1. The isotope $^{238}_{92}\text{U}$ undergoes alpha decay. State the nucleon number and proton number of the daughter nucleus, and name the element. (2 marks)
2. Write the nuclear equation for the beta-minus decay of $^{14}_6\text{C}$, including all particles emitted. (3 marks)
3. In alpha decay, state the change in: (a) proton number Z, (b) nucleon number A, (c) neutron number N. (3 marks)
4. Gamma emission follows alpha or beta decay. State the change in Z and A during gamma emission, and explain why. (2 marks)

Part 1 of 3 | The N-Z Graph and Nuclear Stability

The **N-Z graph** (neutron number vs proton number) shows the region of nuclear stability known as the 'valley of stability'.

- For light nuclei ($Z \leq 20$): the line of stability follows $N = Z$ (equal numbers of protons and neutrons).
- For heavier nuclei: the line curves above $N = Z$, passing through approximately $Z = 80$, $N = 120$.

Why more neutrons in heavy nuclei? Protons repel each other electrostatically. The strong nuclear force acts only at very short range (~1–3 fm). As Z increases, protons further apart no longer feel each other's strong force, only electrostatic repulsion. Extra neutrons provide additional strong nuclear force binding without electrostatic repulsion.

Position on the N-Z graph predicts decay mode:

- **Above** the stability line (too many neutrons): β^- emission
- **Below** the stability line (too many protons): β^+ emission or electron capture
- **Top right** (very large, heavy nuclei): α emission

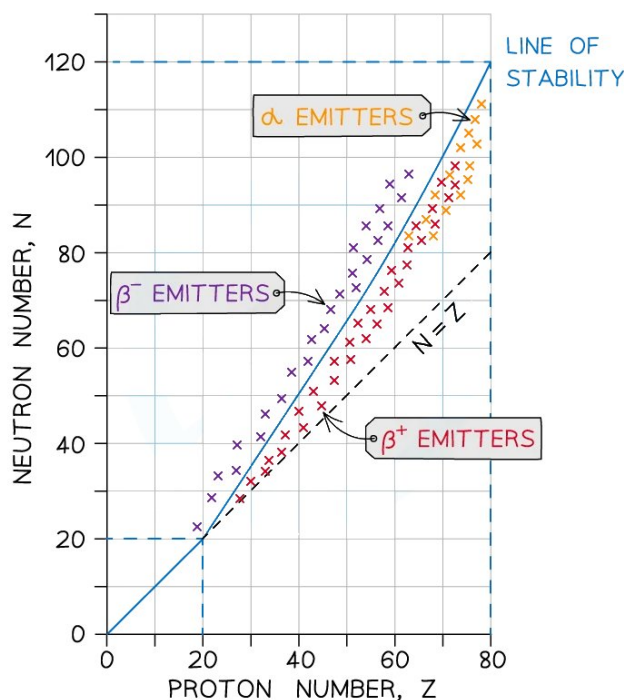


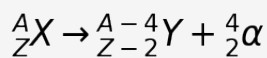
Fig 4.1 — N-Z stability graph (valley of stability)

Questions

1. Sketch a graph of neutron number N against proton number Z for stable nuclei over the range $Z = 0$ to 80. Show suitable values on the N axis.
(2 marks)
2. On your N - Z graph, mark a typical position for a nuclide that decays by: (i) α emission (label W), (ii) β^- emission (label X), (iii) β^+ emission (label Y).
(3 marks)
3. Explain why, for low values of Z , stable nuclei have roughly equal numbers of protons and neutrons ($N \approx Z$), whereas heavier stable nuclei have more neutrons than protons.
(4 marks)

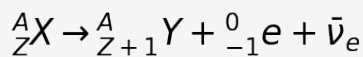
Part 2 of 3 | Alpha, Beta-Minus, and Beta-Plus Decay

Alpha (α) Decay — ejects a helium nucleus:



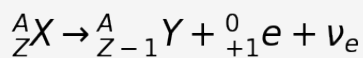
Loss: 2 protons, 2 neutrons. Moves the nuclide 2 left and 2 down on the N - Z graph.

Beta-minus (β^-) Decay — a neutron transforms into a proton:



Loss: 1 neutron; Gain: 1 proton. Also emits an electron antineutrino. Moves the nuclide 1 right and 1 down on the N - Z graph.

Beta-plus (β^+) Decay — a proton transforms into a neutron:



Loss: 1 proton; Gain: 1 neutron. Also emits an electron neutrino. Moves the nuclide 1 left and 1 up on the N - Z graph.

Gamma (γ) emission following alpha or beta decay: the daughter nucleus is left in an excited state and releases the excess energy as a gamma photon. No change to Z or A .

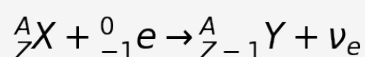
Questions

4. Write the equation for the alpha decay of radium-226 ($Z = 88$) to radon ($Z = 86$).
(2 marks)
5. Write the equation for the beta-minus decay of carbon-14 ($Z = 6$) to nitrogen.
(2 marks)
6. A nuclide undergoes beta-plus decay. Describe what happens to: (a) the proton number, (b) the nucleon number.
(2 marks)
7. Describe what gamma ray emission is and explain why it produces no change in the nuclear structure.
(2 marks)

Part 3 of 3 | Electron Capture and Nucleon Emission

Electron Capture

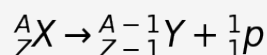
A proton-rich nucleus can capture one of its own orbital electrons. The proton and electron combine to form a neutron and an electron neutrino is emitted:



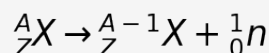
Effect: proton number decreases by 1, nucleon number unchanged. Same effect on N-Z graph as β^+ decay.

Nucleon Emission (rare)

Proton emission (proton-rich nucleus):



Neutron emission (neutron-rich nucleus):



Decay chains: Heavy radioactive isotopes often undergo a series of alpha and beta decays before reaching a stable end-product. The decay sequence can be tracked on the N-Z graph.

Iodine-131 (used to treat overactive thyroid): decays by β^- to xenon, which then emits γ rays.

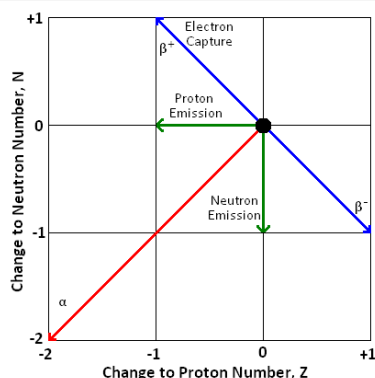
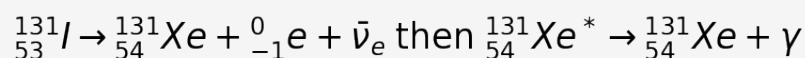


Fig 4.2 – Effect of each decay mode on proton/neutron numbers

Questions

8. Explain the process of electron capture. What change occurs to the proton number? (2 marks)
9. The isotope ${}^{222}\text{Rn}$ decays sequentially to ${}^{206}\text{Pb}$ via alpha and beta-minus emissions. Four alpha particles are emitted. Calculate how many beta-minus particles are emitted. (3 marks)
10. A nuclide is described as proton-rich. Discuss two ways in which it may decay. (4 marks)
11. Write the nuclear equation for the decay of iodine-131 by β^- emission. (2 marks)

Exam-Style Questions – Lesson 4

EXAM QUESTION – Q1: N-Z Graph and Decay Modes (12 marks)

- (a) Sketch an N-Z graph for stable nuclei ($Z = 0$ to 80) and mark positions W (α emitter), X (β^- emitter), and Y (β^+ emitter). (5)
- (b) ${}^{222}\text{Rn}$ decays to ${}^{206}\text{Pb}$ via 4 alpha decays and n beta-minus decays. Calculate n . (2)

- (c) A proton-rich nuclide can decay in two ways. Discuss both. (3)
- (d) A nucleus of ^{208}Pb decays by electron capture to thallium (Tl). Write the equation for this decay. (2)

EXAM QUESTION – Q3: Nuclear Stability and Strong Force (9 marks)

- (a(i)) Explain why, despite electrostatic repulsion between protons, nuclei of atoms of low nucleon number are stable. (3)
- (a(ii)) Suggest why stable nuclei of higher nucleon number have greater numbers of neutrons than protons. (3)
- (a(iii)) All nuclei have approximately the same density. State what this suggests about the strong nuclear force. (3)

Lesson 5: Nuclear Radius

DO NOW — Lesson 5

- Write the formula for electric potential energy between two point charges q and Q separated by distance r . State the unit of each quantity. (2 marks)
- Convert 5.0 MeV into joules. ($1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$) (2 marks)
- State the de Broglie equation ($\lambda = h/p$) and calculate the wavelength of an electron with momentum $1.5 \times 10^{-24} \text{ kg m s}^{-1}$. ($h = 6.63 \times 10^{-34} \text{ J s}$) (2 marks)
- For diffraction to reveal the structure of an object, what must be true of the wavelength of the incident wave relative to the size of the object? (2 marks)

Part 1 of 3 | Closest Approach of Alpha Particles

When an alpha particle is fired head-on at a nucleus, it decelerates as the electrostatic repulsive force does work against it. At the point of closest approach, all kinetic energy has been converted to electric potential energy:

$$E_K = E_P = \frac{qQ}{4\pi\epsilon_0 r}$$

Rearranging for r (distance of closest approach / upper limit of nuclear radius):

$$r = \frac{qQ}{4\pi\epsilon_0 E_K}$$

where q = charge of alpha particle = $2e$, Q = charge of nucleus = Ze , $\epsilon_0 = 8.85 \times 10^{-12} \text{ C}^2 \text{ J}^{-1} \text{ m}^{-1}$.

This is an **upper limit** on the nuclear radius because the alpha particle stops before reaching the nucleus.

Example result for gold: $r \approx 4.55 \times 10^{-14} \text{ m}$. Modern measurements give $\sim 6.5 \text{ fm}$ for gold.

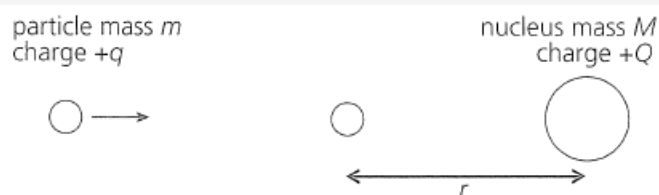


Fig 5.1 — Alpha particle approaching a nucleus head-on

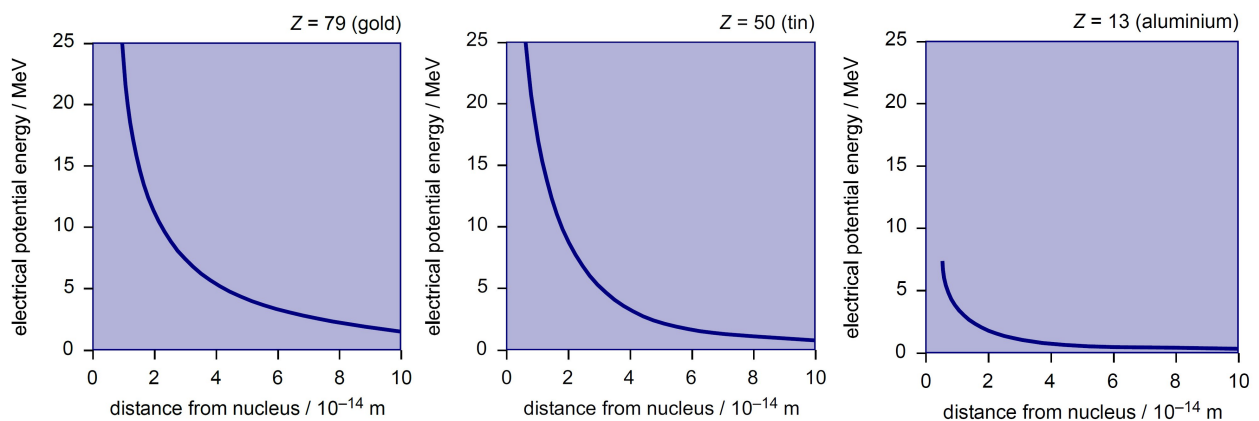


Fig 5.2 — Electrical PE vs distance for gold (Z=79), tin (Z=50) and aluminium (Z=13)

Questions

- An alpha particle (KE = 4.9 MeV) is directed head-on at a gold nucleus (Z = 79). Calculate the electric potential energy in joules at the point of closest approach. (1 eV = 1.6×10^{-19} J) (2 marks)
- Using the answer above, calculate r, the distance of closest approach. ($e = 1.6 \times 10^{-19}$ C, $\epsilon_0 = 8.85 \times 10^{-12}$ C² J⁻¹ m⁻¹, Z_{gold} = 79) (3 marks)
- The target is changed to a nucleus with fewer protons. The alpha particle has the same initial KE. Explain, without calculation, what happens to the distance of closest approach. (2 marks)
- At a distance $r = 1.0 \times 10^{-14}$ m from a gold nucleus (Z = 79), show that the electrical potential energy of an alpha particle is between 20 and 25 MeV. (3 marks)

Part 2 of 3 | Electron Diffraction

High-energy electrons (hundreds of MeV) are diffracted by atomic nuclei. The diffraction pattern shows a minimum at angle θ related to the nuclear radius D:

$$\sin \theta_{\min} = \frac{0.61 \lambda}{D}$$

The de Broglie wavelength of electrons accelerated through a potential difference V:

$$\lambda = \frac{h}{mv} = \frac{h}{\sqrt{2meV}}$$

For relativistic electrons (very high energy, $E \gg$ rest energy):

$$\lambda = \frac{hc}{E}$$

The diffraction pattern shows rings — similar to X-ray diffraction by crystal planes but due to nuclei rather than atoms.

Resolving power: To resolve objects of size d, need wavelength $\lambda \leq d$. Electrons at 400 MeV have $\lambda \approx 3 \times 10^{-15}$ m — comparable to nuclear diameters (~few fm).

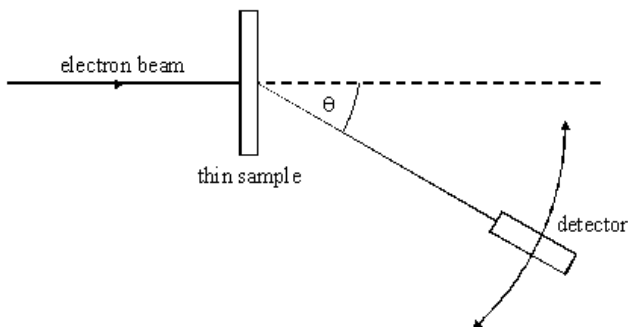


Fig 5.3 — Electron intensity vs angle (first minimum at θ)

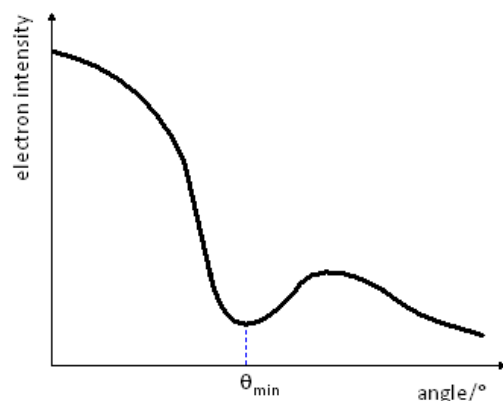


Fig 5.4 — Electron diffraction setup

Questions

- In an electron diffraction experiment, electrons of energy 5.94×10^{-11} J are fired at oxygen-16 nuclei. Show that the de Broglie wavelength is about 3.3×10^{-15} m. (Use approximation: $p = E/c$)

(2 marks)

6. For the oxygen-16 experiment above, the first minimum occurs at $\theta \approx 41^\circ$ (read from graph). Calculate the radius of an oxygen-16 nucleus.

(2 marks)

4. Using the gold potential energy graph ($Z = 79$, Fig 5.2):

- (a) At what distance r will a 5 MeV alpha particle colliding head-on come to rest momentarily?
(b) At what distance r will a 5 MeV alpha particle have lost half its initial kinetic energy?
(c) What energy would an alpha particle need to approach within 2.0×10^{-14} m of the gold nucleus?

(4 marks)

5. The electrical potential energy graphs for gold ($Z = 79$), tin ($Z = 50$) and aluminium ($Z = 13$) are shown in Fig 5.2.

- (a) Why are values of electrical PE smaller at the same r for tin and aluminium than for gold?
(b) At $r = 5.0 \times 10^{-14}$ m: $E_P(\text{gold}) = 4.55$ MeV, $E_P(\text{tin}) = 2.88$ MeV. Explain the ratio $4.55/2.88 = 1.58$.
(c) Approximately how close can a 5 MeV alpha particle get to a tin nucleus?
(d) From the graph, how close could a 5 MeV alpha get to aluminium ($Z = 13$)?

(5 marks)

6. How much kinetic energy is needed to bring two lead nuclei ($Z = 82$) within 1.0×10^{-14} m of one another in a head-on collision in a heavy-ion collider? ($e = 1.6 \times 10^{-19}$ C, $k = 8.85 \times 10^{-12}$ C² J⁻¹ m⁻¹)

(3 marks)

7. Show that 400 MeV electrons have a de Broglie wavelength of about 3.0×10^{-15} m.

(3 marks)

8. A beam of 400 MeV electrons is scattered by carbon-12 nuclei. The first diffraction minimum is at 42° . Calculate the radius of a carbon-12 nucleus.

(3 marks)

Part 3 of 3 | Nuclear Radius Formula and Nuclear Density

Plotting nuclear radius R vs A (nucleon number) produces a curve. Plotting R vs $A^{1/3}$ gives a straight line through the origin, showing:

$$R = r_0 A^{1/3}$$

where $r_0 \approx 1.2\text{--}1.5$ fm (radius of a single nucleon).

Nuclear Density (same for all nuclei!)

Assuming mass = Au (where $u = 1.66 \times 10^{-27}$ kg) and spherical nucleus:

$$\rho = \frac{m}{V} = \frac{Au}{\frac{4}{3}\pi r_0^3 A} = \frac{u}{\frac{4}{3}\pi r_0^3}$$

The A cancels — nuclear density is **independent of nucleon number**. This means the strong nuclear force is saturated (each nucleon only interacts with its nearest neighbours).

$$\rho_{\text{nucleus}} \approx 3.4 \times 10^{17} \text{ kg m}^{-3}$$

This is $\sim 10^{14}$ times denser than ordinary matter ($\sim 10^3 \text{ kg m}^{-3}$), suggesting atoms are almost entirely empty space.

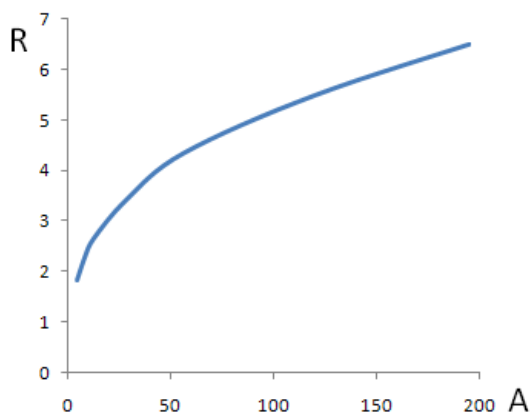


Fig 5.5 – R vs A (curve)

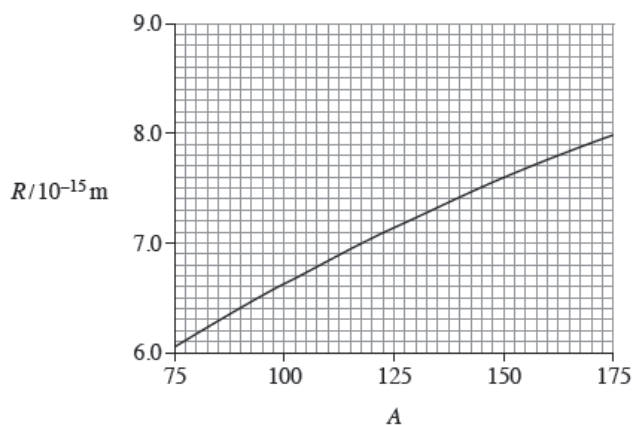


Fig 5.6 – R vs A^(1/3) (linear)

Questions

- The radius of the gold nucleus is $R = 7.16 \times 10^{-15}$ m. Given $R = r_0 A^{1/3}$ and $r_0 = 1.23 \times 10^{-15}$ m, determine the number of nucleons in gold. (3 marks)
- Show that the radius of a ^{51}V nucleus ($A = 51$) is about 5×10^{-15} m. ($r_0 = 1.4 \times 10^{-15}$ m) (2 marks)
- Calculate the density of a ^{51}V nucleus. ($m = 1.66 \times 10^{-27}$ kg, $r_0 = 1.4 \times 10^{-15}$ m) (3 marks)
- What does the fact that all nuclei have approximately the same density suggest about the nature of the strong nuclear force? (2 marks)

Additional: Electrons Measure the Size of Nuclei

High-energy electrons have de Broglie wavelengths comparable to nuclear diameters. When electrons are diffracted by nuclei, the first minimum in intensity occurs at angle θ , where d is the nuclear diameter:

$$\sin \theta = \frac{1.22 \lambda}{d}$$

For relativistic high-energy electrons:

$$p = \frac{E}{c} \Rightarrow \lambda = \frac{h}{p} = \frac{hc}{E}$$

Questions

- Show that if a first dark ring is seen at $\theta = 30^\circ$, the circular objects have diameter approximately twice the wavelength (use the formula below for this question only): (2 marks)

$$\sin \theta = \frac{\lambda}{d}$$
- Use the formula below to find the angle of the first dark ring for particles four wavelengths in diameter. (2 marks)

$$\sin \theta = \frac{1.22 \lambda}{d}$$
- Calculate the energy in joules of an electron with energy 100 MeV. ($1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$)

(2 marks)

4. Calculate the momentum of a 100 MeV electron. ($c = 3.0 \times 10^8 \text{ m s}^{-1}$)

(2 marks)

5. Calculate the de Broglie wavelength of 100 MeV electrons. ($h = 6.63 \times 10^{-34} \text{ J s}$)

(2 marks)

6. The radius of a proton or neutron is $\sim 1.2 \times 10^{-15} \text{ m}$. What is the approximate ratio of the wavelength of 100 MeV electrons to the diameter of a proton?

(2 marks)

7. A beam of 400 MeV electrons is scattered by carbon-12 nuclei ($A = 12$). The first minimum is at $\theta = 42^\circ$ ($\sin \theta = 0.67$). Use the formula ($\lambda = hc/E$) to show the radius of the carbon-12 nucleus is about $2.7 \times 10^{-15} \text{ m}$.

$$\lambda = \frac{hc}{E} \quad \sin \theta_{\min} = \frac{1.22 \lambda}{d}$$

(3 marks)

8. A uranium-238 nucleus has a radius of about $7.4 \times 10^{-15} \text{ m}$. Roughly what energy of electrons would be needed to determine its size?

(2 marks)

Exam-Style Questions — Lesson 5

EXAM QUESTION – Q1: Electron Diffraction and Rutherford Scattering (12 marks)

(a(i)) Show that the de Broglie wavelength of electrons (energy $5.94 \times 10^{-11} \text{ J}$) is about $3.3 \times 10^{-15} \text{ m}$.

(2)

(a(ii)) The first diffraction minimum for O-16 occurs at $\sim 41^\circ$. Calculate the nuclear radius ($\sin \theta = 0.61 \lambda / R$).

(2)

(b(i)) Sketch a labelled diagram of Rutherford's scattering apparatus.

(2)

(b(ii)) State and explain the results of the scattering experiment. Your answer should include: the main observations, their significance, and how they placed an upper limit on the nuclear radius.

(6)

Lesson 6: Mass and Energy

DO NOW — Lesson 6

1. State Einstein's mass-energy equation and calculate the energy released when a mass of 3.0×10^{-29} kg is converted to energy. ($c = 3.0 \times 10^8$ m s⁻¹) (3 marks)
2. $1 \text{ u} = 1.66 \times 10^{-27}$ kg. A proton has mass 1.00728 u. Calculate its mass in kg. (2 marks)
3. A nucleus of ${}^{59}_{27}\text{Co}$ has $Z = 27$. State the number of neutrons. Calculate the total mass of the separated protons and neutrons. ($m_p = 1.00728 \text{ u}$, $m_n = 1.00867 \text{ u}$) (3 marks)
4. State what is meant by the binding energy of a nucleus in one sentence. (2 marks)

Part 1 of 3 | Mass Defect

The mass of a nucleus is **less** than the total mass of its constituent protons and neutrons. This difference is called the **mass defect** Δm :

$$\Delta m = (Z m_p + N m_n) - m_{\text{nucleus}}$$

Example — Helium-4 nucleus (2p + 2n):

$$\text{Mass of nucleons} = 2 \times 1.673 \times 10^{-27} + 2 \times 1.675 \times 10^{-27} = 6.696 \times 10^{-27} \text{ kg}$$

$$\text{Mass of nucleus} = 6.648 \times 10^{-27} \text{ kg}$$

$$\Delta m = 6.696 \times 10^{-27} - 6.648 \times 10^{-27} = 0.048 \times 10^{-27} \text{ kg} = 0.029 \text{ u}$$

The atomic mass unit u is used for convenience: $1 \text{ u} = 1.661 \times 10^{-27} \text{ kg}$

Particle	Mass (kg)	Mass (u)
Proton	1.673×10^{-27}	1.00728
Neutron	1.675×10^{-27}	1.00867
Electron	9.11×10^{-31}	0.00055

Questions

1. Define the mass defect of a nucleus. (2 marks)
2. ${}^1_1\text{H} + {}^7_3\text{Li} \rightarrow {}^4_2\text{He} + {}^4_2\text{He}$. Masses: H = 1.0073 u, Li = 7.0160 u, He = 4.0015 u. Show that the mass decreases and calculate Δm . (3 marks)
3. Each alpha particle produced in Cockcroft and Walton's experiment had energy 8.5 MeV. Calculate the total kinetic energy gained and show it is consistent with $\Delta E = \Delta m c^2$. (3 marks)

Part 2 of 3 | Binding Energy and Einstein's $E = mc^2$

Einstein's mass-energy equivalence:

$$E = mc^2 \Rightarrow \Delta E = \Delta m c^2$$

The **binding energy** of a nucleus is the energy required to completely separate the nucleus into its constituent protons and neutrons. It equals the mass defect $\times c^2$:

$$E_{\text{binding}} = \Delta m \cdot c^2$$

The mass defect arises because energy is released when nucleons bind together (strong force attracts them, they fall into a lower energy state — like a ball rolling downhill). The 'missing' mass has been converted to this released energy.

Convenient unit: **1 u = 931.3 MeV/c²** (or equivalently, 1 u of mass defect corresponds to 931.3 MeV of binding energy)

Example — Helium-4: $\Delta m = 0.029 \text{ u} \rightarrow E = 0.029 \times 931.3 = 27 \text{ MeV}$

For deuteron (H-2): proton (1.0073 u) + neutron (1.0087 u) vs deuteron (2.0136 u):

$$\Delta m = 1.0073 + 1.0087 - 2.0136 = 0.0024 \text{ u} \rightarrow E = 0.0024 \times 931.3 = 2.24 \text{ MeV}$$

Questions

4. State what is meant by the binding energy of a nucleus.

(2 marks)

5. Calculate the binding energy of a ⁵⁹Co nucleus in MeV. (nuclear mass = 58.93320 u; m_p = 1.00728 u; m_n = 1.00867 u; 1 u = 931.3 MeV/c²) Co-59 has Z = 27, N = 32.

(4 marks)

6. Calculate the average binding energy per nucleon of ⁶⁴Zn (Z = 30, N = 34). (atom mass = 63.92915 u; m_p = 1.00728 u; m_n = 1.00867 u; m_e = 0.00055 u; 1 u = 931.3 MeV)

(5 marks)

Part 3 of 3 | The Binding Energy Per Nucleon Graph

The graph of **binding energy per nucleon** (MeV/nucleon) vs **nucleon number A** is one of the most important in nuclear physics:

- Rises steeply for small A (H, He, Li...)
- Peaks at **⁵⁶Fe (iron-56) at ~8.8 MeV/nucleon** — the most stable nucleus.
- Gently decreases for heavier nuclei (uranium ≈ 7.6 MeV/nucleon)

A higher binding energy per nucleon means more energy is needed to remove one nucleon → **more stable**.

Implications:

- **Fusion:** light nuclei (A < 56) fusing releases energy because the product has higher BE/nucleon than the reactants.
- **Fission:** heavy nuclei (A > 56) splitting releases energy because the fragments have higher BE/nucleon than the parent.

Energy released per fission ≈ difference in total binding energies of products vs reactant.

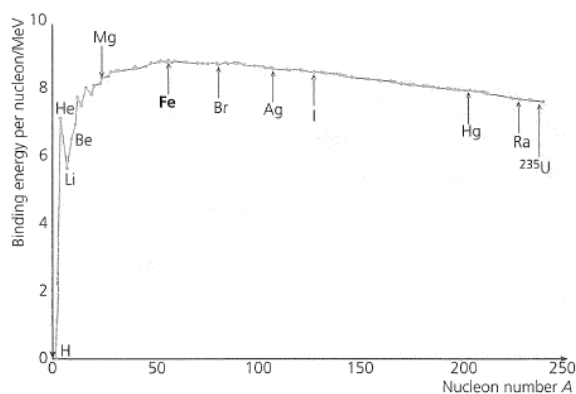


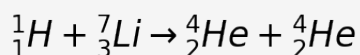
Fig 6.1 — Binding energy per nucleon vs nucleon number

Questions

7. Why would you expect ^{64}Zn to be very stable based on its binding energy per nucleon? (1 mark)
8. Explain why energy is released in nuclear fission of uranium-235. (2 marks)
9. Explain why nuclear fusion of hydrogen isotopes releases energy. (2 marks)
10. The fission of U-235: $^{235}\text{U} + \text{n} \rightarrow ^{133}\text{Sb} + ^{99}\text{Nb} + 4\text{n}$. The mass of $^{235}\text{U} = 235.0439 \text{ u}$, $\text{Sb-133} = 132.9152 \text{ u}$, $\text{Nb-99} = 98.9116 \text{ u}$, neutron = 1.0087 u . Show that the energy change per fission is about 200 MeV. (4 marks)

Additional: Change in Energy — Change in Mass (Cockcroft-Walton)

In Cockcroft and Walton's 1932 experiment, protons (energy 0.8 MeV) bombarded lithium:



Masses (u): H = 1.0073, Li = 7.0160, He = 4.0015. $1 \text{ u} = 931 \text{ MeV}/c^2$.

Questions

1. Show that mass decreases in this reaction. Calculate m in u and kg. ($1 \text{ u} = 1.6605 \times 10^{-27} \text{ kg}$) (3 marks)
2. Each alpha particle had energy 8.5 MeV. Calculate the total kinetic energy gained and show it is consistent with $E = mc^2$. (3 marks)
3. Two deuterium nuclei can fuse: ${}^2\text{H} + {}^2\text{H} \rightarrow {}^3\text{He} + \text{n}$. Masses: ${}^2\text{H} = 2.014102 \text{ u}$, ${}^3\text{He} = 3.016030 \text{ u}$, $\text{n} = 1.008665 \text{ u}$. Calculate the energy released per fusion event in MeV and joules. (4 marks)

Additional: Fusion in a Kettle

The ratio of deuterium (${}^2\text{H}$) atoms to ordinary hydrogen in water is roughly 1 : 7000. A litre of water contains about 55.6 moles (H_2O molar mass $\approx 18 \text{ g mol}^{-1}$). Deuterium fusion releases about 3.27 MeV per pair of nuclei fused.

Questions

1. Write the balanced equation for the fusion of two deuterium nuclei ${}^2\text{H}$ to give ${}^3\text{He}$ plus one other particle. (2 marks)
2. A litre of water contains about 55.6 moles. How many H_2O molecules does it contain? ($N_A = 6.02 \times 10^{23} \text{ mol}^{-1}$) (2 marks)
3. How many molecules of heavy water (D_2O , with two deuterium atoms) are in the kettle? (ratio D:H \approx 1:7000 so 1 in 7000 water molecules is D_2O — approximately) (2 marks)
4. Each pair of deuterium nuclei that fuses releases $5.23 \times 10^{-13} \text{ J}$. Calculate the total energy released if all the deuterium in the kettle fused. (3 marks)

5. It requires 4200 J to heat 1 kg of water by 1 K. How many litres of water could be heated through 100 K by the fusion energy calculated above?

(2 marks)

Exam-Style Questions — Lesson 6

EXAM QUESTION – Q1: Binding Energy of Zinc-64 (12 marks)

- (a(i)) State what is meant by binding energy of a nucleus and explain how it arises. (3)
- (a(ii)) State what is meant by mass difference (mass defect). (2)
- (a(iii)) State the relationship between binding energy and mass difference. (1)
- (b) Calculate the average binding energy per nucleon in MeV/nucleon for ^{64}Zn ($Z=30$). (atom mass = 63.92915 u; $m_p = 1.00728$ u; $m_n = 1.00867$ u; $m_e = 0.00055$ u; $1\text{ u} = 931.3$ MeV) (5)
- (c) Why would you expect the zinc nucleus to be very stable? (1)

EXAM QUESTION – Q2: Reactor Fission (10 marks)

- (a) Uranium nuclei undergo induced fission with thermal neutrons. Explain: (i) induced fission, (ii) thermal neutrons. (3)
- (b(i)) For $^{235}_{92}\text{U} + n \rightarrow ^{92}_{36}\text{Kr} + ^{141}_{56}\text{Ba} + N$ neutrons. Calculate N. (1)
- (b(ii)) How do the product neutrons differ from the initial neutron? (1)
- (b(iii)) Calculate the energy released in MeV per fission. ($m_n = 1.00867$ u; $m(^{235}\text{U nucleus}) = 234.99333$ u; $m(^{92}\text{Kr nucleus}) = 91.90645$ u; $m(^{141}\text{Ba nucleus}) = 140.88354$ u; $1\text{ u} = 931$ MeV) (5)

EXAM QUESTION – Q4: Uranium Fission to Tc and In (8 marks)

- (a) State what is meant by the binding energy of a nucleus. (2)
- (b(i)) When $^{235}_{92}\text{U}$ absorbs a slow neutron it can fission to $^{112}_{43}\text{Tc}$ and $^{122}_{49}\text{In}$. Complete the equation: $^1_0\text{n} + ^{235}_{92}\text{U} \rightarrow ^{112}_{43}\text{Tc} + ^{122}_{49}\text{In} + ?$ (1)
- (b(ii)) Calculate energy released in MeV. (BE/nucleon: $^{235}\text{U} = 7.59$ MeV, $^{112}\text{Tc} = 8.36$ MeV, $^{122}\text{In} = 8.51$ MeV) (3)
- (b(iii)) Calculate the loss of mass in kg. ($1\text{ MeV} = 1.6 \times 10^{-13}$ J, $c = 3.0 \times 10^8$ m s $^{-1}$) (2)

EXAM QUESTION – Q2: Iron-59 and Cobalt-59 (10 marks)

- (a) Calculate the binding energy in MeV of a $^{59}_{27}\text{Co}$ nucleus. (Nuclear mass = 58.93320 u; $m_p = 1.00728$ u; $m_n = 1.00867$ u; $1\text{ u} = 931.3$ MeV) (3)

- (b) Fe-59 decays by β^- to Co-59. Total energy released = 2.52×10^{-13} J. Fe-59 can decay to excited states of Co-59 at energies 2.29×10^{-13} J, 2.06×10^{-13} J, and 1.76×10^{-13} J above the ground state. Calculate the maximum KE in MeV of the β^- when Fe-59 decays to the highest excited state (2.29×10^{-13} J). (3)
- (c) State the maximum number of discrete gamma-ray wavelengths that could be emitted. (1)
- (d) Calculate the longest wavelength of the emitted gamma radiation. ($h = 6.63 \times 10^{-34}$ J s, $c = 3.0 \times 10^8$ m s⁻¹) (3)

Lesson 7: Fission and Fusion

DO NOW — Lesson 7

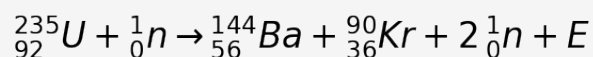
1. Sketch the binding energy per nucleon graph (BE/nucleon vs A). Mark: (a) the peak nucleus and its approximate value in MeV/nucleon, (b) where hydrogen isotopes lie, (c) where uranium lies. (3 marks)
2. State whether energy is released or absorbed when nucleons bind together to form a nucleus. Explain in terms of binding energy per nucleon. (2 marks)
3. A nucleus of $^{235}_{92}\text{U}$ absorbs a thermal neutron. Write the unstable compound nucleus formed. (2 marks)
4. Define 'critical mass' of a fissile material in your own words. (2 marks)

Part 1 of 3 | Nuclear Fission

Nuclear Fission: a heavy nucleus splits into two smaller (daughter) nuclei, releasing energy and free neutrons.

Induced fission: A slow (thermal) neutron is absorbed by a fissile nucleus (e.g. U-235, Pu-239). The resulting unstable nucleus splits.

Example fission of uranium-235:



Typically 2–3 neutrons are released per fission event, along with ~200 MeV of energy.

Chain Reaction: The free neutrons can trigger further fissions, each producing more neutrons — a self-sustaining chain reaction.

Critical Mass: The minimum mass of fissile material needed for a self-sustaining chain reaction. Related to the surface-area-to-volume ratio:

- Mass < critical: more neutrons escape than are produced → reaction stops.
- Mass = critical: rate of neutron production = rate of escape → steady state.
- Mass > critical: more neutrons produced than escape → runaway reaction / meltdown.

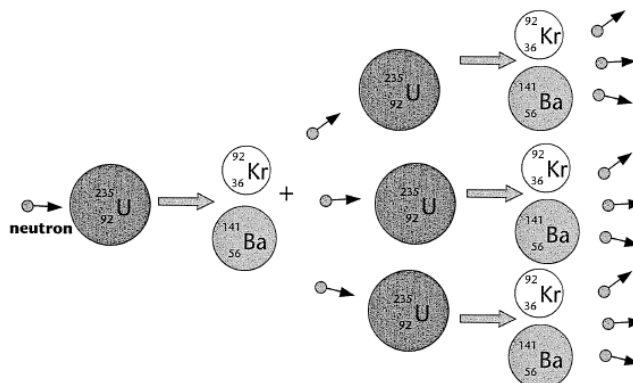


Fig 7.1 — Chain reaction in U-235 fission

Questions

1. Write two balanced equations for the fission of U-235: first showing the formation of the unstable U-236 intermediate, then showing one possible decay to Ba-144 and Kr-90. (3 marks)
2. In the fission $^{235}\text{U} + \text{n} \rightarrow ^{92}\text{Kr} + ^{141}\text{Ba} + \text{N neutrons}$, calculate N. (2 marks)

(3 marks)

(2 marks)

3. Masses: ^{235}U nucleus = 234.993 u, ^{92}Kr nucleus = 91.906 u, ^{141}Ba nucleus = 140.884 u, neutron = 1.009 u. Calculate the energy released in MeV. (1 u = 931 MeV)

(5 marks)

4. Explain what is meant by the critical mass of a fissile material.

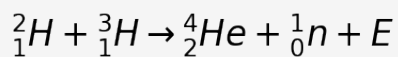
(2 marks)

Part 2 of 3 | Nuclear Fusion

Nuclear Fusion: two light nuclei combine to form a heavier nucleus, releasing energy.

The nuclei must have very high kinetic energies (temperatures of $\sim 10^8$ K in stars or fusion reactors) to overcome the **Coulomb (electrostatic) barrier** – the mutual repulsion of positive charges. Once close enough, the strong nuclear force takes over and pulls them together.

Example – deuterium-tritium fusion (the most promising reaction for fusion reactors):



Energy released ≈ 17.6 MeV per reaction.

Deuterium-deuterium fusion: ${}^2\text{H} + {}^2\text{H} \rightarrow {}^3\text{He} + \text{n} + \text{energy}$

Fusion produces **far more energy per kg of fuel** than fission, and the fuel (hydrogen isotopes from water) is abundant. However, achieving and sustaining the extreme temperatures needed is a major engineering challenge.

Questions

5. Explain why very high temperatures are needed for nuclear fusion.

(3 marks)

6. Write the balanced equation for the deuterium-deuterium fusion: ${}^2\text{H} + {}^2\text{H} \rightarrow {}^3\text{He} + ?$

(2 marks)

7. Masses (u): ${}^2\text{H} = 2.014102$, ${}^3\text{He} = 3.016030$, $\text{n} = 1.008665$. Calculate the energy released per fusion event in MeV and joules.

(4 marks)

8. Explain why fusion releases more energy per kilogram of fuel than fission.

(2 marks)

Part 3 of 3 | Fission vs Fusion: Binding Energy Perspective

Both fission and fusion release energy by increasing the average **binding energy per nucleon** of the products compared to the reactants.

Why fission occurs for heavy nuclei ($A > 56$): The BE/nucleon curve decreases beyond iron. Splitting a heavy nucleus (low BE/nucleon) gives fragments with higher BE/nucleon \rightarrow energy is released.

Why fusion occurs for light nuclei ($A < 56$): The BE/nucleon curve rises steeply for small A. Combining light nuclei gives a product with higher BE/nucleon \rightarrow energy released.

Energy released per nucleon: Fusion releases more energy per nucleon than fission because the increase in BE/nucleon is larger (e.g. $\text{H} \rightarrow \text{He}$: ~ 6 MeV/nucleon gain vs ~ 1 MeV/nucleon for fission).

Fission fragments are neutron-rich: Heavy nuclei ($N \gg Z$) split into fragments that still have the original high N/Z ratio. For lighter, stable nuclei, N/Z is lower. So fission fragments fall above the stability line \rightarrow likely β^- emitters.

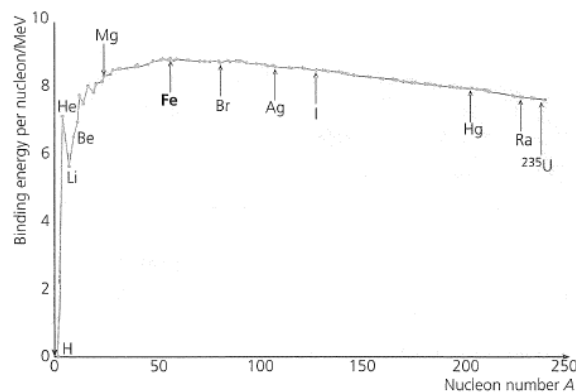


Fig 7.3 — Binding energy per nucleon vs nucleon number

Questions

- Explain, with reference to the binding energy per nucleon graph, why energy is released in both fission and fusion. (4 marks)
- Explain why energy released per nucleon from fusion is greater than from fission, with reference to the graph. (2 marks)
- Explain why fission fragments are unstable and what type of radiation they are likely to emit. (3 marks)
- Calculate the mass difference, in kg, for the O-16 nucleus. (mass of O-16 nucleus = 15.991 u; u = 1.661 × 10⁻²⁷ kg; O-16 has Z = 8, N = 8) (3 marks)

Additional: Fission Practice Questions

A nucleus of ²³U captures a neutron, forming the unstable ²³U which then splits. Mass data (atomic mass units, 1 u = 931 MeV): n = 1.008665 u | Kr = 89.919528 u | ¹Ba = 143.922941 u | ²³U = 235.043923 u | ²Kr = 91.926153 u | Rb = 95.934284 u | ¹³Cs = 137.911011 u | ¹³Ba = 137.905241 u

Questions

- Write two balanced equations for the fission of U-235: first showing formation of unstable ²³U, then showing fission to ¹Ba + Kr. (3 marks)
- Calculate the total mass of the reactants: ²³U + n. (1 mark)
- Calculate the total mass of the products: ¹Ba + Kr + 2n. (2 marks)
- Calculate the change in mass. Does this represent energy gained or lost by the system? (2 marks)
- Convert the mass change into the energy released in MeV. (2 marks)
- Repeat for caesium-138 + rubidium-96 products. Calculate the energy released in MeV. (Masses: ¹³Cs = 137.911011 u, Rb = 95.934284 u) (4 marks)

Exam-Style Questions — Lesson 7

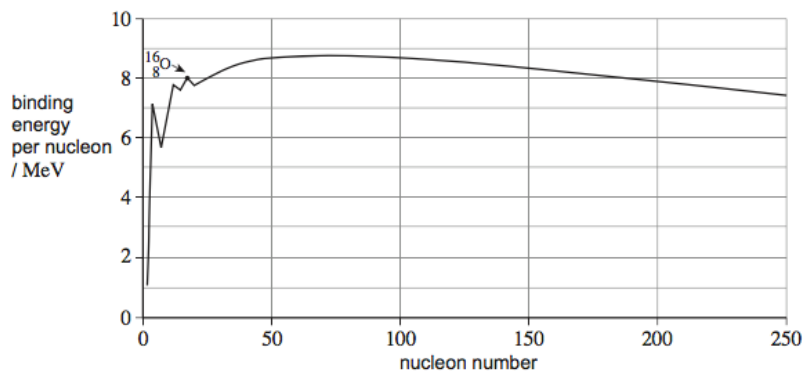


Fig 7.4 — Binding energy per nucleon graph for exam questions

EXAM QUESTION – Q1: Fission, Fusion and Binding Energy (10 marks)

- (a(i))** Explain why nuclei that undergo fission are restricted to high nucleon numbers, while those that undergo fusion are light nuclei. (3)
- (a(ii))** Explain why energy released per nucleon from fusion is greater than from fission. (2)
- (b(i))** Calculate the mass difference of an O-16 nucleus in kg. (nucleus mass = 15.991 u, $Z=8$, $N=8$) (2)
- (b(ii))** Using your answer to (b)(i), calculate the binding energy of O-16 in MeV. (2)
- (b(iii))** Explain how the binding energy of O-16 can be calculated from the BE/nucleon graph. (1)

Lesson 8: Nuclear Reactors

DO NOW — Lesson 8

1. Describe what happens in a nuclear chain reaction and explain why it can be dangerous if uncontrolled. (3 marks)
2. Fission neutrons travel at $\sim 10^7 \text{ m s}^{-1}$. State approximately what speed they must be slowed to before U-235 can capture them, and by roughly what factor. (2 marks)
3. State two materials used as control rods and explain what single property makes them suitable. (2 marks)
4. A reactor produces $2.0 \times 10^9 \text{ W}$ of thermal power with an efficiency of 35%. Calculate the electrical output power in MW. (2 marks)

Part 1 of 3 | Fuel Rods and the Moderator

A nuclear fission reactor generates heat from controlled nuclear fission, which is used to produce steam to drive turbines connected to electrical generators.

Fuel Rods

Made from enriched uranium (higher proportion of U-235 than natural uranium). Natural uranium is 99.28% U-238 and only 0.72% U-235. Enriched fuel has a higher % of U-235 to sustain the chain reaction.

U-238 only undergoes fission with very high-energy (fast) neutrons. U-235 undergoes fission easily with slow (thermal) neutrons.

Moderator

Role: Fission neutrons are released at $\sim 10^7 \text{ m s}^{-1}$ — too fast to cause further fission in U-235. The moderator slows them to thermal speeds ($\sim 2 \times 10^3 \text{ m s}^{-1}$, $\sim 0.025 \text{ eV}$ at 20°C) through repeated collisions.

Requirements: Low mass number (to absorb maximum KE per collision — like a billiard ball collision) and low neutron absorption cross-section (doesn't absorb neutrons itself).

Typical materials: Graphite (Magnox, AGR reactors) or water (PWR reactors).

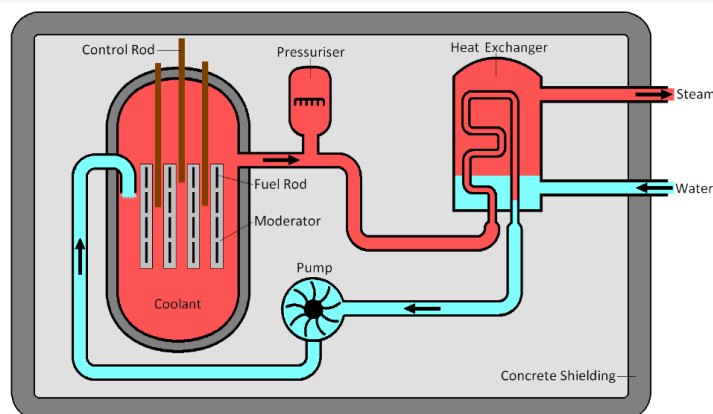


Fig 8.1 — Pressurised water reactor schematic

Questions

1. Fill in the blanks: Nuclear reactors use rods of u_____ rich in ^{235}U as fuel for f_____ reactions. These produce n_____ which induce further fissions — a c_____ r_____. Neutrons must be s_____ down by a m_____ before they can cause fission in ^{235}U . (3 marks)
2. Explain the role of the moderator in a nuclear reactor.

(3 marks)

3. State two properties a good moderator material should have and explain why.

(4 marks)

4. What is meant by 'enriched' uranium?

(1 mark)

Part 2 of 3 | Control Rods and Coolant

Control Rods

Role: Absorb excess neutrons to control the rate of fission and hence the power output. Each fission produces 2–3 neutrons but only 1 is needed to sustain a steady chain reaction.

Rods are inserted deeper to absorb more neutrons (reduce power) or raised to allow more neutrons to cause fission (increase power).

Requirements: High neutron absorption cross-section; high melting point (to withstand reactor temperatures).

Typical materials: Boron or cadmium (both excellent neutron absorbers).

Coolant

Role: Carries heat from the reactor core to the heat exchanger. The pressuriser and pump circulate the hot coolant. At the heat exchanger, heat transfers from the coolant to a secondary water circuit, producing steam to drive turbines.

Requirements: High specific heat capacity (carries lots of heat); liquid or gas; non-corrosive; non-flammable; poor neutron absorber (avoids becoming radioactive).

Typical materials: Carbon dioxide (CO_2) gas (Magnox/AGR) or water (PWR).

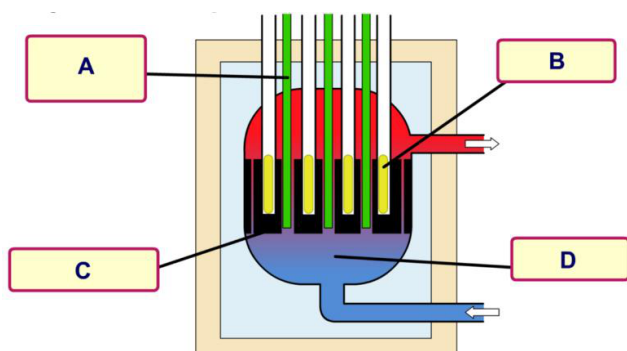


Fig 8.2 – Label the reactor components (A–D)



Fig 8.3 – Nuclear power station cooling towers

Questions

5. Explain the role of control rods in a nuclear reactor and how they are used to vary power output.

(3 marks)

6. State two properties of a good coolant and explain why each is important.

(4 marks)

7. Describe how the heat produced in a nuclear reactor is converted to electrical energy.

(3 marks)

8. What is coming out of a cooling tower at a nuclear power station? Is it radioactive?

(2 marks)

Part 3 of 3 | Chain Reaction Management and Reactor Operation

In normal operation, the reactor is maintained at **criticality**: exactly 1 neutron per fission event goes on to cause another fission (multiplication factor $k = 1$).

Not all produced neutrons cause fission: some escape through the surface, some are absorbed by U-238, some are absorbed by the moderator or coolant, some travel too fast.

Emergency shut-down (SCRAM): Control rods are immediately fully inserted into the core. Some reactors have secondary control rods held up by electromagnets — a power cut drops them automatically.

After shut-down, the fuel rods continue to produce heat (from decay of fission products — radioactive daughter nuclei). Emergency cooling is essential even after the reactor is shut down.

Moderator excited states: Early high-energy neutron collisions may excite nuclei of the moderator. These excited nuclei de-excite by emitting **gamma radiation**. Subsequent elastic collisions gradually transfer kinetic energy to the moderator atoms (heating it).

Shielding becomes radioactive: Neutrons escaping from the core can be absorbed by nuclei in the shielding, making them unstable (radioactive). This is called neutron activation.

Questions

9. Explain what is meant by a chain reaction in a nuclear reactor. (2 marks)
10. Explain why backup generators are essential for nuclear power plants even when the reactor is shut down. (3 marks)
11. Neutrons released in the first collisions with the moderator may excite its nuclei. Describe the radiation emitted and explain subsequent collisions. (4 marks)
12. A rod of U-238 is placed in the reactor core. When U-238 absorbs a neutron, it eventually produces Pu-239. Write the nuclear equation for the decay of Np-239 ($Z=93$) to Pu-239 ($Z=94$). (2 marks)

Exam-Style Questions — Lesson 8

EXAM QUESTION – Q1: Nuclear Reactor Components (8 marks)

- (a) Describe the changes made inside a nuclear reactor to reduce its power output and explain the process. (3)
- (b) State the main source of highly radioactive waste from a nuclear reactor. (1)
- (c(i)) Describe and explain the radiation emitted when a moderator nucleus is excited by a high-energy neutron. (2)
- (c(ii)) Describe what happens to neutrons in subsequent elastic collisions with the moderator. (2)

Lesson 9: Nuclear Safety

DO NOW — Lesson 9

1. A sample of radioactive waste has an initial activity of 5.0×10^8 Bq and a half-life of 30 years. Calculate the activity after 90 years. (3 marks)
2. Name the three components of a nuclear reactor responsible for: (a) controlling the chain reaction, (b) slowing neutrons, (c) removing heat from the core. (3 marks)
3. Explain why a nuclear reactor continues to generate heat after it has been shut down, and why this is a safety concern. (3 marks)
4. State two types of radiation emitted from a reactor core that the shielding must stop, and name a suitable material for absorbing each. (2 marks)

Part 1 of 3 | Reactor Safety Systems

Nuclear reactors require multiple overlapping safety systems to protect workers and the public.

Fuel Design: Solid fuel rods reduce the risk of spills or leaks. Remote-controlled handling equipment is used to insert and remove fuel, eliminating direct human contact.

Reactor Shielding:

- The reactor core is enclosed in a high-strength steel pressure vessel designed to withstand high temperatures and pressures.
- The core is surrounded by a thick, leak-proof concrete shield which absorbs escaping neutrons and gamma radiation.
- A controlled exclusion zone surrounds the concrete shielding — no human access.

Emergency Shut-Down (SCRAM):

- Control rods are fully inserted — absorbing all available neutrons, stopping fission.
- Secondary control rods held by electromagnets fall into the core automatically if power fails.
- Emergency cooling systems flood the core if temperature exceeds safe limits — removing decay heat.

Questions

1. Explain why the shielding around a reactor core becomes radioactive over time.
(3 marks)
2. Describe how an emergency shutdown (SCRAM) of a nuclear reactor is achieved.
(3 marks)
3. Explain why backup cooling is still necessary even after a reactor has been shut down.
(2 marks)

Part 2 of 3 | Classification of Radioactive Waste

Radioactive waste is classified into three levels depending on its radioactivity and half-life:

Level	What it is	Disposal method	Time scale
High-Level	Spent fuel rods; highly radioactive material from reprocessing	Cooling ponds → steel containers underwater → glass blocks → deep underground storage	Up to a year in ponds; dangerous for thousands of years
Intermediate-Level	Fuel cladding; contaminated equipment; hospital radioisotopes; sludge	Steel drums encased in concrete; deep underground storage	Thousands of years
Low-Level	Lab equipment; protective clothing; cooling pond water	Sealed metal drums; buried underground in supervised repositories; treated water released	A few months

Questions

- Describe the steps taken to safely deal with high-level radioactive waste from a nuclear reactor.
(5 marks)
- State one problem in dealing with high-level nuclear waste and suggest a way of overcoming it.
(2 marks)
- State the main source of highly radioactive waste from a nuclear reactor.
(1 mark)

Part 3 of 3 | Extended Nuclear Reactor Questions

The following section brings together concepts from across the nuclear physics topic, requiring extended answers about reactor physics, waste management, and safety.

Remember:

- The moderator slows neutrons (low A material, low absorption)
- The coolant transfers heat (high specific heat, non-radioactive)
- Control rods absorb neutrons (high absorption cross-section)
- For a reactor to operate at constant power: exactly 1 neutron per fission must cause another fission.

Questions

- In a nuclear reactor, uranium-238 absorbs a neutron and eventually produces plutonium-239. Write the nuclear equation for the decay of neptunium-239 ($Z=93$) to plutonium-239.
(2 marks)
- A sample of Np-239 has an initial activity of 4.0×10^{12} Bq. The activity drops to about 2.0×10^{12} Bq after approximately 2.0×10^5 s. Show that the decay constant is about $3.4 \times 10^{-6} \text{ s}^{-1}$.
(3 marks)
- Estimate the number of Np-239 nuclei in a sample at $t = 5.0 \times 10^5$ s, given the activity at this time is about 1.0×10^{12} Bq and $\lambda = 3.4 \times 10^{-6} \text{ s}^{-1}$.
(2 marks)
- Give a full account of the components of a thermal nuclear reactor and the role of each.
(6 marks)

Additional: Reactor Components and Mass Changes

Use the reactor diagram (Fig 8.2) to identify components A–D in the question below. Magnox power stations in the UK produce ~20 TW h of electrical energy per year (sufficient for Greater London). Each fission releases ~200 MeV.

Questions

- Identify reactor components A, B, C and D in Fig 8.2. (4 marks)
- The Magnox network transfers about 20 TW h of electrical energy per year. The process has an efficiency of 40%. How much energy in joules is transferred electrically each second? (3 marks)
- Each fission releases ~200 MeV. How many ^{235}U atoms must fission each second to produce the thermal power calculated in Q2? (1 MeV = 1.6×10^{-13} J) (3 marks)
- What was the mass of these ^{235}U atoms before fission? ($m(^{235}\text{U}) = 235 \times 1.66 \times 10^{-27}$ kg) (2 marks)
- What is the total mass change due to fission in Magnox reactors each second? ($c = 3.0 \times 10^8$ m s $^{-1}$) (2 marks)

Exam-Style Questions — Lessons 8 & 9

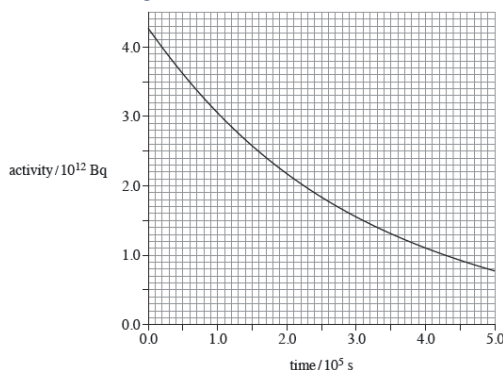


Fig 9.1 — Activity vs time for neptunium-239 sample

EXAM QUESTION – Q1: Reactor Physics and Waste Management (19 marks)

- A rod of uranium-238 is placed in the core of a nuclear reactor where it absorbs free neutrons, eventually forming plutonium-239. Write the nuclear equation for the beta-minus decay of neptunium-239 ($^{239}_{93}\text{Np}$) to plutonium-239. (2)
- Show that the decay constant of Np-239 is about 3.4×10^{-6} s $^{-1}$ (half-life read from activity graph $\approx 2 \times 10^5$ s). (2)
- Estimate the number of Np-239 nuclei present at $t = 5.0 \times 10^5$ s, where $A \approx 1.0 \times 10^{12}$ Bq. (2)
- Explain what is meant by a chain reaction in a thermal nuclear reactor. (2)
- Explain the purpose of a moderator in a thermal nuclear reactor. (3)
- Explain why the shielding around a reactor core becomes radioactive.

(2)

(d) Describe, with reference to the source and treatment, the main problems in dealing with high-level radioactive waste.

(6)