NUCLEAR PHYSICS

AQA A-Level Physics | Topic 3.8

TEACHER EDITION

Contents

This edition contains model answers and mark-scheme guidance for all questions. Answers are shown in green. Keep this edition secure.

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)*

Nucleus at centre (containing protons and neutrons); electrons orbiting outside.

Proton: +1; Neutron: 0; Electron: −1.

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)*

Repulsive — both positively charged. The force is the electrostatic (Coulomb) force.

3. A particle has mass 6.64 × 10^{-27} kg and speed 2.0 × 10^{7} m s^{-1}. Calculate its kinetic energy using $E_K = ½mv^2$. *(2 marks)*

$E_K = ½ \times 6.64\times10^{-27} \times (2.0\times10^{7})^2 = ½ \times 6.64\times10^{-27} \times 4\times10^{14} = 1.33 \times 10^{-12}$ J

4. State which type of radiation (, or) has the shortest range in air and explain why in one sentence. *(2 marks)*

Alpha () has the shortest range (~5 cm) because it is the most strongly ionising, losing energy rapidly through frequent collisions with air molecules.

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.

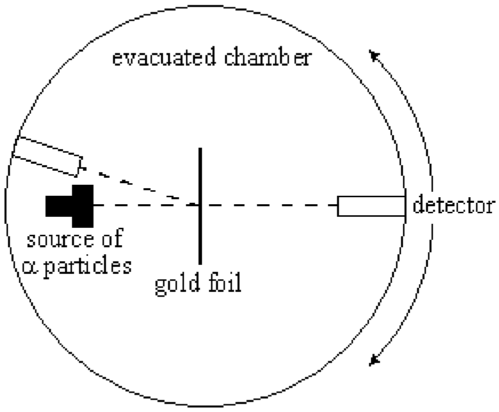


Fig 1.1 — Rutherford scattering apparatus

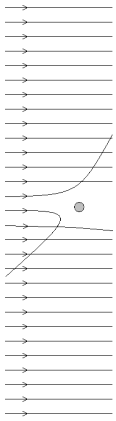


Fig 1.2 — Alpha particle scattering paths

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.

The atom is mostly empty space.

Most of the atom's volume contains no significant mass or charge to deflect the alpha particles.

(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°.

The positive charge and most of the mass of the atom are concentrated in a very small, dense region (the nucleus).

This concentrated charge is large enough to repel the positive alpha particle back.

(2 marks)

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

Alpha particles have a range of only ~5 cm in air.

They would be absorbed by air molecules before reaching the foil or detector if air were present.

(2 marks)

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

A thin foil ensures each alpha particle only encounters a single gold nucleus.

Multiple scattering events in a thick foil would make results uninterpretable.

(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:

$$r = \frac{qQ}{4\pi\varepsilon_0 E_K}$$

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

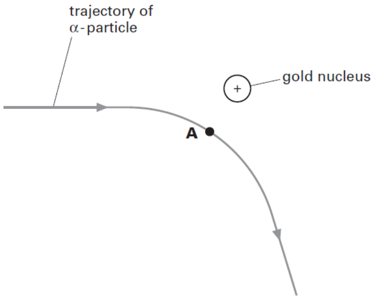


Fig 1.3 — Alpha particle trajectory past a gold nucleus

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.

1. The nucleus has a large positive charge (to provide sufficient repulsion to deflect alpha particles through large angles).

2. The nucleus is very small / has a very large mass (concentrated in a tiny volume), so direct hits are rare.

(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 = 1.6×10^{-19} C, $\varepsilon_o = 8.85 \times 10^{-12}$ $C^2 J^{-1} m^{-1}$)

$E\_K = 1/2mv^2 = 1/2 \times 6.64{\times}10^{-27} \times (1.5{\times}10^{7})^2 = 7.47{\times}10^{-13}$ J

At closest approach: $E\_K = q{\times}Q/(4\pi\varepsilon_o r)$

$r = (2e \times 79e)/(4\pi\varepsilon_o \times E\_K) = (2 \times 79 \times (1.6{\times}10^{-19})^2)/(4\pi \times 8.85{\times}10^{-12} \times 7.47{\times}10^{-13})$

$r \approx 4.8 \times 10^{-14}$ m

(4 marks)

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

Electrostatic (Coulomb) force / electromagnetic force.

(1 mark)

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

~10^{-15} m *(femtometre range) — approximately* 10^{-14} *to* 10^{-15} m.

(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):

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

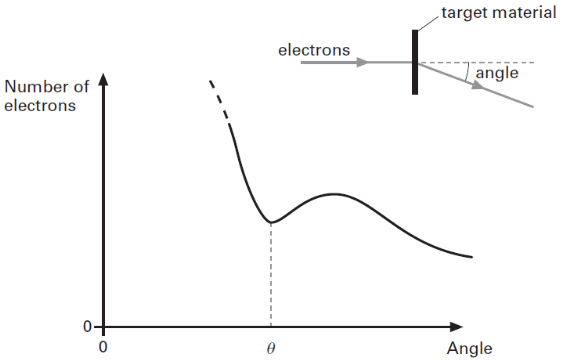


Fig 1.4 — Electron diffraction pattern showing first minimum at θ

Questions

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

1. X-ray diffraction

2. Electron diffraction

3. Neutron diffraction

(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.

(a) Electrons have wave-like properties (wave-particle duality); they have a de Broglie wavelength comparable to nuclear dimensions.

(b) ~10^{-15} m (of order femtometres, comparable to nuclear diameter).

(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. ($m_n = 1.67 \times 10^{-27}$ kg)

(a) $f = c/\lambda = 3\times10^{8} / 2\times10^{-10} = 1.5 \times 10^{18}$ Hz

(b) $p = h/\lambda = 6.63\times10^{-34} / 2\times10^{-10} = 3.315\times10^{-24}$ kg m s^{-1}; $v = p/m = 3.315\times10^{-24} / 9.11\times10^{-31} \approx 3.64 \times 10^{6}$ m s^{-1}

(c) $v = p/m = 3.315\times10^{-24} / 1.67\times10^{-27} \approx 1.99 \times 10^{3}$ m s^{-1}

(5 marks)

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

$E = 420 \times 10^{6} \times 1.6\times10^{-19} = 6.72 \times 10^{-11}$ J

$\lambda = hc/E = (6.63\times10^{-34} \times 3\times10^{8}) / 6.72\times10^{-11} = 2.96 \times 10^{-15}$ m

$\sin 52° = 1.22\lambda/d \rightarrow d = 1.22 \times 2.96\times10^{-15} / \sin 52° = 4.58 \times 10^{-15}$ m

Nuclear diameter $\approx 4.6 \times 10^{-15}$ m

(4 marks)

Additional Questions — Lesson 1

Questions

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

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

(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. ($m_n = 1.67 \times 10^{-27}$ kg)

(a) $f = c/ = 3.0\times10^{8}/2.0\times10^{-10} = 1.5 \times 10^{18}$ Hz

(b) $p = h/ = 3.315\times10^{-24}$ kg m s^{-1}; $v = p/m = 3.64 \times 10^{6}$ m s^{-1}

(c) $v = p/m = 1.99 \times 10^{3}$ m s^{-1}

(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?

The nucleus is about 10^{14} times denser than ordinary matter.

This means atoms are almost entirely empty space — almost all mass is concentrated in the tiny nucleus.

(2 marks)

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

1. Most atomic mass is concentrated in a tiny, dense nucleus.

2. The nucleus is positively charged.

3. Most of the atom is empty space.

(3 marks)

A4. X-rays of wavelength 2.5×10^{-11} 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. ($m_e = 9.11 \times 10^{-31}$ kg)

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

(a) The regular crystal lattice of copper atoms — atomic spacing comparable to the X-ray wavelength.

(b) Approximately 2.5×10^{-10} m (same order as diffraction wavelength).

(c) $p = h/ = 6.63\times10^{-34}/2.5\times10^{-11} = 2.65\times10^{-23}$ kg m s^{-1}; $v = 2.65\times10^{-23}/9.11\times10^{-31} = 2.9 \times 10^{7}$ m s^{-1}

(d) Nuclear diameters ($\sim10^{-15}$ m) are 10000× smaller than the X-ray wavelength. For diffraction to occur must be comparable to the object — so no significant diffraction from nuclei.

(5 marks)

Exam-Style Questions — Lesson 1

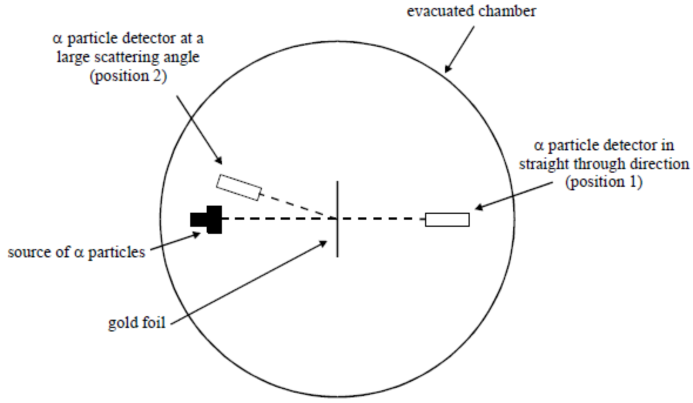


Fig 1.5 — Rutherford scattering apparatus (exam diagram)

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

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

Alpha particles have a very short range in air (~5 cm) and would be absorbed before reaching the foil or detector.

A vacuum ensures the alpha particles travel unimpeded from source to foil to detector.

(2)

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

To ensure each alpha particle encounters only a single gold nucleus.

A thick foil would cause multiple scattering events, making results uninterpretable.

(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.

Most alpha particles travel straight through — the atom is mostly empty space.

Very few (1 in 8000) are deflected through large angles — the nucleus is very small.

Deductions: The nucleus is tiny compared to the atom (atom 10^{-10} m; nucleus 10^{-15} m).

The nucleus is positively charged — electrostatic repulsion deflects positive alpha particles.

The nucleus is very dense and concentrated — it can exert sufficient repulsive force to reverse the alpha particle's direction.

(5)

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

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

Alpha particles have a very short range in air (~5 cm) and would be absorbed before reaching the foil or detector.

A vacuum ensures alpha particles travel unimpeded.

(2)

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

To ensure each alpha particle only interacts with a single gold nucleus.

A thick foil would cause multiple scattering, making results harder to interpret.

(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?

Most alpha particles travel straight through because most of the atom is empty space.

Very few alpha particles approach close enough to the positive nucleus to be significantly deflected.

Deductions: The nucleus is tiny compared to the atom (atom mostly empty space).

The nucleus is positively charged — repels the positive alpha particle.

The nucleus has a large mass concentrated in a small volume.

(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?

Straight through the foil (0° scattering angle / forward direction).

(1)

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

The atom is mostly empty space — most alpha particles pass through without significant deflection.

(1)

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

The atom contains a very small, dense, positively charged nucleus.

The nucleus is concentrated enough to exert a strong enough repulsive force to reverse the direction of the alpha particle.

(2)

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

Electrostatic / Coulomb / electromagnetic force.

(1)

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

The alpha particle is deflected less — a smaller proton number means smaller electrostatic repulsion.

The path curves less sharply; the deflection angle is smaller for the same initial trajectory.

(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)*

Alpha (): 2 protons + 2 neutrons (helium-4 nucleus).

Beta-minus (¯): fast electron from nucleus.

Gamma (): high-energy electromagnetic radiation.

2. State whether each radiation type (, ,) is deflected by an electric field, giving the direction of deflection for each. *(3 marks)*

: deflected towards negative plate (positively charged).

¯: deflected towards positive plate (negatively charged); deflected more than .

: not deflected (uncharged).

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)*

Gamma () has the greatest penetrating power. Several centimetres of lead (or ~1 m of concrete) is needed to significantly reduce its intensity.

4. State what is meant by ionisation and give one reason why ionising radiation is harmful to living tissue. *(2 marks)*

Ionisation: removal of electrons from atoms/molecules to produce ions.

Harmful because it can break chemical bonds in DNA, causing cell death or mutation leading to cancer.

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→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.

Alpha: helium nucleus (2p+2n), mass 4, charge +2, high ionising power, stopped by paper/skin.

Beta-minus: fast electron from nucleus, mass ~1/2000, charge −1, medium ionising power, stopped by ~3 mm aluminium.

(4 marks)

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

Alpha (α) particles — they are heaviest, slowest (for a given energy) and most strongly charged relative to size, causing most ionisation per unit path length.

(1 mark)

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

Alpha particles: typical range = _____ m

Beta particles: typical range = _____ m

Alpha: 0.05 m (5 cm)

Beta: 2–3 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.

Gamma obeys the inverse square law: I 1/x^2.

At 0.5 m a small increase in distance causes a proportionally large drop: moving from 0.50 to 0.55 m gives $(0.50/0.55)^2$ 83% of original intensity.

(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.

The greatest hazard is inhaling or ingesting the dust.

Inside the body, alpha particles have high ionising power and are completely absorbed within a very short distance, causing intense localised cell damage.

This greatly increases the risk of cell death, mutation, and cancer.

(3 marks)

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

(a) Alpha: ~5 cm (0.05 m)

(b) Beta: ~2–3 m

(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.

$$I = \frac{k\,I_0}{x^2}$$

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%

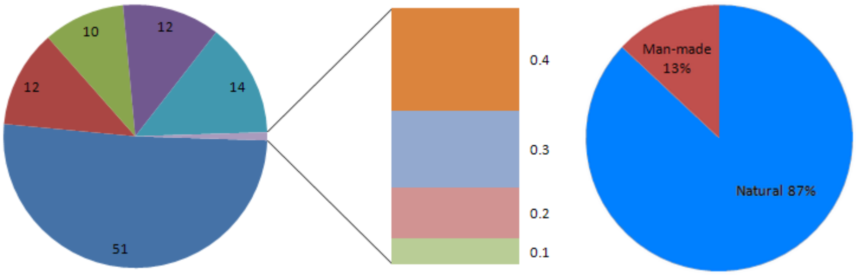


Fig 2.1 — Sources of background radiation in the UK

Questions

4. 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.

I_A × x_A^2 = I_B × x_B^2

2010 × 0.15^2 = I_B × 0.90^2

I_B = 2010 × 0.0225 / 0.81 = 55.8 ≈ 56 counts min^{-1}

(3 marks)

5. 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.

Corrected count at 0.15 m = 2050 − 40 = 2010 counts min^{-1}

I_A x_A^2 = I_B x_B^2

2010 × (0.15)^2 = I_B × (0.90)^2

I_B = 2010 × 0.0225 / 0.81 ≈ 55.8 counts min^{-1}

Total reading ≈ 55.8 + 40 = 95.8 ≈ 96 counts min^{-1}

(3 marks)

6. Explain why a student recording a count rate at 0.90 m from a source might choose to record for longer than 5 minutes.

At greater distances the count rate (above background) is much lower.

A longer recording time gives a larger total count, reducing the statistical/random uncertainty in the measurement.

(1 mark)

7. State one source of background radiation that has increased in the past 100 years.

Medical uses of radiation (e.g. X-rays, radiotherapy) OR nuclear weapons testing OR nuclear power/accidents.

(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.

The greatest hazard is breathing in the dust.

Alpha particles inside the body cause intense localised ionisation, leading to high risk of cell damage, mutation and cancer.

(Alpha presents low danger outside the body as it is stopped by skin.)

(2 marks)

9. Explain why the public need not worry that gamma-sterilised surgical instruments become radioactive.

Gamma rays are electromagnetic radiation (photons). They are absorbed by the instruments but do not make the atoms radioactive.

No neutrons are involved, so the nuclei of atoms in the instruments are not changed.

(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 m → 9013; d = 0.50 m → 1395; d = 1.00 m → 242.

If inverse square law: $I \times d^2$ = constant.

0.20 m: $9013 \times 0.04 = 360.5$

0.50 m: $1395 \times 0.25 = 348.8$

1.00 m: $242 \times 1.00 = 242.0$

The values are not constant (360.5, 348.8, 242), so the data do not follow an inverse square law.

(3 marks)

11. Suggest two reasons why the count rate data in Q10 might not follow the inverse square law.

1. The source is not a point source — at close distances geometric assumptions break down.

2. The source emits other types of radiation (alpha or beta) which are absorbed at different rates with distance.

(Also acceptable: absorption by air; detector size not negligible compared to distance.)

(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.

Alpha decay: proton number decreases by 2; nucleon number decreases by 4.

Gamma emission: no change in proton number or nucleon number (nucleus drops from excited state to ground state, emitting a photon).

(2)

(b) Comment on the relative penetrating powers of alpha and gamma radiation.

Gamma is far more penetrating than alpha.

Alpha is stopped by a few cm of air or a sheet of paper; gamma requires several cm of lead or thick concrete.

(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.

Using inverse square law: $I \propto 1/x^2$

Ratio = $(1.0)^2 / (3.0)^2 = 1/9 \approx 0.11$

(2)

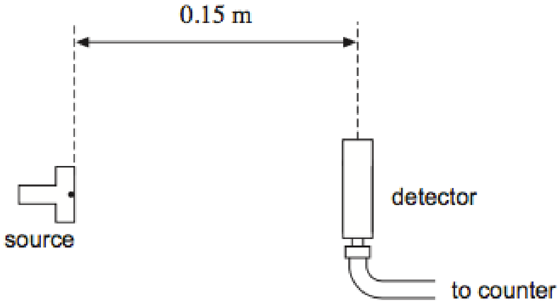


Fig 2.2 — Gamma source and detector arrangement

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}).

$I\_A x\_A^2 = I\_B x\_B^2$

$2010 \times (0.15)^2 = I\_B \times (0.90)^2$

$I\_B = 2010 \times 0.0225 / 0.81 = 55.8 \approx 56$ counts min^{-1}

(3)

(a(ii)) Explain why the student should record for longer than 5 minutes at 0.90 m.

The count rate is much lower at 0.90 m, so a longer recording time gives a higher total count and reduces the percentage random/statistical uncertainty.

(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.

Place a sheet of aluminium (~3 mm thick) between the source and detector.

If the count rate drops further, beta particles (stopped by aluminium) are being detected.

Compare the observed drop to what would be expected from gamma alone.

(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.

Gamma radiation — it is highly penetrating and can pass through sealed packaging and the metal instruments to kill micro-organisms throughout.

(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.

Place a sheet of aluminium (a few mm thick) between the source and detector to absorb all beta particles.

Then add a sheet of paper / hold the detector at a few cm to absorb all alpha particles.

Only gamma will penetrate both absorbers and reach the detector.

(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.

$I\_A x\_A^2 = I\_B x\_B^2$

$64 \times (50)^2 = I\_B \times (80)^2$

$I\_B = 64 \times 2500 / 6400 = 25$ counts s^{-1}

(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 m 9013 min^{1} | d = 0.50 m 1395 min^{1} | d = 1.00 m 242 min^{1} Show with calculations why these data are NOT consistent with an inverse-square law.

If I1/x^2 then I×x^2 = constant:

0.20 m: 9013 × 0.04 = 360.5

0.50 m: 1395 × 0.25 = 348.8

1.00 m: 242 × 1.00 = 242.0

Values are not constant data do not follow inverse-square law.

(3)

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

1. Source is not a true point source — at close distances this affects the geometry.

2. Source may also emit beta (or alpha) radiation which is absorbed at different rates.

(Also accept: air absorption at larger distances; background subtraction error.)

(2)

Lesson 3: Radioactive Decay

DO NOW — Lesson 3

1. A sample starts at 800 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)*

(a) 400 min^{-1} (b) 200 min^{-1} (c) 50 min^{-1}

2. State two reasons why radioactive decay is described as both random and spontaneous. *(2 marks)*

Random: it is impossible to predict which nucleus will decay next, or when.

Spontaneous: decay occurs without any external trigger or influence (unaffected by temperature, pressure, chemical state).

3. Calculate: (a) ln(2), (b) $e^{-1.386}$, (c) the value of λ if $T_{½} = 3600$ s, using $T_{½} = {}^{\ln 2}/_{\lambda}$. *(3 marks)*

(a) ln(2) = 0.693

(b) $e^{-1.386} = 0.25$

(c) = 0.693/3600 = 1.93×10^{-4} s^{-1}

4. Convert 4.5×10^9 years into seconds. (1 year = 3.15×10^7 s) *(2 marks)*

$t = 4.5{\times}10^9 \times 3.15{\times}10^7 = 1.42 \times 10^{17}$ s

---

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.

The decay constant λ is the probability of a given nucleus decaying per unit time.

Units: s^{-1} (per second) — or min^{-1}, year^{-1} etc. depending on the time unit.

(2 marks)

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

Activity is the number of nuclear decays (disintegrations) occurring per second.

Unit: Becquerel (Bq), where 1 Bq = 1 decay per second.

(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 λ → short half-life (decays quickly) • Small λ → long half-life (decays slowly)

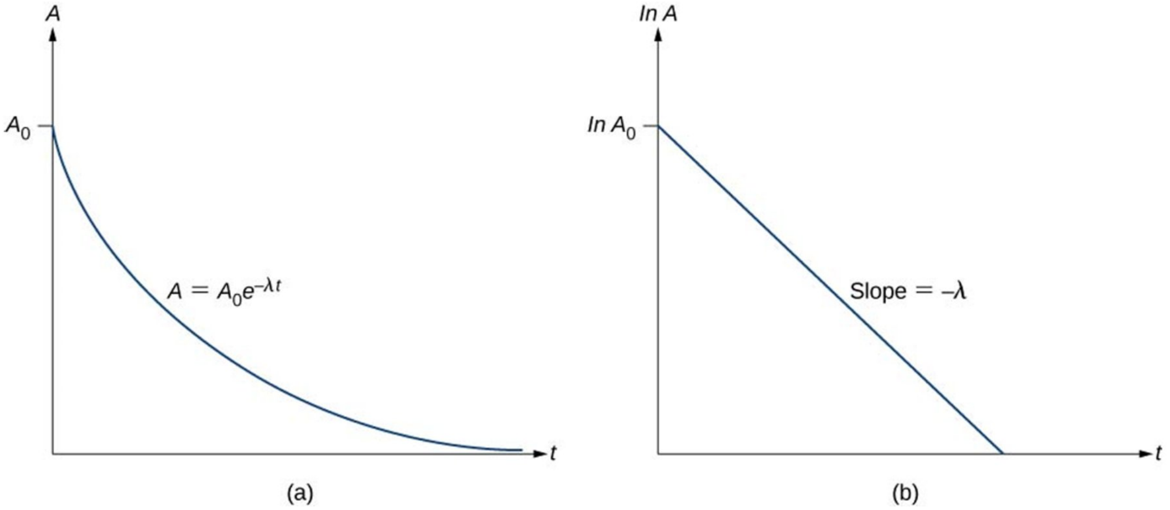
Exponential Decay Equations

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

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 −λ.



(a) activity against time (b) ln (activity) against time — a straight line graph

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.

(a) $T_{1/2} = 2.6 \times 365.25 \times 24 \times 3600 = 8.20\times10^{7}$ s

$\lambda = \ln 2/T_{1/2} = 0.693/8.20\times10^{7} = 8.45\times10^{-8}\ s^{-1}$

(b) $N = 6.02\times10^{23}$; $A = \lambda N = 8.45\times10^{-8} \times 6.02\times10^{23} = 5.09\times10^{16}$ Bq

(4 marks)

4. What type of decay curve describes radioactive decay?

Exponential decay — N (or A) decreases exponentially with time.

(1 mark)

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

T1/2 = ln2 / λ = 0.693 / λ

A large decay constant means a short half-life; a small decay constant means a long half-life.

(2 marks)

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

N/N_0 = e^(−λt)

λ = ln2 / 4.2 = 0.1650 day^{-1}

N/N_0 = e^(−0.1650 × 10) = e^(−1.650) = 0.192

Approximately 19% of the original sample remains.

(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=0.5h: 128; t=1.0h: 71; t=1.5h: 46; t=2.0h: 26; t=2.5h: 19; t=3.0h: 7.

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

(b) Describe how plotting ln(count rate) vs time would give a more reliable value.

(a) Plot count rate vs time. From the graph, select a starting value and read off the time for it to halve. Repeat for 2–3 starting points and average.

(b) ln(count rate) vs time gives a straight line with gradient −λ. The best-fit line averages all data points, reducing random error. T1/2 = 0.693/|gradient|.

This is more reliable because all data contribute to the gradient, not just two points.

(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.

Measure the activity A of a known mass of the substance.

Calculate the number of atoms N from the mass and molar mass (N = mass/molar mass × N_A).

Use A = λN to find λ, then T1/2 = 0.693/λ.

(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 × 10^{-17} s^{-1} and its half-life is 1.2 × 10^{9} years.

$N = (0.6\times10^{-6}/40)\times6.02\times10^{23} = 9.03\times10^{15}$ atoms

$= A/N = 0.16/9.03\times10^{15} = 1.77\times10^{-17}\ s^{-1}\ \ 1.8\times10^{-17}\ s^{-1}$

$T½ = \ln 2/ = 0.693/1.77\times10^{-17} = 3.91\times10^{16}\ s = 3.91\times10^{16}/3.15\times10^{7}\ \ 1.24\times10^{9}$ *years*

(4 marks)

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

$N = (0.6+4.2)\times10^{-6}/40 \times 6.02\times10^{23} = 7.23\times10^{16}$

$N/N = 9.03\times10^{15}/7.23\times10^{16} = 0.1249$

$t = -\ln(0.1249) = 2.079$

$t = 2.079/1.77\times10^{-17} = 1.18\times10^{17}\ s\ \ 3.7\times10^{9}$ *years*

(4 marks)

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

0.16 Bq is an extremely low count rate — less than one decay per second.

Very long counting times are needed for reliable statistics, and careful background subtraction (background is typically larger than the signal) is essential.

(2 marks)

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

$= \ln 2/4.2 = 0.165\ day^{-1}$

$N/N = e^{-0.165\times10} = e^{-1.65} = 0.192$

About 19% of the original sample remains.

(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.

Measure activity A of a known mass of the substance.

Calculate N from mass and molar mass: $N = (m/M) \times N\_A$.

Then $= A/N$ *and* $T½ = 0.693/$.

(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(corrected count rate) vs time; find half-life from the gradient.

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

(a) Corrected rates (subtract 30): 229, 128, 71, 46, 26, 19, 7

From graph: falls from ~229 to ~115 in 0.8 h $T½\ \ 0.8$ *h*

(b) Gradient $= -\ \ -0.86\ h^{-1}$; $T½ = 0.693/0.86\ \ 0.81$ *h*

(c) Method (b) is more reliable — all data points contribute to the gradient, reducing the effect of random scatter in individual measurements.

(5 marks)

9. In living wood, 1 in 10^{12} carbon atoms is radioactive ^{14}C with a decay constant of $3.84 \times 10^{-12}\ s^{-1}$. 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.

(a) $T1/2 = 0.693 / 3.84\times10^{-12} = 1.805\times10^{11}\ s = 1.805\times10^{11} / 3.15\times10^{7} = 5730$ *years (to 3 s.f.)*

(b) $N(^{14}C) = 3.00\times10^{23} / 10^{12} = 3.00\times10^{11}$ *atoms*

$A = \lambda N = 3.84\times10^{-12} \times 3.00\times10^{11} = 1.15$ 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. ($\lambda = 3.84 \times 10^{-12}\ s^{-1}$, 1 year = 3.15×10^{7} s)

$A = A_0\, e^{\wedge}(-\lambda t) \rightarrow 0.65 = 1.15\, e^{\wedge}(-\lambda t)$

$e^{\wedge}(-\lambda t) = 0.65/1.15 = 0.5652$

$-\lambda t = \ln(0.5652) = -0.5702$

$t = 0.5702 / 3.84\times10^{-12} = 1.485\times10^{11}$ s $= 1.485\times10^{11} / 3.15\times10^{7} = 4716$ years ≈ 4700 years

(3 marks)

11. Give two reasons why it is difficult to obtain a reliable age for the ancient boat from carbon dating.

1. The atmospheric ratio of $^{14}C/^{12}C$ may not have been constant throughout history — calibration is needed.

2. The activity of the sample (0.65 Bq) is very low, giving large statistical/random uncertainty in the measurement.

(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.

Gamma: penetrates body tissues so can be detected by external scanners; relatively low ionising effect inside body.

Short half-life means radiation dose to patient is limited.

Alpha: cannot penetrate body tissue to reach external detector; causes intense localised ionisation causing serious cell damage.

(3 marks)

Exam-Style Questions — Lesson 3

EXAM QUESTION – Q1: Carbon Dating (11 marks)

(a) What is meant by the decay constant?

The probability of a given nucleus decaying per unit time.

(1)

(b) Calculate the half-life of ^{14}C in years, given $\lambda = 3.84 \times 10^{-12}\ s^{-1}$ and 1 year = 3.15×10^{7} s. Give your answer to an appropriate number of significant figures.

$T1/2 = \ln2/\lambda = 0.693 / 3.84\times10^{-12} = 1.805\times10^{11}$ s

In years: $1.805\times10^{11} / 3.15\times10^{7} = 5730$ years (to 3 s.f., consistent with λ given to 3 s.f.)

(3)

(c) Show that the rate of decay of ^{14}C atoms in a living wood sample ($N_0(^{14}C) = 3.00 \times 10^{11}$) is 1.15 Bq.

$A = \lambda N = 3.84\times10^{-12} \times 3.00\times10^{11} = 1.152$ Bq ≈ 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.

$t = (1/\lambda) \ln(A_0/A) = (1/3.84\times10^{-12}) \times \ln(1.15/0.65)$

$= (1/3.84\times10^{-12}) \times \ln(1.769) = (1/3.84\times10^{-12}) \times 0.5702$

$= 1.485\times10^{11}$ s $= 1.485\times10^{11} / 3.15\times10^{7} \approx 4700$ years

(3)

(e) Give two reasons why it is difficult to obtain a reliable age from this carbon dating.

1. The atmospheric $^{14}C/^{12}C$ ratio may not have been constant — may need calibration against tree rings etc.

2. Very low activity (0.65 Bq) leads to large statistical uncertainty in the measured count rate.

(2)

Lesson 4: Modes of Decay

DO NOW — Lesson 4

1. The isotope ${}^{238}_{92}U$ undergoes alpha decay. State the nucleon number and proton number of the daughter nucleus, and name the element. *(2 marks)*

A = 238 − 4 = 234; Z = 92 − 2 = 90. Element: Thorium (Th).

2. Write the nuclear equation for the beta-minus decay of ${}^{14}_{6}C$, including all particles emitted. *(3 marks)*

${}^{14}_{6}C\ {}^{14}_{7}N + {}^{0}_{-1}e + {}^{-}_{e}$

3. In alpha decay, state the change in: (a) proton number Z, (b) nucleon number A, (c) neutron number N. *(3 marks)*

(a) Z decreases by 2 (b) A decreases by 4 (c) N decreases by 2

4. Gamma emission follows alpha or beta decay. State the change in Z and A during gamma emission, and explain why. *(2 marks)*

Z and A are both unchanged — gamma emission releases only energy (a photon). No nucleons are lost; the nucleus simply falls from an excited state to its ground state.

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

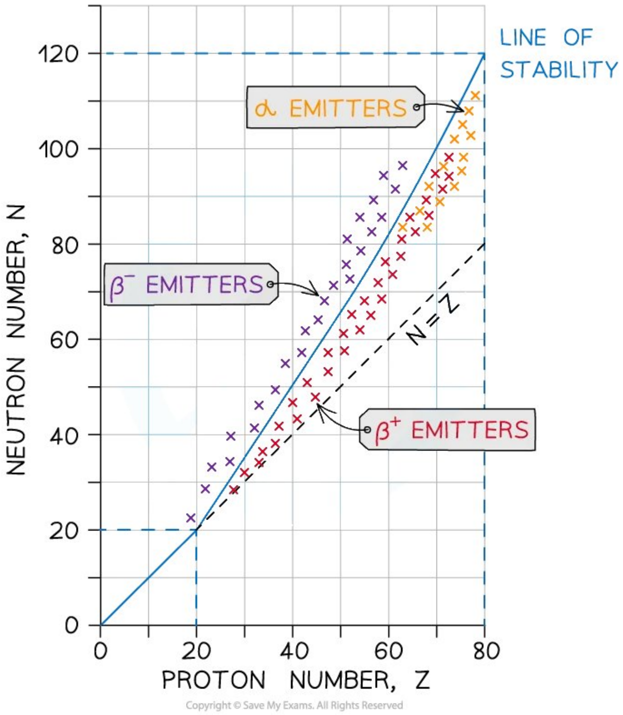


Fig 4.1 — N–Z stability graph (valley of stability)

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.

Graph should show:

• A curve starting at N = Z (0,0) following N = Z for low Z values.

• Curving above N = Z for larger Z, ending around Z = 80, N = 120.

• N axis values marked: 0, 20, 40, 60, 80, 100, 120.

(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).

(i) W: top-right region, above Z = 60 (large, heavy nucleus, e.g. Z=80, N=120+)

(ii) X: above the stability line for a given Z (too many neutrons)

(iii) Y: below the stability line for a given Z (too many protons)

(3 marks)

3. Explain why, for low values of Z, stable nuclei have roughly equal numbers of protons and neutrons (N ≈ Z), whereas heavier stable nuclei have more neutrons than protons.

For low Z: the strong nuclear force (which acts equally between any pair of nucleons) is stronger than electrostatic repulsion at the short distances involved — equal N and Z maximises binding.

For high Z: as more protons are added, protons further apart only feel electrostatic repulsion, not the short-range strong force.

Extra neutrons are needed to provide additional strong-force attraction without increasing electrostatic repulsion.

This shifts the stability line to N > Z for heavy nuclei.

(4 marks)

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

Alpha (α) Decay — ejects a helium nucleus:

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

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:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e + \bar{\nu}_e$$

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:

$${}^{A}_{Z}X \rightarrow {}^{A}_{Z-1}Y + {}^{0}_{+1}e + \nu_e$$

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).

$^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha$

(Mass number: 226−4=222; Proton number: 88−2=86)

(2 marks)

5. Write the equation for the beta-minus decay of carbon-14 (Z = 6) to nitrogen.

$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e + \nu^{-}$

(Mass number unchanged: 14; Proton number: 6+1=7)

(2 marks)

6. A nuclide undergoes beta-plus decay. Describe what happens to: (a) the proton number, (b) the nucleon number.

(a) Proton number decreases by 1 (a proton converts to a neutron).

(b) Nucleon number stays the same (a proton becomes a neutron — total nucleons unchanged).

(2 marks)

7. Describe what gamma ray emission is and explain why it produces no change in the nuclear structure.

Gamma emission occurs when a nucleus in an excited (higher energy) state drops to a lower energy state (ground state).

A gamma photon (electromagnetic radiation) is emitted carrying the energy difference.

No protons or neutrons are gained or lost, so Z and A are unchanged.

(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:

$$^{A}_{Z}X + {}^{0}_{-1}e \rightarrow {}^{A}_{Z-1}Y + \nu_e$$

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):

$$^{A}_{Z}X \rightarrow {}^{A-1}_{Z-1}Y + {}^{1}_{1}p$$

Neutron emission (neutron-rich nucleus):

$$^{A}_{Z}X \rightarrow {}^{A-1}_{Z}X + {}^{1}_{0}n$$

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.

$$^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e + \bar{\nu}_e \text{ then } {}^{131}_{54}Xe^{*} \rightarrow {}^{131}_{54}Xe + \gamma$$

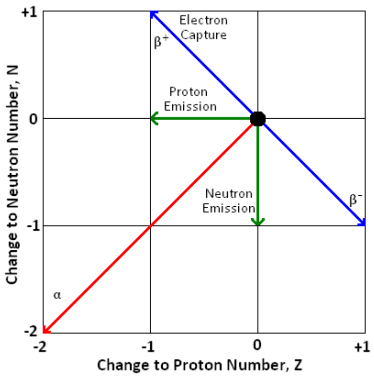


Fig 4.2 — Effect of each decay mode on proton/neutron numbers

Questions

8. Explain the process of electron capture. What change occurs to the proton number?

The nucleus captures one of its own orbital (inner-shell) electrons.

A proton combines with the electron to form a neutron, emitting an electron neutrino.

The proton number decreases by 1; nucleon number is unchanged.

(2 marks)

9. The isotope ^{222}Rn decays sequentially to ^{206}Pb via alpha and beta-minus emissions. Four alpha particles are emitted. Calculate how many beta-minus particles are emitted.

4 alpha decays: A decreases by 4×4=16; Z decreases by 4×2=8.

After alpha decays: Z = 86−8=78, A = 222−16=206

Target: Z = 82, A = 206

Need: ΔZ = 82−78 = +4 (need 4 more protons)

Each β$^-$ increases Z by 1, so 4 β$^-$ particles are emitted.

(3 marks)

10. A nuclide is described as proton-rich. Discuss two ways in which it may decay.

1. Beta-plus (β$^+$) decay: a proton converts to a neutron, emitting a positron and an electron neutrino. This decreases the proton number by 1, moving the nucleus towards the stability line.

2. Electron capture: the nucleus captures an inner orbital electron; a proton converts to a neutron. Same effect on N–Z as β$^+$ but no positron is emitted — a neutrino is emitted instead.

Both processes increase N relative to Z, moving the nucleus back towards the line of stability.

(4 marks)

11. Write the nuclear equation for the decay of iodine-131 by β$^-$ emission.

$^{131}_{53}I \rightarrow {}^{131}_{54}Xe + {}^{0}_{-1}e + \nu^-$

Mass number: 131 (unchanged); Proton number: 53 → 54 (+1). Antineutrino also emitted.

(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).

Curve from (0,0) following N=Z for low Z, curving above N=Z to ~(80, 120).

W: top-right, above and to the right of stable region (Z>60, N>Z by significant margin).

X: above the stability line (excess neutrons) for any Z.

Y: below the stability line (excess protons) for any Z.

(5)

(b) ^{222}Rn decays to ^{206}Pb via 4 alpha decays and n beta-minus decays. Calculate n.

Alpha: A: $222-16=206$; Z: $86-8=78$

Need $Z = 82$: requires 4 β^- decays (each +1 to Z) → $n = 4$

(2)

(c) A proton-rich nuclide can decay in two ways. Discuss both.

β^+ decay: proton → neutron + positron + neutrino; Z decreases by 1, A unchanged.

Electron capture: nucleus captures inner orbital electron; proton → neutron + neutrino; Z decreases by 1, A unchanged.

Both return nucleus towards line of stability by reducing the proton:neutron ratio.

(3)

(d) A nucleus of ^{208}Pb decays by electron capture to thallium (Tl). Write the equation for this decay.

$^{208}_{82}Pb + ^{0}_{-1}e \rightarrow ^{208}_{81}Tl + \nu$

(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.

The strong nuclear force acts between all nucleons (proton-proton, proton-neutron, neutron-neutron).

It is stronger than the electrostatic force at very short range (< ~3 fm) but has negligible effect beyond ~3 fm.

For small nuclei, all nucleons are within each other's strong-force range — the net attractive force exceeds electrostatic repulsion.

(3)

(a(ii)) Suggest why stable nuclei of higher nucleon number have greater numbers of neutrons than protons.

As Z increases, protons further apart no longer experience the short-range strong force from each other, but still electrostatically repel.

Additional neutrons add strong-force binding without adding to the electrostatic repulsion.

So more neutrons are needed to maintain stability, shifting the N/Z ratio above 1 for heavier nuclei.

(3)

(a(iii)) All nuclei have approximately the same density. State what this suggests about the strong nuclear force.

Equal density means each nucleon occupies roughly the same volume regardless of A.

This means the strong nuclear force is saturating — each nucleon only bonds to its nearest neighbours.

If every nucleon attracted every other, adding more nucleons would compress the nucleus further, increasing density. Equal density proves the force is short-range.

(3)

Lesson 5: Nuclear Radius

DO NOW — Lesson 5

1. 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)*

E_P = qQ / (4_0r). Units: q, Q in coulombs (C); r in metres (m); E_P in joules (J). $_0$ = 8.85×10^{-12} C^2 J^{-1} m^{-1}.

2. Convert 5.0 MeV into joules. (1 eV = 1.6 × 10^{-19} J) *(2 marks)*

5.0 MeV = 5.0 × 10^6 × 1.6 × 10^{-19} = 8.0 × 10^{-13} J

3. State the de Broglie equation (= h/p) and calculate the wavelength of an electron with momentum 1.5 × 10^{-24} kg m s^{-1}. (h = 6.63 × 10^{-34} J s) *(2 marks)*

= h/p = 6.63×10^{-34} / 1.5×10^{-24} = 4.42 × 10^{-10} m

4. 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)*

The wavelength must be comparable to (of the same order as) or smaller than the object being studied. If >> object size, no significant diffraction occurs.

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:

$$E_K = E_P = \frac{qQ}{4\pi\varepsilon_0 r}$$

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

$$r = \frac{qQ}{4\pi\varepsilon_0 E_K}$$

where q = charge of alpha particle = 2e, Q = charge of nucleus = Ze, ε_0 = 8.85 × 10^{-12} C^2 J^{-1} 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 ≈ 4.55 × 10^{-14} m. Modern measurements give ~6.5 fm for gold.

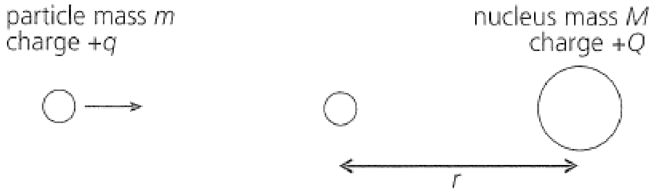


Fig 5.1 — Alpha particle approaching a nucleus head-on

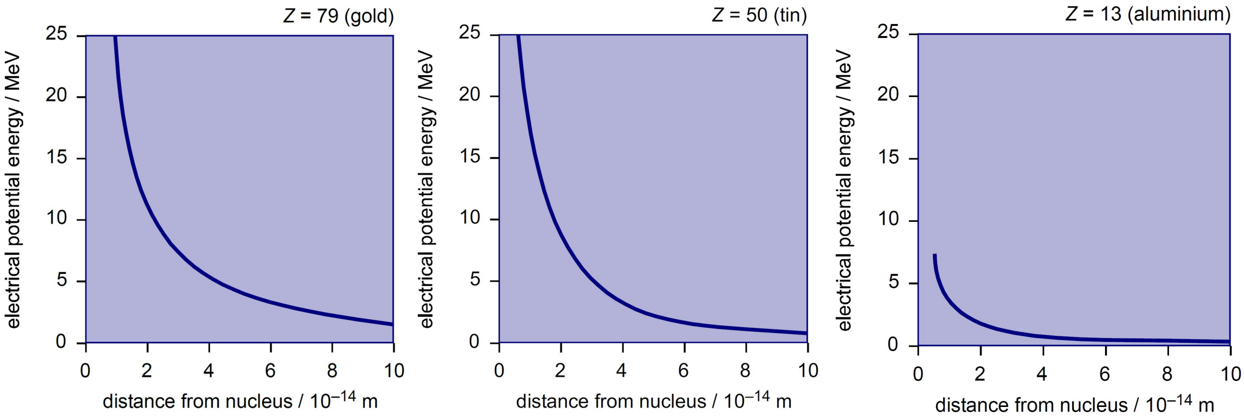


Fig 5.2 — Electrical PE vs distance for gold (Z=79), tin (Z=50) and aluminium (Z=13)

Questions

1. 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)

$E_K = 4.9 \times 10^6 \times 1.6\times10^{-19} = 7.84 \times 10^{-13}$ J

At closest approach: $E_P = E_K = 7.84 \times 10^{-13}$ J

(2 marks)

2. Using the answer above, calculate r, the distance of closest approach. ($e = 1.6 \times 10^{-19}$ C, $\varepsilon_0 = 8.85 \times 10^{-12}$ $C^2 J^{-1} m^{-1}$, Z_gold = 79)

$r = qQ/(4\pi\varepsilon_0 E_K) = (2e \times 79e) / (4\pi\varepsilon_0 \times 7.84\times10^{-13})$

$= (2 \times 79 \times (1.6\times10^{-19})^2) / (4\pi \times 8.85\times10^{-12} \times 7.84\times10^{-13})$

$= (4.046\times10^{-36}) / (8.749\times10^{-23}) = 4.62 \times 10^{-14}$ m ≈ 46 fm

(3 marks)

3. 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.

The distance of closest approach decreases.

Fewer protons means less electrostatic repulsion (smaller Q). The alpha particle can approach more closely before all its KE is converted to PE.

(2 marks)

4. 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.

$E_P = qQ/(4\pi\varepsilon_0 r) = (2 \times 79 \times (1.6\times10^{-19})^2) / (4\pi \times 8.85\times10^{-12} \times 1.0\times10^{-14})$

$= 4.046\times10^{-36} / 1.113\times10^{-24} = 3.634\times10^{-12}$ J

In MeV: $3.634\times10^{-12} / 1.6\times10^{-13} = 22.7$ MeV (between 20 and 25)

(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:

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

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 >> 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).

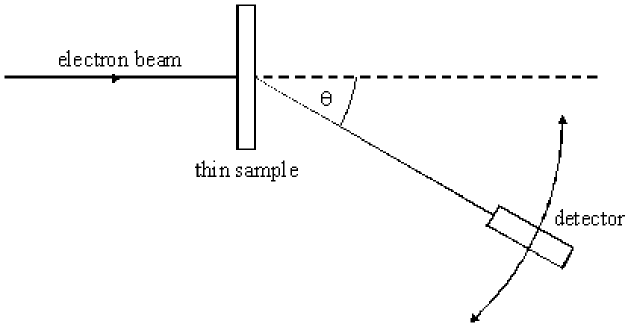


Fig 5.3 — Electron intensity vs angle (first minimum at θ)

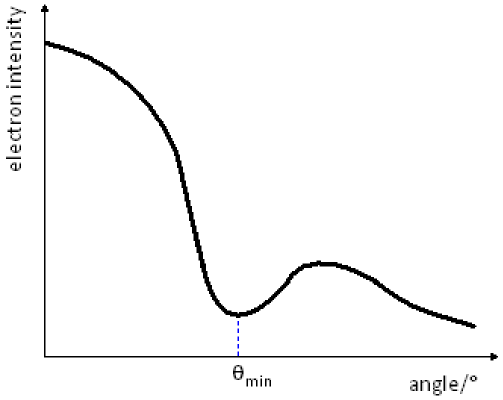


Fig 5.4 — Electron diffraction setup

Questions

5. 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)

$p = E/c = 5.94 \times 10^{-11} / 3 \times 10^{8} = 1.98 \times 10^{-19}$ kg m s^{-1}

$\lambda = h/p = 6.63 \times 10^{-34} / 1.98 \times 10^{-19} = 3.35 \times 10^{-15}$ m $\approx 3.3 \times 10^{-15}$ m

(2 marks)

6. For the oxygen-16 experiment above, the first minimum occurs at θ ≈ 41° (read from graph). Calculate the radius of an oxygen-16 nucleus.

$\sin 41^\circ = 0.656$

$D = 0.61\lambda / \sin\theta = 0.61 \times 3.35 \times 10^{-15} / 0.656 = 3.12 \times 10^{-15}$ m

Nuclear radius ≈ 3.1×10^{-15} m (≈ 3.1 fm)

(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?

(a) From graph: at E_P = 5 MeV, r 4.5×10^{-14} m

(b) Half KE lost when E_P = 2.5 MeV r 9×10^{-14} m (read from graph)

(c) At r = 2.0×10^{-14} m, graph shows E_P 11 MeV — so alpha needs 11 MeV

(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 = 5.0×10^{-14} m: E_P(gold) = 4.55 MeV, E_P(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)?

(a) Smaller nuclear charge (Z) means weaker electrostatic repulsion at the same distance. E_P Z, so tin (Z=50) and aluminium (Z=13) have lower PE curves.

(b) E_P Z: ratio = Z(gold)/Z(tin) = 79/50 = 1.58

(c) From graph: at E_P = 5 MeV for tin, r 2.9×10^{-14} m

(d) From graph: at E_P = 5 MeV for aluminium, r 0.75×10^{-14} m 7.5 fm — very close to the nuclear surface (radius 3 fm), so the strong nuclear force would be felt.

(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 = 1.6×10^{-19} C, = 8.85×10^{-12} C² J^{-1} m^{-1})

E_P = (2e × 82e) / (4 × r) [each nucleus has charge 82e; two nuclei colliding head-on share energy]

Total E_P = qq/(4r) = $(82 \times 1.6{\times}10^{-19})^2 / (4 \times 8.85{\times}10^{-12} \times 1.0{\times}10^{-14})$

= $(1.312{\times}10^{-17})^2 / (1.113{\times}10^{-24}) = 1.72{\times}10^{-34}/1.113{\times}10^{-24}$

= 1.55×10^{-10} J 966 MeV

Each nucleus needs ~483 MeV of kinetic energy.

(3 marks)

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

$E = 400 \times 10^{6} \times 1.6{\times}10^{-19} = 6.4{\times}10^{-11}$ J

$p = E/c = 6.4{\times}10^{-11} / 3{\times}10^{8} = 2.133{\times}10^{-19}$ kg m s^{-1}

$\lambda = h/p = 6.63{\times}10^{-34} / 2.133{\times}10^{-19} = 3.11{\times}10^{-15}$ m $\approx 3.0{\times}10^{-15}$ 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.

$\lambda \approx 3.0{\times}10^{-15}$ m (from Q7)

sin 42° = 0.669

$D = 0.61 \times 3.0{\times}10^{-15} / 0.669 = 2.74{\times}10^{-15}$ m

Radius $\approx 2.7 \times 10^{-15}$ m (2.7 fm)

(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 $r_0 \approx 1.2$–1.5 fm (radius of a single nucleon).

Nuclear Density (same for all nuclei!)

Assuming mass = Au (where u = 1.66×10^{-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 ~10^{14} times denser than ordinary matter (~10^{3} kg m^{-3}), suggesting atoms are almost entirely empty space.

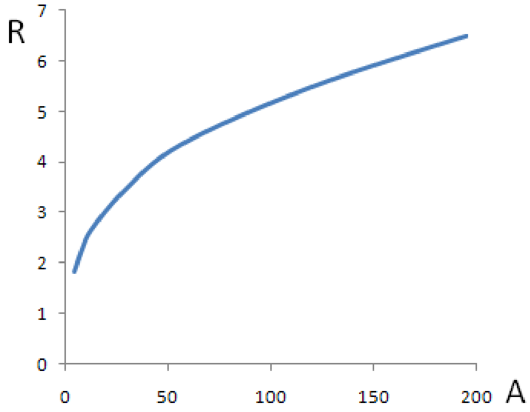


Fig 5.5 — R vs A (curve)

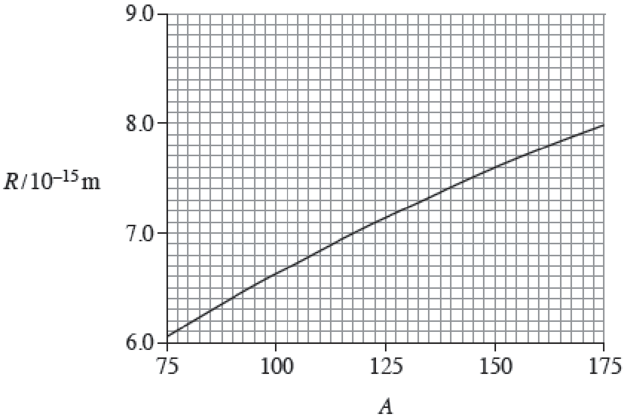


Fig 5.6 — R vs A^(1/3) (linear)

Questions

9. The radius of the gold nucleus is $R = 7.16 \times 10^{-15}$ m. Given $R = r_o$A^(1/3) and $r_o = 1.23 \times 10^{-15}$ m, determine the number of nucleons in gold.

$R = r_o$A^(1/3) → A^(1/3) = $R/r_o = 7.16{\times}10^{-15} / 1.23{\times}10^{-15} = 5.82$

$A = (5.82)^3 = 197.1 \approx 197$ nucleons

(3 marks)

10. Show that the radius of a ^{51}V nucleus (A = 51) is about 5×10^{-15} m. ($r_o = 1.4 \times 10^{-15}$ m)

$R = r_o$A^(1/3) = $1.4{\times}10^{-15}$ × (51)^(1/3) = $1.4{\times}10^{-15} \times 3.708 = 5.19{\times}10^{-15}$ m ≈ $5{\times}10^{-15}$ m

(2 marks)

11. Calculate the density of a ^{51}V nucleus. ($u = 1.66 \times 10^{-27}$ kg, $r_o = 1.4 \times 10^{-15}$ m)

$R = 5.19{\times}10^{-15}$ m

$V = 4/3\,\pi R^3 = 4/3 \times \pi \times (5.19{\times}10^{-15})^3 = 5.86{\times}10^{-43}$ m^3

$m = 51 \times 1.66{\times}10^{-27} = 8.47{\times}10^{-26}$ kg

$\rho = m/V = 8.47{\times}10^{-26} / 5.86{\times}10^{-43} = 1.45{\times}10^{17}$ kg m^{-3} (≈ $1.4{\times}10^{17}$ kg m^{-3})

(3 marks)

12. What does the fact that all nuclei have approximately the same density suggest about the nature of the strong nuclear force?

The strong nuclear force must be short-range and saturating — each nucleon only interacts with its immediate neighbours, not with all other nucleons.

If all nucleons interacted with all others, adding more nucleons would increase the force without limit and the density would change.

(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 , 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

1. Show that if a first dark ring is seen at = 30°, the circular objects have diameter approximately twice the wavelength (use the formula below for this question only):

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

sin 30° = 0.5 d = /sin = /0.5 = 2

(2 marks)

2. Use the formula below to find the angle of the first dark ring for particles four wavelengths in diameter.

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

sin = 1.22/(4) = 1.22/4 = 0.305   = 17.8° 18°

(2 marks)

3. Calculate the energy in joules of an electron with energy 100 MeV. (1 eV = 1.6×10^{-19} J)

$E = 100 \times 10^{6} \times 1.6{\times}10^{-19} = 1.6 \times 10^{-11}$ J

(2 marks)

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

$p = E/c = 1.6{\times}10^{-11} / 3.0{\times}10^{8} = 5.33 \times 10^{-20}$ kg m s^{-1}

(2 marks)

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

* = $h/p = 6.63{\times}10^{-34}/5.33{\times}10^{-20} = 1.24 \times 10^{-14}$ m*

(2 marks)

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

d_proton = $2 \times 1.2{\times}10^{-15} = 2.4{\times}10^{-15}$ m

Ratio = /d = $1.24{\times}10^{-14}/2.4{\times}10^{-15}$ 5.2

The wavelength is about 5× the proton diameter — need higher energy electrons (~500 MeV+) for nuclear scattering.

(2 marks)

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

$$\lambda = \frac{hc}{E} \qquad \sin\theta_{\text{min}} = \frac{1.22\,\lambda}{d}$$

$E = 400{\times}10^{6} \times 1.6{\times}10^{-19} = 6.4{\times}10^{-11}$ J

* = $hc/E = (6.63{\times}10^{-34} \times 3{\times}10^{8})/6.4{\times}10^{-11} = 3.11{\times}10^{-15}$ m*

d = 1.22/sin = $1.22{\times}3.11{\times}10^{-15}/0.67 = 5.66{\times}10^{-15}$ m

Radius $= d/2 = 2.83\times10^{-15}$ *m* $\;\; 2.7\times10^{-15}$ *m*

(3 marks)

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

Need $\;d = 2 \times 7.4\times10^{-15} = 1.48\times10^{-14}$ *m*

$E = hc/ = (6.63\times10^{-34} \times 3\times10^{8})/1.48\times10^{-14} = 1.34\times10^{-11}$ *J*

$E \;\; 1.34\times10^{-11}/1.6\times10^{-19} = 8.4\times10^{7}$ *eV* $\;\;84$ *MeV*

(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 5.94×10^{-11} J) is about 3.3×10^{-15} m.

$p = E/c = 5.94\times10^{-11}/3\times10^{8} = 1.98\times10^{-19}$ *kg m s*$^{-1}$

$\lambda = h/p = 6.63\times10^{-34}/1.98\times10^{-19} = 3.35\times10^{-15}$ *m* $\approx 3.3\times10^{-15}$ *m*

(2)

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

$R = 0.61 \times 3.35\times10^{-15} / \sin(41^\circ) = 0.61 \times 3.35\times10^{-15} / 0.656 = 3.12\times10^{-15}$ *m*

(2)

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

Diagram should show: evacuated chamber, alpha source, gold foil, movable ZnS detector/microscope.

(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.

Observation 1: Most alpha particles pass straight through with little deflection.

Significance: Atom is mostly empty space.

Observation 2: About 1 in 8000 deflected through angles >90°.

Significance: Nucleus is tiny, dense and positively charged.

Upper limit: Distance of closest approach of 5 MeV alpha to gold gives r~45 fm; nucleus must be smaller than this.

(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 × 10^{8} m s^{-1}) *(3 marks)*

$E = mc^2$. $E = 3.0\times10^{-29} \times (3.0\times10^{8})^2 = 3.0\times10^{-29} \times 9\times10^{16} = 2.7 \times 10^{-12}$ J

2. 1 u = 1.66 × 10^{-27} kg. A proton has mass 1.00728 u. Calculate its mass in kg. *(2 marks)*

$m_p = 1.00728 \times 1.66 \times 10^{-27} = 1.672 \times 10^{-27}$ kg

3. A nucleus of $^{59}_{27}$Co has Z = 27. State the number of neutrons. Calculate the total mass of the separated protons and neutrons. (m_p = 1.00728 u, m_n = 1.00867 u) *(3 marks)*

N = 59 − 27 = 32 neutrons.

Total mass = 27 × 1.00728 + 32 × 1.00867 = 27.197 + 32.277 = 59.474 u

4. State what is meant by the binding energy of a nucleus in one sentence. *(2 marks)*

The binding energy is the energy required to completely separate a nucleus into its individual protons and neutrons (or equivalently, the energy released when the nucleus is assembled from its free nucleons).

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):

Mass of nucleons = 2 × 1.673×10^{-27} + 2 × 1.675×10^{-27} = 6.696×10^{-27} kg

Mass of nucleus = 6.648×10^{-27} kg

Δm = 6.696×10^{-27} — 6.648×10^{-27} = 0.048×10^{-27} kg = 0.029 u

The atomic mass unit u is used for convenience: **1 u = 1.661 × 10^{-27} 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.

The mass defect is the difference between the total mass of the separated constituent nucleons (protons and neutrons) and the actual mass of the bound nucleus.

Δm = (Z m_p + N m_n) — m_nucleus

(2 marks)

2. $^{1}H + {}^{7}Li \rightarrow {}^{4}He + {}^{4}He$. Masses: H = 1.0073 u, Li = 7.0160 u, He = 4.0015 u. Show that the mass decreases and calculate Δm.

Mass of reactants: 1.0073 + 7.0160 = 8.0233 u

Mass of products: 2 × 4.0015 = 8.0030 u

Δm = 8.0233 — 8.0030 = 0.0203 u

In kg: $0.0203 \times 1.6605\times10^{-27} = 3.37\times10^{-29}$ kg (mass decreases)

(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 $\Delta E = \Delta mc^2$.

Total KE of 2 alphas = 2 × 8.5 = 17.0 MeV; initial KE of proton ≈ 0.8 MeV; net gain ≈ 16.2 MeV

$\Delta E = \Delta mc^2 = 3.37\times10^{-29} \times (3\times10^{8})^2 = 3.03\times10^{-12}$ J

In MeV: $3.03\times10^{-12} / 1.6\times10^{-13} = 18.9$ MeV

(Consistent to order of magnitude — some energy carried by neutrinos/other effects)

(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 × 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/c^2** (or equivalently, 1 u of mass defect corresponds to 931.3 MeV of binding energy)

Example — Helium-4: Δm = 0.029 u → E = 0.029 × 931.3 = 27 MeV

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

Δm = 1.0073 + 1.0087 — 2.0136 = 0.0024 u → E = 0.0024 × 931.3 = 2.24 MeV

Questions

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

The binding energy is the energy needed to completely separate a nucleus into its individual (isolated) protons and neutrons.

It equals Δmc^2, where Δm is the mass defect of the nucleus.

(2 marks)

5. Calculate the binding energy of a ^{59}Co nucleus in MeV. (nuclear mass = 58.93320 u; m_p = 1.00728 u; m_n = 1.00867 u; 1 u = 931.3 MeV/c^2) Co-59 has Z = 27, N = 32.

Mass of nucleons: 27 × 1.00728 + 32 × 1.00867 = 27.196 + 32.277 = 59.473 u

Mass defect: Δm = 59.473 — 58.93320 = 0.5398 u

BE = 0.5398 × 931.3 = 502.8 MeV ≈ 503 MeV

(4 marks)

6. Calculate the average binding energy per nucleon of ^{64}Zn ($Z = 30$, $N = 34$). (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)

Nuclear mass = atomic mass − 30 × m_e = 63.92915 − 30×0.00055 = 63.92915 − 0.01650 = 63.91265 u

Nucleon mass: 30 × 1.00728 + 34 × 1.00867 = 30.218 + 34.295 = 64.513 u

Δm = 64.513 − 63.91265 = 0.600 u

BE = 0.600 × 931.3 = 558.8 MeV

BE per nucleon = 558.8 / 64 = 8.73 MeV/nucleon

(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 **^{56}Fe (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.

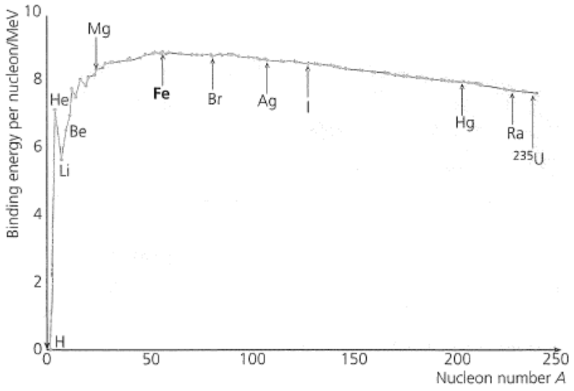


Fig 6.1 — Binding energy per nucleon vs nucleon number

Questions

7. Why would you expect ^{64}Zn to be very stable based on its binding energy per nucleon?

Its binding energy per nucleon (~8.7 MeV) is near the maximum on the BE/nucleon curve (peak is ~8.8 MeV at Fe-56).

A high BE/nucleon means a large amount of energy is needed to remove a nucleon — the nucleus is tightly bound.

(1 mark)

8. Explain why energy is released in nuclear fission of uranium-235.

U-235 has a lower binding energy per nucleon (~7.6 MeV) than its fission fragments (typically ~8.4–8.5 MeV/nucleon).

The fragments are more tightly bound — energy is released equal to the increase in total binding energy.

(2 marks)

9. Explain why nuclear fusion of hydrogen isotopes releases energy.

Deuterium (^2H) has BE/nucleon 1.1 MeV; tritium (^3H) has BE/nucleon 2.8 MeV.

The helium-4 product has BE/nucleon 7.1 MeV — a substantial increase.

The products are more tightly bound than the reactants; energy released as KE.

(2 marks)

10. The fission of U-235: $^{235}U + n \rightarrow {}^{133}Sb + {}^{99}Nb + 4n$. The mass of ^{235}U = 235.0439 u, Sb-133 = 132.9152 u, Nb-99 = 98.9116 u, neutron = 1.0087 u. Show that the energy change per fission is about 200 MeV.

Mass of reactants: 235.0439 + 1.0087 = 236.0526 u

Mass of products: 132.9152 + 98.9116 + 4×1.0087 = 231.8616 + 4.0348 = 235.8964 u

Δm = 236.0526 — 235.8964 = 0.1562 u

ΔE = 0.1562 × 931.3 = 145.5 MeV ≈ ~150 MeV (Note: book says ~200 MeV — different products give different values; typical range is 150–200 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:

$$^1_1H + {}^7_3Li \rightarrow {}^4_2He + {}^4_2He$$

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

Questions

1. Show that mass decreases in this reaction. Calculate m in u and kg. (1 u = 1.6605 × 10^{-27} kg)

Reactants: 1.0073 + 7.0160 = 8.0233 u

Products: 2 × 4.0015 = 8.0030 u

m = 8.0233 − 8.0030 = 0.0203 u = 0.0203 × 1.6605×10^{-27} = 3.37 × 10^{-29} 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.

Total KE of 2 alphas = 2 × 8.5 = 17 MeV; initial proton KE 0.8 MeV (Li 0 KE)

Net gain 17 − 0.8 = 16.2 MeV

E = mc^2 = 0.0203 × 931.3 = 18.9 MeV

These are consistent to within experimental uncertainty (some energy carried by recoil/neutrinos).

(3 marks)

3. Two deuterium nuclei can fuse: $^2H + {}^2H \rightarrow {}^3He + n$. Masses: ^2H = 2.014102 u, ^3He = 3.016030 u, n = 1.008665 u. Calculate the energy released per fusion event in MeV and joules.

m = 2 × 2.014102 − (3.016030 + 1.008665) = 4.028204 − 4.024695 = 0.003509 u

E = 0.003509 × 931.3 = 3.27 MeV

In joules: 3.27 × 10^6 × 1.6×10^{-19} = 5.23 × 10^{-13} J

(4 marks)

Additional: Fusion in a Kettle

> The ratio of deuterium (^2H) atoms to ordinary hydrogen in water is roughly 1 : 7000. A litre of water contains about 55.6 moles (H_2O molar mass ≈ 18 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 ^2H to give ^3He plus one other particle.

$^2H + {}^2H \rightarrow {}^3He + {}^1n$

(Check: A: 2+2=4 → 3+1 ; Z: 1+1=2 → 2+0)

(2 marks)

2. A litre of water contains about 55.6 moles. How many H_2O molecules does it contain? (N_A = 6.02 × 10^{23} mol^{-1})

$N = 55.6 \times 6.02{\times}10^{23} = 3.35 \times 10^{25}$ *molecules*

(2 marks)

3. How many molecules of heavy water (D_2O, with two deuterium atoms) are in the kettle? (ratio D:H ≈ 1:7000 so 1 in 7000 water molecules is D_2O — approximately)

$N(D_2O) = 3.35{\times}10^{25} / 7000 = 4.78 \times 10^{21}$ *molecules*

Each has 2 deuterium atoms, so $2 \times 4.78{\times}10^{21} = 9.56{\times}10^{21}$ *D atoms*

(2 marks)

4. Each pair of deuterium nuclei that fuses releases 5.23×10^{-13} J. Calculate the total energy released if all the deuterium in the kettle fused.

Pairs available $= 9.56{\times}10^{21}/2 = 4.78{\times}10^{21}$

Total energy $= 4.78{\times}10^{21} \times 5.23{\times}10^{-13} = 2.50 \times 10^9$ J

(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?

Energy to heat 1 litre by 100 K = 4200 × 1 × 100 = 420,000 J

Litres heated $= 2.50{\times}10^9 / 4.2{\times}10^5$ *5950 litres*

(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.

The binding energy is the energy required to separate a nucleus into its constituent nucleons (protons and neutrons).

It arises because nucleons are held together by the strong nuclear force. Work must be done against this force to separate them.

Equivalently, energy is released when nucleons bind together — this corresponds to the mass defect via $E = \Delta mc^2$.

(3)

(a(ii)) State what is meant by mass difference (mass defect).

The mass defect is the difference between the sum of masses of the individual (separated) nucleons and the actual mass of the bound nucleus.

$\Delta m = (Z\, m\_p + N\, m\_n) - m\_nucleus > 0$

(2)

(a(iii)) State the relationship between binding energy and mass difference.

E_binding = Δm × c^2 (binding energy equals the mass defect multiplied by the speed of light squared)

(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 u = 931.3 MeV)

Nuclear mass = 63.92915 − 30×0.00055 = 63.91265 u

Total nucleon mass: 30×1.00728 + 34×1.00867 = 30.2184 + 34.2947 = 64.5131 u

Δm = 64.5131 − 63.9127 = 0.6004 u

BE = 0.6004 × 931.3 = 559.1 MeV

BE/nucleon = 559.1/64 = 8.74 MeV/nucleon

(5)

(c) Why would you expect the zinc nucleus to be very stable?

The binding energy per nucleon of ~8.7 MeV is close to the maximum on the BE/nucleon curve (peak at Fe-56, ~8.8 MeV), indicating the nucleus is tightly bound and highly 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.

(i) Induced fission: fission triggered by absorption of a neutron (not spontaneous).

(ii) Thermal neutrons: slow neutrons with KE 0.025 eV (same as moderator atoms at room temperature), slow enough to be captured by ^{23}U.

(3)

(b(i)) For $^{235}{}_{92}$U + n $^{92}{}_{36}$Kr + $^{141}{}_{56}$Ba + N neutrons. Calculate N.

A: 235+1 = 92+141+N N = 3

Z: 92 = 36+56 = 92

(1)

(b(ii)) How do the product neutrons differ from the initial neutron?

Products are fast neutrons (~10^7 m s^{-1}); initial was a slow thermal neutron (~10^3 m s^{-1}).

(1)

(b(iii)) Calculate the energy released in MeV per fission. (m$_n$ = 1.00867 u; m(^{235}U nucleus) = 234.99333 u; m(^{92}Kr nucleus) = 91.90645 u; m(^{141}Ba nucleus) = 140.88354 u; 1 u = 931 MeV)

Reactants: 234.99333 + 1.00867 = 236.00200 u

Products: 91.90645 + 140.88354 + 3×1.00867 = 235.82600 u

m = 236.00200 − 235.82600 = 0.17600 u

E = 0.17600 × 931 = 163.9 MeV 164 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.

The energy needed to completely separate the nucleus into its constituent protons and neutrons.

Equivalently: energy released when the nucleus is assembled from its separated nucleons.

(2)

(b(i)) When ${}^{235}_{92}U$ absorbs a slow neutron it can fission to ${}^{112}_{43}Tc$ and ${}^{122}_{49}In$. Complete the equation: ${}^{1}n + {}^{235}U\ \ {}^{112}Tc + {}^{122}In$ + ?

${}^{1}n + {}^{23}U\ \ {}^{112}Tc + {}^{122}In + 2{}^{1}n$

Check: A: 1+235=236 112+122+2=236 ; Z: 92=43+49

(1)

(b(ii)) Calculate energy released in MeV. (BE/nucleon: ${}^{235}U$ = 7.59 MeV, ${}^{112}Tc$ = 8.36 MeV, ${}^{122}In$ = 8.51 MeV)

BE(U) = 235×7.59 = 1783.65 MeV

BE(Tc) = 112×8.36 = 936.32 MeV

BE(In) = 122×8.51 = 1038.22 MeV

Energy released = (936.32+1038.22) − 1783.65 = 190.9 MeV

(3)

(b(iii)) Calculate the loss of mass in kg. (1 MeV = 1.6×10^{-13} J, c = 3.0×10^{8} m s^{-1})

$E = 190.9 \times 1.6 \times 10^{-13} = 3.054 \times 10^{-11}$ J

$m = E/c^2 = 3.054 \times 10^{-11}/(3 \times 10^{8})^2 = 3.4 \times 10^{-28}$ kg

(2)

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

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

Z=27, N=32

Total nucleon mass: 27×1.00728 + 32×1.00867 = 59.473 u

m = 59.473 − 58.93320 = 0.5398 u

BE = 0.5398 × 931.3 = 502.7 MeV

(3)

(b) Fe-59 decays by 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 when Fe-59 decays to the highest excited state (2.29×10^{-13} J).

Available energy = $(2.52 - 2.29) \times 10^{-13} = 0.23 \times 10^{-13}$ J

Max KE = $0.23 \times 10^{-13}/1.6 \times 10^{-13}$ = 0.14 MeV

(Maximum KE when antineutrino carries negligible energy.)

(3)

(c) State the maximum number of discrete gamma-ray wavelengths that could be emitted.

3 excited states 6 possible transitions (32, 31, 30, 21, 20, 10) maximum 6 wavelengths.

(1)

(d) Calculate the longest wavelength of the emitted gamma radiation. (h = 6.63×10^{-34} J s, c = 3.0×10^{8} m s^{-1})

Lowest energy transition: $(2.06 - 1.76) \times 10^{-13} = 0.30 \times 10^{-13}$ J

$= hc/E = (6.63 \times 10^{-34} \times 3 \times 10^{8})/0.30 \times 10^{-13}$

$= 6.6 \times 10^{-12}$ m

(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)*

Curve rising steeply from H (low BE/nucleon ~1 MeV), peaking at Fe-56/Ni-62 (~8.8 MeV/nucleon), then gradually decreasing to U-238 (~7.6 MeV/nucleon).

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)*

Energy is released. The bound nucleus has lower total energy (higher BE/nucleon) than the separated nucleons; the difference is released as kinetic energy or radiation.

3. A nucleus of $^{235}_{92}U$ absorbs a thermal neutron. Write the unstable compound nucleus formed. *(2 marks)*

$^{235}_{92}U + ^{1}_{0}n$ $^{236}_{92}U$ *(unstable)*

4. Define 'critical mass' of a fissile material in your own words. *(2 marks)*

The critical mass is the minimum mass of fissile material needed to sustain a self-sustaining chain reaction — where on average at least one neutron from each fission triggers another fission.

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:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{144}_{56}Ba + ^{90}_{36}Kr + 2\,^{1}_{0}n + E$$

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.

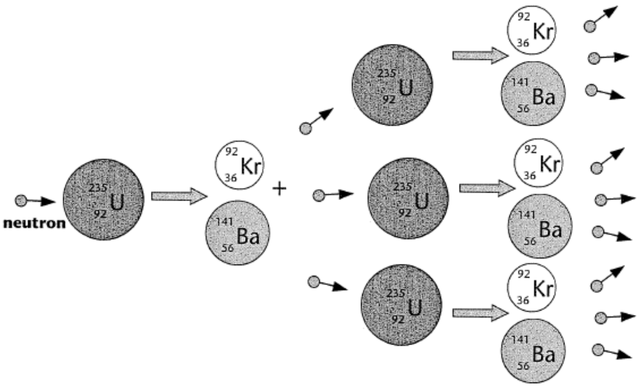


Fig 7.1 — Chain reaction in U-235 fission

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.

Eq 1: $^{235}U + ^{1}n \rightarrow ^{236}U$ *(unstable compound nucleus)*

Eq 2: $^{236}U \rightarrow ^{144}Ba + ^{90}Kr + 2^{1}n$

(Check: A: 235+1=236 → 144+90+2=236 ; Z: 92 → 56+36=92)

(3 marks)

2. In the fission $^{235}U + n \rightarrow ^{92}Kr + ^{141}Ba$ + N neutrons, calculate N.

Nucleon number: 235 + 1 = 92 + 141 + N

236 = 233 + N → N = 3

(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)

Reactant mass: 234.993 + 1.009 = 236.002 u

Product mass: 91.906 + 140.884 + 3×1.009 = 235.817 u

Δm = 236.002 — 235.817 = 0.185 u

ΔE = 0.185 × 931 = 172 MeV ≈ 170 MeV

(5 marks)

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

The critical mass is the minimum mass of fissile material needed to sustain a chain reaction.

Below this mass, too many neutrons escape through the surface before causing further fissions, and the reaction dies out.

(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 ~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):

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + ^{1}_{0}n + E$$

Energy released ≈ 17.6 MeV per reaction.

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

Nuclei are positively charged, so they repel each other electrostatically (Coulomb barrier).

Very high temperature means very high kinetic energy, so nuclei move fast enough to overcome this repulsion.

At sufficiently small separation (~few fm), the strong nuclear force takes over and pulls the nuclei together.

(3 marks)

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

$^{2}H + ^{2}H \rightarrow ^{3}He + ^{1}n$

Check: $A: 2+2=4 \rightarrow 3+1=4$; $Z: 1+1=2 \rightarrow 2+0=2$

(2 marks)

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

$\Delta m = 2 \times 2.014102 - (3.016030 + 1.008665) = 4.028204 - 4.024695 = 0.003509$ u

$\Delta E = 0.003509 \times 931.3 = 3.268$ MeV

In joules: $3.268 \times 10^{6} \times 1.6 \times 10^{-19} = 5.23 \times 10^{-13}$ J

(4 marks)

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

The binding energy per nucleon change is larger for fusion of the lightest nuclei than for fission of heavy nuclei.

Light nuclei (H, He) have much lower BE/nucleon than iron — fusion causes a large increase in BE/nucleon per nucleon involved.

Also, the reactant nuclei are much lighter, so fewer kg contain a given number of nuclei.

(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 → 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 → energy released.

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

Fission fragments are neutron-rich: Heavy nuclei ($N >> Z$) 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 → likely β^{-} emitters.

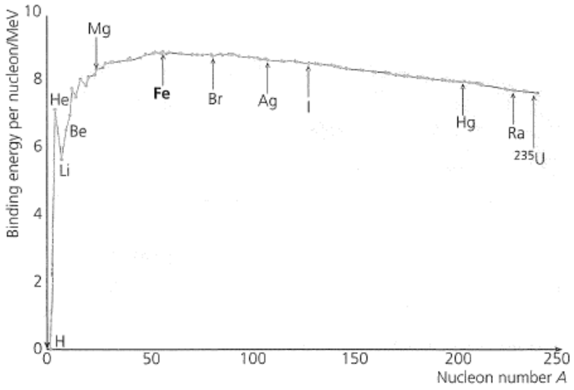


Fig 7.3 — Binding energy per nucleon vs nucleon number

Questions

9. Explain, with reference to the binding energy per nucleon graph, why energy is released in both fission and fusion.

Both processes move nuclei towards the iron-56 peak (maximum BE/nucleon ≈ 8.8 MeV).

Fission: heavy nuclei (A > 56) have lower BE/nucleon. Splitting them gives fragments closer to iron with higher BE/nucleon. Energy = increase in total binding energy.

Fusion: light nuclei (A < 56) have lower BE/nucleon. Combining gives a heavier product with higher BE/nucleon. Energy = increase in total binding energy.

In both cases: products have greater total binding energy than reactants → this energy difference is released.

(4 marks)

10. Explain why energy released per nucleon from fusion is greater than from fission, with reference to the graph.

On the BE/nucleon graph, the slope is much steeper on the left (low A) side than the right.

Fusion of light nuclei (small A) causes a large jump up the steep left side.

Fission of heavy nuclei causes a smaller increase (gentle slope on the right).

Therefore the change in BE/nucleon — and hence energy released per nucleon — is greater for fusion.

(2 marks)

11. Explain why fission fragments are unstable and what type of radiation they are likely to emit.

Heavy fissile nuclei (e.g. U-235) have a high neutron-to-proton ratio (N >> Z).

When they split, the fragments inherit this high N/Z ratio.

For the lower-A fragments, stable nuclei have a much lower N/Z ratio.

So fission fragments fall above the line of stability on the N–Z graph (too many neutrons).

They are likely to emit β^- radiation (neutron → proton + electron + antineutrino) to move towards stability.

(3 marks)

12. 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)

Mass of nucleons: $8 \times 1.00728 + 8 \times 1.00867 = 8.0582 + 8.0694 = 16.1276$ u

$\Delta m = 16.1276 - 15.991 = 0.1366$ u

In kg: $0.1366 \times 1.661 \times 10^{-27} = 2.269 \times 10^{-28}$ kg

(3 marks)

Additional: Fission Practice Questions

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

Questions

1. Write two balanced equations for the fission of U-235: first showing formation of unstable ^{23}U, then showing fission to ^{1}Ba + Kr.

Eq 1: ^{23}U + ^{1}n ^{23}U (unstable compound nucleus)

Eq 2: ^{23}U ^{1}Ba + Kr + 2^{1}n

Check: A: 236 144+90+2 = 236 ; Z: 92 56+36 = 92

(3 marks)

2. Calculate the total mass of the reactants: ^{23}U + n.

235.043923 + 1.008665 = 236.052588 u

(1 mark)

3. Calculate the total mass of the products: ^{1}Ba + Kr + 2n.

143.922941 + 89.919528 + 2×1.008665 = 235.859799 u

(2 marks)

4. Calculate the change in mass. Does this represent energy gained or lost by the system?

m = 236.052588 − 235.859799 = 0.192789 u

Mass decreases energy is released (the system loses rest mass energy, which is converted to KE).

(2 marks)

5. Convert the mass change into the energy released in MeV.

E = 0.192789 × 931 = 179.5 MeV 180 MeV

(2 marks)

6. Repeat for caesium-138 + rubidium-96 products. Calculate the energy released in MeV. (Masses: ^{13}Cs = 137.911011 u, Rb = 95.934284 u)

Equation: ^{23}U ^{13}Cs + Rb + 2n

Check: A: 236 138+96+2 = 236 ; Z: 92 55+37 = 92

Product mass = 137.911011 + 95.934284 + 2×1.008665 = 235.862625 u

m = 236.052588 − 235.862625 = 0.189963 u

E = 0.189963 × 931 = 176.8 MeV 177 MeV

(4 marks)

Exam-Style Questions — Lesson 7

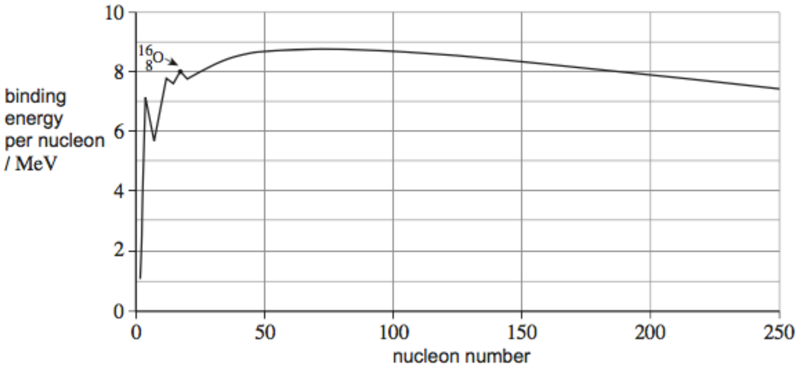


Fig 7.4 — Binding energy per nucleon graph for exam questions

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.

Energy is released when BE/nucleon increases (towards the iron-56 peak).

Heavy nuclei (A > 56, right of peak): splitting into fragments increases BE/nucleon → fission releases energy.

Light nuclei (A < 56, left of peak): fusing increases BE/nucleon → fusion releases energy.

If heavy nuclei fused or light nuclei split, BE/nucleon would decrease → energy would need to be input, not released.

(3)

(a(ii)) Explain why energy released per nucleon from fusion is greater than from fission.

The binding energy per nucleon curve rises more steeply on the left (low A) than it falls on the right.

Fusion of light nuclei gives a larger increase in BE/nucleon per nucleon than fission of heavy nuclei → more energy released per nucleon.

(2)

(b(i)) Calculate the mass difference of an O-16 nucleus in kg. (nucleus mass = 15.991 u, Z=8, N=8)

Total nucleon mass: $8 \times 1.00728 + 8 \times 1.00867 = 16.1276$ *u*

$\Delta m = 16.1276 - 15.991 = 0.1366$ *u* $= 0.1366 \times 1.661 \times 10^{-27} = 2.27 \times 10^{-28}$ *kg*

(2)

(b(ii)) Using your answer to (b)(i), calculate the binding energy of O-16 in MeV.

$\Delta E = \Delta mc^2 = 2.27 \times 10^{-28} \times (3 \times 10^8)^2 = 2.04 \times 10^{-11}$ *J*

In MeV: $2.04 \times 10^{-11} / 1.6 \times 10^{-13} = 127.5$ *MeV*

(Alternatively: $0.1366 \times 931.3 = 127.2$ *MeV)*

(2)

(b(iii)) Explain how the binding energy of O-16 can be calculated from the BE/nucleon graph.

Read off the binding energy per nucleon for A = 16 from the graph (~8.0 MeV/nucleon).

Multiply by 16 (the nucleon number) to get total binding energy: ~128 MeV.

(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)*

Each fission releases 2–3 neutrons which can trigger further fissions, each releasing more neutrons — an exponential increase.

If uncontrolled, the reaction rate and energy release grows rapidly, potentially causing a meltdown or explosion.

2. Fission neutrons travel at ~10^7 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)*

Thermal neutrons: speed ~10^3 m s^{-1} (same order as moderator atoms at room temperature). Factor of ~10^4 reduction in speed.

3. State two materials used as control rods and explain what single property makes them suitable. *(2 marks)*

Boron and cadmium (also hafnium accepted). They have very high neutron absorption cross-sections — they readily capture neutrons without themselves undergoing fission.

4. A reactor produces 2.0×10^9 W of thermal power with an efficiency of 35%. Calculate the electrical output power in MW. *(2 marks)*

$P_{electrical} = 0.35 \times 2.0{\times}10^9 = 7.0 \times 10^8$ W = 700 MW

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 ~10^7 m s^{-1} — too fast to cause further fission in U-235. The moderator slows them to thermal speeds (~$2{\times}10^3$ m s^{-1}, ~0.025 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).

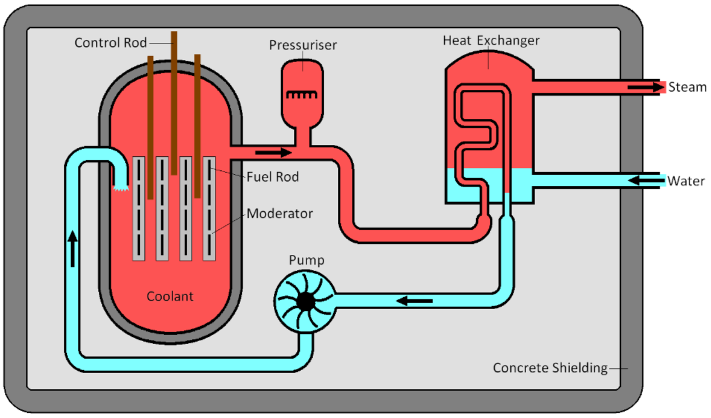


Fig 8.1 — Pressurised water reactor schematic

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.

uranium; fission; neutrons; chain reaction; slowed; moderator.

(3 marks)

2. Explain the role of the moderator in a nuclear reactor.

The moderator slows down the fast neutrons produced by fission (from ~10^7 m/s to ~10^3 m/s).

Slow (thermal) neutrons are much more likely to be absorbed by U-235 and cause further fissions.

Without the moderator, the chain reaction in U-235 fuel could not be sustained at thermal neutron energies.

(3 marks)

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

1. Low mass number (e.g. H, C): in elastic collisions, maximum energy transfer occurs when masses are equal. A low-mass-number nucleus absorbs more KE per collision, slowing neutrons in fewer collisions.

2. Low neutron absorption probability (small neutron capture cross-section): the moderator should slow neutrons without absorbing them, so they remain available to cause fission in U-235.

(4 marks)

4. What is meant by 'enriched' uranium?

Uranium in which the proportion of fissile U-235 has been increased above the natural level (0.72%) — typically to 3–5% for reactor use.

(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).

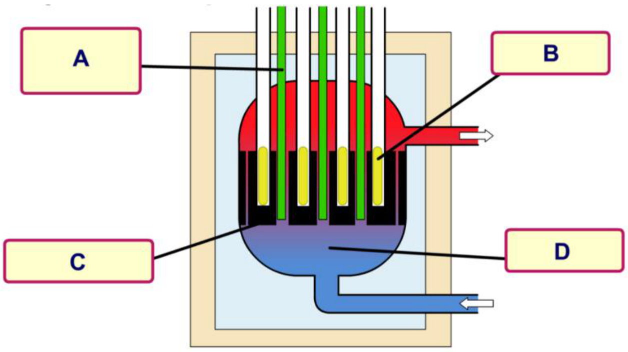


Fig 8.2 — Label the reactor components (A–D)

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.

Control rods absorb neutrons (using boron or cadmium).

Lowering the rods further into the core absorbs more neutrons → fewer fissions per second → power output decreases.

Raising the rods allows more neutrons to cause fission → power output increases.

For steady operation, exactly 1 neutron per fission must trigger another fission.

(3 marks)

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

1. High specific heat capacity: can carry more heat energy per kg per degree of temperature rise → more efficient heat transfer to turbines.

2. Poor neutron absorber: avoids the coolant becoming radioactive, which would create additional hazards and waste.

(4 marks)

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

Fission in fuel rods heats the moderator/coolant.

The coolant carries heat to the heat exchanger, where it heats a secondary water circuit.

Steam from the secondary circuit drives a turbine, which is coupled to a generator that produces electricity.

Used steam is condensed and recycled.

(3 marks)

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

Water vapour (steam condensed from the secondary circuit) — not radioactive.

The secondary coolant circuit is isolated from the primary (reactor) circuit, so it is not contaminated with radioactive material.

(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.

Each fission of a U-235 nucleus (induced by absorbing a thermal neutron) releases 2–3 fast neutrons.

After being slowed by the moderator, these cause further fissions, releasing more neutrons — a self-sustaining sequence.

(2 marks)

10. Explain why backup generators are essential for nuclear power plants even when the reactor is shut down.

Even after shutdown, the fission products (radioactive daughter nuclei) continue to decay, generating significant heat ('decay heat').

Without cooling, this heat would cause the core temperature to rise to dangerous levels, risking fuel rod damage and potential meltdown.

Backup generators power the emergency cooling systems and control systems.

(3 marks)

11. Neutrons released in the first collisions with the moderator may excite its nuclei. Describe the radiation emitted and explain subsequent collisions.

In the first few collisions: neutrons have enough energy to excite moderator nuclei to higher energy states.

These excited nuclei emit gamma radiation (electromagnetic) as they return to ground state.

Subsequent collisions: once below excitation energies, collisions are elastic — the neutron transfers kinetic energy to the moderator atom.

The neutron slows down gradually; the moderator heats up.

(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).

${}^{239}Np \rightarrow {}^{239}Pu + {}^{0}{}_{1}e + \nu^{-}$

(Beta-minus decay: Z increases by 1 from 93 to 94; A unchanged at 239)

(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.

The control rods are lowered further into the reactor core.

Control rods (boron or cadmium) absorb neutrons — inserting them more deeply reduces the number of neutrons available for fission.

Fewer fissions per second → less energy released → lower power output.

(3)

(b) State the main source of highly radioactive waste from a nuclear reactor.

Spent fuel rods — they contain fission products (radioactive daughter nuclei) and un-fissioned uranium and plutonium.

(1)

(c(i)) Describe and explain the radiation emitted when a moderator nucleus is excited by a high-energy neutron.

The excited nucleus emits a gamma ray photon (electromagnetic radiation).

This occurs as the nucleus transitions from an excited energy state back to its ground state, releasing the energy difference as a photon.

(2)

(c(ii)) Describe what happens to neutrons in subsequent elastic collisions with the moderator.

In elastic collisions, kinetic energy is transferred from the fast neutron to the moderator nuclei.

The neutron loses kinetic energy (slows down); the moderator nuclei gain kinetic energy (temperature rises).

After many collisions, neutrons reach thermal energy (~0.025 eV) and can then be absorbed by U-235.

(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)*

90 years = 3 half-lives. $A = 5.0\times10^8 \times (\tfrac{1}{2})^3 = 5.0\times10^8 / 8 = 6.25 \times 10^7$ *Bq*

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)*

(a) Control rods (boron/cadmium)

(b) Moderator (graphite or water)

(c) Coolant (water, CO or liquid metal)

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)*

Fission products in the fuel rods are highly radioactive and continue to decay, releasing heat (decay heat).

If cooling fails after shutdown, this heat can cause the fuel to melt (meltdown), releasing radioactive material.

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)*

Gamma radiation: absorbed by thick lead or concrete.

Neutron radiation: absorbed by water, polyethylene, or borated concrete (hydrogen-rich material).

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.

Neutrons escape from the reactor core into the shielding material.

These neutrons are absorbed by nuclei in the concrete and steel shielding.

The nuclei become unstable (neutron-rich) and are now radioactive — this is called neutron activation.

The shielding must therefore be treated as radioactive waste when the reactor is decommissioned.

(3 marks)

2. Describe how an emergency shutdown (SCRAM) of a nuclear reactor is achieved.

Control rods are immediately fully inserted into the reactor core.

They absorb all available free neutrons, stopping the chain reaction.

In some designs, secondary control rods are held above the core by electromagnets — a power failure releases them and they fall into the core by gravity.

Emergency cooling systems activate to remove decay heat from the fuel rods.

(3 marks)

3. Explain why backup cooling is still necessary even after a reactor has been shut down.

After shutdown, fission ceases but the radioactive fission products (daughter nuclei) continue to decay.

This radioactive decay generates heat ('decay heat'), which is significant and could cause the core to overheat without active cooling.

(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

4. Describe the steps taken to safely deal with high-level radioactive waste from a nuclear reactor.

1. Spent fuel rods removed from reactor and stored in cooling ponds within the power station for up to a year — allows short-lived radioactivity to decay.

2. Transported to a reprocessing plant; encased in steel containers kept under water.

3. Cladding removed; fuel separated into: unused uranium/plutonium (stored for possible future use) and highly radioactive waste.

4. Radioactive waste converted to powder, fused into glass blocks (vitrification), sealed in air-cooled containers.

5. Stored for ~50 years then buried deep underground in stable rock formations.

(5 marks)

5. State one problem in dealing with high-level nuclear waste and suggest a way of overcoming it.

Problem: The waste remains at dangerous radioactivity levels for thousands of years, far beyond any reliable human institution or structure.

Solution: Store in stable geological formations deep underground, in areas with low water flow to prevent leaching; design with multiple containment barriers.

(2 marks)

6. State the main source of highly radioactive waste from a nuclear reactor.

Spent fuel rods from the reactor core (containing fission products and residual radioactive material).

(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

7. 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.

${}^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + {}^{0}_{1}e + \nu^{-}$

(Beta-minus decay: A unchanged at 239; Z increases from 93 to 94)

(2 marks)

8. 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 3.4×10^{-6} s^{-1}.

Two half-lives have elapsed ($4.0 \rightarrow 2.0 \rightarrow 1.0 \times 10^{12}$ Bq)

$T1/2 = 2.0{\times}10^{5} / 2 = 1.0{\times}10^{5}$ s

$\lambda = \ln 2 / T1/2 = 0.693 / 1.0{\times}10^{5} = 6.93{\times}10^{-6}\ s^{-1} \approx 7{\times}10^{-6}\ s^{-1}$

(Note: using the graph to read half-life directly and calculating λ gives ≈ $3.4{\times}10^{-6}$ — depends on graph values read.)

(3 marks)

9. 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 $\lambda = 3.4 \times 10^{-6}\ s^{-1}$.

$A = \lambda N \rightarrow N = A/\lambda = 1.0{\times}10^{12} / 3.4{\times}10^{-6} = 2.9{\times}10^{17}$ nuclei

(2 marks)

10. Give a full account of the components of a thermal nuclear reactor and the role of each.

Fuel rods: enriched U-235/238 — fissile material where fission occurs and heat is generated.

Moderator (e.g. graphite, water): slows fast fission neutrons to thermal energies so they can be captured by U-235 and cause further fission.

Control rods (boron/cadmium): absorb excess neutrons to control the chain reaction and power output; inserted to reduce power, raised to increase power.

Coolant (CO_2 or water): transfers heat from core to heat exchanger; must have high specific heat, low neutron absorption, be non-flammable.

Heat exchanger: transfers thermal energy from primary (radioactive) coolant to secondary water circuit, producing steam.

Concrete shielding: absorbs neutrons and gamma radiation, protecting workers outside.

(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

1. Identify reactor components A, B, C and D in Fig 8.2.

A = Control rods B = Fuel rods C = Coolant/moderator region D = Heat exchanger

(Exact labels depend on diagram orientation — ensure arrows match components described in lesson.)

(4 marks)

2. 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?

Total electrical: 20 TW h/year = $20{\times}10^{12} \times 3600/3.15{\times}10^{7} = 2.29{\times}10^{9}$ W

Total thermal = $2.29{\times}10^{9}/0.40 = 5.7{\times}10^{9}\ J\ s^{-1}$

Electrical output 2.3×10^{9} J per second (2.3 GW)

(3 marks)

3. Each fission releases ~200 MeV. How many ${}^{23}U$ atoms must fission each second to produce the thermal power calculated in Q2? (1 MeV = 1.6×10^{-13} J)

Energy per fission = $200 \times 1.6\times10^{-13} = 3.2\times10^{-11}$ J

Fissions per second = $5.7\times10^{9}/3.2\times10^{-11} = 1.78 \times 10^{20}\ s^{-1}$

(3 marks)

4. What was the mass of these ${}^{23}U$ atoms before fission? (m(${}^{23}U$) = $235 \times 1.66\times10^{-27}$ kg)

Mass per atom = $235 \times 1.66\times10^{-27} = 3.90\times10^{-25}$ kg

Total mass = $1.78\times10^{20} \times 3.90\times10^{-25} = 6.94\times10^{-5}$ kg 0.07 g per second

(2 marks)

5. What is the total mass change due to fission in Magnox reactors each second? ($c = 3.0 \times 10^{8}\ m\ s^{-1}$)

$m = E/c^2 = 5.7\times10^{9}/(3\times10^{8})^2 = 6.3 \times 10^{-8}$ kg 63 g per second

(2 marks)

Exam-Style Questions — Lessons 8 & 9

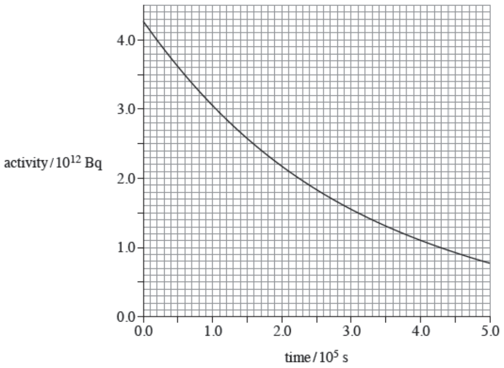


Fig 9.1 — Activity vs time for neptunium-239 sample

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

(a) 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 (${}^{239}_{93}Np$) to plutonium-239.

$${}^{239}_{93}Np \rightarrow {}^{239}_{94}Pu + {}^{0}_{1}e + \nu^{-}$$

(2)

(b(i)) Show that the decay constant of Np-239 is about $3.4 \times 10^{-6}\ s^{-1}$ (half-life read from activity graph ≈ 2×10^{5} s).

$\lambda = \ln 2 / T1/2 = 0.693 / 2\times10^{5} = 3.47\times10^{-6}\ s^{-1} \approx 3.4\times10^{-6}\ s^{-1}$

(2)

(b(ii)) 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.

$N = A/\lambda = 1.0\times10^{12} / 3.4\times10^{-6} = 2.9\times10^{17}$ nuclei

(2)

(c(i)) Explain what is meant by a chain reaction in a thermal nuclear reactor.

A chain reaction is where each fission event produces neutrons which, after moderation, go on to cause further fission events.

In U-235, fission releases 2–3 neutrons per event; in a steady reactor, exactly 1 of these causes another fission.

(2)

(c(ii)) Explain the purpose of a moderator in a thermal nuclear reactor.

The moderator slows down fast neutrons produced by fission (from ~10^7 m/s to ~10^3 m/s).

Slow (thermal) neutrons are far more likely to be captured by U-235 nuclei and cause fission.

The moderator must have low mass number (efficient energy transfer per collision) and low neutron absorption.

(3)

(c(iii)) Explain why the shielding around a reactor core becomes radioactive.

Neutrons escaping from the core are absorbed by nuclei in the shielding material.

These nuclei become unstable (neutron-rich) — they are now radioactive isotopes. This is neutron activation.

(2)

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

Source: Spent fuel rods (fission products — radioactive daughter nuclei — and residual uranium/plutonium).

Problem 1: Intensely radioactive and hot → must be stored in cooling ponds initially; direct handling impossible.

Treatment: Cooled in water ponds for ~1 year; then transported in thick steel/lead flasks.

Problem 2: Remains dangerous for thousands of years → no material container lasts long enough.

Treatment: Vitrified (converted to glass blocks), stored in steel canisters, then in deep geological repositories in stable rock.

Problem 3: Risk of leaching into groundwater → sites chosen for low water flow; multiple containment barriers used.

(6)