3.8 Nuclear Physics

AQA 7408 · Calculator allowed · about 195 minutes · Write-in edition

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 A cobalt-60 source (proton number 27) used in radiotherapy decays by β-minus emission to an excited nucleus of nickel-60, which subsequently decays to its ground state by emitting γ radiation.

(a) Determine the proton number and nucleon number of the nickel nucleus formed by this β-minus decay, and write a balanced nuclear equation for the decay, including the antineutrino. **(3)**

(b) Explain why the nickel-60 nucleus produced is described as 'excited', and state how it loses its excess energy. **(2)**

(c) State why the emission of a γ photon does not change the proton number or nucleon number of the nucleus, and state why γ radiation, unlike α and β particles, is not deflected by electric or magnetic fields. **(3)**

(Total for Question 1 is 8 marks)

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2 This question tests core definitions in nuclear physics.

(a) Define the decay constant of a radioactive isotope. **(1)**

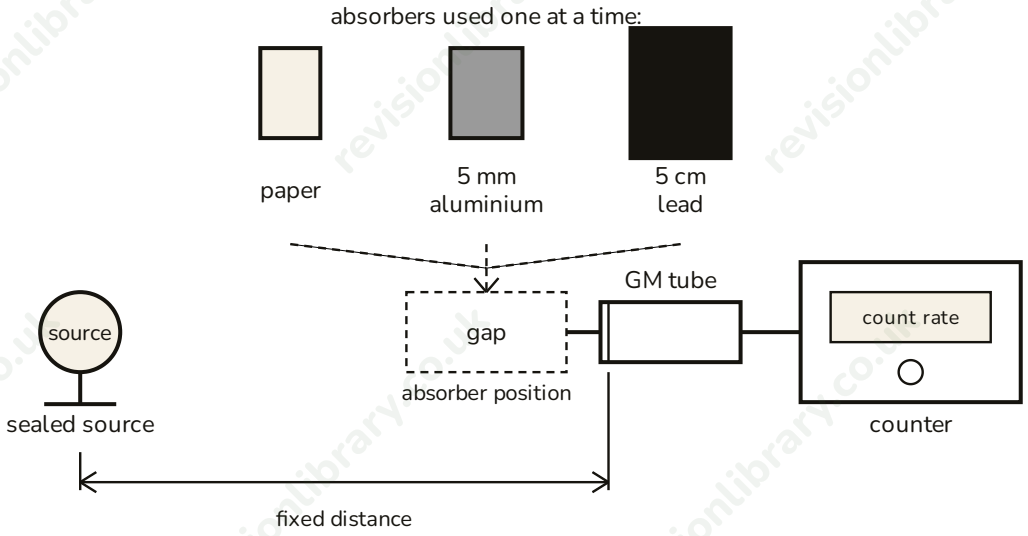
(b) State the equation linking the activity A of a source, its decay constant λ, and the number of undecayed nuclei N. **(1)**

(c) State two properties of the strong nuclear force. **(1)**

(Total for Question 2 is 3 marks)

3 Required practical: a student uses a GM tube and counter to investigate the absorption of radiation from a sealed, unknown radioactive source, placing different absorbers between the source and the tube at a fixed distance. The background count rate, measured with no source present, is 22 counts per minute. The student's results are shown below.

Absorber used	Measured count rate / counts per minute
None	850
Paper	845
5 mm aluminium	210
5 cm lead	26



(a) Explain why the student should measure the background count rate before the experiment, and explain how this measurement should be used with the readings in the table. **(2)**

(b) Determine the corrected count rate for each absorber, and use these values to identify the type(s) of radiation emitted by the source, justifying your answer using the data. **(4)**

(c) State one precaution, other than repeating readings, that the student should take to improve the reliability of each count rate measurement. **(1)**

(Total for Question 3 is 7 marks)

4 An archaeological wood sample has a measured activity per unit mass of carbon of 6.9 disintegrations per minute per gram. Living wood has an activity per unit mass of carbon of 15.0 disintegrations per minute per gram. The half-life of carbon-14 is 5730 years. Use $A = A0 \exp(-\lambda t)$, where $\lambda = \ln 2 / (\text{half-life})$.

(a) Show that the decay constant of carbon-14 is about 1.21×10^{-4} per year. **(2)**

(b) Calculate the age of the wood sample. **(4)**

(c) The sample is later found to have been contaminated with a small amount of modern carbon during excavation. State and explain the effect this contamination would have on the calculated age of the sample compared with its true age. **(2)**

(Total for Question 4 is 8 marks)

5 Mass of proton = 1.00728 u, mass of neutron = 1.00867 u, mass of a helium-4 nucleus = 4.00151 u. 1 u is equivalent to 931.5 MeV of energy.

(a) Show that the mass defect of a helium-4 nucleus is 0.0304 u. **(2)**

(b) Calculate the binding energy of the helium-4 nucleus in MeV, and hence the binding energy per nucleon. **(4)**

(c) State why binding energy per nucleon, rather than total binding energy, is used to compare the stability of different nuclides. **(1)**

(Total for Question 5 is 7 marks)

6 Iodine-131, used as a medical tracer, has a half-life of 8.02 days.

(a) Calculate the decay constant of iodine-131 in per second. **(3)**

(b) A sample contains 5.0×10^{13} undecayed iodine-131 nuclei. Calculate the initial activity of the sample. **(2)**

(c) Calculate the activity of the sample after 24.06 days. **(3)**

(Total for Question 6 is 8 marks)

7 In a deuterium-tritium fusion reaction: ^2_1 H + ^3_1 H -> ^4_2 He + ^1_0 n. Masses: deuterium = 2.01410 u, tritium = 3.01605 u, helium-4 = 4.00260 u, neutron = 1.00867 u. 1 u = 931.5 MeV = 1.6605 x 10^{-27} kg. 1 MeV = 1.602 x 10^{-13} J.

(a) Calculate the energy released, in MeV, in a single deuterium-tritium fusion reaction. **(4)**

(b) A future fusion reactor aims to produce a continuous power output of 500 MW using this reaction. Calculate the number of deuterium-tritium fusion reactions required per second, and hence estimate the mass of deuterium fuel consumed per day. **(6)**

(Total for Question 7 is 10 marks)

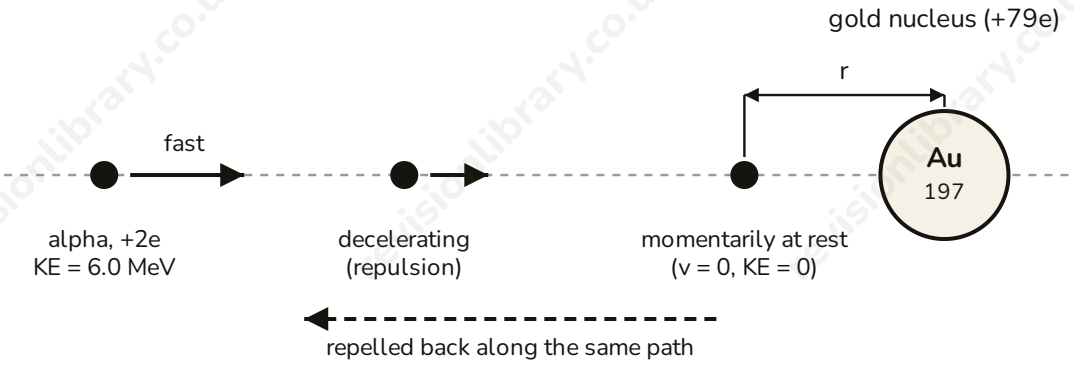
8 A thermal nuclear power station reactor uses uranium-235 fuel rods, a graphite moderator, boron control rods, and a pressurised water coolant.

Explain the function of the moderator, the control rods and the coolant in sustaining and controlling a chain reaction, and explain why each is necessary for the reactor to operate safely at a steady power output.

(Total for Question 8 is 6 marks)

9 In an α-particle scattering experiment, α particles of kinetic energy 6.0 MeV are fired directly (head-on) at gold-197 nuclei (proton number 79). At the point of closest approach, all the initial kinetic energy of the α particle has been converted to electric potential energy. Use the equation for electric potential energy between two point charges, Ep = Q1 Q2 / (4 π epsilon0 r), from the Physics Equations Sheet. Elementary charge e = 1.60 x 10^{-19} C, epsilon0 = 8.85 x 10^{-12} F/m, 1 eV = 1.60 x 10^{-19} J.

Head-on alpha-particle scattering (not to scale)



(a) Show that the kinetic energy of the α particle in joules is 9.6 x 10^{-13} J. **(1)**

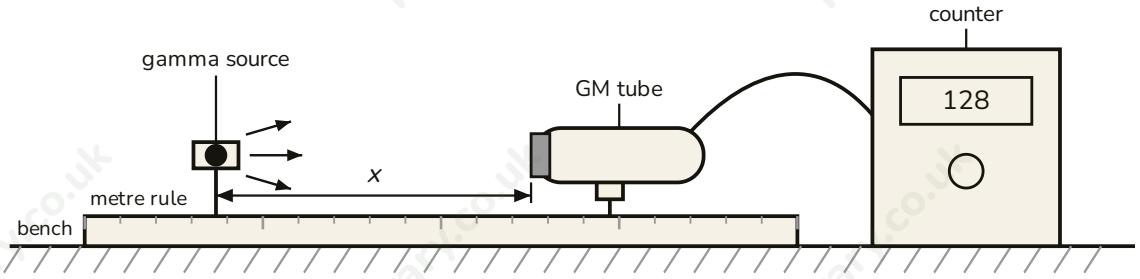
(b) Calculate the distance of closest approach, r, of the α particle to the gold nucleus, and state what this calculation gives an estimate of. **(5)**

(c) The measured radius of a gold-197 nucleus is about 7.0 fm (7.0×10^{-15} m). Using $R = R0\ A^{1/3}$, calculate the value of R0 suggested by this measurement, and comment on whether it is consistent with the accepted value of R0 = 1.2 fm. **(4)**

(Total for Question 9 is 10 marks)

10 Required practical: a student investigates how the corrected count rate, C, from a small γ source varies with distance, x, from a GM tube, to test whether C is inversely proportional to x^2. All readings have already been corrected for background. Results:

x / cm	C / counts per second
10	96.0
20	24.1
30	10.7
40	6.0
50	3.8



(a) Explain how the student could use a graph of ln(C) against ln(x) to test whether C = k / x^2, and state the gradient expected if this relationship holds. **(3)**

(b) Two data points give ln(x) = 2.30, ln(C) = 4.564 (at x = 10 cm) and ln(x) = 3.91, ln(C) = 1.335 (at x = 50 cm). Calculate the gradient between these two points and comment on whether it supports the inverse square law. **(3)**

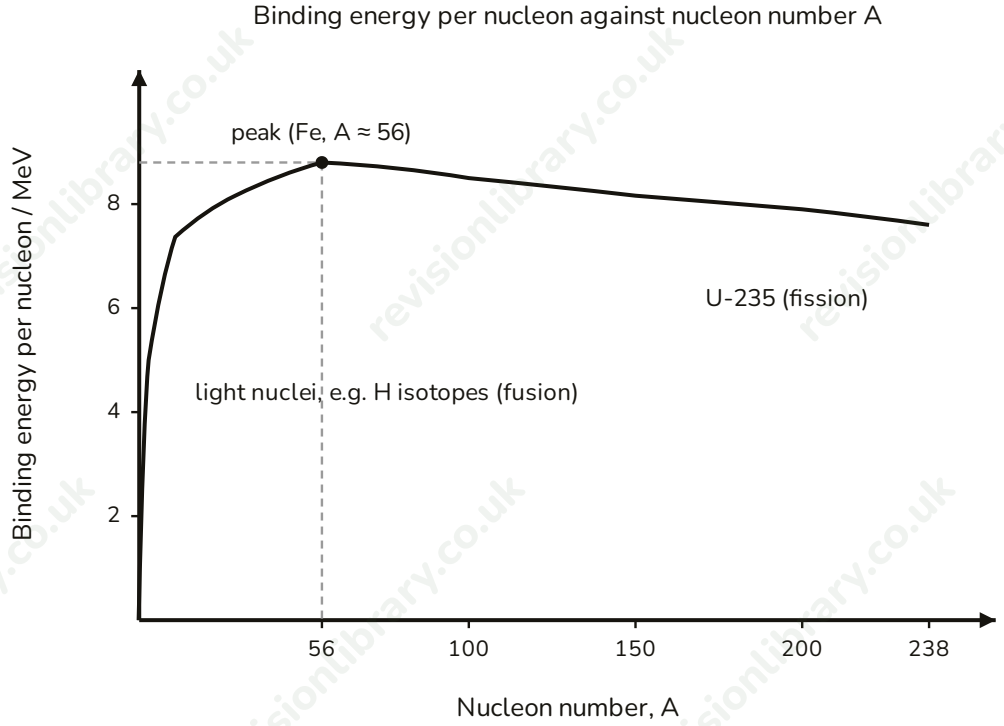
(c) State two control variables the student should keep constant to ensure this is a valid test. **(2)**

(d) Suggest one reason why the experimental gradient found in part (b) might differ slightly from the theoretical value of exactly -2. **(1)**

(Total for Question 10 is 9 marks)

11 The graph of binding energy per nucleon (MeV) against nucleon number, A, for stable nuclides rises steeply for light nuclei, reaches a maximum at around A = 56 (near iron), then decreases slowly for heavier nuclei up to A = 238.

Using ideas about binding energy per nucleon, explain why both the fission of a very heavy nucleus (such as uranium-235) and the fusion of very light nuclei (such as isotopes of hydrogen) release energy.



(Total for Question 11 is 6 marks)

12 A possible fission reaction is: n + U-235 -> Ba-141 + Kr-92 + 3n. Masses: U-235 = 235.0439 u, Ba-141 = 140.9144 u, Kr-92 = 91.9262 u, neutron = 1.00867 u. 1 u is equivalent to 931.5 MeV, and 1 MeV = 1.602×10^{-13} J.

(a) Show that the total mass before the reaction (a neutron plus a U-235 nucleus) is 236.0526 u. **(1)**

(b) The total mass of the products (Ba-141 + Kr-92 + 3 neutrons) is 235.8666 u. Calculate the mass defect for this fission reaction. **(2)**

(c) Calculate the energy released in this single fission reaction, in MeV and in joules. **(4)**

(d) A nuclear power station generates 1200 MW of electrical power output at an overall efficiency of 33%. Calculate the number of fission reactions like the one above that must occur per second in the reactor to produce this electrical output. **(4)**

(Total for Question 12 is 11 marks)

13 A student measures the count rate from a radioactive source over time, with the detector's background count rate measured separately as 22 counts per minute.

Time (min): 0, 10, 20, 30

Raw count rate (counts/min): 542, 314, 189, 118

(a) Calculate the background-corrected count rate at t = 30 min. **(2)**

(b) The background-corrected count rates at t = 0 min and t = 30 min are 520 and 96 counts/min respectively. Using these two values, calculate the decay constant of the source. **(4)**

(c) Hence calculate the half-life of the source in minutes. **(2)**

(d) Explain why the background count rate must be subtracted from the raw readings before the decay of the source can be analysed correctly. **(2)**

(Total for Question 13 is 10 marks)

14 REQUIRED PRACTICAL. A student investigates the attenuation of γ radiation by lead. The corrected count rate is measured for different thicknesses of lead placed between the source and the detector.

Lead thickness (mm): 0, 5, 10, 15

Corrected count rate (counts/min): 860, 430, 215, 108

(a) State what is meant by the half-value thickness of an absorbing material. **(1)**

(b) Using the data for 0 mm and 15 mm of lead, calculate the linear attenuation coefficient μ of lead for this γ source (in mm^{-1}), using $I = I0\ e^{-\mu x}$. **(4)**

(c) Hence calculate the half-value thickness of lead for this source, and comment on how well it agrees with the pattern seen in the data table. **(3)**

(d) Suggest why lead, rather than aluminium, is used as the absorbing material in this investigation. **(1)**

(Total for Question 14 is 9 marks)

15 In an electron diffraction experiment, high-energy electrons of de Broglie wavelength 1.8×10^{-15} m are diffracted by the nuclei of a target material. The first diffraction minimum is observed at an angle of 42 degrees. The nuclear radius can be estimated from the diffraction minimum condition $R \sin(\theta) = 1.22 \lambda$.

(a) Calculate the radius of the nucleus. **(4)**

(b) Using $R = r0\ A^{1/3}$, where $r0 = 1.4 \times 10^{-15}$ m, estimate the nucleon number A of the nucleus, rounding to the nearest integer, and suggest a plausible nuclide with this nucleon number. **(3)**

(c) State one advantage of using high-energy electrons, rather than α particles, to investigate the size of a nucleus. **(2)**

(Total for Question 15 is 9 marks)

16 A student uses a GM tube and counter to record 400 counts from a radioactive source in a fixed time of 5.0 minutes (background is negligible in this measurement).

(a) Explain why there is a statistical uncertainty associated with this measured count, even though the detector and timer are assumed to work perfectly. **(2)**

(b) For a measured count of N, the standard uncertainty is given by $\sqrt{N}$. Calculate the percentage uncertainty in the count of 400. **(2)**

(c) Calculate the count rate and its absolute uncertainty, in counts per minute. **(3)**

(d) Suggest and explain one way the student could reduce the percentage uncertainty in the measured count rate. **(2)**

(Total for Question 16 is 9 marks)

17 The graph of binding energy per nucleon against nucleon number rises steeply for light nuclei, peaks around iron-56, and falls slowly for heavier nuclei. Both nuclear fission (splitting a heavy nucleus into two lighter ones) and nuclear fusion (combining two light nuclei into a heavier one) can release energy, and both processes are being explored as sources of electrical power generation. Evaluate the safety and practical challenges of fission-based nuclear power compared with fusion-based nuclear power, using the shape of the binding energy per nucleon curve to explain why both processes can release energy, and discussing issues such as radioactive waste, half-life of fission products, and the difficulty of containing a fusion plasma.

(Total for Question 17 is 6 marks)

Mark scheme · 3.8 Nuclear Physics

Question 1

(a) proton number of nickel nucleus = 28 **B1**

(a) nucleon number of nickel nucleus = 60 (unchanged by β-minus decay) **B1**

(a) correct equation: ^60_27 Co -> ^60_28 Ni + ^0_-1 e + antineutrino$_e$ (allow β^- symbol for the electron) **B1**

(a) Answer: ^60_27 Co -> ^60_28 Ni + ^0_-1 e + antineutrino$_e$

(b) the nucleus is produced with excess (internal) energy, i.e. it is not in its lowest possible energy state (ground state), oe **B1**

(b) it loses this excess energy by emitting one or more γ-ray photons as it de-excites to the ground state, oe **B1**

(b) Answer: The nucleus has excess internal energy above its ground state; it loses this energy by emitting γ-ray photon(s).

(c) a γ photon is electromagnetic radiation (energy) with no mass and no charge, not a particle made of nucleons, so its emission does not alter the proton or nucleon number, oe **B1**

(c) γ radiation carries no (electric) charge, so it experiences no force in an electric or magnetic field, oe **B1**

(c) α and β particles are charged and are therefore deflected (in opposite senses, since they have opposite-sign charge), unlike γ, oe **B1**

(c) Answer: Gamma photons carry no charge and no nucleons, so proton/nucleon numbers are unchanged and γ is undeflected by fields, unlike the charged α and β particles.

Question 2

(a) the probability of decay of an individual nucleus per unit time oe **B1**

(a) Answer: The probability that an individual nucleus will decay per unit time.

(b) A = λ N cao **B1**

(b) Answer: A = λ N

(c) any two of: short range (acts only over a few femtometres); attractive at typical nucleon separations (and repulsive at very short range); acts equally between all nucleons regardless of charge (charge-independent) oe **B1**

(c) Answer: It has a very short range (a few femtometres) and it acts equally between all nucleons regardless of charge (charge-independent).

Question 3

(a) background radiation (e.g. from cosmic rays and rocks) is present at all times and would be added to (counted along with) the readings from the source, oe **B1**

(a) the background count rate (22 counts per minute) must be subtracted from each measured reading to give the corrected count rate due to the source alone, oe **B1**

(a) Answer: Background radiation adds to every reading, so 22 counts per minute must be subtracted from each measured value to find the count rate due to the source alone.

(b) corrected count rates calculated: none = 828, paper = 823, aluminium = 188, lead = 4 (counts per minute) **B1**

(b) no detectable α component, since the count rate barely changes when paper is added (828 to 823); α emission cannot be ruled out because the sealed source casing or intervening air could absorb α particles, oe **B1**

(b) β radiation is emitted, since the count rate falls greatly when aluminium is added (823 to 188), showing β particles are being absorbed, oe **B1**

(b) γ radiation is emitted, since the count rate only falls to (near) background level once thick lead is added (188 to 4), showing γ radiation was passing through the paper and aluminium but is absorbed by lead, oe **B1**

(b) Answer: Corrected count rates: 828, 823, 188, 4 counts per minute. The source emits β and γ radiation, with no detectable α component; α emission cannot be ruled out.

(c) count for a long time period (e.g. several minutes) at each absorber, to reduce the percentage (statistical) uncertainty caused by the random nature of radioactive decay, oe **B1**

(c) Answer: Count for a long time period at each setting, to reduce the statistical uncertainty in the count rate.

Question 4

(a) λ = ln2 / 5730 correctly substituted **M1**

(a) λ = 1.21 x 10^{-4} per year (cso, answer given) **A1**

(a) Answer: λ = 1.21 x 10^{-4} per year

(b) equation rearranged: ln(A0 / A) = λ t, oe **M1**

(b) correct substitution: ln(15.0 / 6.9) = 0.777 (or ln(6.9/15.0) = -0.777) **M1**

(b) t = 0.777 / (1.21 x 10^{-4}), ft from (a) **A1**

(b) t = 6.4 x 10^3 years (awrt, allow 6300 to 6500 years) **A1**

(b) Answer: About 6.4 x 10^3 years (6400 years)

(c) the calculated age would be an underestimate (too young), oe **B1**

(c) because the modern carbon has a much higher carbon-14 activity than the old sample, it increases the measured activity above the true value for the sample's actual age, making it appear to have decayed less (and so be younger) than it really is, oe **B1**

(c) Answer: The calculated age would be too young (an underestimate), because the modern carbon raises the measured activity above the true value for the sample's real age.

Question 5

(a) total mass of separate nucleons = 2(1.00728) + 2(1.00867) = 4.0319 u **M1**

(a) mass defect = 4.0319 - 4.00151 = 0.0304 u (cso, answer given) **A1**

(a) Answer: Mass defect = 0.0304 u

(b) binding energy = mass defect x 931.5 MeV/u, ft from (a) **M1**

(b) binding energy = 28.3 MeV (awrt) **A1**

(b) binding energy per nucleon = total binding energy / 4 **M1**

(b) binding energy per nucleon = 7.08 MeV (awrt 7.1) **A1**

(b) Answer: Binding energy = 28.3 MeV; binding energy per nucleon = 7.08 MeV

(c) it allows nuclei of different sizes (different numbers of nucleons) to be compared fairly, since it represents the average energy needed to remove one nucleon, oe **B1**

(c) Answer: It gives a fair, size-independent measure of stability, as it is the average energy needed to remove one nucleon.

Question 6

(a) convert half-life to seconds: 8.02 x 24 x 3600 = 692,928 s **M1**

(a) use $\lambda = \ln(2) / \text{half-life}$ **M1**

(a) $\lambda = 1.00 \times 10^{-6}\ s^{-1}$ cao **A1**

(a) Answer: $1.00 \times 10^{-6}\ s^{-1}$

(b) $A = \lambda N = 1.00 \times 10^{-6} \times 5.0 \times 10^{13}$ **M1**

(b) $A = 5.0 \times 10^{7}$ Bq cao **A1**

(b) Answer: 5.0×10^{7} Bq

(c) recognise 24.06 days = 3 half-lives (24.06/8.02 = 3) **M1**

(c) use $A = A0\ (1/2)^{n}$ with n = 3 **M1**

(c) $A = 6.3 \times 10^{6}$ Bq cao **A1**

(c) Answer: 6.3×10^{6} Bq

Question 7

(a) total mass of reactants = 2.01410 + 3.01605 = 5.03015 u **M1**

(a) total mass of products = 4.00260 + 1.00867 = 5.01127 u, and mass defect = 5.03015 - 5.01127 = 0.01888 u **M1**

(a) energy = 0.01888 x 931.5 correctly evaluated **A1**

(a) 17.6 MeV (awrt) **A1**

(a) Answer: 17.6 MeV

(b) energy per reaction converted to joules: 17.6 MeV x 1.602×10^{-13}, ft from (a) **M1**

(b) number of reactions per second = power / energy per reaction (in J) **M1**

(b) 1.77×10^{20} reactions per second (awrt, accept 1.77 to 1.78) **A1**

(b) mass of deuterium per reaction = $2.01410 \times 1.6605 \times 10^{-27}$ kg correctly evaluated **M1**

(b) mass per day = (reactions per second) x (mass of deuterium per reaction) x (86400 s), ft **M1**

(b) about 0.051 kg (51 g) per day (awrt, allow 50 to 52 g) **A1**

(b) Answer: About 1.77×10^{20} reactions per second, consuming about 0.051 kg (51 g) of deuterium per day

Question 8

Level 3 A full, coherent explanation of the function of all three components (moderator, control rods, coolant), correctly explaining why fast fission neutrons must be slowed to sustain further fission, how control rods regulate the number of neutrons available to maintain a steady (critical) chain reaction, and how the coolant removes heat to prevent overheating, with a clear link to safe, steady operation. **5-6**

Level 2 The function of at least two of the three components is explained correctly, or all three are mentioned but with less clarity or detail, for example without fully explaining why neutrons need to be slowed or how the reaction rate is kept constant. **3-4**

Level 1 Basic or partial statements are made about the reactor, for example that control rods absorb neutrons or that coolant removes heat, without a clear explanation of how the chain reaction is controlled. **1-2**

Level 0 No relevant content, or the answer does not relate to the question. **0**

Indicative content:

- Fission of a uranium-235 nucleus, following absorption of a slow (thermal) neutron, produces (on average) two or three fast neutrons, together with fission fragments and energy.
- Fast neutrons are much less likely to cause further fission in uranium-235 than slow neutrons, so they must be slowed down (thermalised) for the chain reaction to continue.
- The moderator (graphite, or the water itself) slows the fast neutrons through repeated elastic collisions, increasing the probability that they go on to cause further fission.
- Control rods (e.g. boron or cadmium) absorb neutrons; inserting them further into the core removes more neutrons and reduces the rate of fission, while withdrawing them increases the rate of fission.
- By adjusting the position of the control rods, the reactor is kept critical, so that on average exactly one neutron from each fission goes on to cause another fission, giving a constant, controlled rate of energy release rather than a runaway (supercritical) or dying-out (subcritical) reaction.
- Control rods can be inserted fully in an emergency to absorb enough neutrons to shut the chain reaction down quickly (an important safety feature).
- The coolant (pressurised water) carries heat away from the reactor core to a heat exchanger, generating steam to drive turbines, and prevents the core from overheating.

Question 9

(a) $6.0 \times 10^{6} \times 1.60 \times 10^{-19} = 9.6 \times 10^{-13}$ J (cso, answer given) **B1**

(a) Answer: 9.6×10^{-13} J

(b) charge of α particle = 2e and charge of gold nucleus = 79e correctly identified **M1**

(b) Ep = KE equation rearranged to make r the subject: r = (2e)(79e) / (4 π epsilon0 x KE), oe **M1**

(b) correct substitution of values into the rearranged equation **M1**

(b) $r = 3.8 \times 10^{-14}$ m (awrt $3.7\text{-}3.8 \times 10^{-14}$) **A1**

(b) this gives an estimate of an upper limit for the radius of the gold nucleus, because electrostatic repulsion reverses the α particle outside the nucleus; the distance of closest approach does not locate the nuclear surface, oe **B1**

(b) Answer: $r = 3.8 \times 10^{-14}$ m, an estimate of an upper limit for the nuclear radius

(c) $A^{1/3}$ evaluated for A = 197: $A^{1/3} = 5.82$ **M1**

(c) equation rearranged: $R0 = R / A^{1/3}$, correctly substituted **M1**

(c) R0 = 1.20 fm (awrt 1.20-1.21) **A1**

(c) this is (very close to) consistent with the accepted value of 1.2 fm, supporting the idea that nuclear density is approximately constant for all nuclei, oe **B1**

(c) Answer: R0 = 1.20 fm, consistent with the accepted value of 1.2 fm

Question 10

(a) taking logs of $C = k / x^{n}$ gives $\ln(C) = \ln(k) - n \ln(x)$, a linear equation, oe **B1**

(a) a graph of ln(C) (y-axis) against ln(x) (x-axis) that is a straight line confirms a power-law relationship between C and x, oe **B1**

(a) the gradient of this line equals -n, so a gradient of -2 would confirm the inverse square law (n = 2) **B1**

(a) Answer: $\ln(C) = \ln(k) - n \ln(x)$, so a straight-line graph of ln(C) against ln(x) with gradient -2 would confirm the inverse square law.

(b) gradient = (change in ln(C)) / (change in ln(x)) correctly substituted **M1**

(b) gradient = -2.0 (awrt -2.0) **A1**

(b) this is very close to -2, supporting the inverse square law for this γ source, ft from calculated gradient **B1**

(b) Answer: Gradient = -2.0, which supports the inverse square law.

(c) the same counting time is used at each distance (e.g. a fixed time such as 60 s), long enough to obtain a reliable count, oe **B1**

(c) the same source, GM tube and detector alignment are used throughout, with no other radioactive sources nearby affecting the background, oe **B1**

(c) Answer: Same counting time at each distance; same source, GM tube and alignment used throughout.

(d) the background count rate may not have been fully or accurately subtracted, or the source may not behave as a true point source, or there is greater statistical (random) uncertainty in the count rate at larger distances where count rates are low, oe (any one valid reason) **B1**

(d) Answer: For example, incomplete background subtraction, the source not being a true point source, or greater statistical uncertainty in the low count rates at large distances.

Question 11

Level 3 A full, coherent explanation that correctly links both fission and fusion to the shape of the binding energy per nucleon graph, explaining that the products of each process lie closer to the peak (iron) than the reactants, with a clear reference to mass-energy equivalence linking the increase in binding energy per nucleon to the energy released. **5-6**

Level 2 The explanation addresses either fission or fusion in good detail, or addresses both but with less clarity or a minor inaccuracy in linking to the shape of the graph or to mass-energy equivalence. **3-4**

Level 1 Basic, largely descriptive statements are made, for example that energy is released in fission and/or fusion, without a clear explanation of why this follows from the binding energy per nucleon graph. **1-2**

Level 0 No relevant content, or the answer does not relate to the question. **0**

Indicative content:

- Binding energy per nucleon measures the average energy needed to separate one nucleon from the nucleus (or the average energy released per nucleon when the nucleus is assembled from separate nucleons).
- The graph rises steeply for light nuclei, reaches a maximum near A = 56 (iron), then falls gradually for heavier nuclei.
- In fission, a very heavy nucleus (such as uranium-235), which lies on the falling, right-hand side of the graph, splits into two medium-mass nuclei that lie closer to the peak and so have a higher binding energy per nucleon than the original nucleus.
- In fusion, very light nuclei (such as isotopes of hydrogen), which lie on the steeply rising, left-hand side of the graph, combine to form a heavier nucleus that lies closer to the peak and so has a higher binding energy per nucleon than the separate light nuclei.
- In both processes, the total binding energy of the products is greater than that of the reactants, meaning the nucleons in the products are, on average, more tightly bound.
- By mass-energy equivalence (E = mc^2), this increase in total binding energy corresponds to a decrease in total mass (a mass defect) between reactants and products, which appears as kinetic energy of the products and/or gamma radiation - the energy released.

Question 12

(a) 235.0439 + 1.00867 = 236.0526 u (cso, answer given) **B1**

(a) Answer: 236.0526 u

(b) mass defect = 236.0526 - 235.8666, ft from (a) **M1**

(b) 0.1860 u (awrt) **A1**

(b) Answer: 0.1860 u

(c) energy in MeV = mass defect x 931.5, ft from (b) **M1**

(c) 173 MeV (awrt 172-174) **A1**

(c) conversion to joules: energy x 1.602 x 10^{-13} **M1**

(c) 2.78 x 10^{-11} J (awrt, ft) **A1**

(c) Answer: About 173 MeV, or 2.78 x 10^{-11} J

(d) thermal (input) power = electrical power / efficiency = 1200 / 0.33, oe **M1**

(d) thermal power = 3.64 x 10^{9} W (awrt) **A1**

(d) number of reactions per second = thermal power / energy released per reaction (in J), ft from (c) **M1**

(d) 1.31 x 10^{20} reactions per second (awrt) **A1**

(d) Answer: About 1.31 x 10^{20} fission reactions per second

Question 13

(a) corrected rate = raw rate - background = 118 - 22 **M1**

(a) corrected rate = 96 counts/min cao **A1**

(a) Answer: 96 counts/min

(b) quote A = A0 $e^{-\lambda t}$ **M1**

(b) rearrange to $\lambda = \ln(A0/A) / t$ **M1**

(b) substitute $\lambda = \ln(520/96) / 30$ **M1**

(b) λ = 0.0563 min^{-1} cao **A1**

(b) Answer: 0.0563 min^{-1}

(c) use half-life = $\ln(2) / \lambda$ **M1**

(c) half-life = 12.3 minutes cao **A1**

(c) Answer: 12.3 minutes

(d) the background count rate arises from other sources (e.g. cosmic rays, other radioactive materials nearby) and is not part of the decay of the source being studied **B1**

(d) if not subtracted, the background would make the count rate appear to decay more slowly than the source actually does (it would never fall below the constant background level), giving an incorrect (overestimated) half-life oe **B1**

(d) Answer: Background radiation comes from sources other than the sample and does not decay, so it must be removed; otherwise the raw count rate would level off at the background value rather than falling to zero, making the source appear to decay more slowly than it really does and giving an inaccurate half-life.

Question 14

(a) the thickness of the material needed to reduce the intensity (or count rate) of the radiation to half its original value oe **B1**

(a) Answer: The thickness of absorber required to reduce the radiation intensity (or count rate) to half its original value.

(b) quote $I = I0\ e^{-\mu x}$ **M1**

(b) rearrange to $\mu = \ln(I0/I) / x$ **M1**

(b) substitute $\mu = \ln(860/108) / 15$ **M1**

(b) $\mu = 0.138\ mm^{-1}$ cao **A1**

(b) Answer: 0.138 mm^{-1}

(c) use half-value thickness = $\ln(2) / \mu$ **M1**

(c) half-value thickness = 5.0 mm cao **A1**

(c) this agrees well with the data, since the count rate approximately halves for every 5 mm of lead added (860 to 430 to 215 to 108) oe **B1**

(c) Answer: 5.0 mm; this matches the data, where the count rate roughly halves every 5 mm.

(d) lead has a much higher density (and higher proton number), so it attenuates γ radiation far more strongly than aluminium, allowing a measurable change in count rate over a practical (small) range of thicknesses oe **B1**

(d) Answer: Lead has a much higher density and proton number than aluminium, so it attenuates γ rays far more strongly, giving a measurable change in count rate using practical (small) thicknesses.

Question 15

(a) quote $R \sin(\theta) = 1.22\ \lambda$, rearranged to $R = 1.22\ \lambda / \sin(\theta)$ **M1**

(a) substitute $R = (1.22 \times 1.8 \times 10^{-15}) / \sin(42)$ **M1**

(a) carry out the calculation **M1**

(a) $R = 3.28 \times 10^{-15}$ m cao **A1**

(a) Answer: 3.28×10^{-15} m

(b) rearrange to $A = (R/r0)^3$ **M1**

(b) substitute $A = (3.28 \times 10^{-15} / 1.4 \times 10^{-15})^3$ **M1**

(b) A = 13 (nearest integer); a plausible nuclide is carbon-13 or nitrogen-13, both A = 13 (accept any real nuclide with A = 13) cao **A1**

(b) Answer: A = 13 (e.g. carbon-13 or nitrogen-13)

(c) electrons interact with nuclei via the (much weaker, longer-range) electromagnetic force only, not the strong nuclear force, so the diffraction pattern probes the nuclear charge distribution directly without the result being complicated by the strong interaction that affects α-particle scattering at close range oe (allow 1 mark for a partial statement, e.g. simply that electrons do not feel the strong force) **B2**

(c) Answer: Electrons interact with the nucleus only via the electromagnetic force (not the strong nuclear force), so electron diffraction gives a cleaner probe of the nuclear charge distribution, unaffected by strong-interaction effects that complicate α-particle scattering at small distances.

Question 16

(a) radioactive decay is a random (spontaneous) process, so the number of decays detected in a fixed time interval varies from one measurement to the next **B1**

(a) repeated measurements of the same time interval would give a spread of count values, so any single count has an inherent statistical uncertainty regardless of how precise the equipment is oe **B1**

(a) Answer: Radioactive decay is random, so the number of decays in a fixed time varies between repeated measurements even with perfect equipment; this randomness gives every single count an inherent statistical uncertainty.

(b) uncertainty = $\sqrt{400} = 20$; percentage uncertainty = (20/400) x 100 **M1**

(b) percentage uncertainty = 5.0% cao **A1**

(b) Answer: 5.0%

(c) count rate = 400 / 5.0 = 80 counts/min **M1**

(c) absolute uncertainty in rate = 5.0% of 80 **M1**

(c) count rate = (80 ± 4) counts/min cao **A1**

(c) Answer: (80 ± 4) counts/min

(d) count for a longer time (or accumulate a larger total count) oe **B1**

(d) because the percentage uncertainty ($\sqrt{N}$ /N x 100) decreases as N increases, so a larger total count gives a smaller percentage uncertainty oe **B1**

(d) Answer: Count for a longer time so that a larger total number of counts N is recorded; since the percentage uncertainty is $\sqrt{N}$ /N x 100, which decreases as N increases, a larger count gives a smaller percentage uncertainty.

Question 17

Level 3 Correctly explains, using the binding energy per nucleon curve, that both fission of heavy nuclei and fusion of light nuclei move products towards the peak of the curve (around iron-56), increasing the average binding energy per nucleon and releasing energy in both cases. Gives a well-balanced evaluation covering at least two relevant issues for each process (e.g. fission: long-lived radioactive waste products with a wide range of half-lives requiring secure long-term storage, risk of a runaway chain reaction/meltdown, availability of fissile fuel; fusion: extreme difficulty of confining and heating plasma to the temperatures/pressures needed for net energy gain, but comparatively short-lived or less hazardous waste and no risk of runaway reaction/meltdown). Reaches a clear, justified conclusion. **5-6**

Level 2 Explains, with reasonable accuracy, why fission and/or fusion release energy using the binding energy curve, and identifies at least one relevant safety or practical issue for each process, though the comparison is not fully balanced or some detail is missing. **3-4**

Level 1 States that fission and fusion both release energy, or mentions one issue (e.g. radioactive waste) without correctly linking it to the binding energy curve or making a meaningful comparison. **1-2**

Indicative content:

- Binding energy curve: binding energy per nucleon rises steeply for light nuclei, peaks near iron-56 (the most stable nuclide), and falls slowly for heavier nuclei.
- Fission: splitting a heavy nucleus (to the right of the peak) into two lighter nuclei closer to the peak increases the total binding energy per nucleon of the products, so energy is released (mass is converted to energy, consistent with E = mc^2).
- Fusion: combining two very light nuclei (to the left of the peak) into a heavier nucleus closer to the peak also increases binding energy per nucleon, releasing energy by the same mass-energy argument; the energy released per unit mass of fuel is typically much greater for fusion than for fission.
- Fission safety/practical issues: fission produces a range of radioactive daughter products, some with very long half-lives, requiring secure storage for thousands of years; risk of an uncontrolled chain reaction (meltdown) if the reactor is not properly controlled/cooled; requires mined, processed and enriched fissile fuel (e.g. uranium-235).
- Fusion safety/practical issues: requires extremely high temperatures and pressures to overcome electrostatic repulsion between light nuclei, and confining this plasma (e.g. magnetically) without it touching and cooling on the reactor walls is a major unsolved engineering challenge; no chain reaction is possible so there is no meltdown risk, and any radioactive activation of reactor materials is generally shorter-lived than fission waste; fuel (isotopes of hydrogen) is comparatively abundant.
- Overall evaluation: fusion offers potential safety and waste advantages over fission, but remains far from commercial viability due to the plasma confinement challenge, whereas fission is a mature, currently deployed technology whose main drawbacks are long-term waste management and the (small but non-zero) risk of serious accidents.