3.8 Nuclear Physics: 1-hour Pack

AQA 7408 · Calculator allowed · about 60 minutes

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 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 1 is 8 marks)

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2 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 = 1.6605×10^{-27} kg. 1 MeV = 1.602×10^{-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 2 is 10 marks)

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

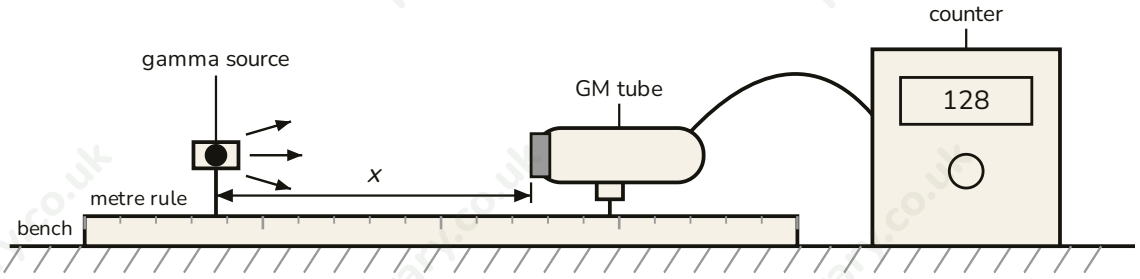
Explain the function of the moderator, the control rods and the coolant in sustaining and controlling a chain reaction, and explain why each is necessary for the reactor to operate safely at a steady power output.

(Total for Question 3 is 6 marks)

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4 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 4 is 9 marks)

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5 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 5 is 10 marks)

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Mark scheme · 3.8 Nuclear Physics: 1-hour Pack

Question 1

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

(a) use λ = ln(2) / 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 2

(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 3

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.

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Question 4

(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 5

(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) $\lambda = 0.0563\ \text{min}^{-1}$ 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.

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