AP8D Nuclear Physics: Depth and Exam Drill

AQA 7408 · Calculator allowed · about 125 minutes

Total Marks

Name: ______________________________ Date: ____ / ____ / ______

Answer ALL questions. Show all your working.

1 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 1 is 3 marks)

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2 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 2 is 8 marks)

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3 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 3 is 10 marks)

4 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 4 is 9 marks)

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5 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(θ) = 1.22 λ.

(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 5 is 9 marks)

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6 A lithium-7 nucleus (3 protons, 4 neutrons) has a nuclear mass of 7.01435 u. The mass of a free proton is 1.00728 u and the mass of a free neutron is 1.00867 u. Take 1 u = 931.5 MeV/c^2.

(a) Calculate the total mass of the separate, unbound nucleons that make up a lithium-7 nucleus. **(2)**

(b) Calculate the mass defect of the lithium-7 nucleus. **(2)**

(c) Calculate the binding energy of the lithium-7 nucleus, in MeV. **(3)**

(d) Calculate the binding energy per nucleon of lithium-7. **(2)**

(Total for Question 6 is 9 marks)

7 Radium-226 (proton number 88) decays by α emission to radon. Separately, sodium-22 (proton number 11) decays by β-plus (positron) emission to neon-22 (proton number 10).

(a) Complete the nuclear equation for the α decay of radium-226: (226,88)Ra -> (?,?)Rn + (4,2)He. State the nucleon number and proton number of the radon nucleus produced. **(2)**

(b) Complete the nuclear equation for the β-plus decay of sodium-22 to neon-22: (22,11)Na -> (22,10)Ne + positron + X. Identify particle X, and state why it must be included for the equation to balance. **(3)**

(c) Explain, in terms of the fundamental particles involved, what happens to a proton inside the nucleus during β-plus decay. **(2)**

(Total for Question 7 is 7 marks)

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8 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 8 is 9 marks)

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9 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 9 is 6 marks)

Mark scheme · AP8D Nuclear Physics: Depth and Exam Drill

Question 1

- (a) **B1** the probability of decay of an individual nucleus per unit time oe
- **(a) Answer: The probability that an individual nucleus will decay per unit time.**
- (b) **B1** $A = \lambda N$ cao
- **(b) Answer: $A = \lambda N$**
- (c) **B1** 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
- **(c) Answer: It has a very short range (a few femtometres) and it acts equally between all nucleons regardless of charge (charge-independent).**

Question 2

- (a) **M1** convert half-life to seconds: 8.02 x 24 x 3600 = 692,928 s
- (a) **M1** use $\lambda = \ln(2)$ / half-life
- (a) **A1** $\lambda = 1.00 \times 10^{-6}\ s^{-1}$ cao
- **(a) Answer: $1.00 \times 10^{-6}\ s^{-1}$**
- (b) **M1** $A = \lambda N = 1.00 \times 10^{-6} \times 5.0 \times 10^{13}$
- (b) **A1** $A = 5.0 \times 10^{7}$ Bq cao
- **(b) Answer: 5.0×10^{7} Bq**
- (c) **M1** recognise 24.06 days = 3 half-lives (24.06/8.02 = 3)
- (c) **M1** use $A = A0\ (1/2)^{n}$ with n = 3
- (c) **A1** $A = 6.3 \times 10^{6}$ Bq cao
- **(c) Answer: 6.3×10^{6} Bq**

Question 3

- (a) **M1** corrected rate = raw rate - background = 118 - 22
- (a) **A1** corrected rate = 96 counts/min cao
- **(a) Answer: 96 counts/min**
- (b) **M1** quote $A = A0\ e^{-\lambda t}$
- (b) **M1** rearrange to $\lambda = \ln(A0/A) / t$
- (b) **M1** substitute $\lambda = \ln(520/96) / 30$
- (b) **A1** $\lambda = 0.0563\ min^{-1}$ cao
- **(b) Answer: $0.0563\ min^{-1}$**
- (c) **M1** use half-life = $\ln(2) / \lambda$
- (c) **A1** half-life = 12.3 minutes cao
- **(c) Answer: 12.3 minutes**
- (d) **B1** 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
- (d) **B1** 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
- **(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 4

- (a) **B1** the thickness of the material needed to reduce the intensity (or count rate) of the radiation to half its original value oe
- **(a) Answer: The thickness of absorber required to reduce the radiation intensity (or count rate) to half its original value.**
- (b) **M1** quote $I = I0\ e^{-\mu x}$
- (b) **M1** rearrange to $\mu = \ln(I0/I) / x$
- (b) **M1** substitute $\mu = \ln(860/108) / 15$
- (b) **A1** $\mu = 0.138\ mm^{-1}$ cao
- **(b) Answer: 0.138 mm^{-1}**
- (c) **M1** use half-value thickness = $\ln(2) / \mu$
- (c) **A1** half-value thickness = 5.0 mm cao
- (c) **B1** 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
- **(c) Answer: 5.0 mm; this matches the data, where the count rate roughly halves every 5 mm.**
- (d) **B1** 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
- **(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 5

- (a) **M1** quote $R \sin(\theta) = 1.22\ \lambda$, rearranged to $R = 1.22\ \lambda / \sin(\theta)$
- (a) **M1** substitute $R = (1.22 \times 1.8 \times 10^{-15}) / \sin(42)$
- (a) **M1** carry out the calculation
- (a) **A1** $R = 3.28 \times 10^{-15}$ m cao
- **(a) Answer: 3.28×10^{-15} m**
- (b) **M1** rearrange to $A = (R/r0)^3$
- (b) **M1** substitute $A = (3.28 \times 10^{-15} / 1.4 \times 10^{-15})^3$
- (b) **A1** A = 13 (nearest integer); a plausible nuclide is carbon-13 or nitrogen-13, both A = 13 (accept any real nuclide with A = 13) cao
- **(b) Answer: A = 13 (e.g. carbon-13 or nitrogen-13)**
- (c) **B2** 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)
- **(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 6

- (a) **M1** mass = (3 x 1.00728) + (4 x 1.00867)
- (a) **A1** mass = 7.05652 u cao
- **(a) Answer: 7.05652 u**
- (b) **M1** mass defect = 7.05652 - 7.01435
- (b) **A1** mass defect = 0.04217 u cao
- **(b) Answer: 0.04217 u**
- (c) **M1** quote binding energy = mass defect x 931.5 MeV per u
- (c) **M1** substitute BE = 0.04217 x 931.5
- (c) **A1** BE = 39.3 MeV cao
- **(c) Answer: 39.3 MeV**
- (d) **M1** BE per nucleon = 39.3 / 7
- (d) **A1** BE per nucleon = 5.61 MeV cao
- **(d) Answer: 5.61 MeV**

Question 7

- (a) **M1** nucleon number conserved: 226 = A + 4, so A(Rn) = 222
- (a) **A1** proton number conserved: 88 = Z + 2, so Z(Rn) = 86 cao
- **(a) Answer: Radon-222 (nucleon number 222, proton number 86)**
- (b) **B1** X is an electron neutrino cao
- (b) **B1** without X, energy (and momentum) would not be conserved between the different possible energies/directions of the emitted positron for a fixed total energy release oe
- (b) **B1** including the (near massless, chargeless) neutrino also correctly conserves lepton number and charge in the decay oe
- **(b) Answer: X is an electron neutrino; it is needed so that energy, momentum and lepton number are all conserved in the decay (the positron alone is observed with a range of energies, which would violate conservation of energy without a third particle sharing the energy released).**
- (c) **B1** a proton (an up-up-down combination of quarks) is converted into a neutron (up-down-down)
- (c) **B1** with the emission of a positron and an electron neutrino, i.e. p -> n + positron + electron neutrino oe
- **(c) Answer: A proton is converted into a neutron, with the emission of a positron and an electron neutrino: p -> n + positron + neutrino.**

Question 8

- (a) **B1** 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
- (a) **B1** 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
- **(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) **M1** uncertainty = $\sqrt{400}$ = 20; percentage uncertainty = (20/400) x 100
- (b) **A1** percentage uncertainty = 5.0% cao
- **(b) Answer: 5.0%**
- (c) **M1** count rate = 400 / 5.0 = 80 counts/min
- (c) **M1** absolute uncertainty in rate = 5.0% of 80
- (c) **A1** count rate = (80 ± 4) counts/min cao
- **(c) Answer: (80 ± 4) counts/min**
- (d) **B1** count for a longer time (or accumulate a larger total count) oe
- (d) **B1** because the percentage uncertainty ($\sqrt{N}$/N x 100) decreases as N increases, so a larger total count gives a smaller percentage uncertainty oe
- **(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 9

- **Level 3** (5-6): 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.
- **Level 2** (3-4): 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.
- **Level 1** (1-2): 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.
- **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.