3.11 Physics: Nuclear and Particle Physics: Test Pack

AQA 7408 · Calculator allowed · about 45 minutes

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 Four different types of radioactive decay are described below. Nuclide notation $^{A}_{Z}X$ is used throughout, where A is the nucleon (mass) number and Z is the proton (atomic) number.

(a) Americium-241, ^241_95 Am, is used as an α source in household ionisation smoke detectors: α particles ionise air between two electrodes, producing a small current that smoke disrupts, triggering the alarm. Americium-241 decays by α emission to an isotope of neptunium (Np). Write a balanced nuclear equation for this decay, and show that both nucleon number and proton number are conserved. **(3)**

(b) Potassium-40, ^40_19 K, occurs naturally in the body (for example in bananas and muscle tissue) and undergoes β-minus decay to an isotope of calcium (Ca). Write the full decay equation, including any additional particle emitted, and describe the change at the quark level. **(4)**

(c) Fluorine-18, ^18_9 F, is used in PET (positron emission tomography) scanning and decays by β-plus (positron) emission to an isotope of oxygen (O). Write the full decay equation, and state one difference between this decay process and electron capture, which can produce a similar change in proton number. **(3)**

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(d) Beryllium-7, ^7_4 Be, decays by electron capture to lithium-7, ^7_3 Li: an inner-shell atomic electron is absorbed by the nucleus, converting a proton into a neutron and releasing an electron neutrino. Write a balanced nuclear equation for this process, and suggest one experimental signature, other than detecting the neutrino itself, that indicates electron capture has taken place. **(3)**

(Total for Question 1 is 13 marks)

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2 For each proposed reaction below, use conservation of charge, baryon number, lepton number and strangeness (as appropriate) to state whether the reaction is possible or must be forbidden, giving a reason in each case. Assume there is enough energy available for the reaction to proceed, except where told otherwise.

(a) p + p -> p + p + pi0 (two protons colliding to produce two protons and a neutral pion) **(2)**

(b) μ- -> e- + γ (a muon decaying into an electron and a photon only) **(2)**

(c) p -> n + e+ + neutrino$_e$ (a free proton decaying into a neutron, a positron and an electron neutrino) **(2)**

(d) Lambda0 -> p + π- (a Lambda baryon, strangeness -1, decaying into a proton and a negative pion, both strangeness 0) **(2)**

(Total for Question 2 is 8 marks)

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3 A possible induced fission reaction is: n + U-235 -> Xe-140 + Sr-94 + 2n. Masses: U-235 = 235.0439 u, Xe-140 = 139.9216 u, Sr-94 = 93.9154 u, neutron = 1.00867 u. 1 u is equivalent to 931.5 MeV, and 1 MeV = 1.60 x 10^{-13} J.

(a) Show that nucleon number is conserved in this fission reaction, and state the total proton number of the products. **(2)**

(b) Calculate the mass defect for this fission reaction, in u. **(2)**

(c) Calculate the energy released in a single fission of this type, giving your answer in MeV and in joules. **(3)**

(d) A chain reaction is described as critical when, on average, exactly one neutron produced by each fission goes on to cause a further fission (a multiplication factor k = 1); it is subcritical if k < 1 and supercritical if k > 1. Using the neutrons released in this reaction, explain the roles of the moderator and the control rods in keeping a reactor operating steadily at k = 1. **(4)**

(Total for Question 3 is 11 marks)

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Mark scheme · 3.11 Physics: Nuclear and Particle Physics: Test Pack

Question 1

(a) correct neptunium nuclide: ^237_93 Np **B1**

(a) correct α particle notation: ^4_2 He **B1**

(a) conservation shown: nucleon number 241 = 237 + 4; proton number 95 = 93 + 2 **B1**

(a) Answer: ^241_95 Am -> ^237_93 Np + ^4_2 He

(b) correct calcium nuclide: ^40_20 Ca **B1**

(b) correct β particle: ^0_-1 e **B1**

(b) electron antineutrino (antineutrino$_e$) included on the right-hand side **B1**

(b) quark-level description: a down quark inside a neutron changes into an up quark (turning the neutron into a proton), emitting a virtual W- boson, which decays into the electron and the antineutrino$_e$, oe **B1**

(b) Answer: ^40_19 K -> ^40_20 Ca + ^0_-1 e + antineutrino$_e$; at the quark level a down quark converts to an up quark, emitting a W- boson that decays to e- + antineutrino$_e$.

(c) correct oxygen nuclide: ^18_8 O **B1**

(c) correct positron and neutrino included: ^0_+1 e and neutrino$_e$ **B1**

(c) valid difference stated, e.g. β-plus decay creates a new positron and neutrino from within the nucleus (a proton converts to a neutron), whereas electron capture absorbs an existing inner-shell atomic electron into the nucleus (a proton converts to a neutron by absorbing the electron), oe **B1**

(c) Answer: ^18_9 F -> ^18_8 O + ^0_+1 e + neutrino$_e$. Difference: β-plus decay emits a newly created positron and neutrino, whereas electron capture absorbs an existing atomic electron and emits only a neutrino, with no positron.

(d) correct equation: ^7_4 Be + ^0_-1 e -> ^7_3 Li + neutrino$_e$ **B1**

(d) conservation shown: nucleon number 7 + 0 = 7 + 0; proton number 4 + (-1) = 3 + 0 **B1**

(d) valid experimental signature suggested, e.g. characteristic X-rays (or Auger electrons) are emitted as an outer atomic electron falls to fill the inner-shell vacancy left by the captured electron, oe **B1**

(d) Answer: ^7_4 Be + ^0_-1 e -> ^7_3 Li + neutrino$_e$; the vacancy left in the inner electron shell is filled by an outer electron, releasing characteristic X-rays (or Auger electrons), which can be detected.

Question 2

(a) allowed **B1**

(a) charge (1 + 1 = 1 + 1 + 0) and baryon number (1 + 1 = 1 + 1 + 0, since the pion has baryon number 0) are both conserved **B1**

(a) Answer: Allowed: charge and baryon number are both conserved (the pion carries baryon number 0).

(b) not allowed (forbidden) **B1**

(b) muon lepton number is not conserved: the muon (muon lepton number +1) disappears with no muon-neutrino produced to balance it, and electron lepton number is not conserved either, since an electron (electron lepton number +1) appears with nothing to balance it **B1**

(b) Answer: Forbidden: neither muon lepton number nor electron lepton number is conserved.

(c) charge, baryon number and lepton number are all conserved (charge: 1 = 0 + 1 + 0; baryon number: 1 = 1 + 0 + 0; lepton number: 0 = 0 - 1 + 1), so the reaction is not forbidden by these conservation laws **B1**

(c) however, this decay is forbidden in practice for an isolated (free) proton because the neutron has greater rest mass-energy than the proton, so the decay would violate conservation of energy for a free proton at rest, oe **B1**

(c) Answer: All the usual conservation laws are satisfied, but the decay is still forbidden for a free proton because it would require energy to be created (the neutron is more massive than the proton).

(d) allowed **B1**

(d) even though strangeness changes (from -1 to 0), this is a weak interaction, and strangeness need only be conserved in strong and electromagnetic interactions, not in weak interactions, oe **B1**

(d) Answer: Allowed: strangeness need not be conserved in a weak interaction.

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Question 3

(a) nucleon number balance shown: 235 + 1 = 140 + 94 + 2 (= 236) **B1**

(a) total proton number of products = 92 (54 for Xe + 38 for Sr), matching uranium's proton number of 92 **B1**

(a) Answer: 236 = 236 (nucleon number conserved); total proton number of products = 54 + 38 = 92.

(b) reactant mass (235.0439 + 1.00867 = 236.0526 u) minus product mass (139.9216 + 93.9154 + 2 x 1.00867 = 235.8543 u) correctly set up **M1**

(b) mass defect = 0.198 u (awrt 3 s.f.) **A1**

(b) Answer: mass defect = 0.198 u

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

(c) E = 185 MeV (awrt 3 s.f.) **A1**

(c) E = 2.95 x 10^{-11} J (awrt 3 s.f., ecf, using 1 MeV = 1.60 x 10^{-13} J) **A1**

(c) Answer: E = 185 MeV = 2.95 x 10^{-11} J

(d) the neutrons released by fission are fast, and fast neutrons are unlikely to cause further fission of uranium-235, which fissions best with slow (thermal) neutrons, oe **B1**

(d) the moderator (e.g. water or graphite) slows the fast neutrons by (elastic) collisions, without absorbing them, increasing the chance that each one causes a further fission, oe **B1**

(d) the control rods (e.g. boron or cadmium) absorb some of the neutrons produced, and are inserted or withdrawn to remove just enough neutrons to keep the multiplication factor at exactly k = 1, oe **B1**

(d) if too many neutrons were absorbed (or too few moderated), k would fall below 1 and the reaction would die out (subcritical); if too few were absorbed, k would rise above 1 and the reaction would escalate (supercritical), oe **B1**

(d) Answer: The moderator slows fast neutrons so they are likely to cause further fission; the control rods absorb just enough neutrons to keep the multiplication factor at k = 1, avoiding both a dying-out (subcritical) and an escalating (supercritical) reaction.

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