3.2 Particles and Radiation

AQA 7408 · Calculator allowed · about 215 minutes · Write-in edition

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 The specific charge of a particle is used to compare how strongly different particles respond to electric and magnetic fields.

(a) State what is meant by the specific charge of a particle. **(1)**

(b) Calculate the specific charge of a proton. Mass of proton = 1.673×10^{-27} kg, charge of proton = 1.60×10^{-19} C. **(2)**

(c) An α particle consists of 2 protons and 2 neutrons bound together, with mass of neutron = 1.675×10^{-27} kg. Calculate the specific charge of an α particle. **(3)**

(d) A hydrogen nucleus (a single proton) has a greater specific charge than an α particle, even though the α particle carries twice the charge of a proton. Explain why this is the case, without further calculation. **(2)**

(Total for Question 1 is 8 marks)

2 This question concerns three radioactive decay processes. Use nuclide notation $^{A}_{Z}X$ throughout, represent the β-minus particle as $^{0}_{-1}e$ and the positron as $^{0}_{1}e$, and write neutrinos and antineutrinos in words.

(a) Americium-241 ($^{241}_{95}Am$), used in household smoke detectors, decays by α emission. Write a balanced nuclear equation for this decay, giving the correct nucleon number and proton number for the daughter nuclide. **(2)**

(b) Potassium-40 ($^{40}_{19}K$), present naturally in rocks and used in potassium-argon dating, can decay by β-minus emission. Write a balanced nuclear equation for this decay, including correct notation for the β particle and the antineutrino produced, and give the correct nucleon number and proton number for the daughter nuclide. **(2)**

(c) Sodium-22 ($^{22}_{11}Na$), used to calibrate medical PET scanners, decays by β-plus emission (positron emission). Write a balanced nuclear equation for this decay, including correct notation for the positron and the neutrino produced, and give the correct nucleon number and proton number for the daughter nuclide. **(2)**

(d) Beta-plus decay occurs when a proton inside the nucleus is transformed into a neutron. Describe what happens to the quark content of the proton during this process, and name the exchange particle involved. **(3)**

(Total for Question 2 is 9 marks)

3 In the α-scattering experiment, a narrow beam of α particles was directed at a thin gold foil in an evacuated chamber, and the number of α particles scattered was measured at various angles using a rotatable detector screen.

(a) Explain how the results of the α-scattering experiment led scientists to reject the 'plum pudding' model of the atom in favour of the nuclear model. **(6)**

(b) The radius of a gold nucleus is of order 10^{-14} m, while the radius of a gold atom is of order 10^{-10} m. Calculate the ratio of the atomic radius to the nuclear radius. **(2)**

(Total for Question 3 is 8 marks)

4 A student determines the half-life of the radioisotope protactinium-234m, which is separated from a sealed generator bottle containing a uranium-238 salt. A Geiger-Muller (GM) tube connected to a counter is positioned just above the separated sample, and a stopclock is started at the moment the sample is isolated.

(a) State why the gross count rate recorded by the GM tube must be corrected by subtracting the background count rate before it is used to determine the half-life. **(1)**

(b) Before the experiment, the background count is measured over 300 s with no radioactive sample present, giving a total of 90 counts. Calculate the background count rate in counts per second. **(2)**

(c) After background correction, the count rate from the protactinium-234m sample is 32.0 counts/s at t = 20 s after the sample is isolated, falling to 4.0 counts/s at t = 160 s. Calculate the half-life of protactinium-234m from these two measurements, showing your working. **(4)**

(d) Each of the two count-rate readings used in part (c) has a percentage uncertainty of 4%, due to the random nature of radioactive decay. Estimate the percentage uncertainty in the ratio of the two count rates, and use it to comment on the precision of the half-life value calculated in part (c). **(2)**

(e) State one precaution, other than background correction, that should be taken when using the GM tube in this experiment to ensure the count-rate readings are reliable. **(1)**

(Total for Question 4 is 10 marks)

5 A hospital uses the medical tracer isotope technetium-99m, which has a half-life of 6.01 hours. At 09:00 the hospital receives a sealed sample with an initial activity of 640 MBq.

(a) Calculate the decay constant, λ, of technetium-99m in s^{-1}. **(2)**

(b) Calculate the activity of the sample at 15:00 on the same day, using $A = A0\ e^{-\lambda t}$. **(3)**

(c) The sample must not be used clinically once its activity falls below 15 MBq. **(3)**
Calculate the time, in hours after 09:00, at which the activity of the sample first falls below 15 MBq.

(Total for Question 5 is 8 marks)

6 The fundamental forces between particles are mediated by the exchange of virtual particles (gauge bosons).

(a) An electron scatters elastically off a proton by exchanging a virtual particle associated with the electromagnetic force. State the name of this exchange particle and one property of it that distinguishes it from the W and Z bosons. **(2)**

(b) A neutron decays via the weak interaction: n -> p + e- + antineutrino$_e$. At the quark level, this occurs when a down quark inside the neutron emits a virtual W- boson and changes into an up quark; the W- boson then decays into an electron and an electron antineutrino. State the quark change that occurs at this interaction vertex, and the exchange particle emitted. **(2)**

(c) Explain why the range of the weak interaction is much shorter than the range of the electromagnetic force, referring to the exchange particles involved in each. **(3)**

(Total for Question 6 is 7 marks)

7 Dr Aisha Khan analyses a wooden artefact to estimate its age using carbon-14 dating. Carbon-14 has a half-life of 5730 years. Use the Physics Equations Sheet for $A = \lambda N$, $N = N0\ e^{-\lambda t}$ and $\lambda = \ln 2 / t(1/2)$. Take 1 year = 3.156×10^7 s.

(a) Calculate the decay constant, λ, of carbon-14 in s^{-1}. **(3)**

(b) A 1.00 g sample of carbon from the artefact has an activity of 0.230 Bq from carbon-14 decay. Calculate the number of carbon-14 nuclei present in the sample, using $A = \lambda N$. **(2)**

(c) A freshly-cut sample of the same mass of wood has an activity of 0.250 Bq. Calculate the age of the artefact, using $A = A0\ e^{-\lambda t}$. **(3)**

(d) State one assumption made in using this method to estimate the age of the artefact. **(1)**

(Total for Question 7 is 9 marks)

8 A negative pion, π-, with quark composition d u-bar (a down quark and an up antiquark), decays at rest via the weak interaction: π- -> μ- + antineutrino$_\mu$. Use the Physics Equations Sheet for $E = mc^2$. c = 3.00 x 10^8 m/s.

(a) State the quark composition of the π- meson's antiparticle, the π+ meson. **(1)**

(b) Show that charge is conserved in the decay π- -> μ- + antineutrino$_\mu$. **(2)**

(c) The rest mass of the π- meson is 2.49 x 10^{-28} kg and the rest mass of the muon is 1.88 x 10^{-28} kg. Assuming the antineutrino produced has negligible mass, calculate the total kinetic energy released in this decay, using $E = mc^2$. **(3)**

(d) This kinetic energy is shared between the muon and the antineutrino, which move off in opposite directions to conserve momentum. State and explain which of the two particles gains the greater share of the kinetic energy. **(2)**

(Total for Question 8 is 8 marks)

9 Particles can be classified as hadrons or leptons.

(a) State two properties of leptons that distinguish them from hadrons. **(2)**

(b) Classify each of the following particles as a hadron or a lepton: proton, neutron, electron, muon-neutrino, pion, kaon. **(3)**

(c) State whether the pion and the kaon named in part (b) are baryons or mesons, and justify your answer in terms of the number of quarks in each. **(2)**

(Total for Question 9 is 7 marks)

10 Protons and neutrons are hadrons made up of up (u) and down (d) quarks, with charges of +2/3 e and -1/3 e respectively.

(a) State the quark composition of a proton and of a neutron. **(2)**

(b) Show that the neutron (quark composition udd) has zero overall charge. **(2)**

(c) In β-minus decay, a neutron transforms into a proton, an electron and an antineutrino. At the quark level this involves a down quark changing into an up quark. State the exchange particle involved and the fundamental force responsible for this interaction. **(2)**

(d) A neutral kaon, K0, has quark composition d s-bar (a down quark and a strange antiquark), giving it a strangeness of +1. Use conservation of strangeness to explain why a K0 cannot be created alone in a strong interaction between two protons (each of strangeness zero), but must be produced together with another strange particle. **(2)**

(Total for Question 10 is 8 marks)

11 Four proposed particle interactions are given below. For each, deduce whether the interaction is allowed, giving a reason based on the conservation of charge, baryon number, lepton number or strangeness (as appropriate). Where a proposed interaction is not allowed, state the conservation law that is violated.

(a) $\mu^- \rightarrow e^- + \text{antineutrino}_e + \text{neutrino}_\mu$ **(2)**

(b) $p \rightarrow e^+ + \pi^0$ (a proton decaying into a positron and a neutral pion) **(2)**

(c) $n \rightarrow p + e^-$ (a neutron decaying into a proton and an electron only, with no antineutrino) **(2)**

(d) $K^+ \rightarrow \mu^+ + \text{neutrino}_\mu$ (a positive kaon, strangeness +1, decaying into a muon and a muon-neutrino, both of strangeness 0) **(2)**

(Total for Question 11 is 8 marks)

12 An electron and a positron, each with negligible kinetic energy, undergo mutual annihilation, producing two identical γ-ray photons travelling in opposite directions. Use the Physics Equations Sheet for $E = mc^2$ and $E = hf$. Mass of electron = mass of positron = 9.11×10^{-31} kg, $c = 3.00 \times 10^8$ m/s, $h = 6.63 \times 10^{-34}$ Js.

(a) Using $E = mc^2$, calculate the total energy released in this annihilation. **(3)**

(b) Calculate the energy of each individual photon produced, and hence use $E = hf$ to find its frequency. **(3)**

(c) In pair production, a photon converts into an electron-positron pair only in the presence of a nucleus, never in empty space. State and explain the additional condition, besides conservation of energy, that requires a nucleus to be present for pair production to occur. **(2)**

(Total for Question 12 is 8 marks)

13 Required practical: Priya investigates the relationship between the striking (threshold) voltage of light-emitting diodes (LEDs) and the wavelength of light they emit, in order to determine an approximate value for the Planck constant. Her circuit connects an LED in series with a variable resistor, a milliammeter and a low-voltage d.c. supply, with a voltmeter connected across the LED. She increases the p.d. across the LED slowly from zero until it just begins to emit light (the striking voltage, V). At the striking voltage, assume that all of the electrical energy gained by an electron passing through the LED converts into the energy of a single emitted photon, so that $eV = hc/\lambda$, where λ is the wavelength of the emitted light. Her results for four LEDs are: Red, $\lambda = 660$ nm, $V = 1.62$ V; Yellow, $\lambda = 590$ nm, $V = 1.82$ V; Green, $\lambda = 525$ nm, $V = 2.15$ V; Blue, $\lambda = 470$ nm, $V = 2.45$ V. $e = 1.60 \times 10^{-19}$ C, $c = 3.00 \times 10^{8}$ m/s.

(a) Explain why the circuit must include a variable resistor connected in series with the LED, rather than connecting the LED directly across the supply. **(2)**

(b) Describe how Priya should determine the striking voltage of each LED, and suggest one precaution she should take to improve the precision of this reading. **(3)**

(c) Show that the equation $eV = hc/\lambda$ can be rearranged to give $V = (hc/e) \times (1/\lambda)$, and explain how a graph could be used with this equation to determine a value for the Planck constant, h. **(3)**

(d) Calculate the value of $1/\lambda$, in m^{-1}, for the green LED ($\lambda = 525$ nm). **(1)**

(e) The graph of V against $1/\lambda$ for Priya's four data points has a gradient of 1.26×10^{-6} V m. Use this gradient to calculate a value for the Planck constant, h. **(3)**

(f) The accepted value of the Planck constant is 6.63×10^{-34} Js. Calculate the percentage difference between Priya's value (from part e) and the accepted value. **(2)**

(g) Suggest one reason, other than random error in judging the striking voltage, why Priya's experimental value of h might differ systematically from the accepted value. **(1)**

(h) Identify one variable that Priya should keep constant across all four LEDs to ensure a fair comparison of striking voltages. **(1)**

(Total for Question 13 is 16 marks)

14 Synoptic question. Caesium-137 is a radioactive isotope used in industrial and medical calibration sources. It decays by β-minus emission to an excited state of barium-137, which then de-excites to its ground state by emitting a single γ-ray photon of energy 0.662 MeV. The half-life of caesium-137 is 30.1 years. Take $h = 6.63 \times 10^{-34}$ Js, $c = 3.00 \times 10^{8}$ m/s and 1 MeV $= 1.60 \times 10^{-13}$ J.

(a) Calculate the frequency of the γ-ray photon emitted, given its energy is 0.662 MeV. **(2)**

(b) Calculate the wavelength of this γ-ray photon. **(2)**

(c) The γ photon emitted always has this one precise energy, rather than a continuous range of energies. Explain how this observation provides evidence that, like an atom, the barium-137 nucleus can only exist in discrete, quantised energy states. **(2)**

(d) A sealed calibration source initially contains 3.70×10^{8} nuclei of caesium-137. Calculate the number of caesium-137 nuclei remaining in the source after 10.0 years. **(3)**

(e) State and explain one reason why an antineutrino must also be emitted alongside the β particle in this β-minus decay of caesium-137. **(2)**

(Total for Question 14 is 11 marks)

15 This question tests quark composition, charge, and the use of conservation laws to decide whether a proposed particle interaction is allowed. Quark charges: up quark (u) = +2/3 e, down quark (d) = -1/3 e, strange quark (s) = -1/3 e; each antiquark carries the opposite charge to its quark. A strange quark is assigned strangeness -1 (so a strange antiquark, s-bar, has strangeness +1). Baryon number is +1/3 per quark and -1/3 per antiquark. Lepton number is +1 for a lepton and -1 for an antilepton.

(a) An antiproton is the antiparticle of the proton, with quark composition u-bar u-bar d-bar (two up antiquarks and one down antiquark). Show that the overall charge of the antiproton is -1e. **(2)**

(b) A neutral pion, pi0, can be represented (in a simplified treatment) by the quark-antiquark pair u u-bar. Show that this combination gives the pi0 zero overall charge. **(2)**

(c) A positive kaon, K^+, has quark composition u s-bar and decays via the weak interaction as $K^+ \rightarrow \pi+ + pi0$, where $\pi+$ has quark composition u d-bar. Determine whether strangeness is conserved in this decay, and state whether the decay is allowed. **(2)**

(d) A proposed reaction is p + n -> p + p + π-, where π- has charge -1e. Determine whether this reaction is allowed, by checking conservation of charge and baryon number. **(2)**

(e) A student suggests that an electron could be captured by a proton according to the reaction e- + p -> n + γ (a photon), with no other particles produced. Determine whether this reaction, as written, is allowed by checking conservation of lepton number. **(2)**

(f) A second student suggests that a free proton could decay according to the reaction p -> π+ + pi0, using the same π+ and pi0 as in part (c). Determine whether this reaction is allowed, by checking conservation of baryon number. **(2)**

(Total for Question 15 is 12 marks)

16 A neutral pion (pi0) at rest decays into two γ-ray photons: pi0 -> γ + γ. The rest mass energy of the pi0 is 135.0 MeV. Take 1 MeV = 1.60 x 10^{-13} J and c = 3.00 x 10^{8} m/s.

(a) State why, by the conservation of momentum, the two photons must travel in exactly opposite directions with equal energy. **(1)**

(b) Calculate the energy of each of the two photons produced, in MeV. **(3)**

(c) Calculate the momentum of each photon, in kg m/s. **(3)**

(d) If instead the pi0 were travelling at high speed when it decayed, rather than being at rest, explain qualitatively how the energies of the two photons produced would compare with each other. **(1)**

(Total for Question 16 is 8 marks)

17 High-energy electron scattering experiments (deep inelastic scattering) off protons and neutrons provide evidence that these nucleons are not fundamental particles but are made up of point-like constituents called quarks. Evaluate how the results of deep inelastic electron scattering experiments provide evidence for the existence of quarks inside nucleons, and discuss the limitations of this evidence.

(Total for Question 17 is 6 marks)

Mark scheme · 3.2 Particles and Radiation

Question 1

(a) the charge of a particle divided by its mass (charge-to-mass ratio) oe **B1**

(a) Answer: Specific charge = charge / mass of the particle.

(b) correct substitution: specific charge = $1.60 \times 10^{-19} / 1.673 \times 10^{-27}$ **M1**

(b) 9.56×10^{7} C/kg (awrt, cao) **A1**

(b) Answer: 9.56×10^{7} C/kg

(c) total mass = $2(1.673 \times 10^{-27}) + 2(1.675 \times 10^{-27}) = 6.696 \times 10^{-27}$ kg **M1**

(c) total charge = $2 \times 1.60 \times 10^{-19} = 3.20 \times 10^{-19}$ C, and specific charge = charge/mass correctly substituted **M1**

(c) 4.78×10^{7} C/kg (awrt, ft from their total mass) **A1**

(c) Answer: 4.78×10^{7} C/kg

(d) the α particle's mass is about 4 times the proton's mass (2 protons + 2 neutrons vs 1 proton), while its charge is only 2 times the proton's charge **B1**

(d) since specific charge = charge/mass, the proportionally much larger increase in mass than in charge results in a smaller specific charge for the α particle oe **B1**

(d) Answer: The α particle's mass increases by a factor of about 4 while its charge only increases by a factor of 2, so its charge-to-mass ratio (specific charge) is smaller than the proton's.

Question 2

(a) identify daughter nuclide with A = 237, Z = 93 (neptunium) **M1**

(a) correct full equation: ^241_95 Am -> ^237_93 Np + ^4_2 He, cao **A1**

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

(b) identify daughter nuclide with A = 40, Z = 20 (calcium) **M1**

(b) correct full equation: ^40_19 K -> ^40_20 Ca + ^0_-1 e + electron antineutrino, cao **A1**

(b) Answer: ^40_19 K -> ^40_20 Ca + ^0_-1 e + electron antineutrino

(c) identify daughter nuclide with A = 22, Z = 10 (neon) **M1**

(c) correct full equation: ^22_11 Na -> ^22_10 Ne + ^0_1 e + electron neutrino, cao **A1**

(c) Answer: ^22_11 Na -> ^22_10 Ne + ^0_1 e + electron neutrino

(d) an up quark (u) within the proton (quark composition uud) changes into a down quark (d), so the proton (uud) becomes a neutron (udd) **M1**

(d) this change occurs via the weak interaction, with the emission of a virtual W+ boson (the exchange particle for this process) **M1**

(d) the virtual W+ boson then decays into a positron and an electron neutrino, the particles emitted from the nucleus **A1**

(d) Answer: An up quark changes to a down quark (uud to udd), via the weak interaction, emitting a virtual W+ boson which decays to a positron and an electron neutrino

Question 3

(a) **L3** A full, coherent explanation linking all three key observations (most alpha particles undeflected, some deflected through small angles, a very small fraction deflected through large angles including back-scattering) to specific features of the nuclear model (mostly empty space, a small region of concentrated positive charge, and a large concentrated positive charge/mass), with a clear comparison to why the plum pudding model could not account for the large-angle scattering. **5-6**

(a) **L2** The answer describes at least two of the key observations and links them to features of the nuclear model, but the explanation is incomplete or does not fully explain why the plum pudding model is inconsistent with the large-angle scattering. **3-4**

(a) **L1** A basic statement that most particles passed through with few deflections, with little or no explanation of what this implies about atomic structure. **1-2**

(a) **L0** No relevant content, or the answer does not relate to the question. **0**

(a) Indicative content:

- Most alpha particles passed straight through the foil with little or no deflection, showing that most of the atom is empty space.
- A small proportion of alpha particles were deflected through small angles, showing that there is a concentration of positive charge somewhere in the atom that repels the (positive) alpha particles.
- A very small fraction (about 1 in 8000) of alpha particles were deflected through angles greater than 90 degrees, with some rebounding almost back the way they came.
- This large-angle scattering could only happen if the alpha particles were repelled by an extremely concentrated positive charge and mass, far smaller than the size of the whole atom - the nucleus.
- The plum pudding model, in which positive charge is spread thinly throughout the whole atom, predicts only small deflections everywhere and cannot account for any large-angle scattering, since the electric field from such spread-out charge is never strong enough at any point to reverse an alpha particle's direction.
- The observation of large-angle scattering therefore directly contradicted the plum pudding model and supported a model with a small, dense, positively charged nucleus at the centre of a mostly empty atom.

(a) Answer: The undeflected majority showed the atom is mostly empty space; the small-angle deflections showed a concentration of positive charge; the rare large-angle deflections showed that charge and mass are concentrated in a tiny nucleus, which the plum pudding model (with charge spread throughout the atom) could not explain.

(b) ratio = $10^{-10} / 10^{-14}$ **M1**

(b) 1×10^{4} (i.e. the atom is about 10000 times larger than its nucleus) cao **A1**

(b) Answer: About 1×10^{4} (the atom is roughly 10000 times larger than its nucleus).

Question 4

(a) the GM tube also detects background radiation (e.g. cosmic rays, other radioactive materials nearby) unrelated to the protactinium-234m sample, which would otherwise be wrongly counted as part of the sample's decay oe **B1**

(a) Answer: Background radiation is also detected by the tube and must be removed so only counts from the sample are used

(b) substitute into count rate = total counts / time = 90 / 300 **M1**

(b) 0.30 counts/s, cao **A1**

(b) Answer: 0.30 counts/s

(c) calculate the ratio of count rates: 32.0 / 4.0 = 8 **M1**

(c) recognise that a factor of 8 is 2^3, so 3 half-lives have elapsed between the two measurements **M1**

(c) half-life = (160 - 20) / 3 **M1**

(c) 46.7 s, cao (3 s.f.) **A1**

(c) Answer: 46.7 s

(d) combine percentage uncertainties for a ratio by addition: 4% + 4% = 8% **M1**

(d) an 8% uncertainty is fairly large (a few seconds out of 46.7 s), so the half-life should be quoted with a substantial uncertainty (e.g. approximately 47 ± 4 s), and more repeat readings would improve the precision oe **A1**

(d) Answer: Approximately 8% uncertainty in the ratio, so the half-life is only known to within a few seconds

(e) e.g. keep the GM tube at a fixed distance from the sample throughout; avoid very high count rates that cause dead-time losses; use the same GM tube and settings for every reading oe (any one sensible precaution) **B1**

(e) Answer: Keep the GM tube at a fixed distance from the sample for every reading (or other valid precaution)

Question 5

(a) convert half-life to seconds (6.01 x 3600 = 21636 s) and substitute into λ = ln2 / half-life **M1**

(a) 3.20×10^{-5} s^{-1}, cao **A1**

(a) Answer: 3.20×10^{-5} s^{-1}

(b) identify t = 6 hours = 21600 s **M1**

(b) substitute $A = 640 \times e^{-3.20 \times 10^{-5} \times 21600}$, ft from (a) **M1**

(b) 320 MBq (accept 315-325 MBq), awrt **A1**

(b) Answer: 320 MBq

(c) rearrange $A = A0\ e^{-\lambda t}$ to give t = ln(A0/A) / λ **M1**

(c) substitute t = ln(640/15) / (3.20×10^{-5}) in seconds, ft from (a) **M1**

(c) 32.5 hours (accept 32-33 hours), awrt **A1**

(c) Answer: 32.5 hours

Question 6

(a) the (virtual) photon **B1**

(a) the photon is massless and uncharged, whereas the W and Z bosons have (large) mass, and the W boson is charged **B1**

(a) Answer: The photon; unlike the W and Z bosons, the photon is massless (and uncharged).

(b) a down quark changes into an up quark **B1**

(b) a (virtual) W- boson is emitted **B1**

(b) Answer: A down quark changes into an up quark, emitting a virtual W- boson.

(c) the range of a force is inversely related to the mass of its exchange particle, because a more massive virtual particle can only exist for a shorter time/travel a shorter distance before violating energy conservation **B1**

(c) the W and Z bosons that mediate the weak interaction have a very large mass, giving the weak interaction a very short range (of order 10^{-18} m) **B1**

(c) the photon that mediates the electromagnetic force is massless, giving the electromagnetic force (in principle) an infinite range **B1**

(c) Answer: The range of a force decreases as the mass of its exchange particle increases. The massive W/Z bosons give the weak force a very short range, while the massless photon gives the electromagnetic force an effectively infinite range.

Question 7

(a) converts the half-life to seconds: t(1/2) = 5730 x 3.156 x 10^7 = 1.808 x 10^{11} s **M1**

(a) correct substitution: λ = ln2 / 1.808 x 10^{11} **M1**

(a) 3.83 x 10^{-12} s^{-1} (awrt, cao) **A1**

(a) Answer: λ = 3.83 x 10^{-12} s^{-1}

(b) rearranges: N = A / λ = 0.230 / (their value of λ from a) **M1**

(b) 6.00 x 10^{10} nuclei (awrt, ft from a) **A1**

(b) Answer: N = 6.00 x 10^{10} nuclei

(c) rearranges to make t the subject: t = ln(A0/A) / λ **M1**

(c) correct substitution: t = ln(0.250/0.230) / (their value of λ from a) **M1**

(c) awrt 690 years (ft from a; accept 2.18 x 10^{10} s) **A1**

(c) Answer: t = 690 years (2 s.f.)

(d) the proportion (activity) of carbon-14 in the atmosphere, and hence in living wood, has remained constant over time; or the sample has not been contaminated since the tree died oe **B1**

(d) Answer: The atmospheric (and hence living-wood) proportion of carbon-14 has remained constant over time, and the sample has not been contaminated.

Question 8

(a) u d-bar (an up quark and a down antiquark) **B1**

(a) Answer: u d-bar (up quark + down antiquark).

(b) states the charges: π- has charge -1e; μ- has charge -1e; antineutrino$_{\mu}$ has charge 0 **M1**

(b) total charge on the right = -1e + 0 = -1e, equal to the charge on the left, so charge is conserved (cso) **A1**

(b) Answer: Charge on the left (-1e) equals charge on the right (-1e + 0), so charge is conserved.

(c) mass converted to energy = $2.49 \times 10^{-28} - 1.88 \times 10^{-28} = 6.10 \times 10^{-29}$ kg **M1**

(c) correct substitution: $E = 6.10 \times 10^{-29} \times (3.00 \times 10^{8})^2$ **M1**

(c) 5.49×10^{-12} J (awrt, cao) **A1**

(c) Answer: 5.49×10^{-12} J

(d) since the pion was at rest, total momentum after the decay must also be zero, so the muon and antineutrino move off with equal and opposite momentum (equal magnitude, p) **B1**

(d) kinetic energy = $p^2/(2m)$; for the same magnitude of momentum, the much less massive antineutrino gains far more kinetic energy than the more massive muon oe **B1**

(d) Answer: The antineutrino gains the greater share of the kinetic energy, because it has (effectively) far less mass than the muon, and for equal and opposite momenta, kinetic energy ($p^2/2m$) is much larger for the lighter particle.

Question 9

(a) leptons are fundamental particles (not made up of quarks), unlike hadrons, which are composed of quarks **B1**

(a) leptons do not experience the strong nuclear force (they interact only via the weak force, and the electromagnetic force if charged), whereas hadrons do experience the strong force **B1**

(a) Answer: Leptons are fundamental (not made of quarks) and do not feel the strong nuclear force, unlike hadrons.

(b) proton: hadron and neutron: hadron (both correct) **B1**

(b) electron: lepton and muon-neutrino: lepton (both correct) **B1**

(b) pion: hadron and kaon: hadron (both correct) **B1**

(b) Answer: Hadrons: proton, neutron, pion, kaon. Leptons: electron, muon-neutrino.

(c) both the pion and the kaon are mesons **B1**

(c) mesons are made of a quark and an antiquark (two quarks), whereas baryons are made of three quarks; the pion and kaon each contain a quark-antiquark pair, not three quarks **B1**

(c) Answer: Both are mesons, as each is made from a quark-antiquark pair (two quarks), not the three quarks that make up a baryon.

Question 10

(a) proton = uud (2 up quarks, 1 down quark) **B1**

(a) neutron = udd (1 up quark, 2 down quarks) **B1**

(a) Answer: Proton: uud. Neutron: udd.

(b) total charge = (+2/3 e) + (-1/3 e) + (-1/3 e), summing the charges of u, d and d **M1**

(b) = 0 (cso, answer given) **A1**

(b) Answer: Charge = +2/3 e - 1/3 e - 1/3 e = 0.

(c) exchange particle: W- boson (a virtual W-minus boson) **B1**

(c) force: the weak (nuclear) interaction/force **B1**

(c) Answer: A (virtual) W- boson is exchanged; the weak nuclear force is responsible.

(d) the total strangeness before the strong interaction is zero, since the two protons each have strangeness zero **B1**

(d) strangeness must be conserved in a strong interaction, so a K0 (strangeness +1) can only be produced if it is accompanied by another particle with strangeness -1, keeping the total strangeness at zero (associated production) oe **B1**

(d) Answer: Since strangeness is conserved in the strong interaction and the initial protons have total strangeness zero, a K0 (S = +1) must be produced alongside another particle of strangeness -1 so that the total strangeness remains zero.

Question 11

(a) allowed **B1**

(a) charge, muon lepton number and electron lepton number are all conserved (e.g. electron lepton number: 0 on the left = +1 - 1 = 0 on the right) oe **B1**

(a) Answer: Allowed: charge and both lepton numbers (muon and electron) are conserved.

(b) not allowed **B1**

(b) baryon number is not conserved: the proton has baryon number +1, but the positron and pion both have baryon number 0, so total baryon number changes from +1 to 0 **B1**

(b) Answer: Not allowed: baryon number is violated (+1 on the left, 0 on the right).

(c) not allowed **B1**

(c) lepton number is not conserved: the left-hand side has lepton number 0, but the electron alone gives a total of +1 on the right; an antineutrino$_{e}$ (lepton number -1) is needed to restore the balance to zero **B1**

(c) Answer: Not allowed: lepton number is violated; the correct decay requires an antineutrino$_{e}$ as well.

(d) allowed **B1**

(d) even though strangeness changes (from +1 to 0), this is a weak interaction, and strangeness only has to 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, only in strong and electromagnetic interactions.

Question 12

(a) total mass converted = 2 x 9.11 x 10^{-31} = 1.822 x 10^{-30} kg **M1**

(a) correct substitution: E = 1.822 x 10^{-30} x (3.00 x 10^{8})^{2} **M1**

(a) 1.64 x 10^{-13} J (awrt, cao) **A1**

(a) Answer: 1.64 x 10^{-13} J

(b) energy per photon = half the total energy = 1.64 x 10^{-13} / 2 = 8.20 x 10^{-14} J (ft from a) **M1**

(b) rearranges and substitutes: f = E/h = 8.20 x 10^{-14} / 6.63 x 10^{-34} **M1**

(b) 1.24 x 10^{20} Hz (awrt, ft) **A1**

(b) Answer: Energy per photon = 8.20 x 10^{-14} J; frequency = 1.24 x 10^{20} Hz.

(c) momentum must also be conserved in the interaction **B1**

(c) a single photon in empty space cannot produce an electron-positron pair moving in a way that conserves both energy and momentum simultaneously; a nearby nucleus is needed to absorb/take up the recoil momentum oe **B1**

(c) Answer: Momentum, as well as energy, must be conserved; a nucleus is needed nearby to absorb the recoil momentum, which is impossible in empty space with a single incoming photon.

Question 13

(a) an LED has a very low resistance once it starts conducting, so without a series resistance the current would become too large and could damage the LED **B1**

(a) the variable resistor allows the p.d. across the LED to be increased gradually from zero, so the striking voltage can be found precisely **B1**

(a) Answer: The series resistor limits the current so the LED is not damaged, and allows the p.d. across the LED to be increased gradually so the striking voltage can be measured precisely.

(b) the room should be darkened (or the LED viewed against a dark background/through a tube) so that the first faint light is visible **B1**

(b) the p.d. is increased slowly from zero and the voltmeter reading recorded at the instant light is first just seen **B1**

(b) the reading is repeated several times (e.g. by the same observer, or by increasing then decreasing the voltage) and averaged, to reduce the effect of human judgement/reaction on the result oe **B1**

(b) Answer: Darken the room, increase the p.d. slowly from zero, record the voltmeter reading when light is just first seen, and repeat several times to average out variation in human judgement.

(c) divides both sides of eV = hc/λ by e to give V = hc/(e x λ), which is V = (hc/e) x (1/λ) (cso) **M1**

(c) a graph of V (y-axis) against 1/λ (x-axis) gives a straight line through the origin with gradient equal to hc/e **B1**

(c) h can then be found from h = gradient x e / c oe **B1**

(c) Answer: V = (hc/e) x (1/λ); plotting V against 1/λ gives a straight line of gradient hc/e, from which h = gradient x e/c.

(d) 1.90 x 10^{6} m^{-1} (awrt, cao) **B1**

(d) Answer: 1.90 x 10^{6} m^{-1}

(e) rearranges h = gradient x e / c **M1**

(e) correct substitution: h = 1.26 x 10^{-6} x 1.60 x 10^{-19} / 3.00 x 10^{8} **M1**

(e) 6.72 x 10^{-34} Js (awrt, cao) **A1**

(e) Answer: h = 6.72 x 10^{-34} Js

(f) percentage difference = |6.72 - 6.63| / 6.63 x 100 (ft from e) **M1**

(f) 1.36% (awrt, accept 1.4%) **A1**

(f) Answer: 1.36% (or awrt 1.4%)

(g) the assumption that all of the electrical energy converts into a single photon's energy ignores energy losses (e.g. as heat/lattice vibrations) inside the LED, so eV may not exactly equal the true photon energy oe (or: resistance of the connecting wires/voltmeter affects the true p.d. across the LED junction) **B1**

(g) Answer: The assumption that eV equals the photon energy ignores energy losses to heat within the LED, which introduces a systematic error.

(h) the ambient lighting/level of darkness in the room (or: the same observer/method used to judge 'just visible' light) oe **B1**

(h) Answer: The level of room darkness (or the observer/method used to judge when light is 'just visible') must be kept the same for every LED.

Question 14

(a) convert 0.662 MeV to J: 0.662 x 1.60 x 10^{-13} = 1.06 x 10^{-13} J **M1**

(a) f = E/h = 1.60 x 10^{20} Hz, cao **A1**

(a) Answer: 1.60 x 10^{20} Hz

(b) substitute into λ = c / f, ft from (a) **M1**

(b) 1.88 x 10^{-12} m, cao/ft **A1**

(b) Answer: 1.88 x 10^{-12} m

(c) a photon of one single, sharply-defined energy can only be produced if the nucleus drops between two specific, fixed energy levels (the excited state and the ground state), with the photon energy equal to the difference between these two discrete levels **B1**

(c) this is directly analogous to the discrete spectral lines produced when electrons in atoms fall between fixed, quantised atomic energy levels, showing that nuclei, like atoms, have quantised internal energy states rather than a continuous range of allowed energies oe **B1**

(c) Answer: A single fixed photon energy shows the nucleus drops between two fixed energy levels, analogous to atomic energy levels producing line spectra

(d) calculate λ = ln2 / 30.1 = 0.0230 per year **M1**

(d) substitute into N = N0 $e^{-\lambda t}$ with t = 10.0 years, ft **M1**

(d) 2.94 x 10^{8} nuclei, cao (3 s.f.) **A1**

(d) Answer: 2.94 x 10^{8} nuclei

(e) β particles from this decay are observed experimentally to have a continuous range of kinetic energies up to a fixed maximum, rather than a single fixed value, which could not be explained by energy and momentum conservation with only the β particle and the barium nucleus produced **B1**

(e) the antineutrino must be emitted to carry away the remaining energy and momentum in each individual decay (the split between β particle and antineutrino varying from decay to decay), so that energy, momentum and lepton number are all conserved overall oe **B1**

(e) Answer: The antineutrino carries away the variable remaining energy and momentum, which explains the continuous β energy spectrum and conserves lepton number

Question 15

(a) substitute antiquark charges: (-2/3 e) + (-2/3 e) + (+1/3 e) **M1**

(a) cso: sum = -1e **A1**

(a) Answer: -1e

(b) substitute quark charges: (+2/3 e) + (-2/3 e) **M1**

(b) cso: sum = 0 **A1**

(b) Answer: 0

(c) calculate strangeness before (K^{+}: s-bar gives +1) and after (π+: 0, pi0: 0, total 0) **M1**

(c) strangeness changes from +1 to 0 so is not conserved, but the decay is allowed because it proceeds via the weak interaction, which does not have to conserve strangeness oe **A1**

(c) Answer: Strangeness is not conserved (+1 to 0), but the decay is allowed via the weak interaction

(d) charge: LHS = +1 + 0 = +1, RHS = +1 + 1 - 1 = +1 (conserved); baryon number: LHS = 1 + 1 = 2, RHS = 1 + 1 + 0 = 2 (conserved) **M1**

(d) both charge and baryon number are conserved (strangeness and lepton number are unaffected, remaining 0 throughout), so the reaction is allowed **A1**

(d) Answer: Allowed: charge and baryon number are both conserved

(e) calculate lepton number before (electron = +1, proton = 0, total +1) and after (neutron = 0, photon = 0, total 0) **M1**

(e) lepton number is not conserved (+1 does not equal 0), so the reaction as written is not allowed; an electron neutrino must also be produced for lepton number to be conserved oe **A1**

(e) Answer: Not allowed as written: lepton number is not conserved

(f) calculate baryon number before (proton = +1) and after (π+ = 0, pi0 = 0, total 0) **M1**

(f) baryon number is not conserved (+1 does not equal 0), so the reaction is not allowed, consistent with the observation that free protons do not decay oe **A1**

(f) Answer: Not allowed: baryon number is not conserved

Question 16

(a) the pi0 is initially at rest so total momentum before decay is zero; by conservation of momentum the two photon momenta must be equal in magnitude and opposite in direction, and since photon momentum p = E/c is proportional to energy, equal momenta mean equal energies oe **B1**

(a) Answer: Zero total momentum before decay means the photons must have equal and opposite momenta, and hence equal energies

(b) recognise that, since the pion is at rest, the total energy released equals its rest mass energy, 135.0 MeV **M1**

(b) this energy is shared equally between the two photons **M1**

(b) 67.5 MeV each, cao **A1**

(b) Answer: 67.5 MeV

(c) convert 67.5 MeV to J: $67.5 \times 1.60 \times 10^{-13} = 1.08 \times 10^{-11}$ J, ft from (b) **M1**

(c) substitute into p = E / c **M1**

(c) 3.60×10^{-20} kg m/s, cao **A1**

(c) Answer: 3.60×10^{-20} kg m/s

(d) the two photons would no longer have equal energies: the one emitted closer to the direction of the pion's motion would be boosted to a higher energy, and the other would have a lower energy, although the sum of their energies would still equal the total energy of the moving pion oe **B1**

(d) Answer: The photon emitted in the direction of motion gains energy and the other loses energy, but their total stays equal to the pion's total energy

Question 17

Level 3 Detailed and balanced evaluation: explains why high-energy electrons are needed to resolve internal structure, describes how the scattering pattern differs from that expected for a uniform charge distribution, links this to point-like quark constituents and the quark-parton model, and gives at least one clear limitation of the evidence (e.g. quark confinement, or the simplification of the three-quark picture). Clear, well-organised reasoning throughout. **5-6**

Level 2 Moderate evaluation: describes that scattering results show more large-angle scattering than expected for a uniform charge distribution, and links this to internal structure or point-like constituents, but with limited detail on the quark-parton model or limited discussion of limitations. **3-4**

Level 1 Basic comments: states that scattering experiments suggest nucleons have internal structure or contain quarks, with little development, explanation or discussion of limitations. **1-2**

Indicative content:

- High-energy electrons are used because their de Broglie wavelength is much smaller than the diameter of a nucleon, giving enough resolution to probe internal structure.
- If a nucleon had no internal structure (a smooth, uniform charge distribution), the scattering intensity would be expected to fall smoothly with increasing scattering angle.
- Deep inelastic scattering shows more electrons scattered through large angles than predicted for a uniform charge distribution, in a manner conceptually similar to the unexpected large-angle scattering seen in Rutherford's alpha-particle experiment.
- This unexpected large-angle scattering indicates the presence of small, point-like, charged constituents (quarks) inside the nucleon rather than a smooth continuous charge distribution.
- The detailed variation of scattering intensity with electron energy and angle matches predictions of the quark-parton model, in which the nucleon's momentum is shared mainly between three quarks.
- Limitation: individual quarks are never observed as free particles, because of colour confinement, so their existence is inferred indirectly from the scattering data rather than observed directly.
- Limitation: the simple three-quark picture is itself a simplification, since scattering data also show contributions from virtual quark-antiquark pairs and gluons inside the nucleon.
- Results have been reproduced and refined at several accelerator facilities, increasing confidence in the interpretation, but the conclusions always rely on a theoretical model relating scattering cross-sections to internal structure.