3.11 Physics: Nuclear and Particle Physics

AQA 7408 · Calculator allowed · about 140 minutes · Write-in edition

Total Marks

Name: _____ Date: ____ / ____ / _____

Answer ALL questions. Show all your working.

1 The radius R of a nucleus with nucleon (mass) number A can be modelled using $R = R0 \times A^{1/3}$, where $R0 = 1.05 \times 10^{-15}$ m. Take the mass of a nucleon to be approximately $u = 1.66 \times 10^{-27}$ kg, whatever the nuclide.

(a) Calculate the radius of a carbon-12 nucleus. Give your answer in metres to 3 significant figures. **(2)**

(b) Show that the radius of a uranium-238 nucleus is about 6.51×10^{-15} m. **(2)**

(c) By modelling each nucleus as a uniform sphere of volume $(4/3) \times \pi \times R^3$ and mass $A \times u$, calculate the density of a carbon-12 nucleus and the density of a uranium-238 nucleus, using your radii from parts (a) and (b). State what your two values show about nuclear density. **(5)**

(d) Explain how this approximately constant nuclear density supports the idea that the strong nuclear force has a very short range, acting only between neighbouring nucleons rather than between every pair of nucleons in the nucleus. **(2)**

(Total for Question 1 is 11 marks)

2 Iodine-131 is used to treat an overactive thyroid gland, with a half-life of 8.02 days. Use $A = \lambda \times N$ and $A = A0 \times e^{-\lambda \times t}$, where $\lambda = \ln 2 / (\text{half-life})$. Take $1\ u = 1.66 \times 10^{-27}$ kg.

(a) Show that the decay constant of iodine-131 is about 1.00×10^{-6} per second. **(2)**

(b) A hospital pharmacy prepares a dose of iodine-131 with an initial activity of 4.00×10^{8} Bq (400 MBq). Calculate the number of iodine-131 nuclei present in this dose. **(2)**

(c) Calculate the mass of iodine-131 in this dose, given that the mass of one iodine-131 atom is approximately 131 u. **(2)**

(d) Calculate the activity of the dose 5.00 days after preparation. **(3)**

(e) Technetium-99m, used only for short diagnostic imaging scans, has a half-life of about 6 hours, far shorter than iodine-131's 8.02 days. Explain why a longer half-life, such as iodine-131's, is more appropriate for a therapeutic (treatment) dose, and suggest why a half-life of days, rather than an extremely long-lived alternative of many years, is still preferred. **(3)**

(Total for Question 2 is 12 marks)

3 Mass of proton = 1.00728 u, mass of neutron = 1.00867 u, mass of an iron-56 nucleus = 55.9206 u. 1 u is equivalent to 931.5 MeV of energy.

(a) State what is meant by the binding energy of a nucleus. **(1)**

(b) Show that the mass defect of an iron-56 nucleus (26 protons, 30 neutrons) is about 0.529 u. **(3)**

(c) Calculate the binding energy per nucleon of iron-56, in MeV. **(2)**

(d) The graph of binding energy per nucleon against nucleon number A rises steeply from hydrogen, peaks close to iron/nickel (A about 56), then falls gradually towards the heaviest nuclides. Using this graph, explain why energy is released in both the fusion of light nuclei and the fission of heavy nuclei. **(4)**

(Total for Question 3 is 10 marks)

4 In a deuterium-deuterium fusion reaction: ^2_1 H + ^2_1 H -> ^3_2 He + ^1_0 n. Masses: deuterium = 2.01410 u, helium-3 = 3.01603 u, neutron = 1.00867 u. 1 u = 931.5 MeV = 1.66 x 10^{-27} kg. 1 MeV = 1.60 x 10^{-13} J.

(a) State why two neutrons do not appear on the right-hand side, given that two deuterium (hydrogen-2) nuclei are used, each containing one neutron. **(1)**

(b) Show that the energy released in a single deuterium-deuterium fusion reaction of this type is about 3.26 MeV. **(3)**

(c) Calculate the total energy released, in joules, if 1.00 g of deuterium is completely consumed by this reaction (remember that two deuterium nuclei are used per reaction). **(4)**

(d) Fusion reactors on Earth require plasma temperatures above 100 million kelvin. Explain why such high temperatures are needed, and suggest one reason why sustaining these conditions is a significant engineering challenge. **(3)**

(Total for Question 4 is 11 marks)

5 In a particle detector, a charged particle moving perpendicular to a uniform magnetic flux density B follows a circular arc of radius r, since the magnetic force provides the centripetal force: $B \times Q \times v = m \times v^2 / r$, where Q is the magnitude of the particle's charge.

(a) Show that the particle's momentum $p = m \times v$ can be written $p = B \times Q \times r$. **(2)**

(b) A particle track in a detector, with B = 0.850 T, has a measured radius of curvature r = 0.320 m, and the particle is known to carry a charge of magnitude $e = 1.60 \times 10^{-19}$ C. Calculate its momentum. **(2)**

(c) Two particle tracks are produced from the same point, curving in opposite directions in the magnetic field. State what this indicates about the two particles, and explain how the direction of curvature, combined with the known direction of B, can be used to determine the sign of a particle's charge. **(3)**

(d) Explain why particles with greater momentum produce tracks of larger radius of curvature, for a fixed magnetic flux density and charge. **(2)**

(e) A neutral particle leaves no track of its own, but its presence and momentum can sometimes still be inferred. Suggest how physicists identify the existence of a short-lived, electrically neutral particle that itself decays into charged particles, using track data alone. **(2)**

(Total for Question 5 is 11 marks)

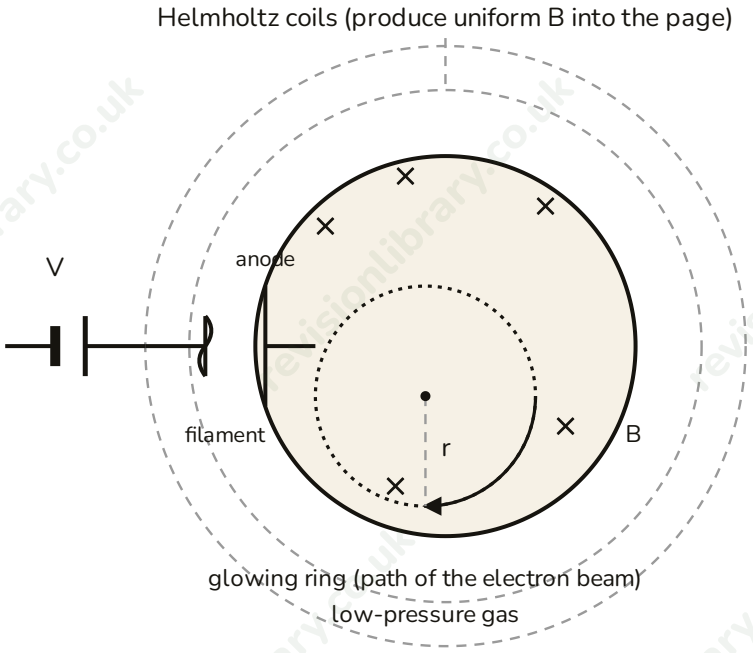
6 Before the neutrino was proposed, physicists observed that β particles emitted from a given radioactive source did not all have the same, fixed kinetic energy, but instead showed a continuous range (spectrum) of energies up to a single maximum value.

(a) State the change in proton number Z and nucleon number A of a nucleus undergoing β-minus decay. **(2)**

(b) Discuss how the observation of a continuous range of β particle energies, rather than a single fixed energy, led physicists to propose the existence of the neutrino, referring to the conservation of energy and momentum. **(6)**

(Total for Question 6 is 8 marks)

7 Required practical: in a fine beam tube experiment, electrons are accelerated from rest through a potential difference V, then enter a region of low-pressure gas where a uniform magnetic flux density B, produced by a pair of Helmholtz coils, acts perpendicular to their velocity. The electrons then travel in a circular path of radius r, visible as a glowing ring due to ionisation of the gas. Use $v = \sqrt{2 \times e \times V / m}$ and $r = m \times v / (e \times B)$, where e/m is the electron's specific charge.



(a) Show that the speed v of an electron leaving the electron gun, having been accelerated from rest through potential difference V, is given by $v = \sqrt{2 \times e \times V / m}$. **(2)**

(b) By combining $v = \sqrt{2eV/m}$ with $r = mv/(eB)$, show that the specific charge of the electron can be found using $e/m = 2V / (B^2 \times r^2)$. **(3)**

(c) In one trial, V = 200 V and B = 4.00 x 10^{-4} T, giving a measured path radius r = 11.9 cm. Calculate a value for e/m from this data. **(3)**

(d) The accepted value of e/m for the electron is 1.76 x 10^{11} C/kg. Calculate the percentage difference between the value found in (c) and this accepted value. **(2)**

(e) State two adjustments a student could make to reduce the percentage uncertainty in their measurement of r. **(2)**

(f) Explain why this method could not be used with useful precision to determine the specific charge of a proton, using the same apparatus and typical laboratory values of V and B. **(2)**

(Total for Question 7 is 14 marks)

8 The up (u), down (d) and strange (s) quarks have charges of +2/3 e, -1/3 e and -1/3 e respectively; only the strange quark (or antiquark) carries non-zero strangeness, with the s quark having strangeness -1 and the s-bar antiquark having strangeness +1.

(a) The Sigma-plus baryon, Sigma+, has strangeness S = -1 and overall charge +1 e, and (like the proton) is made of three quarks chosen from up, down and strange. Deduce its quark composition, explaining your reasoning. **(3)**

(b) The K- meson has quark composition: one strange quark (s) and one up antiquark (u-bar). Calculate its overall charge and state its strangeness, explaining your reasoning for each. **(3)**

(c) State one property that is always identical between a particle and its corresponding antiparticle, and one property that is equal in magnitude but always opposite in sign. **(2)**

(d) The muon (μ-) and the tau (tau-), like the electron, are classified as leptons. State two similarities and one difference between the electron, the muon and the tau. **(3)**

(Total for Question 8 is 11 marks)

9 The four fundamental interactions are mediated by the exchange of virtual particles (gauge bosons).

(a) State the exchange particle associated with the strong (nuclear) force between quarks, state one property of this exchange particle that is different from the photon, and give one consequence of this difference. **(3)**

(b) In β-plus decay, such as the fluorine-18 to oxygen-18 decay described earlier, an up quark inside a proton changes into a down quark, converting the proton into a neutron. Describe, in terms of a Feynman diagram, what is exchanged in this process and what it subsequently decays into. **(4)**

(c) State the strong, electromagnetic and weak interactions in order of decreasing relative strength, and suggest why particle decays proceeding via the weak interaction (such as this one) typically take much longer than those proceeding via the strong interaction. **(3)**

(Total for Question 9 is 10 marks)

Mark scheme · 3.11 Physics: Nuclear and Particle Physics

Question 1

(a) $12^{1/3}$ = 2.29 (or 2.289) **M1**

(a) R = 2.40 x 10^{-15} m (awrt, cao) **A1**

(a) Answer: R = 2.40 x 10^{-15} m

(b) $238^{1/3}$ = 6.20 (or 6.198) **M1**

(b) R = 1.05 x 10^{-15} x 6.198 = 6.51 x 10^{-15} m shown (cso, answer given) **A1**

(b) Answer: R = 6.51 x 10^{-15} m

(c) volume of carbon-12 nucleus = (4/3) x π x (2.404 x 10^{-15})^3 = 5.82 x 10^{-44} m^3 (5.79 x 10^{-44} m^3 if the rounded R = 2.40 x 10^{-15} m is used; ecf from a) **M1**

(c) density of carbon-12 = (12 x 1.66 x 10^{-27}) / 5.82 x 10^{-44} = 3.42 x 10^{17} kg/m^3 (awrt, ecf; accept 3.42 to 3.44 x 10^{17}) **A1**

(c) volume of uranium-238 nucleus = (4/3) x π x (6.51 x 10^{-15})^3 = 1.156 x 10^{-42} m^3 (ecf from b) **M1**

(c) density of uranium-238 = (238 x 1.66 x 10^{-27}) / 1.156 x 10^{-42} = 3.42 x 10^{17} kg/m^3 (awrt, ecf) **A1**

(c) the two densities are (almost) equal, showing that nuclear density is approximately independent of (constant regardless of) nucleon number A, oe **B1**

(c) Answer: Density of C-12 nucleus = density of U-238 nucleus = approximately 3.4 x 10^{17} kg/m^3, confirming nuclear density is roughly constant for all nuclides.

(d) a roughly constant density means each nucleon occupies about the same amount of volume, regardless of how many nucleons (A) are present, oe **B1**

(d) this is consistent with each nucleon being strongly attracted only to its nearest neighbours (a short-range, saturated force); if the strong force instead acted between every pair of nucleons at all separations, the nucleus would be pulled ever more tightly together as A increased, and density would rise with A rather than staying constant, oe **B1**

(d) Answer: Because density does not increase with A, each nucleon must be held by a force that only reaches its nearest neighbours (short range), not by a force acting on every nucleon in the whole nucleus.

Question 2

(a) half-life converted to seconds: 8.02 x 24 x 3600 = 6.93 x 10^5 s **M1**

(a) λ = ln2 / 6.93 x 10^5 = 1.00 x 10^{-6} s^{-1} shown (cso, answer given) **A1**

(a) Answer: λ = 1.00 x 10^{-6} s^{-1}

(b) N0 = A0 / λ correctly substituted, ft from (a) **M1**

(b) N0 = 4.00 x 10^{14} (awrt) **A1**

(b) Answer: N0 = 4.00 x 10^{14} nuclei

(c) mass = N0 x 131 x 1.66 x 10^{-27} correctly substituted, ft from (b) **M1**

(c) mass = 8.70 x 10^{-11} kg (or 87.0 ng), awrt, ecf **A1**

(c) Answer: mass = 8.70 x 10^{-11} kg (87.0 nanograms)

(d) t converted to seconds (5.00 x 86400 = 4.32 x 10^5 s) and substituted into A = A0 x $e^{-\lambda \times t}$ **M1**

(d) exponent evaluated correctly: λ x t = 0.432, giving $e^{-0.432}$ = 0.649 **M1**

(d) A = 2.60 x 10^8 Bq (awrt, ft from a and b) **A1**

(d) Answer: A = 2.60 x 10^8 Bq

(e) a longer half-life allows the isotope to remain active and continue delivering radiation to the target tissue over the several days needed for the treatment to take effect, whereas a short-lived isotope like technetium-99m would decay away almost completely within a day, delivering too little dose, oe **B1**

(e) a half-life of only days (rather than years) still means the patient's activity falls to a safe level within a reasonably short time after treatment, limiting the total radiation dose received by the patient and by other people, oe **B1**

(e) coherent balance of both points made explicit, i.e. the half-life needs to be long enough for treatment but short enough for safety, oe **B1**

(e) Answer: A longer half-life sustains the dose over the days needed for treatment to work, unlike a short-lived isotope; but a half-life of days (not years) still allows activity to fall to a safe level soon after treatment, limiting total radiation exposure.

Question 3

(a) the energy needed to completely separate all the nucleons of a nucleus to infinity (or the energy released when a nucleus is assembled from its separate nucleons), oe **B1**

(a) Answer: The energy needed to separate a nucleus into its individual, separate protons and neutrons.

(b) mass of the separate protons and neutrons found: 26 x 1.00728 = 26.189 u and 30 x 1.00867 = 30.260 u **M1**

(b) total mass of separate nucleons = 26.189 + 30.260 = 56.449 u, and the nucleus mass subtracted from it **M1**

(b) mass defect = 56.449 - 55.9206 = 0.529 u shown (cso, answer given) **A1**

(b) Answer: mass defect = 0.529 u

(c) binding energy = 0.529 x 931.5 = 493 MeV (492.6 MeV from the unrounded 0.5288 u) (ft from b), then divided by 56 **M1**

(c) binding energy per nucleon = 8.80 MeV (awrt 8.8; accept 8.79 to 8.80), ecf **A1**

(c) Answer: 8.80 MeV per nucleon

(d) binding energy per nucleon is greatest (a maximum) around A = 56, i.e. nuclei near iron/nickel are the most stable, oe **B1**

(d) in fusion, light nuclei combine to form a heavier nucleus with a greater binding energy per nucleon than the original (separate) light nuclei, oe **B1**

(d) in fission, a heavy nucleus splits into two lighter nuclei of greater binding energy per nucleon than the original heavy nucleus, oe **B1**

(d) in both cases the products are more tightly bound (higher total binding energy) than the reactants, and this increase in total binding energy is released as energy, oe **B1**

(d) Answer: Nuclei near A = 56 are most stable (highest BE per nucleon). Fusion and fission both move nuclei towards this region, increasing the total binding energy, and the increase is released as energy.

Question 4

(a) one neutron from the two deuterium nuclei becomes bound inside the helium-3 nucleus (which contains 1 proton and 2 neutrons... i.e. only one of the two original neutrons is released as a free neutron, the other remaining bound in He-3), oe **B1**

(a) Answer: One of the two neutrons remains bound inside the helium-3 nucleus produced; only the other is released as a free neutron.

(b) total reactant mass = 2 x 2.01410 = 4.02820 u **M1**

(b) mass defect = 4.02820 - (3.01603 + 1.00867) = 0.00350 u **M1**

(b) E = 0.00350 x 931.5 = 3.26 MeV shown (cso, answer given) **A1**

(b) Answer: E = 3.26 MeV

(c) number of deuterium atoms in 1.00 g: N = $(1.00 \times 10^{-3}) / (2.01410 \times 1.66 \times 10^{-27}) = 2.99 \times 10^{23}$ (awrt) **M1**

(c) number of fusion reactions = N / 2 = 1.50×10^{23} (awrt, ecf), since each reaction consumes two deuterium nuclei **M1**

(c) energy per reaction converted to joules: $3.26 \times 1.60 \times 10^{-13} = 5.22 \times 10^{-13}$ J, and total E = (number of reactions) x (energy per reaction) **M1**

(c) total E = 7.80×10^{10} J (awrt 3 s.f., ecf) **A1**

(c) Answer: total E = 7.80×10^{10} J

(d) both nuclei are positively charged, so the electrostatic (Coulomb) repulsion between them must be overcome for them to approach closely enough for the strong nuclear force to bind them together, oe **B1**

(d) extremely high temperature gives the nuclei enough kinetic energy (high enough speeds) to overcome this repulsion (or to quantum tunnel through it), oe **B1**

(d) valid engineering challenge identified, e.g. no solid material can withstand direct contact with plasma at such temperatures, so the plasma must be confined without touching a surface (e.g. by strong magnetic fields), which is difficult to sustain stably, oe **B1**

(d) Answer: High temperature gives nuclei enough kinetic energy to overcome their mutual electrostatic repulsion and get close enough for the strong force to act. A key challenge is that no solid container can touch plasma this hot, so it must be confined (e.g. magnetically) without contact.

Question 5

(a) B x Q x v = m x v^2 / r rearranged to give B x Q = m x v / r **M1**

(a) p = m x v = B x Q x r (cso, answer given) **A1**

(a) Answer: p = BQr

(b) p = B x Q x r correctly substituted **M1**

(b) p = 4.35 x 10^{-20} kg m/s (awrt 3 s.f.) **A1**

(b) Answer: p = 4.35 x 10^{-20} kg m/s

(c) the two particles carry charge of opposite sign, since they experience the magnetic force in opposite senses (curving in opposite directions) for the same field and similar initial velocity, oe **B1**

(c) with the direction of B and the initial velocity known, the force direction expected for a positive charge (from F = qv x B) can be predicted, and compared with the observed curvature, oe **B1**

(c) a particle curving the way expected for a positive charge is positive; a particle curving the opposite way is negative, oe **B1**

(c) Answer: Opposite curvature indicates opposite-sign charges. Comparing the observed curvature with the direction predicted by F = qv x B for a positive charge (given B and the initial velocity) identifies the sign of each particle's charge.

(d) rearranging p = BQr gives r = p / (BQ), so for fixed B and Q, r is directly proportional to p, oe **B1**

(d) a higher-momentum particle is harder to deflect (needs a larger radius to provide the required centripetal force at that momentum), so its track curves more gently, oe **B1**

(d) Answer: Since r = p/(BQ), radius is directly proportional to momentum for fixed B and Q; higher-momentum particles are harder to deflect and so curve more gently (larger radius).

(e) the neutral particle's decay point appears as a 'vertex' where two or more charged tracks begin from an empty point, with no incoming charged track leading to it, oe **B1**

(e) applying conservation of momentum and energy to the visible charged decay products (working backwards from their measured momenta) allows the momentum, energy and identity of the original neutral particle to be reconstructed, oe **B1**

(e) Answer: The decay shows up as charged tracks appearing to originate from an empty point (no incoming track). Applying conservation of momentum and energy to these visible tracks allows the neutral parent particle's properties to be reconstructed.

Question 6

(a) proton number Z increases by 1 **B1**

(a) nucleon number A stays the same (unchanged) **B1**

(a) Answer: Z increases by 1; A is unchanged.

(b) **L3** A coherent, logically structured account that explains why a genuine two-body decay (nucleus -> nucleus + beta particle only) would give the beta particle a single, fixed kinetic energy, contrasts this with the observed continuous spectrum up to a maximum, and explains how introducing a third particle (the neutrino), sharing the released energy and momentum with the beta particle in varying proportions from decay to decay, resolves the discrepancy while conserving both energy and momentum in every individual decay. **5-6**

(b) **L2** Some relevant, largely correct physics is given, such as recognising that a two-body decay would predict a fixed beta particle energy and that the observed continuous spectrum was therefore unexpected, and/or that a third, unseen particle carrying away a variable share of energy and momentum was proposed, but the explanation is incomplete, lacks detail on momentum conservation, or is not fully coherent. **3-4**

(b) **L1** Basic, largely isolated relevant statements are made, such as noting that beta particles have a range of energies or that a neutrino is emitted, with little or no explanation of why this observation implies a third particle or which conservation principle is involved. **1-2**

(b) **L0** No creditable response, or the answer does not relate to the question. **0**

(b) Indicative content:

- If beta decay were a genuine two-body process (parent nucleus -> daughter nucleus + beta particle only), conservation of energy and momentum would require the beta particle to be emitted with one single, fixed kinetic energy for a given parent and daughter pair, as is observed for alpha decay.
- Experimentally, however, beta particles from a given source were observed to have a continuous range of kinetic energies, from zero up to a single maximum value, not one fixed energy.
- This appeared to violate conservation of energy (individual decays seemed to 'lose' varying amounts of energy) and, when momenta were considered, conservation of momentum too.
- Pauli proposed that a third, initially unseen particle, later named the neutrino, is also emitted in every beta decay.
- The total energy and momentum released in the decay is shared, in varying proportions from decay to decay, between the beta particle, the neutrino and the recoiling nucleus, so the beta particle's individual energy can vary continuously up to a maximum (when the neutrino carries away almost none of the energy), while total energy and momentum are always conserved in each individual decay.
- Because the neutrino has negligible mass, no charge, and interacts extremely weakly with matter, it was not directly detected in these early experiments, which explains why its existence had to be inferred indirectly from the shape of the beta energy spectrum rather than being observed directly.

Question 7

(a) the work done accelerating the electron equals the kinetic energy gained: e x V = (1/2) x m x v^2, oe **M1**

(a) correctly rearranged to v = $\sqrt{2 \text{ x e x V / m}}$ (cso, answer given) **A1**

(a) Answer: e x V = (1/2) x m x v^2, rearranged to give v = $\sqrt{2eV/m}$.

(b) r = mv/(eB) rearranged to give v = eBr/m **M1**

(b) correct substitution of v = eBr/m into eV = (1/2)mv^2 to eliminate v **M1**

(b) correctly rearranged to e/m = 2V / (B^2 x r^2) (cso, answer given) **A1**

(b) Answer: e/m = 2V / (B^2 r^2)

(c) r converted to metres (0.119 m) and correctly substituted into e/m = 2V/(B^2 r^2) **M1**

(c) B^2 r^2 correctly evaluated (2.27 x 10^{-9}, awrt) **M1**

(c) e/m = 1.77 x 10^{11} C/kg (awrt 3 s.f., allow 1.76 to 1.77 x 10^{11}) **A1**

(c) Answer: e/m = 1.77 x 10^{11} C/kg

(d) percentage difference = |experimental - accepted| / accepted x 100, correctly substituted (ft from c) **M1**

(d) 0.3% (awrt, allow 0.3 to 0.4%) **A1**

(d) Answer: approximately 0.3%

(e) use a lower B or higher V so that the path radius r is larger, making the (fixed) absolute uncertainty in reading r a smaller percentage of the measurement, oe **B1**

(e) use a method that reduces parallax/reading error, e.g. a mirror behind the scale, or measure the diameter across the ring at several points and average, oe **B1**

(e) Answer: Increase r (by lowering B or raising V) so the fixed reading uncertainty is a smaller percentage; use a mirror scale or average several diameter readings to reduce parallax error.

(f) a proton has a much larger mass than an electron, so for the same B and V, its radius of curvature r = mv/(eB) (or equivalently derived from e/m = 2V/(B^2r^2)) would be far larger, oe **B1**

(f) within a laboratory-sized fine beam tube, the resulting radius would be too large to measure accurately (the path would appear almost straight), so useful precision could not be achieved, oe **B1**

(f) Answer: A proton's much greater mass means, for the same V and B, its path radius would be far larger than an electron's - too large to curve appreciably or be measured accurately within a laboratory-sized tube.

Question 8

(a) since Sigma+ has strangeness -1 and only a strange quark carries strangeness -1, it must contain exactly one strange (s) quark **B1**

(a) the remaining two quarks must together contribute a charge of +1 - (-1/3) = +4/3 e **B1**

(a) this is only achieved by two up quarks (+2/3 + 2/3 = +4/3), giving a composition of uus **B1**

(a) Answer: Sigma+ = uus (two up quarks and one strange quark).

(b) charge of u-bar = -2/3 e (opposite of the up quark's +2/3 e), so total charge = -1/3 + (-2/3) = -1 e **B1**

(b) strangeness = -1, since the s quark contributes strangeness -1 and the u-bar (containing no strange quark) contributes 0 **B1**

(b) correct overall reasoning shown linking quark charges/strangeness to the totals (cso for both final values) **B1**

(b) Answer: Charge = -1 e; strangeness = -1.

(c) identical property: rest mass (or spin) **B1**

(c) opposite-sign property: charge (or baryon number, lepton number, or strangeness) **B1**

(c) Answer: Rest mass is identical for a particle and its antiparticle; charge (and quantum numbers such as baryon number, lepton number and strangeness) are equal in magnitude but opposite in sign.

(d) first valid similarity, e.g. all three carry charge -1 e **B1**

(d) second valid similarity, e.g. each is a fundamental (point-like) lepton, not made of quarks, and each has its own associated neutrino **B1**

(d) valid difference, e.g. they have very different (increasing) rest masses, electron less than muon less than tau, and only the electron is stable (the muon and tau are unstable and decay) **B1**

(d) Answer: Similarities: all carry charge -1e and are fundamental leptons (not made of quarks), each with its own neutrino. Difference: their rest masses differ greatly (electron < muon < tau), and only the electron is stable.

Question 9

(a) gluon **B1**

(a) the gluon itself carries colour charge (and so can interact with other gluons/self-interact), unlike the (electrically neutral, non-self-interacting) photon **B1**

(a) valid consequence given, e.g. this self-interaction contributes to quark confinement, or to the strong force's unusual short-range, strength-increasing-with-distance behaviour, oe **B1**

(a) Answer: The gluon; unlike the photon, gluons carry colour charge and can interact with each other, contributing to quark confinement.

(b) an up quark converts into a down quark at the first vertex **B1**

(b) a (virtual) W+ boson is emitted at this vertex, shown as the exchange particle **B1**

(b) the W+ boson decays at a second vertex into a positron and an electron neutrino, which leave the diagram **B1**

(b) correct overall structure described: two vertices joined by an internal W+ line, with an incoming up-quark line becoming an outgoing down-quark line, and outgoing positron and neutrino lines from the second vertex **B1**

(b) Answer: An up quark converts to a down quark, emitting a virtual W+ boson, which decays at a second vertex into a positron and an electron neutrino.

(c) correct order: strong, then electromagnetic, then weak (strongest to weakest) **B1**

(c) the weak interaction is intrinsically much less probable (a much weaker coupling) per unit time than the strong interaction, oe **B1**

(c) so a particle that can only decay via the weak interaction must wait, on average, far longer before this much less probable process happens, compared with a strong-interaction decay, which happens almost instantly, oe **B1**

(c) Answer: Strong > electromagnetic > weak. Weak-interaction decays are much less probable per unit time than strong-interaction decays, so they take far longer to occur on average.