AP2D Particles and Radiation: Depth and Exam Drill

AQA 7408 · Calculator allowed · about 180 minutes

Total Marks

Name: ________________________________ Date: ____ / ____ / ______

Answer ALL questions. Show all your working.

1 This question tests core definitions used when classifying particles and applying conservation laws.

(a) State the baryon number of a meson and the baryon number of a baryon. **(1)**

(b) State the lepton number assigned to an electron antineutrino, and the lepton number assigned to a positron. **(1)**

(c) In the nuclide notation ^A$_Z$ X, state what the symbols A and Z represent. **(1)**

(Total for Question 1 is 3 marks)

2 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+ -> π+ + pi0, where π+ 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 2 is 12 marks)

3 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 3 is 9 marks)

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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. Calculate the time, in hours after 09:00, at which the activity of the sample first falls below 15 MBq. **(3)**

(Total for Question 5 is 8 marks)

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6 Radium-226 decays by α emission to radon-222: Ra-226 -> Rn-222 + α. The atomic masses are: radium-226 = 226.0254 u, radon-222 = 222.0175 u, α particle = 4.0026 u. Take 1 u = 1.66×10^{-27} kg and c = 3.00×10^{8} m/s. 1 MeV = 1.60×10^{-13} J.

(a) State what is meant by the mass defect of a nuclear decay. **(1)**

(b) Calculate the mass defect of this decay, in kg. **(3)**

(c) Use $E = mc^2$ to calculate the total energy released in this decay, in MeV. **(3)**

(d) This energy is shared as kinetic energy between the α particle and the recoiling radon-222 nucleus, with no other particles emitted. Explain, using conservation of momentum, why the α particle gains most of this kinetic energy. **(2)**

(Total for Question 6 is 9 marks)

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7 A clean zinc surface has a work function of 6.90×10^{-19} J. Take h = 6.63×10^{-34} Js, c = 3.00×10^{8} m/s and e = 1.60×10^{-19} C.

(a) State what is meant by the work function of a metal surface. **(1)**

(b) Calculate the threshold frequency for photoemission from zinc, using E = hf. **(2)**

(c) Calculate the threshold wavelength corresponding to this frequency, and explain why visible light (wavelength range approximately 400-700 nm) cannot cause photoemission from zinc. **(2)**

(d) Ultraviolet light of wavelength 200 nm is now shone onto the zinc surface. Calculate the maximum kinetic energy of the emitted photoelectrons, in J. **(3)**

(e) Calculate the stopping potential needed to stop the fastest photoelectrons emitted in part (d) from reaching the collector. **(2)**

(Total for Question 7 is 10 marks)

8 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 = 1.60×10^{-13} J and c = 3.00×10^{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 8 is 8 marks)

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9 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 9 is 6 marks)

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10 This question concerns the exchange particles and ranges of the fundamental forces.

(a) State the name of the exchange (gauge boson) particle associated with the strong nuclear force between quarks. **(1)**

(b) According to theory, state the name of the (as yet unobserved) exchange particle predicted to be associated with the gravitational force. **(1)**

(c) Two protons inside a nucleus are separated by a distance of about 1×10^{-15} m (1 fm), while two protons in neighbouring atoms are typically separated by distances of order 1×10^{-10} m (0.1 nm) or more. Explain why the strong nuclear force must dominate over the electromagnetic repulsion between the two protons inside the nucleus, but has no significant effect on the structure of atoms at this larger atomic scale. **(3)**

(Total for Question 10 is 5 marks)

11 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 x 10^{-34} Js, c = 3.00 x 10^{8} m/s and 1 MeV = 1.60 x 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 x 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 11 is 11 marks)

Mark scheme · AP2D Particles and Radiation: Depth and Exam Drill

Question 1

- (a) **B1** meson baryon number = 0 and baryon baryon number = +1 (both required) oe
- **(a) Answer: Meson baryon number = 0; baryon baryon number = +1**
- (b) **B1** electron antineutrino lepton number = -1 and positron lepton number = -1 (both required) oe
- **(b) Answer: Electron antineutrino lepton number = -1; positron lepton number = -1**
- (c) **B1** A = nucleon (mass) number, total number of protons and neutrons; Z = proton (atomic) number, number of protons (both required) oe
- **(c) Answer: A = nucleon (mass) number; Z = proton (atomic) number**

Question 2

- (a) **M1** substitute antiquark charges: (-2/3 e) + (-2/3 e) + (+1/3 e)
- (a) **A1** cso: sum = -1e
- **(a) Answer: -1e**
- (b) **M1** substitute quark charges: (+2/3 e) + (-2/3 e)
- (b) **A1** cso: sum = 0
- **(b) Answer: 0**
- (c) **M1** calculate strangeness before (K+: s-bar gives +1) and after (π+: 0, pi0: 0, total 0)
- (c) **A1** 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
- **(c) Answer: Strangeness is not conserved (+1 to 0), but the decay is allowed via the weak interaction**
- (d) **M1** charge: LHS = +1 + 0 = +1, RHS = +1 + 1 - 1 = +1 (conserved); baryon number: LHS = 1 + 1 = 2, RHS = 1 + 1 + 0 = 2 (conserved)
- (d) **A1** both charge and baryon number are conserved (strangeness and lepton number are unaffected, remaining 0 throughout), so the reaction is allowed
- **(d) Answer: Allowed: charge and baryon number are both conserved**
- (e) **M1** calculate lepton number before (electron = +1, proton = 0, total +1) and after (neutron = 0, photon = 0, total 0)
- (e) **A1** 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
- **(e) Answer: Not allowed as written: lepton number is not conserved**
- (f) **M1** calculate baryon number before (proton = +1) and after (π+ = 0, pi0 = 0, total 0)
- (f) **A1** 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
- **(f) Answer: Not allowed: baryon number is not conserved**

Question 3

- (a) **M1** identify daughter nuclide with A = 237, Z = 93 (neptunium)
- (a) **A1** correct full equation: ^241_95 Am -> ^237_93 Np + ^4_2 He, cao
- **(a) Answer: ^241_95 Am -> ^237_93 Np + ^4_2 He**
- (b) **M1** identify daughter nuclide with A = 40, Z = 20 (calcium)
- (b) **A1** correct full equation: ^40_19 K -> ^40_20 Ca + ^0_-1 e + electron antineutrino, cao
- **(b) Answer: ^40_19 K -> ^40_20 Ca + ^0_-1 e + electron antineutrino**
- (c) **M1** identify daughter nuclide with A = 22, Z = 10 (neon)
- (c) **A1** correct full equation: ^22_11 Na -> ^22_10 Ne + ^0_1 e + electron neutrino, cao
- **(c) Answer: ^22_11 Na -> ^22_10 Ne + ^0_1 e + electron neutrino**
- (d) **M1** an up quark (u) within the proton (quark composition uud) changes into a down quark (d), so the proton (uud) becomes a neutron (udd)
- (d) **M1** this change occurs via the weak interaction, with the emission of a virtual W+ boson (the exchange particle for this process)
- (d) **A1** the virtual W+ boson then decays into a positron and an electron neutrino, the particles emitted from the nucleus
- **(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 4

- (a) **B1** 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
- **(a) Answer: Background radiation is also detected by the tube and must be removed so only counts from the sample are used**
- (b) **M1** substitute into count rate = total counts / time = 90 / 300
- (b) **A1** 0.30 counts/s, cao
- **(b) Answer: 0.30 counts/s**
- (c) **M1** calculate the ratio of count rates: 32.0 / 4.0 = 8
- (c) **M1** recognise that a factor of 8 is 2^3, so 3 half-lives have elapsed between the two measurements
- (c) **M1** half-life = (160 - 20) / 3
- (c) **A1** 46.7 s, cao (3 s.f.)
- **(c) Answer: 46.7 s**
- (d) **M1** combine percentage uncertainties for a ratio by addition: 4% + 4% = 8%
- (d) **A1** 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
- **(d) Answer: Approximately 8% uncertainty in the ratio, so the half-life is only known to within a few seconds**
- (e) **B1** 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)
- **(e) Answer: Keep the GM tube at a fixed distance from the sample for every reading (or other valid precaution)**

Question 5

- (a) **M1** convert half-life to seconds (6.01 x 3600 = 21636 s) and substitute into λ = ln2 / half-life
- (a) **A1** 3.20×10^{-5} s^{-1}, cao
- **(a) Answer: 3.20×10^{-5} s^{-1}**
- (b) **M1** identify t = 6 hours = 21600 s
- (b) **M1** substitute $A = 640 \times e^{-3.20 \times 10^{-5} \times 21600}$, ft from (a)
- (b) **A1** 320 MBq (accept 315-325 MBq), awrt
- **(b) Answer: 320 MBq**
- (c) **M1** rearrange $A = A0\ e^{-\lambda t}$ to give t = ln(A0/A) / λ
- (c) **M1** substitute t = ln(640/15) / (3.20×10^{-5}) in seconds, ft from (a)
- (c) **A1** 32.5 hours (accept 32-33 hours), awrt
- **(c) Answer: 32.5 hours**

Question 6

- (a) **B1** the difference between the total mass of the parent nucleus and the total mass of the decay products, which is converted into the energy released in the decay oe
- **(a) Answer: The difference between the mass of the parent nucleus and the total mass of the products**
- (b) **M1** mass defect in u = 226.0254 - 222.0175 - 4.0026 = 0.0053 u
- (b) **M1** convert to kg using 1 u = 1.66×10^{-27} kg
- (b) **A1** 8.80×10^{-30} kg, cao
- **(b) Answer: 8.80×10^{-30} kg**
- (c) **M1** substitute mass defect from (b) into $E = mc^2$, ft
- (c) **M1** compute E in J: $8.80 \times 10^{-30} \times (3.00 \times 10^8)^2 = 7.92 \times 10^{-13}$ J
- (c) **A1** convert to MeV using 1 MeV = 1.60×10^{-13} J to give 4.95 MeV (accept 4.9-5.0 MeV), ft
- **(c) Answer: 4.95 MeV**
- (d) **B1** the radium nucleus starts at rest, so total momentum after decay is zero; the α particle and the radon-222 nucleus must therefore recoil with equal and opposite momenta
- (d) **B1** since kinetic energy = $p^2 / (2m)$ for a given magnitude of momentum, the much lighter α particle has a correspondingly much greater kinetic energy than the far more massive radon-222 nucleus oe
- **(d) Answer: Equal and opposite momenta mean the lighter α particle carries far more kinetic energy than the heavy recoiling nucleus**

Question 7

- (a) **B1** the minimum energy needed to remove an electron from the surface of the metal, giving it zero kinetic energy just outside the surface oe
- **(a) Answer: The minimum energy needed to remove an electron from the metal surface**
- (b) **M1** correct substitution into $f0 = \varphi / h$
- (b) **A1** 1.04×10^{15} Hz, cao
- **(b) Answer: 1.04×10^{15} Hz**
- (c) **M1** lambda0 = c / f0, ft from (b), giving 2.88×10^{-7} m (288 nm)
- (c) **A1** this wavelength lies in the ultraviolet, shorter than the visible range, so visible photons have less energy than the threshold energy and cannot release photoelectrons however intense the light oe
- **(c) Answer: 2.88×10^{-7} m (288 nm), which is in the ultraviolet**
- (d) **M1** calculate $f = c / \lambda = 1.50 \times 10^{15}$ Hz
- (d) **M1** substitute into $Ek(max) = hf - \varphi$
- (d) **A1** 3.05×10^{-19} J (accept $3.0\text{-}3.1 \times 10^{-19}$ J), awrt
- **(d) Answer: 3.05×10^{-19} J**
- (e) **M1** substitute into $Vs = Ek(max) / e$, ft from (d)
- (e) **A1** 1.90 V (ft), cao
- **(e) Answer: 1.90 V**

Question 8

- (a) **B1** 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
- **(a) Answer: Zero total momentum before decay means the photons must have equal and opposite momenta, and hence equal energies**
- (b) **M1** recognise that, since the pion is at rest, the total energy released equals its rest mass energy, 135.0 MeV
- (b) **M1** this energy is shared equally between the two photons
- (b) **A1** 67.5 MeV each, cao
- **(b) Answer: 67.5 MeV**
- (c) **M1** convert 67.5 MeV to J: 67.5 x 1.60 x 10^{-13} = 1.08 x 10^{-11} J, ft from (b)
- (c) **M1** substitute into p = E / c
- (c) **A1** 3.60 x 10^{-20} kg m/s, cao
- **(c) Answer: 3.60 x 10^{-20} kg m/s**
- (d) **B1** 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
- **(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 9

- **Level 3** (5-6): 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.
- **Level 2** (3-4): 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.
- **Level 1** (1-2): Basic comments: states that scattering experiments suggest nucleons have internal structure or contain quarks, with little development, explanation or discussion of limitations.
- **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.

Question 10

- (a) **B1** gluon
- **(a) Answer: Gluon**
- (b) **B1** graviton
- **(b) Answer: Graviton**
- (c) **M1** at nuclear separations (about 1 fm) the strong nuclear force between the protons is attractive and stronger than their electromagnetic (Coulomb) repulsion, which is why the nucleus stays bound rather than flying apart
- (c) **M1** the strong nuclear force has a very short range (of the order of a few fm) and falls to a negligible size beyond this range
- (c) **A1** at atomic separations (about 0.1 nm, roughly 100000 times larger than a fm) the strong force has fallen to essentially zero, so only the long-range electromagnetic force acts, meaning atomic structure is governed by the electromagnetic force, not the strong force
- **(c) Answer: The strong force is short-range and dominates only at nuclear separations; at atomic separations it is negligible and only the electromagnetic force acts**

Question 11

- (a) **M1** convert 0.662 MeV to J: 0.662 x 1.60 x 10^{-13} = 1.06 x 10^{-13} J
- (a) **A1** f = E/h = 1.60 x 10^{20} Hz, cao
- **(a) Answer: 1.60 x 10^{20} Hz**
- (b) **M1** substitute into λ = c / f, ft from (a)
- (b) **A1** 1.88 x 10^{-12} m, cao/ft
- **(b) Answer: 1.88 x 10^{-12} m**
- (c) **B1** 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
- (c) **B1** 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
- **(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) **M1** calculate λ = ln2 / 30.1 = 0.0230 per year
- (d) **M1** substitute into N = N0 $e^{-\lambda t}$ with t = 10.0 years, ft
- (d) **A1** 2.94 x 10^{8} nuclei, cao (3 s.f.)
- **(d) Answer: 2.94 x 10^{8} nuclei**
- (e) **B1** 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
- (e) **B1** 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
- **(e) Answer: The antineutrino carries away the variable remaining energy and momentum, which explains the continuous β energy spectrum and conserves lepton number**