

Particle interactions and conservation laws solutions

Matching worked solutions and teaching prompts | 38 marks

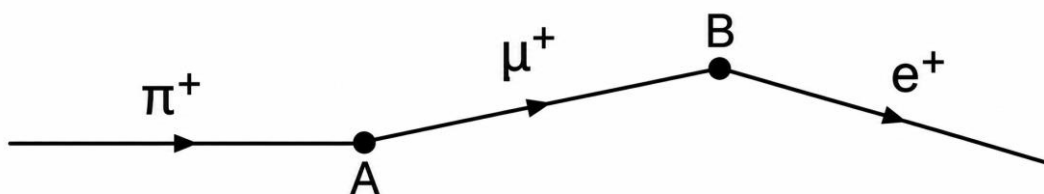
AQA AS Physics 7407 • First-year A Level 7408

Specification points covered

AQA AS 7407 / first-year A Level 7408: 3.2.1.4 — interactions and exchange particles; 3.2.1.5 — classification, lepton families and strangeness; 3.2.1.6 — quarks and antiquarks; 3.2.1.7 — conservation laws.
Supporting content: 3.2.1.3 — annihilation, rest energy and $E = hf = hc/\lambda$; 3.2.2.2 — electronvolt conversion.
No $E = mc^2$ or relativistic-momentum calculation is required.

Commission a particle detector

A research team is commissioning particle-detector software. It must reconstruct events from charged tracks and account for particles that leave no recorded track. The team checks decay sequences, nuclear calibration sources and proton-collision records before accepting the software's particle identifications.



charged tracks only — schematic

Use $h = 6.63 \times 10^{-34} \text{ J s}$, $c = 3.00 \times 10^8 \text{ m s}^{-1}$ and $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. Quark charges: $u = +\frac{2}{3}e$; d and $s = -\frac{1}{3}e$. Antiquarks have opposite charge, baryon number and strangeness to their quarks. Use the supplied rounded rest energies throughout. Show equations and calculations in blank spaces; explanations on ruled lines.

For event checks, use baryon number B , strangeness S , electron-lepton number L_e and muon-lepton number L_μ . Quarks have $B = +\frac{1}{3}$, antiquarks $B = -\frac{1}{3}$; s has $S = -1$ and other quarks have $S = 0$. A lepton has $+1$ in its own lepton family; its antilepton has -1 . Other family numbers are zero. Electric charge is quoted in units of e .

1. Prepare the event checks [2 marks]

(a) State the property that distinguishes hadrons from leptons. [1 mark]

Hadrons are subject to the strong interaction; leptons are not. [1] Being charged, massive or unstable does not by itself make a particle a hadron.

(b) A positive kaon K^+ has quark structure $u\bar{s}$. Calculate its charge in units of e from the quark charges. [1 mark]

$Q/e = +\frac{2}{3} + \frac{1}{3} = +1$. [1] The antistrange quark has charge $+\frac{1}{3}e$, opposite to the strange quark.

Teaching prompt: The overbar means antiparticle. It changes the signs of the relevant quantum numbers, not the rest mass.

Continue your physics journey

Videos, practice and support for your next step

www.physicsuk.co.uk



2. Reconstruct particles with no recorded tracks [10 marks]

The opening diagram shows only the charged tracks. At A, π^+ decays to μ^+ and one undetected neutral particle X. At B, μ^+ decays to e^+ and two undetected neutral particles Y and Z. The labels identify the charged particles; no information about momentum magnitude is encoded by the line lengths.

(a) Identify X by name or symbol. Show the muon-lepton numbers before and after the decay at A to justify your answer. [2 marks]

X is a muon neutrino, ν_μ . [1] For $\pi^+ \rightarrow \mu^+ + \nu_\mu$, L_μ is $0 \rightarrow -1 + 1 = 0$. [1] The positive muon is an antilepton. An electron neutrino would not balance the muon-lepton number.

(b) Identify Y and Z by name or symbol. Demonstrate conservation of both electron-lepton number and muon-lepton number in the decay at B. [3 marks]

The two particles are an electron neutrino ν_e and a muon antineutrino $\bar{\nu}_\mu$, in either order. [1] $\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$. Electron family: L_e is $0 \rightarrow -1 + 1 + 0 = 0$. [1] Muon family: L_μ is $-1 \rightarrow 0 + 0 - 1 = -1$. [1] Both families must be conserved separately.

(c) In a separate check, a positron is repelled by a nearby positive ion. Identify the interaction and its exchange particle. Explain why the strong interaction cannot cause this force on the positron. [3 marks]

The interaction is electromagnetic. [1] Its exchange particle is a virtual photon. [1] The positron is an antilepton and is not subject to the strong interaction. [1] The repulsion is between charges of the same sign; being charged does not make the positron a hadron.

(d) The software finds that the recorded charged particles alone do not account for all the initial total energy or momentum. Explain why this does not necessarily show a failure of either conservation law. [2 marks]

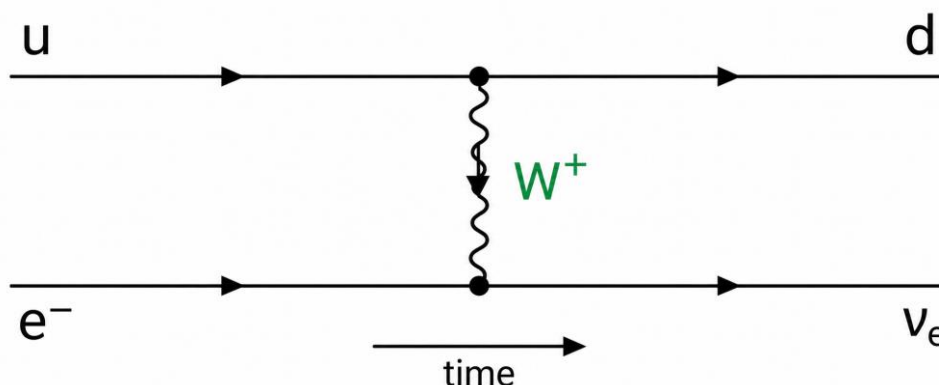
The undetected neutrinos/antineutrinos carry energy, so the energy total must include them as well as the charged particles. [1] They also carry momentum, so only the vector sum for all products must equal the initial momentum. [1] Energy here means total energy, including rest energy, not kinetic energy alone.

Teaching prompt: Positive electrons and positive muons have lepton number -1 in their own family. A neutral particle is not automatically a neutrino, and electron and muon families are not interchangeable.



3. Check an electron-capture diagram [8 marks]

A nuclear calibration source undergoes electron capture. The diagram shows one quark in a bound nucleon and the captured electron. Time increases to the right. The arrow on the wavy line shows the direction in which the exchange particle X transfers charge.



(a) Identify X, including its charge sign. Use charge conservation at the upper vertex to justify your answer. [2 marks]

X is a W^+ boson. [1] At the upper vertex the u quark changes from charge $+\frac{2}{3}e$ to the d quark's $-\frac{1}{3}e$, so $+1e$ is transferred downward: $+\frac{2}{3} = -\frac{1}{3} + 1$. [1] A W^- drawn in the shown downward transfer direction is incorrect; a reversed W^- exchange would be an alternative representation, not this diagram.

(b) Identify the nucleon change and give its initial and final quark structures. [2 marks]

A proton changes into a neutron. [1] $uud \rightarrow udd$: one u changes to d and the other two quarks are unchanged. [1] This is not a whole proton turning into an electron.

(c) Write the complete nucleon-level electron-capture equation, including the emitted lepton. [1 mark]

$p + e^- \rightarrow n + \nu_e$. [1] Charge: $+1 - 1 = 0 + 0$; B: $1 = 1$; L_e : $+1 = +1$. The emitted particle is an electron neutrino, not an antineutrino.

(d) A second calibration source undergoes beta-minus decay. Write the complete quark-level beta-minus equation, including the emitted leptons, and identify the weak exchange boson. [3 marks]

$d \rightarrow u + e^- + \bar{\nu}_e$. The $d \rightarrow u$ change earns [1]; the electron and electron antineutrino together earn [1]. The exchange boson is W^- : $d \rightarrow u + W^-$, followed by $W^- \rightarrow e^- + \bar{\nu}_e$. [1] Charge at the quark vertex is $-\frac{1}{3} = +\frac{2}{3} - 1$.

Teaching prompt: An exchange-particle sign must match its stated transfer direction. In beta-minus decay d becomes u; in electron capture and beta-plus decay u becomes d.



4. Check strange-particle production [7 marks]

In a separate detector test, equal and opposite proton beams collide. One proposed strong-interaction event is $p + p \rightarrow p + p + K^+ + X$. K^+ has structure $u\bar{s}$. The proton has $B = +1$ and $S = 0$. Assume no other products are present.

(a) Determine the charge Q/e , baryon number B and strangeness S of X . Show your conservation checks. [2 marks]

Required values: $Q/e = -1$, $B = 0$, $S = -1$. Before: $Q/e = 2$, $B = 2$, $S = 0$. Known products $p + p + K^+$ give $Q/e = 3$, $B = 2$, $S = +1$, so X supplies $(-1, 0, -1)$. Award [1] for two correct values supported by totals and [2] for all three with correct totals.

(b) Deduce the quark structure of X and identify the particle. Explain how the strangeness and baryon number constrain the structure. [2 marks]

Nonzero strangeness requires a strange quark or antiquark, so X is a hadron; $B = 0$ makes it a meson, and $S = -1$ requires an s quark. [1] The remaining charge must be $-\frac{2}{3}e$, supplied by an anti- u quark: $X = s\bar{u}$, a negative kaon K^- . [1] Equivalently verify $Q/e = -\frac{1}{3} - \frac{2}{3} = -1$ and $B = \frac{1}{3} - \frac{1}{3} = 0$. $B = 0$ alone would not distinguish a meson from a lepton.

(c) X later decays to $\pi^- + \pi^0$. Each pion has $S = 0$. Explain why this decay is weak rather than strong. [2 marks]

Strangeness changes from -1 to 0 , so $\Delta S = +1$. [1] Strangeness is conserved in strong interactions but this change is allowed in a weak interaction. [1] Baryon number and charge still remain conserved; “weak” does not mean that every conservation law may fail.

(d) The software suggests that X could instead be an antiproton, because its charge would fit. Use baryon number to reject this identification. [1 mark]

An antiproton has $B = -1$, giving final $B = 1 + 1 + 0 - 1 = 1$ rather than the initial 2 . [1] Charge matching alone is insufficient.

Teaching prompt: The s quark has negative strangeness; the anti- s quark has positive strangeness. Strong production creates compensating strangeness. Weak decay can change strangeness while conserving charge and baryon/lepton numbers.



5. Audit the collision energy budget [5 marks]

Use the $p + p \rightarrow p + p + K^+ + K^-$ event. Each proton has rest energy 938 MeV; each charged kaon has rest energy 494 MeV. The initial proton momenta are equal and opposite, so the total initial momentum is zero. Assume there are no additional products.

(a) The two incident protons have combined kinetic energy 1.20 GeV. Calculate the combined kinetic energy of all four products in MeV. [2 marks]

Initial total energy = $2 \times 938 + 1200 = 3076$ MeV; final rest energy = $2 \times 938 + 2 \times 494 = 2864$ MeV.
 [1] Product kinetic energy = $3076 - 2864 = 212$ MeV. [1] Equivalently $1200 - 2 \times 494 = 212$ MeV because the proton rest-energy terms cancel.

(b) Convert your product kinetic energy from (a) to joules. [1 mark]

$212 \text{ MeV} = 212 \times 10^6 \times 1.60 \times 10^{-19} = 3.39 \times 10^{-11} \text{ J}$. [1] Accept a consistent conversion of the candidate's answer from (a).

(c) The combined incident kinetic energy is reduced to 0.900 GeV, with the beams still equal and opposite. Is the same event energetically possible? Calculate any energy excess or shortfall. [2 marks]

Creating the kaon pair requires $2 \times 494 = 988$ MeV of additional rest energy, but only 900 MeV of incident kinetic energy is available. [1] The shortfall is $988 - 900 = 88$ MeV, so the event is not energetically possible. [1] The final kinetic energy cannot be negative. This is an opposing-beam energy check, not a fixed-target threshold calculation.

Teaching prompt: Total energy is conserved; rest energy and kinetic energy need not be conserved separately. The product momenta must also sum to zero; energy and quantum-number checks are necessary conditions, not a guarantee of an event rate.



6. Check positrons and annihilation photons [6 marks]

A bound proton in another nuclear calibration source undergoes beta-plus decay; the full nucleus supplies the necessary energy. The emitted positron slows down and annihilates with an electron that is also approximately at rest. The rest energy of each lepton is 0.511 MeV.

(a) Write the complete quark-level beta-plus equation, including the two emitted leptons. [2 marks]

$u \rightarrow d + e^+ + \nu_e$. Award [1] for $u \rightarrow d$ and [1] for the positron plus electron neutrino. Charge: $+\frac{2}{3} = -\frac{1}{3} + 1 + 0$; $L_e: 0 = 0 - 1 + 1$. This describes a bound proton in an energetically allowed nuclear decay, not spontaneous decay of a free proton.

(b) The annihilation produces two photons. Explain why, in the stated approximation, they have equal energies and travel in opposite directions. [2 marks]

The initial electron–positron system has approximately zero total momentum. [1] The two photon momenta must therefore be equal in magnitude and opposite in direction; equal photon momentum magnitudes mean equal photon energies. [1] A single photon could not conserve the zero total momentum. Also, total photon energy is 2×0.511 MeV.

(c) Calculate the wavelength of either annihilation photon in pm. [2 marks]

Each photon has energy $0.511 \text{ MeV} = 0.511 \times 10^6 \times 1.60 \times 10^{-19} = 8.176 \times 10^{-14} \text{ J}$. [1] $\lambda = hc/E = (6.63 \times 10^{-34} \times 3.00 \times 10^8)/(8.176 \times 10^{-14}) = 2.43 \times 10^{-12} \text{ m} = 2.43 \text{ pm}$. [1] Do not give each photon the full 1.022 MeV pair energy.

Teaching prompt: A positron is an electron antiparticle, not a proton. The electron neutrino in beta-plus decay balances the positron's electron-lepton number; beta-minus decay instead emits an electron antineutrino.

