

AQA AS Antiparticles, Annihilation and Fundamental Interactions solutions

Matching solutions and teaching prompts for the class review

Specification points covered

- 3.2.1.3(a-c) Relate particles to antiparticles by mass, charge and rest energy, and identify common antiparticles.
- 3.2.1.3(d-e) Use the photon model and $E = hf = hc/\lambda$.
- 3.2.1.3(f) Describe annihilation and pair production and calculate the energies involved from supplied data.
- 3.2.1.4(a-c) Name the four fundamental interactions and describe exchange particles, including virtual photons.
- 3.2.1.4(d-f) Describe weak processes, identify W^+ and W^- bosons, and draw or interpret simple particle-interaction diagrams.

Teaching focus

Require complete working, correct SI units and precision justified by the data.
Use the common-error prompt to make pupils correct the method or language, not only the final number.

1. Antiparticles and rest energy

1. State what is meant by an antiparticle. Give two properties in your answer. [2 marks]

Answer / mark points: An antiparticle has the same rest mass or rest energy as its corresponding particle but opposite charge and opposite relevant quantum numbers, such as baryon or lepton number.

Teacher prompt / common error: Same mass alone is insufficient; a sign-reversed property or quantum number is also needed.

2. Name the antiparticle of the electron, proton, neutron and electron neutrino. For each pair, state one property that changes sign. [4 marks]

Answer / mark points: Electron $\rightarrow$ positron: charge and lepton number change sign. Proton $\rightarrow$ antiproton: charge and baryon number change sign. Neutron $\rightarrow$ antineutron: baryon number changes sign although both are neutral. Electron neutrino $\rightarrow$ electron antineutrino: electron-lepton number changes sign.

Teacher prompt / common error: Neutral does not mean identical: neutron and antineutron have opposite baryon number.

3. The rest energy of an electron or positron is 0.511 MeV. Calculate the minimum photon energy needed to create an electron-positron pair, first in MeV and then in joules. [3 marks]

Answer / mark points: Minimum energy = $2 \times 0.511 = 1.022$ MeV. In joules, $E = 1.022 \times 10^6 \times 1.60 \times 10^{-19} = 1.64 \times 10^{-13}$ J.

Teacher prompt / common error: Pair production requires the rest energy of both particles, not one electron rest energy.

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2. Annihilation, photons and pair production

4. An electron and positron annihilate from rest. Explain why two gamma photons are produced in opposite directions and state the energy of each photon. [3 marks]

Answer / mark points: The initial total momentum is zero. Two photons travel in opposite directions with equal momenta so momentum remains zero. The rest energy is shared equally, so each photon has energy 0.511 MeV; total energy and charge are conserved.

Teacher prompt / common error: Opposite directions follow from momentum conservation, not from an electrostatic repulsion between photons.

5. Calculate the frequency and wavelength of a 0.511 MeV photon. Use $h = 6.63 \times 10^{-34} \text{ J s}$, $c = 3.00 \times 10^8 \text{ m s}^{-1}$ and $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. [3 marks]

Answer / mark points: $E = 0.511 \times 10^6 \times 1.60 \times 10^{-19} = 8.18 \times 10^{-14} \text{ J}$. $f = E/h = 8.18 \times 10^{-14} / 6.63 \times 10^{-34} = 1.23 \times 10^{20} \text{ Hz}$. $\lambda = c/f = 2.43 \times 10^{-12} \text{ m}$.

Teacher prompt / common error: Convert MeV to joules before using $E = hf$. The wavelength should be in the picometre range.

6. A gamma photon of energy 1.40 MeV produces an electron-positron pair. Calculate the total kinetic energy after creation and the kinetic energy of each particle if it is shared equally. [2 marks]

Answer / mark points: Total kinetic energy = $1.40 - 1.022 = 0.378 \text{ MeV}$. If shared equally, each receives 0.189 MeV.

Teacher prompt / common error: Subtract the total rest energy 1.022 MeV before sharing the excess.

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3. Fundamental interactions

7. Four observations are made: a test mass falls; two electrons repel; neighbouring nucleons bind; a neutron undergoes beta-minus decay. Identify the fundamental interaction responsible for each observation. [2 marks]

Answer / mark points: Falling test mass: gravitational. Electron repulsion: electromagnetic. Binding neighbouring nucleons: strong nuclear. Beta-minus decay: weak nuclear. Award one mark for two correct and two marks for all four.

Teacher prompt / common error: Use interaction rather than force where possible; 'nuclear' alone does not distinguish strong from weak.

8. State the exchange particle associated with: (a) the electromagnetic interaction; (b) the strong nuclear interaction between nucleons; (c) the weak interaction. [3 marks]

Answer / mark points: (a) Virtual photon. (b) Pion between nucleons. (c) W^+ or W^- boson, with the sign determined by the charge transfer.

Teacher prompt / common error: For the strong interaction between nucleons AQA expects the pion; gluon knowledge is not required here.

9. Explain why a single photon cannot produce an electron-positron pair in empty space, and state the role of a nearby nucleus. [2 marks]

Answer / mark points: A single photon cannot conserve both energy and momentum when it creates the pair in empty space. A nearby nucleus recoils and carries momentum, allowing both conservation laws to be satisfied.

Teacher prompt / common error: The nucleus is needed as a momentum sink; saying it supplies the pair energy is incorrect.

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4. Weak-interaction diagrams

10. Draw a simple particle-interaction diagram for beta-minus decay at quark level. Show the incoming and outgoing quarks, the W boson, the electron and the electron antineutrino. [4 marks]

Answer / mark points: The diagram should show $d \rightarrow u + W^-$ at one vertex, followed by $W^- \rightarrow e^- + \text{electron antineutrino}$ at the second vertex. Lines must meet at vertices and the incoming/outgoing directions must be clear. Award for the quark change, W^- label, lepton products and coherent diagram structure.

Teacher prompt / common error: Check charge at each vertex: $d = u + W^-$ and $W^- = e^- + \text{electron antineutrino}$.

11. In electron capture, an electron and a proton produce a neutron and an electron neutrino. Describe the quark change and explain how a charged W boson transfers charge between the two vertices. [4 marks]

Answer / mark points: At quark level, an up quark in the proton changes to a down quark, so uud becomes dud and the proton becomes a neutron. The electron becomes an electron neutrino. A charged W boson transfers one unit of negative charge from the electron vertex to the quark vertex. A W^- drawn from electron to quark, or the equivalent reversed W^+ convention, is acceptable if charge is conserved at both vertices.

Teacher prompt / common error: The W sign depends on the chosen direction of the exchange line; the charge balance at both vertices decides whether the diagram is valid.

12. A detector records $e^- + p \rightarrow \nu_e + n$. Show that charge, baryon number and electron-lepton number are conserved, and identify the fundamental interaction. [4 marks]

Answer / mark points: Initial charge = $-1 + 1 = 0$; final charge = $0 + 0 = 0$. Initial and final baryon numbers are both 1 because p and n are baryons. Initial electron-lepton number is 1 from the electron; final electron-lepton number is 1 from ν_e . The process is a weak interaction mediated by a charged W boson.

Teacher prompt / common error: Write the conserved totals on both sides rather than saying only that they are conserved.

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5. Unfamiliar application

13. In a PET scanner, an electron and positron annihilate inside a head of diameter 0.240 m. Explain why detectors on opposite sides are triggered. Calculate the greatest possible difference in arrival times at two opposite detectors, assuming the annihilation lies on their diameter and gamma photons travel at $3.00 \times 10^8 \text{ m s}^{-1}$. [4 marks]

Answer / mark points: For annihilation from rest, the two photons have equal and opposite momenta, so they travel in opposite directions and trigger an opposite detector pair. The largest path difference occurs at one edge of the 0.240 m diameter: $\Delta t_{\text{max}} = 0.240 / (3.00 \times 10^8) = 8.00 \times 10^{-10} \text{ s} = 0.800 \text{ ns}$.

Teacher prompt / common error: The maximum timing difference comes from the path difference across the head, not twice the diameter.

Language and method check

Award marks for independent, creditworthy physics steps rather than the amount of working shown.

Where an equivalent method is valid, accept it only when the reasoning, units and final precision remain consistent.

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