Fundamental particles solutions

Quarks, beta decay and accelerator event records

Matching answers and examiner-style commentary

OCR A H556 | A-level physics | Module 6 | 35 marks

Specification points covered

6.4.2(a–g) Particles and antiparticles, hadrons and leptons, and the u d s quark model.

6.4.2(h–l) Beta-minus/beta-plus decay and charge conservation in quark transformations.

No Feynman diagrams, exchange-boson identification or strangeness-number calculations are required.

Use quark charges u = +⅔e, d = −⅓e, s = −⅓e. Each antiquark has the opposite electric charge to its corresponding quark. Neutrinos and antineutrinos are electrically neutral.

1 Prepare the identity checks

An accelerator team must accept or reject particle identity cards and reconstruct beta-decay events before approving its calibration software. Use the supplied event information, charge and particle composition to justify decisions.

Other than the proton and neutron, any unfamiliar hadron composition needed is supplied. Do not assume that particles with the same electric charge must be the same particle.

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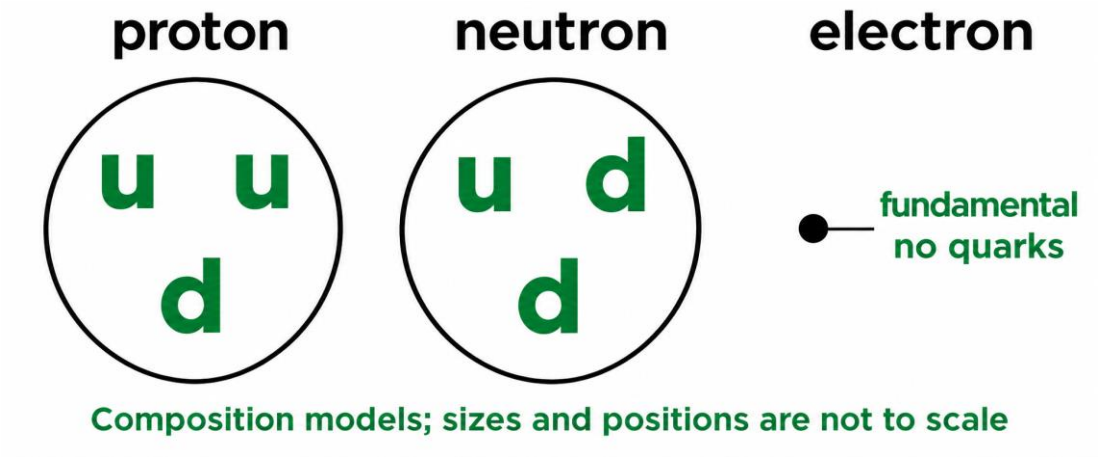


Figure 1 Quark compositions; schematic positions only

1(a) In blank space, draw a simple quark-content model for a proton and for a neutron. Label each quark. These are composition models, not drawings of fixed quark positions. **[2 marks]**

A proton contains two up quarks and one down quark: uud. A neutron contains one up quark and two down quarks: udd.

The teacher figure shows these compositions; the positions of its labels are schematic, not measured quark locations.

Marking guidance Correct proton uud; correct neutron udd.

1(b) State one physical distinction between hadrons and leptons that the software should use, rather than comparing their masses. **[1 mark]**

Hadrons experience the strong nuclear interaction; leptons do not. Both classes can experience the weak interaction.

Alternatively, hadrons are composite particles made of quarks, whereas leptons are fundamental and are not made of quarks. A complete distinction describes both sides.

Marking guidance Correct hadron statement; matching correct lepton contrast.

2 Check antiparticle and interaction records

2(a) The software stores an electron's rest mass as m_e and charge as $-e$, and a proton's rest mass as m_p and charge as $+e$. Give the rest mass and charge of the corresponding positron and antiproton. **[2 marks]**

The positron has the same rest mass m_e as the electron and opposite charge $+e$.

The antiproton has the same rest mass m_p as the proton and opposite charge $-e$.

Marking guidance 1: correct positron pair of properties. 1: correct antiproton pair.

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2(b) An antineutron and a neutron have equal rest masses and are both electrically neutral. Can those two properties alone distinguish them? Explain. **[1 mark]**

No. These two stored properties are identical for the corresponding neutral particle and antiparticle. Neutrality does not mean they are the same particle.

Marking guidance No, with the stated indistinguishable-property explanation.

2(c) A database labels a particle as an electron, but says that it experiences the strong nuclear force. Identify the error and state which nuclear interaction an electron can experience. **[2 marks]**

The electron is a lepton and does not experience the strong nuclear interaction. It can experience the weak nuclear interaction.

Its electric charge also allows electromagnetic interactions, but that does not make it a hadron.

Marking guidance Electron does not experience strong force; weak nuclear interaction identified.

2(d) A programmer suggests classifying particles as hadrons whenever their mass is greater than an electron's mass. Explain why this is not an appropriate defining rule. **[1 mark]**

Mass is not the defining distinction. Use quark composition or whether the particle experiences the strong interaction; a heavier fundamental lepton would still be a lepton.

Marking guidance Composition/strong-interaction criterion replaces a mass threshold.

3 Audit quark-content cards

3(a) Card A gives a hadron with composition uds. Card B gives u and anti-s. Calculate the charge of each in units of e. **[2 marks]**

Card A: $Q/e = +\frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$.

Card B: anti-s has charge $+\frac{1}{3}e$, so $Q/e = +\frac{2}{3} + \frac{1}{3} = +1$.

Marking guidance Card A neutral; Card B +1.

3(b) Card C has composition uus and charge +e. The software identifies it as a proton because its charge matches. Evaluate this identification. **[2 marks]**

Its charge is indeed $+\frac{2}{3} + \frac{2}{3} - \frac{1}{3} = +1$ in units of e.

However, the proton's composition is uud, not uus. Charge alone does not establish the proton identity; reject the card's identification. The unfamiliar hadron need not be named.

Marking guidance Correct charge check; composition mismatch and rejection.

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3(c) A neutral neon-22 calibration atom has Z = 10. Determine the total numbers of up quarks, down quarks and electrons in its simple constituent model. **[2 marks]**

Step 1 Count the nucleons

There are 10 protons and 22 − 10 = 12 neutrons.

Step 2 Count the quarks in those nucleons

Up quarks = 2(10) + 12 = 32. Down quarks = 10 + 2(12) = 34. Neutrality gives 10 electrons.

Marking guidance Correct up/down totals 32 and 34; correct 10 electrons with constituent reasoning.

3(d) Use those quark charges to check the nucleus's total charge. Then include the electrons to check the atom's net charge. **[2 marks]**

Nuclear charge/e = 32(⅔) + 34(−⅓) = (64 − 34)/3 = +10.

The 10 electrons contribute −10e, giving zero total charge for the neutral atom. Quark fractions combine to the correct integer nuclear charge.

Marking guidance Nuclear charge +10e; neutral total after electrons.

4 Reconstruct beta-minus events

4(a) Potassium-40 has proton number 19 and undergoes beta-minus decay to calcium. Write its complete nuclear equation, including the emitted lepton pair. **[2 marks]**

$^{40}_{19}\mathrm{K} \rightarrow {}^{40}_{20}\mathrm{Ca} + {}^{0}_{-1}\mathrm{e} + \bar{\nu}_e$

The emitted particles are an electron and an electron antineutrino. Nucleon number stays 40; nuclear proton number increases from 19 to 20.

Marking guidance Correct daughter A and Z; electron plus electron antineutrino included.

4(b) Write the quark-level beta-minus transformation and verify electric charge conservation in units of e. **[2 marks]**

$\mathrm{d} \rightarrow \mathrm{u} + \mathrm{e}^- + \bar{\nu}_e$.

Initial charge is −⅓. Final charge is +⅔ − 1 + 0 = −⅓, so charge is conserved.

Marking guidance Correct d-to-u transformation and emitted leptons; correct charge check.

4(c) Explain why the nucleus's proton number increases but its nucleon number stays the same. **[2 marks]**

One neutron (udd) becomes a proton (uud) when one d quark becomes a u quark.

A nucleon has changed type rather than being added to or removed from the nucleus: Z increases by one while A is unchanged.

Marking guidance Neutron-to-proton change; unchanged nucleon count with increased Z.

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4(d) Name both emitted leptons in beta-minus decay. Distinguish the neutral one from the neutral lepton emitted in beta-plus decay. **[1 mark]**

Beta-minus emits an electron and an electron antineutrino. Beta-plus emits an electron neutrino instead of the antineutrino.

Marking guidance Both beta-minus leptons correctly named with neutrino/antineutrino distinction.

5 Reconstruct beta-plus events

5(a) A suitable nitrogen-13 nucleus has Z = 7 and undergoes beta-plus decay to carbon. Write the complete nuclear equation, including the emitted lepton pair. **[2 marks]**

$^{13}_{7}\mathrm{N} \rightarrow {}^{13}_{6}\mathrm{C} + {}^{0}_{+1}\mathrm{e} + \nu_e$

The emitted particles are a positron and an electron neutrino. The whole nuclear system supplies the energy; this is not spontaneous decay of an isolated free proton.

Marking guidance Correct daughter A and Z; positron plus electron neutrino included.

5(b) Write the quark-level beta-plus transformation and verify electric charge conservation. **[2 marks]**

$u \rightarrow d + e^{+} + \nu_e$.

Initial charge/e = +⅔. Final charge/e = −⅓ + 1 + 0 = +⅔.

Marking guidance Correct u-to-d transformation and leptons; correct charge check.

5(c) A record says that the emitted positron was an electron already orbiting the nitrogen nucleus. Explain the error. **[1 mark]**

The positron is produced in the nuclear beta-plus transformation. It is not an orbital electron: an electron has negative charge, whereas the emitted positron has positive charge.

Marking guidance Nuclear production/opposite charge clearly distinguishes positron from an existing orbital electron.

5(d) State the changes in proton and neutron numbers during this beta-plus event and explain why A is unchanged. **[1 mark]**

Proton number decreases by one and neutron number increases by one. A bound proton changes into a neutron, so the total number of nucleons stays the same.

Marking guidance Both changes with the unchanged total nucleon count.

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6 Judge unfamiliar event records

6(a) A supplied model event has $s \rightarrow u + e^- + \bar{\nu}_e$ inside a suitable hadron. Check charge conservation and explain why the presence of a strange quark does not invalidate that check. **[2 marks]**

Initial charge/e = $-\frac{1}{3}$. Final charge/e = $+\frac{2}{3} - 1 + 0 = -\frac{1}{3}$.

The strange quark has the supplied charge $-\frac{1}{3}e$. The unfamiliar identity does not change the charge-conservation calculation. No strangeness-number rule is required.

Marking guidance Correct initial/final charges; relevant use of supplied s charge.

6(b) Record L describes a fundamental particle that experiences the weak interaction but not the strong interaction. Record H describes a quark-composite particle that experiences both. Classify each. **[1 mark]**

L is a lepton. H is a hadron. The stated composition and interaction properties support those classifications.

Marking guidance L lepton and H hadron.

6(c) Correct both claims: “A neutrino cannot carry energy because it has zero charge” and “A neutron is fundamental because it has zero charge.” **[2 marks]**

Electrical neutrality does not prevent a particle from carrying energy. Neutral leptons carry energy in beta-decay events.

The neutron is composite, with quark content udd. Its zero net electric charge is the sum of non-zero quark charges, not evidence that it has no constituents.

Marking guidance Neutrality does not imply zero energy; neutron composite udd despite zero net charge.

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