

4.7 Particles, antiparticles and conservation

Name: _____ Class: _____ Date: _____

Total: 30 marks

KEY WORDS quark–lepton model – • baryon • meson • lepton • antiparticle
 • Mass–energy equivalence • pair production • annihilation

Objective

Develop the methods for particles, antiparticles and conservation before the curated WPH14 questions. Use $g = 9.81 \text{ m s}^{-2}$ where needed. These are original training questions, not copied past-paper questions.

1 Key knowledge and worked examples

■ Families and antiparticles

In the **quark–lepton model** –, baryons and mesons contain quarks. Leptons are fundamental particles in the model.

- A **baryon** contains three quarks, for example a proton uud or neutron udd . An antibaryon contains three antiquarks.
- A **meson** contains one quark and one antiquark, for example a pion.
- A **lepton** is fundamental, for example an electron or neutrino. A positron is an antilepton, not a meson.
- A photon is the quantum of electromagnetic radiation; it is neither a baryon nor a lepton.

Up-type quarks have charge $+2e/3$ and down-type quarks $-e/3$. Antiquarks have opposite charges. For example, uud sums to $+e$ and udd to zero. The symmetry of the quark families predicted a top quark before it was observed. Classification models make testable predictions, not just lists of known particles.

An **antiparticle** has the same rest mass as its particle and opposite electric charge when charged. Other relevant additive quantum numbers also reverse. An electron has lepton number $+1$; its positron has -1 . Both have baryon number zero. A neutral antiparticle can differ in quantum numbers despite having no electric charge.

■ Check conserved totals

Assign baryon number +1 to a baryon, −1 to an antibaryon, and zero to mesons/leptons/photons. Quarks carry +1/3 and antiquarks −1/3. Assign lepton number +1 to a lepton and −1 to an antilepton. Compare total charge, baryon number and lepton number on both sides of a proposed reaction. Also check energy and momentum. Passing the listed conservation checks alone does not prove that an interaction will occur; it establishes that those laws do not forbid it.

Worked example. Test $n \rightarrow p + e^- + \bar{\nu}_e$.

Quantity	Before	After
Charge / e	0	$+1 - 1 + 0 = 0$
Baryon number	1	$1 + 0 + 0 = 1$
Lepton number	0	$0 + 1 - 1 = 0$

The antineutrino balances the electron's lepton number. Changing it to a neutrino would make the final total +2, so that proposed equation would fail this check. Preserve bars and charge signs when interpreting supplied particle symbols.

■ Rest energy, creation and annihilation

Mass–energy equivalence relates a rest-mass change to energy:

$$\Delta E = c^2 \Delta m$$

In **pair production**, energy creates a particle–antiparticle pair. The energy must at least supply both rest masses; extra energy can become kinetic energy or recoil. Momentum must also be conserved, so the surrounding interaction matters. In **annihilation**, particle and antiparticle can turn into photons. A pair initially at rest producing two photons gives equal photon energies and opposite momenta. Each photon carries one particle's rest energy for an equal-mass pair; the total is twice that value.

One electronvolt is e joules: $1 \text{ eV} = 1.60 \times 10^{-19} \text{ J}$. MeV means 10^6 eV and GeV means 10^9 eV . A quoted mass in MeV/c^2 is a mass unit, not an energy unit. Multiply by c^2 to get its corresponding rest energy.

Worked example. Convert a mass of $140 \text{ MeV}/c^2$ to kilograms.

$$mc^2 = 140 \times 10^6 \times 1.60 \times 10^{-19} \text{ J} = 2.24 \times 10^{-11} \text{ J}$$

$$m = \frac{E}{c^2} = \frac{2.24 \times 10^{-11} \text{ J}}{(3.00 \times 10^8 \text{ m s}^{-1})^2} = 2.49 \times 10^{-28} \text{ kg}$$

Use the same units before comparing masses. Percentage difference from an accepted value is $100 \times |m_{\text{predicted}} - m_{\text{accepted}}| / m_{\text{accepted}}$. State the reference value. In threshold questions, distinguish rest-energy supply from kinetic energy; do not use $p = mv$ for a photon or a particle close to c .

2 Practice

2.1 Classify a proton, pion, electron, positron and photon as baryon, meson, lepton/antilepton or neither. Give the quark content of the proton and explain its charge. [5]

proton / pion

electron / positron

photon

2.2 State two properties relating a charged particle and its antiparticle. Explain why “a neutral particle has no different antiparticle” is not a reliable rule. Describe how the quark model’s family pattern supported prediction of the top quark. [4]

particle

antiparticle

2.3 Convert $135 \text{ MeV}/c^2$ to kilograms. A calculation predicts $2.35 \times 10^{-28} \text{ kg}$ for this particle. Calculate percentage difference relative to the converted mass. Use $c = 3.00 \times 10^8 \text{ m s}^{-1}$. [4]

$m = 135 \text{ MeV}/c^2$

3 Exam-style questions

3.1 Test both $n \rightarrow p + e^- + \nu_e$ and $n \rightarrow p + e^- + \bar{\nu}_e$ against charge, baryon-number and lepton-number conservation. Identify the admissible equation under these checks and explain why conservation checks alone do not prove that any proposed interaction will occur. [5]

$n \rightarrow p + e^- + \nu_e$ or $n \rightarrow p + e^- + \bar{\nu}_e$

3.2 An electron and positron annihilate with negligible initial kinetic energy and total momentum zero. Each has rest mass 9.11×10^{-31} kg. Calculate total photon energy and the energy of each photon if two are produced. Explain their directions and why a single photon cannot carry the initial total energy and momentum. [6]



initial total momentum zero

3.3 A photon of energy 1.20 MeV creates an electron–positron pair near a nucleus. Calculate the minimum rest energy needed and the maximum energy available as kinetic energy of the pair if nuclear recoil energy is negligible. Explain the nucleus’s role and why $p = mv$ cannot be used for the incident photon. State the baryon and lepton totals before and after pair creation. [6]

photon 1.20 MeV



Solutions

Original-task marks: M1 = method, A1 = accuracy, B1 = stated reasoning point.

2.1 Proton: baryon; pion: meson. Electron: lepton; positron: antilepton. Photon: neither baryon nor lepton. Proton is uud , whose charges sum $2/3 + 2/3 - 1/3 = +1$ in units of e .

2.2 Equal rest mass and opposite electric charge. A neutral antiparticle can have opposite additive quantum numbers, for example lepton number, despite both charges being zero. The pattern/symmetry of the established quark families suggested a missing partner with predicted properties, later tested experimentally as the top quark.

2.3 Convert MeV to joules then divide by c^2 .

$$m = \frac{E}{c^2} = \frac{135 \times 10^6 \times 1.60 \times 10^{-19} \text{ J}}{(3.00 \times 10^8 \text{ m s}^{-1})^2} = 2.40 \times 10^{-28} \text{ kg}$$

Mass. Compare to the specified reference value.

$$\% \text{ difference} = 100 \frac{|m_{\text{pred}} - m_{\text{ref}}|}{m_{\text{ref}}} = 100 \frac{|2.35 - 2.40| \times 10^{-28} \text{ kg}}{2.40 \times 10^{-28} \text{ kg}} = 2.08\%$$

Percentage difference.

3.1 Both equations conserve charge: $0 = +1 - 1 + 0$. Both conserve baryon number: $1 = 1 + 0 + 0$. With neutrino, final lepton number is $0 + 1 + 1 = 2$, unlike initial zero. With antineutrino, final total is $0 + 1 - 1 = 0$, so the second passes all three checks. These are necessary constraints; passing them alone does not establish the interaction mechanism or probability.

3.2 Both rest masses contribute.

$$E_{\text{total}} = 2m_e c^2 = 2 \times 9.11 \times 10^{-31} \text{ kg} \times (3.00 \times 10^8 \text{ m s}^{-1})^2 = 1.64 \times 10^{-13} \text{ J}$$

Total energy.

$$E_\gamma = \frac{E_{\text{total}}}{2} = \frac{1.6398 \times 10^{-13} \text{ J}}{2} = 8.20 \times 10^{-14} \text{ J}$$

Each energy. Photon momenta must be opposite and equal in magnitude for initial zero momentum, so energies are equal. One photon with nonzero energy has nonzero momentum and cannot alone balance initial zero momentum.

3.3 Both rest masses are required.

$$E_{\text{min}} = 2m_e c^2 = 2 \times 9.11 \times 10^{-31} \text{ kg} \times (3.00 \times 10^8 \text{ m s}^{-1})^2 = 1.64 \times 10^{-13} \text{ J}$$

$$E_{\text{min}} = \frac{2m_e c^2}{1.60 \times 10^{-13} \text{ J per MeV}} = \frac{1.6398 \times 10^{-13} \text{ J}}{1.60 \times 10^{-13} \text{ J per MeV}} = 1.025 \text{ MeV}$$

Threshold approximately 1.02 MeV.

$$E_{k,\text{max}} = E_\gamma - 2m_e c^2 = (1.20 - 1.024875) \text{ MeV} = 0.175 \text{ MeV}$$

Available kinetic energy. The nucleus takes recoil momentum, allowing total momentum conservation; finite recoil reduces available pair kinetic energy. A photon has zero rest mass and travels at c ; use photon momentum E/c , not the massive non-relativistic formula mv . Pair baryon total stays zero; electron/positron lepton numbers $+1, -1$ sum to zero as before.