inkPhysics

ANSWER BOOK

Antimatter and photons

Particles · Year 12

AQA 3.2.1.3 · CIE 11.1.8 · OCR A 6.4.2(a), 6.4.2(b), 6.4.4(c)

19 questions · 57 marks

NAVY EDITION

SECTION A · Warm-up

A1 An antiparticle has the same mass (and rest energy) as its corresponding particle (1) but the opposite charge, and opposite values of the other quantum numbers such as baryon number and lepton number (1). For a neutral pair, the neutron and antineutron for example, both members carry zero charge, and it is the reversed baryon number that distinguishes them. [2]

A2 $E = hf = 6.63 \times 10^{-34} \times 1.0 \times 10^{15}$ (1) [2]
$E = 6.63 \times 10^{-19}$ J (1)

A3 A particle meets its antiparticle and the two are destroyed (1), their mass-energy being carried away as photons (1). When the pair meets essentially at rest, the standard case, the products are two equal photons travelling in opposite directions. [2]

A4 Rest energy is the energy equivalent of the particle's mass, the energy locked up in its mass when it is at rest (1). Electron rest energy = 0.511 MeV (1). [2]

A5 Electron: the positron (1). Proton: the antiproton; electron neutrino: the electron antineutrino (1). [2]

A6 The pair's total momentum is (almost) zero and momentum must be conserved (1). A single photon would carry momentum away, whereas two photons emitted in opposite directions can have zero total momentum (1). [2]

SECTION B · Standard

B1 $E = hc/\lambda = (6.63 \times 10^{-34} \times 3.0 \times 10^{8})/(500 \times 10^{-9})$ (1) [2]
$E = 3.98 \times 10^{-19}$ J (1)

B2 Rest energy of one particle $= m_e c^2 = 9.11 \times 10^{-31} \times (3.0 \times 10^{8})^2$ (1) [4]
$= 8.20 \times 10^{-14}$ J (1)
For a pair, $E_{min} = 2m_e c^2 = 1.64 \times 10^{-13}$ J (1)
$f_{min} = E/h = 2.47 \times 10^{20}$ Hz (1)

B3 Each photon carries the rest energy of one particle (1) [3]
$E = m_e c^2 = 8.20 \times 10^{-14}$ J (1)
$f = E/h = 1.24 \times 10^{20}$ Hz (1)

B4 $E = (6.63 \times 10^{-19})/(1.60 \times 10^{-19})$ (1) [2]
$E = 4.14$ eV (1)

B5 $E = 60 \times 10^{3} \times 1.60 \times 10^{-19} = 9.6 \times 10^{-15}$ J (1). $\lambda = hc/E$ (1) $= (6.63 \times 10^{-34} \times 3.0 \times 10^{8})/(9.6 \times 10^{-15}) = 2.07 \times 10^{-11}$ m (1). [3]

B6 Photon energy $E = hc/\lambda = (6.63 \times 10^{-34} \times 3.0 \times 10^{8})/(650 \times 10^{-9}) = 3.06 \times 10^{-19}$ J (1). Number per second = power/photon energy = $(1.5 \times 10^{-3})/(3.06 \times 10^{-19})$ (1) $= 4.9 \times 10^{15}$ photons per second (1). [3]

B7 $E = hc/\lambda = (6.63 \times 10^{-34} \times 3.0 \times 10^{8})/(2.0 \times 10^{-12}) = 9.94 \times 10^{-14}$ J (1). In MeV: $9.94 \times 10^{-14}/(1.60 \times 10^{-13}) = 0.62$ MeV, which is about 0.6 MeV (1). Pair production needs at least $2 \times 0.511 = 1.022$ MeV (1). 0.62 MeV < 1.022 MeV, so this photon cannot produce the pair (1). [4]

SECTION C · Stretch

C1 Rest energy of the pair = $2 \times 0.511 = 1.022$ MeV (1). Kinetic energy shared = 2.0 - 1.022 = 0.978 MeV (1) $= 0.978 \times 10^{6} \times 1.60 \times 10^{-19} = 1.56 \times 10^{-13}$ J (1). A lone photon in empty space could not create the pair at all, because energy and momentum cannot both be conserved; the massive nucleus recoils to absorb the surplus momentum while carrying off almost no energy, so its share can be neglected here (1). [4]

C2 $E_{min} = 1.022 \times 10^{6} \times 1.60 \times 10^{-19}$ (1) [4]
$E_{min} = 1.64 \times 10^{-13}$ J (1)
$\lambda_{max} = hc/E = (6.63 \times 10^{-34} \times 3.0 \times 10^{8})/(1.64 \times 10^{-13})$ (1)
$\lambda_{max} = 1.22 \times 10^{-12}$ m (1)

C3 A single photon has momentum, and this momentum must be conserved when the pair is created (1). A nearby massive nucleus can recoil and take up momentum (1), allowing both energy and momentum to be conserved (1); without some second body the process could not satisfy both. It is the lone photon that is forbidden, not the vacuum: two photons colliding can create a pair with no other body present. [3]

C4 The minimum photon energy for each pair is twice the rest energy of the particle (1). Thresholds: electron–positron 1.022 MeV, muon–antimuon 211.4 MeV, proton–antiproton 1876.6 MeV (1). 200 MeV exceeds only the 1.022 MeV threshold; it falls short of 211.4 MeV and 1876.6 MeV (1). So only an electron–positron pair can be created, the surplus energy becoming the pair's kinetic energy (1). [4]

C5 The photons carry both rest energies plus the kinetic energy: $E = 2 \times 0.511 + 0.35$ (1) = 1.372 MeV (1). In joules: $1.372 \times 10^{6} \times 1.60 \times 10^{-19} = 2.2 \times 10^{-13}$ J (1). [3]

C6 In annihilation a particle meets its antiparticle and both are destroyed, so mass is not conserved (1). Their mass-energy is carried away as photons, and for a pair annihilating at rest these are two photons travelling in opposite directions, conserving momentum (1); for an electron–positron pair each photon then carries a minimum of 0.511 MeV (1). In pair production a high-energy photon passing close to a nucleus converts into a particle and its antiparticle, so mass is created (1); this needs a photon of at least the pair's total rest energy, 1.022 MeV for an electron–positron pair (1). So the student is wrong about mass, but total energy, with rest energy included, is conserved in both processes (1). [6]