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ANSWER BOOK

# Fission and fusion

Nuclear physics · Year 13

AQA 3.8.1.6, 3.8.1.7 · CIE 23.1.2, 23.1.5, 23.1.6, 23.1.7 · OCR A 6.4.4(b), 6.4.4(g), 6.4.4(j), 6.4.4(k)

18 questions · 50 marks

NAVY EDITION



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## SECTION A · Warm-up

**A1** A heavy nucleus, such as uranium-235, absorbs a slow (thermal) neutron and becomes unstable (1); it splits into two smaller nuclei, releasing two or three neutrons and a large amount of energy (1). [2]

**A2** Neutrons released by one fission are absorbed by other nuclei and cause further fissions (1); each fission releases more neutrons, so the reaction sustains itself and can grow (1). [2]

**A3** The minimum mass for a self-sustaining chain reaction (1); on average at least one neutron per fission goes on to cause another fission rather than escaping from the material (1). [2]

**A4** A slow neutron, with kinetic energy comparable to that of particles in thermal motion, which uranium-235 captures far more readily than a fast neutron (1). [1]

**A5** The total nucleon (mass) number is the same before and after the reaction (1); the total proton (atomic) number is the same before and after (1). [2]

**A6** As kinetic energy of the two fission fragments (1). [1]

## SECTION B · Standard

**B1** Nucleon numbers: $235 + 1 = 141 + 92 + x$ (1) [3]
$236 = 233 + x$, so $x = 3$ neutrons (1)
Proton numbers: $92 + 0 = 56 + 36 = 92$, so they balance (1).

**B2** $E = mc^2 = 3.5 \times 10^{-28} \times (3.0 \times 10^8)^2$ (1) [3]
$E = 3.15 \times 10^{-11}$ J (1)
$E = 3.15 \times 10^{-11}/(1.60 \times 10^{-13}) = 197$ MeV (1)

**B3** The fusing nuclei are both positively charged, so they repel each other electrostatically (1); they must approach to within the very short range of the strong nuclear force to fuse (1); only at very high temperatures do the nuclei have enough kinetic energy to work against that repulsion and get close enough (1). Beyond the mark scheme: even at stellar temperatures the average nucleus falls hundreds of times short of the top of the barrier, and fusion proceeds because quantum tunnelling carries the fastest nuclei through it. [3]

**B4** $E = 17.6 \times 10^{6} \times 1.60 \times 10^{-19} = 2.82 \times 10^{-12}$ J (1) [3]
$m = E/c^2 = 2.82 \times 10^{-12}/(3.0 \times 10^{8})^2$ (1)
$m = 3.13 \times 10^{-29}$ kg (1)

**B5** The fragments form with roughly the same neutron-to-proton ratio as uranium-235 (1); nuclei of their smaller size are stable at a lower neutron-to-proton ratio, so the fragments are neutron-rich and lie above the line of stability (1); they therefore decay by beta-minus emission, often in chains, until stability is reached (1). [3]

**B6** Mass before = 2 × 2.01355 = 4.02710 u (1) [3]
Mass after = 3.01493 + 1.00867 = 4.02360 u, so $\Delta m$ = 0.00350 u (1)
E = 0.00350 × 931.5 = 3.3 MeV (1)

**B7** Energy per fission = $200 \times 1.60 \times 10^{-13} = 3.2 \times 10^{-11}$ J (1) [4]
Rate = $P/E = (600 \times 10^{6})/(3.2 \times 10^{-11}) = 1.9 \times 10^{19}$ fissions per second (1)
Energy in one day = $600 \times 10^{6} \times 86\,400 = 5.2 \times 10^{13}$ J (1)
$m = E/c^2 = 5.2 \times 10^{13}/(3.0 \times 10^{8})^2 = 5.8 \times 10^{-4}$ kg (about 0.6 g) (1)

## SECTION C · Stretch

**C1** Number of nuclei in 1.0 kg = $N_A \times 1000/235 = 2.56 \times 10^{24}$ (1) [4]
Energy per fission = $200 \times 1.60 \times 10^{-13} = 3.20 \times 10^{-11}$ J (1)
Total energy = $2.56 \times 10^{24} \times 3.20 \times 10^{-11}$ (1)
$E = 8.2 \times 10^{13}$ J (1)

**C2** Fuel: fission uses heavy nuclei such as uranium-235; fusion uses light nuclei such as hydrogen isotopes (1). Conditions: fission needs slow neutrons and a critical mass, and proceeds at ordinary temperatures (1); fusion needs extremely high temperatures and densities to bring nuclei close against electrostatic repulsion, with quantum tunnelling doing the rest (1). Products: fission gives radioactive fragments plus neutrons; fusion gives helium with far less long-lived radioactive waste (1). [4]

**C3** In both processes the products have a higher binding energy per nucleon than the original nuclei (1); fusion moves light nuclei up the steep rise of the curve, and fission moves heavy nuclei towards the peak near iron-56 (1); the increase in binding energy per nucleon corresponds to a decrease in mass, and the equivalent energy is released (1). [3]

**C4** Equal masses of fuel contain almost equal numbers of nucleons, so energy per kilogram is compared using energy per nucleon (1) [4]
Fusion: 17.6/5 = 3.52 MeV per nucleon (1)
Fission: 200/236 = 0.85 MeV per nucleon (1)
Fusion releases about 4 times more energy per kilogram of fuel, so the journalist is not correct (1)

**C5** Neutrons are lost by escaping through the surface of the material (1); a sphere has the smallest surface area for a given volume (1); so the smallest fraction of neutrons escapes and the largest fraction remains to cause further fissions, making a self-sustaining chain most likely (1). [3]