Chapter 4 Fission and fusion

Section 4.1 Nuclear fission and energy

Worked example: Try yourself 4.1.1

FISSION

Plutonium-239 is a fissile material. When a plutonium-239 nucleus is struck by and absorbs a neutron, it can split in many different ways. Consider the example of a nucleus that splits into lanthanum-143 and rubidium-94 and releases some neutrons.

The nuclear equation for this is:

$^{1}_{0}\text{n} + {}^{239}_{94}\text{Pu} + {}^{143}_{57}\text{La} + {}^{94}_{37}\text{Rb} + a\,{}^{1}_{0}\text{n} + \text{energy}$

a How many neutrons are released during this fission process, i.e. what is the value of *a*?	
Thinking	**Working**
Analyse the mass numbers (A).	$1 + 239 = 143 + 94 + (a \times 1)$ $a = (1 + 239) - (143 + 94)$ $= 3$ 3 neutrons are released during this fission.

b During this single fission reaction, there is a loss of mass (a mass defect) of 4.58×10^{-28} kg. Calculate the amount of energy that is released during fission of a single plutonium-239 nucleus. Give your answer in both MeV and joules to two significant figures.	
Thinking	**Working**
The energy released during the fission of this plutonium nucleus can be found by using $\Delta E = \Delta mc^2$.	$\Delta E = \Delta mc^2$ $= (4.58 \times 10^{-28}) \times (3.00 \times 10^8)^2$ $= 4.12 \times 10^{-11}$ J
To convert J into eV, divide by 1.6×10^{-19}. Remember that 1 MeV = 10^6 eV.	$\Delta E = \frac{4.12 \times 10^{-11}}{1.6 \times 10^{-19}}$ $= 2.58 \times 10^8$ eV $= 258$ MeV

c The combined mass of the plutonium nucleus and bombarding neutron is 2.86×10^{-25} kg. What percentage of this initial mass is converted into the energy produced during the fission process?	
Thinking	**Working**
Use the relationship percentage of initial mass converted into energy $= \frac{\text{mass defect}}{\text{initial mass}} \times \frac{100}{1}$	percentage of initial mass converted into energy $= \frac{\text{mass defect}}{\text{initial mass}} \times \frac{100}{1}$ $= \frac{4.58 \times 10^{-28}}{2.86 \times 10^{-25}} \times \frac{100}{1}$ $= 0.16\%$

Section 4.1 Review

KEY QUESTIONS SOLUTIONS

1 The strong nuclear force is a force of attraction that acts between every nucleon but only over relatively short distances. This force acts like a nuclear cement.

2 The decay products of the nuclear fission process comprise many different, often highly radioactive isotopes. This is what makes up the waste.

3 As the neutron is neutral it will only experience attractive forces from other nucleons due to the strong nuclear force.

4 $5.0 \times 10^6 \times 1.6 \times 10^{-19} = 8.0 \times 10^{-13}$ J

 ISBN 978 1 4886 17713

5 $\frac{6.0 \times 10^{-15}}{1.6 \times 10^{-19}} = 3.8 \times 10^{4}$ eV

6 Fissile—uranium-235 and plutonium-239

Non-fissile—uranium-238 and cobalt-60

7 Balance the mass numbers: $1 + 235 = 148 + 85 + x$

$x = 3$

8 **a** $\Delta E = \Delta mc^2$

$= (2.12 \times 10^{-28}) \times (3.00 \times 10^{8})^2$

$= 1.91 \times 10^{-11}$ J

b $1\text{ J} = 1.6 \times 10^{-19}$ eV

Energy in eV $= \frac{1.9 \times 10^{-11}}{1.6 \times 10^{-19}}$

$= 1.19 \times 10^{8}$ eV

9 $\Delta E = \Delta mc^2$

$= 3.48 \times 10^{-28} \times (3 \times 10^{8})^2$

$= 3.13 \times 10^{-11}$ J

$1\text{ J} = 1.6 \times 10^{-19}$ eV

Energy in eV $= \frac{3.13 \times 10^{-11}}{1.6 \times 10^{-19}}$

$= 1.96 \times 10^{8}$ eV

10 Energy in J $= 1.33 \times 10^{6} \times 1.6 \times 10^{-19} = 2.128 \times 10^{-13}$ J

$m = \frac{E}{c^2}$

$= \frac{2.128 \times 10^{-13}}{(3 \times 10^{8})^2}$

$= 2.36 \times 10^{-30}$ kg

11 Balance the mass numbers:

$1 + x = 130 + 106 + 4$

$x = 239$

Balance the atomic numbers:

$0 + 94 = 54 + y + 0$

$y = 40$

Section 4.2 **Chain reactions and nuclear reactors**

Section 4.2 **Review**

KEY QUESTIONS SOLUTIONS

1 B. Uranium-235 is highly fissionable with slow neutrons. The reaction produces two daughter nuclei, more neutrons and energy.

2 There not a high enough concentration of fissile uranium-235 to sustain a chain reaction.

3 B. This is the concentration needed to sustain a chain reaction in the reactor core.

4 The moderator slows neutrons, which allows them to induce fission in the nuclear fuel.

5 Control rods absorb neutrons and maintain a controlled chain reaction.

 ISBN 978 1 4886 17713

6 The mass of material must exceed the critical mass and it must have the correct shape to sustain a chain reaction.

7 As a result of the flat shape a high proportion of the neutrons emitted in the fission reaction will escape.

8 The lead nucleus is too heavy so the incident neutron will keep most of its energy after collision. It will not have slowed down sufficiently to be captured by a fissile nucleus.

9 Parts a and c would sustain a chain reaction; part b would not be able to sustain a chain reaction.

10 **a** A fast neutron is unlikely to be captured by a nucleus.

b A slow neutron is likely to be absorbed by the nucleus and cause fission.

11 **a** The uranium-238 will transmute to plutonium-239.

b Plutonium-239 is highly radioactive, with a half-life of 24 000 years, so will need to be stored for a long time.

12 Only one neutron is needed to sustain a chain reaction, leaving the remaining neutrons to breed more plutonium.

13 **a** ${}^{238}_{92}\text{U} + {}^{1}_{0}\text{n} \rightarrow {}^{239}_{92}\text{U}$

${}^{239}_{92}\text{U} \rightarrow {}^{239}_{93}\text{Np} + {}^{0}_{-1}\text{e}$

${}^{239}_{94}\text{Np} \rightarrow {}^{239}_{94}\text{Pu} + {}^{0}_{-1}\text{e}$

b ${}^{239}_{94}\text{Pu} + {}^{1}_{0}\text{n} \rightarrow {}^{134}_{54}\text{Xe} + {}^{103}_{40}\text{Zr} + 3{}^{1}_{0}\text{n}$

14 Over time the number of fissile nuclei in the fuel rods becomes depleted, resulting in a reduced number of fission reactions and hence fewer mobile neutrons in the core. In order to maintain a chain reaction the control rods must be gradually withdrawn over time.

Section 4.3 Nuclear fusion

Worked example: Try yourself 4.3.1

FUSION

One of the possible nuclear fusion reactions in a star involves the fusion of two helium-3 nuclei to produce a helium-4 nucleus, two protons and energy according to the equation below. Calculate the energy, in joules and MeV, released in this reaction. Use the following data in your calculations: mass of helium-3 nucleus = 3.014 932 u, mass of helium-4 nucleus = 4.001 505 u and mass of a proton = 1.007 276 u.

${}^{3}_{2}\text{He} + {}^{3}_{2}\text{He} \rightarrow {}^{4}_{2}\text{He} + 2{}^{1}_{1}\text{H} + \text{energy}$

Thinking	Working
Determine the mass of the reactants.	mass of reactants = 2 × mass of helium-3 = 2 × 3.014 932 u = 6.029 864 u
Determine the mass of the products.	mass of products = mass of helium-4 + 2 × mass of proton = 4.001 505 + 2 × 1.007 276 = 6.016 067 u
Determine the mass defect.	mass defect = mass of reactants – mass of products = 6.029 864 – 6.016 067 = 0.013 797 u
Determine the energy equivalent.	= mass defect × 931 MeV = 0.013 797 × 931 MeV = 12.85 MeV
Convert to joules.	$= 12.85 \times 10^{6} \times 1.60 \times 10^{-19}$ $= 2.06 \times 10^{-12}$ J

 ISBN 978 1 4886 17713

Worked example: Try yourself 4.3.2

BINDING ENERGY

Calculate the average binding energy per nucleon for the uranium-235 nucleus in MeV and joules. Use the following data in your calculations: mass of a uranium-235 nucleus = 234.993 462 u, mass of a proton = 1.007 276 u and mass of a neutron = 1.008 664 u.	
Thinking	**Working**
Determine the total mass of the nucleons in a uranium-235 nucleus.	total mass = mass of 143 neutrons + mass of 92 protons = 143 × 1.008 664 + 92 × 1.007276 = 236.908 344 u
Determine the mass defect.	= mass of nucleons – actual mass of nucleus = 236.908 344 – 234.993 462 = 1.914 882 u
Determine the binding energy in MeV.	= mass defect × 931 MeV = 1.914 882 × 931 = 1784 MeV
Determine the binding energy per nucleon in MeV.	$= \frac{1784}{235}$ = 7.59 MeV per nucleon
Determine the binding energy per nucleon in J.	$= 7.59 \times 10^{6} \times 1.60 \times 10^{-19}$ J $= 1.21 \times 10^{-12}$ J

Section 4.3 Review

KEY QUESTIONS SOLUTIONS

1 Fusion is the joining together of two small nuclei to form a larger nucleus. Fission is the splitting apart of one large nucleus into smaller fragments.

2 The mass of the products is less than the mass of the reactants. The mass difference is related to the energy released via $\Delta E = \Delta mc^2$.

3 The amount of energy released per nucleon during a single nuclear fission reaction is less than the amount for a single fusion reaction.

4 less than 1%

5 **a** Balance the mass numbers:

$2 + 3 = a + 1$

$a = 4$

Balance the atomic numbers:

$1 + 1 = b + 0$

$b = 2$

X is helium, He

b $\Delta E = \Delta mc^2$

$$\Delta m = \frac{E}{c^2}$$

$$= \frac{33 \times 10^{6} \times 1.6 \times 10^{-19}}{(3.0 \times 10^{8})^2}$$

$\Delta m = 5.9 \times 10^{-29}$ kg

 ISBN 978 1 4886 17713

6 Electrostatic forces of repulsion act on the protons. If the protons are moving slowly they will not have enough energy to overcome the repulsive forces and they will not fuse together.

7 Electrostatic forces of repulsion act on the protons, but they are travelling fast enough to overcome these forces. The protons will get close enough for the strong nuclear force to take effect and they will fuse together. These protons have overcome the energy barrier.

8 **a** Balance the mass numbers:

$4 + 1 + 1 - 3 = 3$

Balance the atomic numbers:

$2 + 1 + 1 - 2 = 2$

Particle X is ${}^{3}_{2}\text{He}$

b $\Delta E = 23 \times 10^{6} \times 1.6 \times 10^{-19} = 3.7 \times 10^{-12}\,\text{J}$

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

$$\Delta m = \frac{E}{c^2}$$

$$= \frac{3.7 \times 10^{-12}}{(3 \times 10^{8})^2}$$

$$= 4.1 \times 10^{-29}\,\text{kg}$$

9 When two hydrogen-2 nuclei are fused together to form a helium-4 nucleus, the binding energy per nucleon increases and the nucleus becomes more stable.

10 The number of nucleons is conserved as there are five nucleons on each side of the reaction.

CHAPTER 4 **REVIEW**

1 A nuclide that is able to split in two when hit by a neutron is fissile.

2 No, only a few nuclides (e.g. uranium-235 and plutonium-239) are fissile.

3 The strong nuclear force causes the proton to be attracted to all other nucleons. It will also experience a smaller electrostatic force of repulsion between itself and other protons.

4 Neutrons are uncharged and are not repelled by the nucleus as alpha particles are.

5 **a** $\Delta E = \Delta mc^2$

$= 3.48 \times 10^{-28} \times (3.0 \times 10^{8})^2$

$= 3.1 \times 10^{-11}\,\text{J}$

b $\Delta E = \dfrac{3.1 \times 10^{-11}}{1.6 \times 10^{-19}}$

$= 1.96 \times 10^{8}$

$= 196\,\text{MeV}$

6 $1 + x = 130 + 106 + 4 \times 1$

$x = 239$

$0 + 94 = 54 + y + 4 \times 0$

$y = 40$

7 Balance the mass numbers:

$1 + 235 = 127 + 102 + x$

$x = 7$

8 The nuclei are all positively charged and so repel each other. They need a massively large amount of energy to overcome these forces and get close enough for the strong nuclear force to take effect. 100 million degrees provides the required energy for this to occur.

9 $\Delta E = \Delta mc^2$

$= 4.99 \times 10^{-28} \times (3.0 \times 10^{8})^2$

$= 4.49 \times 10^{-11}\,\text{J}$

 ISBN 978 1 4886 17713

10 a The combined mass of the hydrogen and helium-3 nuclei is greater than the combined mass of the helium-4 nucleus, positron and neutrino.

b The energy has come from the lost mass (or mass defect) via $\Delta E = \Delta mc^2$.

c $21\,\text{MeV} = 21 \times 10^6 \times 1.6 \times 10^{-19} = 3.4 \times 10^{-12}\,\text{J}$

d $\Delta E = \Delta mc^2$

$$\Delta m = \frac{E}{c^2}$$

$$= \frac{3.4 \times 10^{-12}}{(3 \times 10^8)^2}$$

$$= 3.8 \times 10^{-29}\,\text{kg}$$

11 Fission reactors create a great deal more waste. Fusion releases more energy per nucleon than fission.

12 The binding energy per nucleon increases and the nucleus becomes more stable.

13 The higher the binding energy, the more stable the nucleus. This is because higher binding energy means that it takes more energy to completely separate particles in the nucleus. Iron therefore has the most stable nuclei of all the elements.

14 gamma rays

15 When uranium-238 absorbs neutrons and undergoes transmutation it produces plutonium-239 as one of the daughter nuclei.

16 a The coolant transfers the heat from the reactor to the heat exchanger.

b The moderator slows down, or moderates, the speed of the neutrons.

c The control rods control the number of neutrons involved in the chain reaction.

17 a ${}^1_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$

b energy released $= 20 \times 10^6 \times 1.6 \times 10^{-19} = 3.2 \times 10^{-12}\,\text{J}$

c $$m = \frac{E}{c^2}$$

$$= \frac{3.2 \times 10^{-12}}{(3 \times 10^8)^2}$$

$$= 3.56 \times 10^{-29}\,\text{kg}$$

18 a ${}^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + {}^{0}_{+1}\text{e}$

${}^1_1\text{H} + {}^2_1\text{H} \rightarrow {}^3_2\text{He} + \gamma$

${}^3_2\text{He} + {}^3_2\text{He} \rightarrow {}^4_2\text{He} + 2{}^1_1\text{H}$

b Mass of reactants $= 2 \times 3.01493 \times 1.66054 \times 10^{-27} = 1.00128 \times 10^{-26}\,\text{kg}$

Mass of products $= (4.00151 + 2 \times 1.00728) \times 1.66054 \times 10^{-27} = 9.98992 \times 10^{-27}\,\text{kg}$

Mass defect $= 1.00128 \times 10^{-26} - 9.98992 \times 10^{-27} = 2.28751 \times 10^{-29}\,\text{kg}$

$\Delta E = \Delta mc^2 = 2.28751 \times 10^{-29} \times (3 \times 10^8)^2 = 2.05876 \times 10^{-12}\,\text{J}$

$$\text{power} = \frac{\text{energy}}{\text{time}}$$

$$= \frac{2.05876 \times 10^{-12}}{(24 \times 60 \times 60)}$$

$$= 2.38282 \times 10^{-17}\,\text{W per reaction}$$

Power from 100 g = power per reaction × number of reactions per 100 g

$$= \frac{2.38282 \times 10^{-17} \times 0.1}{1.00128 \times 10^{-26}}$$

$$= 2.38 \times 10^8\,\text{W}$$

$$= 238\,\text{MW}$$

 ISBN 978 1 4886 17713