23. Nuclear Physics

23.1 Mass defect and nuclear binding energy

Paper 4

Marking Scheme

Q1.

(a)	energy required to separate (all) the nucleons (in the nucleus)	**M1**
	to infinity	**A1**
(b)(i)	Δm = {[(84 × 1.007276) + (128 × 1.008665)] – 211.942749} (u) (= 1.778 u)	**C1**
	= 1.778 × 1.66 × 10^{-27} (kg)	**C1**
	= 2.95 × 10^{-27} kg	**A1**
(b)(ii)	$E = (\Delta)mc^2$	**C1**
	binding energy = 2.95 × 10^{-27} × (3.00 × 10^8)^2 = 2.66 × 10^{-10} J	**A1**
(b)(iii)	binding energy per nucleon = (2.66 × 10^{-10}) / 212 = 1.25 × 10^{-12} J	**A1**
(c)(i)	line rising to a single peak that is to the left of the '9' in the Fig. 9.1 label and then continually decreasing	**B1**
	steep positive gradient on the left of the peak and shallow negative gradient on the right	**B1**
(c)(ii)	X shown on the line at a value of *A* that is to the right of the left-hand edge of the '*A*' in the axis label, and to the left of '2' in the 250 label	**B1**
(c)(iii)	nucleus formed (as a result of the decay) has a lower nucleon number	**B1**
	(nucleus formed has a) greater binding energy per nucleon	**B1**

Q2.

(b)(i)	• large nuclei undergo fission whereas small nuclei undergo fusion • fission involves one nucleus splitting into two (or more) (smaller) nuclei • fusion involves two nuclei joining together to form one (larger) nucleus • fission is (usually) initiated by neutron bombardment • fusion is (usually) initiated by (very) high temperatures *Any three points, 1 mark each*	**B3**
(b)(ii)	binding energy <u>per nucleon</u> is greatest for intermediate nucleon numbers (may be shown on sketch graph with axes labelled 'binding energy <u>per nucleon</u>' and 'nucleon number')	**B1**
	both fusion and fission involve an increase in binding energy (per nucleon)	**B1**

Q3.

(a)	difference between mass of nucleus and (total) mass of nucleons	**M1**
	when infinitely separated	**A1**
(b)(i)	neutron	**B1**
(b)(ii)	$E = \Delta m\, c^2$	**C1**
	Δm = (0.030377 – 0.002388 – 0.009105)u (= 0.018884u)	**C1**
	energy release = (0.030377 – 0.002388 – 0.009105) × 1.66 × 10^{-27} × (3.00 × 10^8)^2 = 2.8 × 10^{-12} J	**A1**
(c)(i)	number of atoms per unit time = (1.4 × 10^{28}) / (2.8 × 10^{-12}) (= 5.0 × 10^{39} s^{-1})	**C1**
	mass of one atom = 4 × 1.66 × 10^{-27} or (4 × 10^{-3}) / (6.02 × 10^{23}) (= 6.64 × 10^{-27} kg)	**C1**
	mass per unit time = 6.64 × 10^{-27} × 5.0 × 10^{39} = 3.3 × 10^{13} kg s^{-1}	**A1**

Q4.

(a)	(two small) nuclei join together	**M1**
	to form one larger nucleus	**A1**
(b)	line with a peak at $A \approx 56$	**B1**
	line with steep initial positive gradient on the left of peak and shallower negative gradient at all points to the right of peak and line does not return to 0 binding energy	**B1**
(c)(i)	X shown at value of A to the right of the peak	**B1**
(c)(ii)	Y shown at value of A close to 1	**B1**
(d)	energy from 1 nucleus = $(1.77 \times 10^{13}) / (6.02 \times 10^{23})$ $(= 2.94 \times 10^{-11}\ \text{J})$	**C1**
	binding energy of Z = $[(1.25 + 1.81) \times 10^{-10}] - 2.94 \times 10^{-11}$ $(= 2.77 \times 10^{-10}\ \text{J})$	**C1**
	nucleon number of Z = 93 + 139 + 2 – 1 (= 233)	**C1**
	binding energy per nucleon = $(2.77 \times 10^{-10}) / (233 \times 1.60 \times 10^{-13})$ = 7.43 MeV	**A1**

Q5.

(a)(ii)	X = β^+ **or** e^+ **and** $P = 1$	**B1**
	$Q = 0$ **and** $R = 18$	**B1**

Q6.

(a)(i)	energy required to separate the nucleons (in the nucleus)	**M1**
	to infinity	**A1**
(a)(ii)	curve starting close to the origin and forming a single peak	**B1**
	peak shown to left of centre, with steep line on LHS of peak and shallow line on RHS of peak	**B1**
(b)(i)	fusion	**B1**
(b)(ii)	both particles have low A values **or** both particles are at left-hand end of graph	**B1**
	He-3 has higher binding energy (per nucleon) than H-2	**B1**
(c)	$\Delta m = [(2 \times 2.014102) – (3.016029 + 1.008665)]$ u $(= 0.00351$ u)	**C1**
	$E = \Delta mc^2$	**C1**
	$= 0.00351 \times 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2$ $(= 5.24 \times 10^{-13}\ \text{J})$	**C1**
	1.00 mol of deuterium forms 0.500 mol of helium-3	**C1**
	total energy = $0.500 \times 6.02 \times 10^{23} \times 5.24 \times 10^{-13}$ $= 1.58 \times 10^{11}\ \text{J}$	**A1**

Q7.

(c)	(for reaction to occur,) energy is released	**B1**
	energy release comes from fall in mass so total mass of products must be less (than mass of carbon-15)	**B1**

Q8.

(a)(i)	$E = mc^2$	**C1**
	$= 9.11 \times 10^{-31} \times (3.0 \times 10^8)^2$ $= 8.2 \times 10^{-14}$ J	**A1**

Q9.

(a)	difference between mass of nucleus and mass of (constituent) nucleons	**M1**
	where nucleons are separated to infinity	**A1**
(b)(i)	$E = mc^2$	**C1**
	$= 1.66 \times 10^{-27} \times (3.00 \times 10^8)^2 / (1.60 \times 10^{-13}) = 934$ MeV	**A1**
(b)(ii)	mass defect = $2 \times (1.007276 + 1.008665) - 4.001506$ $(= 0.030376)$	**B1**
	binding energy per nucleon = $(0.030376 \times 934) / 4 = 7.09$ MeV	**A1**
(c)	binding energy per nucleon is much greater	**M1**
	so would require a large amount of energy to separate the nucleons in helium	**A1**
	or	
	amount of energy released in forming hydrogen isotopes	**(M1)**
	is less than energy required to break apart helium nucleus	**(A1)**

Q10.

(a)(i)	energy required to separate nucleons (of nucleus)	**M1**
	to infinity	**A1**
(a)(ii)	a (single) large nucleus <u>divides</u> to form (smaller) nuclei	**B1**
	any one point from: • initiated by neutron bombardment • resulting nuclei are of similar size • binding energy per nucleon increases • total binding energy increases • neutrons released • combined mass of smaller nuclei is less than mass of large nucleus	**B1**
(b)	binding energy per nucleon is a maximum at around $A = 56$	**B1**
	products of splitting a ^{56}Fe nucleus must have a lower total binding energy	**B1**
	(reaction would require) a net input of energy	**B1**

Q11.

(b)(i)	**1.** mass change = 5.60×10^{-3} u	**A1**
	2. energy $= (\Delta)mc^2$	**C1**
	$= 5.6 \times 10^{-3} \times 1.66 \times 10^{-27} \times (3.0 \times 10^8)^2$ $(= 8.36 \times 10^{-13}$ J)	**C1**
	$= 0.84$ pJ	**A1**
(b)(ii)	kinetic energy (of recoil) of lead (nucleus)	**B1**
	energy of γ-ray photon	**B1**

Q12.

(a)	energy required to separate the nucleons (in a nucleus)	**M1**
	to infinity	**A1**
	or	
	energy released when nucleons come together (to form nucleus)	**(M1)**
	from infinity	**(A1)**
(b)	mass defect = 140.911 – (57 × 1.007) – (84 × 1.009)	**C1**
	= 140.911 – 142.155 = (–)1.244 (u)	**C1**
	energy = $c^2(\Delta)m$	**C1**
	= $(3.00 \times 10^8)^2 \times 1.244 \times 1.66 \times 10^{-27}$ = 1.9×10^{-10} J	**A1**

Q13.

(a)	$E = (3.0 \times 10^8)^2 \times 1.66 \times 10^{-27}$ (= 1.49×10^{-10} J)	**M1**
	= $(1.49 \times 10^{-10}) / (1.60 \times 10^{-19}) = 9.34 \times 10^8$ = 934 MeV	**A1**
	or	
	binding energy = 8.443 × 95 [or equivalent using La-139 nucleus]	**(M1)**
	binding energy / mass defect = (8.443 × 95) / 0.859 = 934 MeV	**(A1)**
(b)(i)	binding energy = 1.865 × 934 (= 1741.91 MeV)	**C1**
	binding energy per nucleon = 1741.91 / 235 = 7.41 (MeV)	**A1**
(b)(ii)	less (than)	**B1**
(c)	energy = {(1.219 + 0.859) – 1.865)} × 934 **or** energy = (95 × 8.443) + (139 × 8.189) – (235 × 7.412)	**C1**
	= 199 MeV	**A1**
(d)	number of reactions = $1.2 \times 10^{-7} \times 6.02 \times 10^{23}$ = 7.22×10^{16}	**C1**
	energy release (for one reaction) = $199 \times 1.60 \times 10^{-13}$ (= 3.18×10^{-11} J)	**C1**
	power = $(7.22 \times 10^{16} \times 3.18 \times 10^{-11}) / (25 \times 10^{-3})$ = 9.2×10^7 W	**A1**

Q14.

(c)(i)	$E = c^2\Delta m$	**C1**
	$\Delta m = (0.51 \times 1.60 \times 10^{-13}) / (3.00 \times 10^8)^2$ = 9.1×10^{-31} kg	**A1**

Q15.

(a)	fusion: two nuclei <u>combine</u> to form a (single) nucleus	**B1**
	fission: a (single) large nucleus <u>divides</u> to form (smaller) nuclei	**B1**
	Any one from: • fusion is initiated by (very) high temperatures • fission is initiated by neutron bombardment • resulting nuclei in fission are of similar size • (both processes) release energy • binding energy per nucleon increases • total binding energy increases • fission involves release of neutrons	**B1**
(b)(i)	neutron	**B1**
(b)(ii)	**1.** zero	**A1**
	2. $(4 \times 11.3290 \times 10^{-13}) - (2 \times 1.7813 \times 10^{-13}) - (3 \times 4.5285 \times 10^{-13})$	**C1**
	energy change $= 45.316 \times 10^{-13} - 17.148 \times 10^{-13}$ $= 2.82 \times 10^{-12}$ J	**A1**
(b)(iii)	1.0 mol or N_A nuclei of each energy $= 2.817 \times 10^{-12} \times 6.02 \times 10^{23}$ $= 1.7 \times 10^{12}$ J	**A1**