23. Nuclear Physics

23.1 Mass defect and nuclear binding energy

Paper 4

Question Paper

1 **(a)** State what is meant by the binding energy of a nucleus.

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.....

..... [2]

(b) Table 9.1 shows the masses of two sub-atomic particles and a polonium-212 ($^{212}_{84}$Po) nucleus.

Table 9.1

	mass / u
proton	1.007 276
neutron	1.008 665
polonium-212 nucleus	211.942 749

For the polonium-212 nucleus, determine:

(i) the mass defect Δm, in kg

Δm = ... kg [3]

(ii) the binding energy

binding energy = ... J [2]

(iii) the binding energy per nucleon.

binding energy per nucleon = ... J [1]

(c) (i) On Fig. 9.1, sketch the variation with nucleon number A of binding energy per nucleon for values of A from 1 to 250.

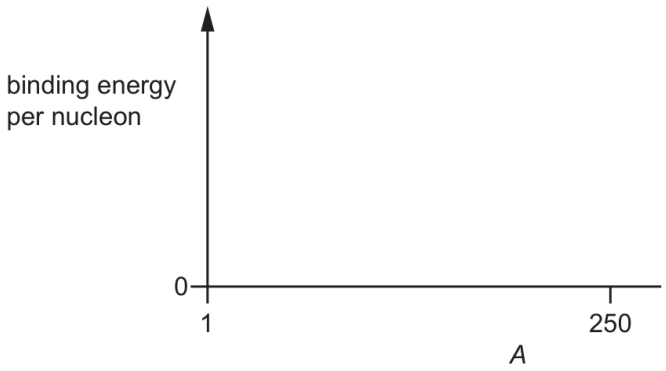


Fig. 9.1

[2]

(ii) On your line in Fig. 9.1, draw an X to show the approximate position of polonium-212.

[1]

(iii) Polonium-212 is radioactive and undergoes alpha-decay.

Suggest and explain, with reference to Fig. 9.1, why the alpha-decay of polonium-212 results in a release of energy.

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..... [2]

2 (b) (i) Describe the differences between nuclear fission and nuclear fusion.

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..... [3]

(ii) Explain, with reference to the variation of binding energy per nucleon with nucleon number, why the processes of nuclear fission and nuclear fusion both result in a release of energy.

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..... [2]

3 **(a)** Define mass defect.

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..... [2]

(b) Table 9.1 shows the mass defects of three nuclei.

Table 9.1

nucleus	mass defect / u
$^{2}_{1}H$	0.002 388
$^{3}_{1}H$	0.009 105
$^{4}_{2}He$	0.030 377

The nuclear fusion process in a particular star is described by

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

where X is a particle that has no mass defect.

(i) State the name of particle X.

..... [1]

(ii) Show that the energy released when one nucleus of $^{4}_{2}He$ is formed in this fusion reaction is 2.8×10^{-12} J.

[3]

(c) The star in **(b)** has a radius of 2.3×10^{9} m and a luminosity of 1.4×10^{28} W.
All the energy released from the formation of $^{4}_{2}He$ is radiated away from the star.
All the energy that is radiated from the star has been released in the formation of $^{4}_{2}He$.

Determine:

(i) the mass of $^{4}_{2}\text{He}$ produced per unit time by the fusion process

mass per unit time = ... kg s^{-1} [3]

4 **(a)** State what is meant by nuclear fusion.

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..... [2]

(b) On Fig. 9.1, sketch the variation of binding energy per nucleon with nucleon number *A* for values of *A* between 1 and 250.

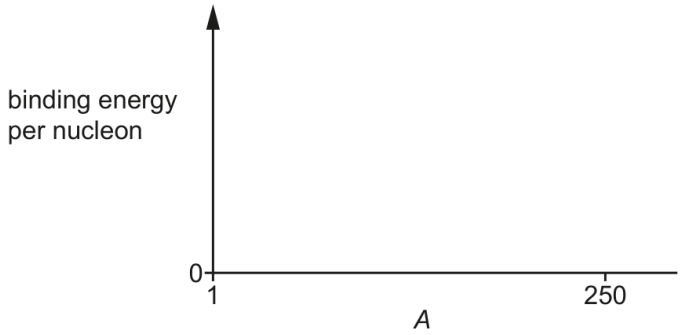


Fig. 9.1

[2]

(c) On your line in Fig. 9.1, label:

(i) a point X that could represent a nucleus that undergoes alpha-decay [1]

(ii) a point Y that could represent a nucleus that undergoes nuclear fusion. [1]

(d) A nucleus Z undergoes nuclear fission to form strontium-93 ($^{93}_{38}$Sr) and xenon-139 ($^{139}_{54}$Xe) according to

$$^{1}_{0}n + Z \longrightarrow {}^{93}_{38}Sr + {}^{139}_{54}Xe + 2{}^{1}_{0}n.$$

Table 9.1 shows the binding energies of the strontium-93 and xenon-139 nuclei.

Table 9.1

nucleus	binding energy / J
$^{93}_{38}$Sr	1.25×10^{-10}
$^{139}_{54}$Xe	1.81×10^{-10}

The fission of 1.00 mol of Z releases 1.77×10^{13} J of energy.

Determine the binding energy per nucleon, in MeV, of Z.

binding energy per nucleon = ... MeV [4]

5 Fluorine-18 ($^{18}_{9}F$) is a radioactive nuclide that is used as a tracer in positron emission tomography (PET scanning). Fluorine-18 decays to a nuclide of oxygen (O) according to

$$^{18}_{9}F \longrightarrow {}^{Q}_{P}X + {}^{R}_{8}O.$$

(a) (ii) State the symbol of the particle that is represented by X and the values of *P*, *Q* and *R*.

X: ..... *P*: .....

Q: ..... *R*: .....

[2]

6 **(a)** **(i)** State what is meant by nuclear binding energy.

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..... [2]

(ii) On Fig. 8.1, sketch a line to show the variation with nucleon number A of the binding energy per nucleon E of a nucleus.

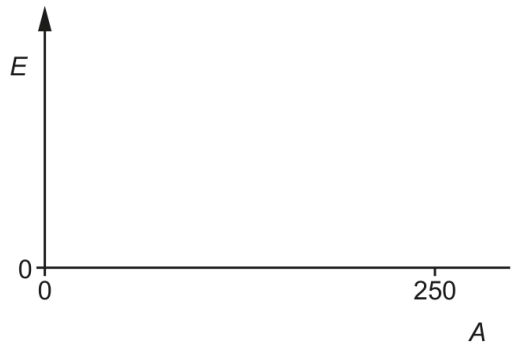


Fig. 8.1

[2]

(b) In one type of nuclear process, deuterium ($^{2}_{1}H$) undergoes the reaction

$$^{2}_{1}H + {}^{2}_{1}H \longrightarrow {}^{3}_{2}He + {}^{1}_{0}n.$$

(i) State the name of this type of nuclear process.

..... [1]

(ii) Explain, with reference to your line in **(a)(ii)**, why this reaction results in the release of energy.

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..... [2]

(c) Table 8.1 shows the masses of the particles involved in the reaction in **(b)**.

Table 8.1

particle	mass / u
$^{1}_{0}n$	1.008 665
$^{2}_{1}H$	2.014 102
$^{3}_{2}He$	3.016 029

Calculate the energy released when 1.00 mol of deuterium undergoes the reaction.

energy = ... J [5]

7 Carbon-15 ($^{15}_{6}C$) is an isotope of carbon that undergoes radioactive decay to nitrogen-15 ($^{15}_{7}N$), which is a stable isotope of nitrogen.

Radioactive decay is both a random and a spontaneous process.

(c) The equation for the decay of carbon-15 can be written as

$$^{15}_{6}C \rightarrow {}^{15}_{7}N + {}^{0}_{-1}\beta + {}^{0}_{0}\bar{\nu}.$$

State and explain how the mass of the products of the decay must compare with the mass of the carbon-15 nucleus.

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..... [2]

8 An electron, at rest, has mass m_e and charge $-q$.

A positron is a particle that, at rest, has mass m_e and charge $+q$.

A positron interacts with an electron. The electron and the positron may be considered to be at rest.
The outcome of this interaction is that the electron and the positron become two gamma-ray (γ-ray) photons, each having the same energy.

(a) Calculate, for one of the γ-ray photons:

(i) the photon energy, in J

energy = ... J [2]

9 **(a)** State what is meant by the *mass defect* of a nucleus.

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..... [2]

(b) Some masses are shown in Table 12.1.

Table 12.1

	mass / u
proton $^{1}_{1}p$	1.007 276
neutron $^{1}_{0}n$	1.008 665
helium-4 ($^{4}_{2}He$) nucleus	4.001 506

Show that:

(i) the energy equivalence of 1.00 u is 934 MeV

[2]

(ii) the binding energy per nucleon of a helium-4 nucleus is 7.09 MeV.

[2]

(c) Isotopes of hydrogen have binding energies per nucleon of less than 3 MeV.

Suggest why a nucleus of helium-4 does not spontaneously break down to become nuclei of hydrogen.

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..... [2]

10 (a) (i) Define nuclear *binding energy*.

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..... [2]

(ii) Explain what is meant by a *nuclear fission* reaction.

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..... [2]

(b) A student suggests that one possible nuclear reaction is

$$^{56}_{26}\text{Fe} + ^{1}_{0}\text{n} \rightarrow ^{20}_{9}\text{F} + ^{37}_{17}\text{C}l.$$

The binding energy per nucleon of a nucleus varies with the nucleon number.
Use this variation to explain why the reaction would **not** result in an overall release of energy.

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..... [3]

11 (b) The isotope polonium-208 ($^{208}_{84}$Po) is radioactive and decays to form lead-204 ($^{204}_{82}$Pb). The nuclear equation for this decay is

$$^{208}_{84}\text{Po} \longrightarrow {}^{204}_{82}\text{Pb} + {}^{4}_{2}\text{He}.$$

Data for nuclear masses are given in Fig. 12.1.

	mass / u
$^{4}_{2}$He	4.002 603
$^{204}_{82}$Pb	203.973 043
$^{208}_{84}$Po	207.981 245

Fig. 12.1

(i) Determine, for the decay of one nucleus of polonium-208:

1. the change, in u, of the mass

mass change = ... u [1]

2. the total energy, in pJ, released.

energy = ... pJ [3]

(ii) The polonium-208 nucleus is initially stationary. The initial kinetic energy of the $^{4}_{2}$He nucleus (α-particle) is found to be less than the energy calculated in **(i) part 2**.

Suggest **two** possible reasons for this difference.

1. .....

.....

2. .....

.....

[2]

12 **(a)** State what is meant by the *binding energy* of a nucleus.

.....

.....

.....[2]

(b) Some masses are shown in Fig. 12.1.

	mass / u
proton ($^{1}_{1}$p)	1.007
neutron ($^{1}_{0}$n)	1.009
lanthanum-141 ($^{141}_{57}$La) nucleus	140.911

Fig. 12.1

Calculate the binding energy of a nucleus of lanthanum-141.

binding energy = ... J [4]

13 One possible nuclear reaction that takes place is

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{95}_{42}Mo + ^{139}_{57}La + 2^{1}_{0}n + 7^{0}_{-1}e$$

Data for nuclei in this reaction are given in Fig. 12.1.

nucleus	mass / u	total mass of separate nucleons / u	mass defect / u	binding energy per nucleon / MeV
$^{95}_{42}Mo$	94.906	95.765	0.859	8.443
$^{139}_{57}La$	138.906	140.125	1.219	8.189
$^{235}_{92}U$	235.044	236.909	1.865	.....

Fig. 12.1

(a) Show that the energy equivalent to a mass of 1.00 u is 934 MeV.

[2]

(b) (i) Use data from Fig. 12.1 to calculate the binding energy per nucleon of a nucleus of uranium-235 ($^{235}_{92}U$). Complete Fig. 12.1.

[2]

(ii) The nucleon number of an isotope of the element rutherfordium is 267.

State whether the binding energy per nucleon of this isotope will be greater than, equal to or less than the binding energy per nucleon of uranium-235.

..... [1]

(c) Calculate the total energy, in MeV, released in this nuclear reaction.

energy = ... MeV [2]

(d) The nuclei in 1.2×10^{-7} mol of uranium-235 all undergo this reaction in a time of 25 ms.

Calculate the average power release during the time of 25 ms.

power = ... W [3]

14 A stationary isolated nucleus emits a γ-ray photon of energy 0.51 MeV.

(c) (i) For this nucleus, determine the change in mass Δm during the decay that gives rise to the energy of the γ-ray photon.

Δm = ... kg [2]

15 (a) State what is meant by *nuclear fusion* and *nuclear fission*.

nuclear fusion: .....

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.....

nuclear fission: .....

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.....

[3]

(b) A nuclear reaction which may, in the future, be used for the generation of electrical energy is

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow ^{4}_{2}\mathrm{He} + \mathrm{x}.$$

(i) Name the particle x.

.....[1]

(ii) Data for the binding energy per nucleon E_B of some nuclei are given in Fig. 12.1.

		binding energy per nucleon $E_B/10^{-13}$ J
deuterium	$^{2}_{1}\mathrm{H}$	1.7813
tritium	$^{3}_{1}\mathrm{H}$	4.5285
helium	$^{4}_{2}\mathrm{He}$	11.3290

Fig. 12.1

1. State the binding energy per nucleon of x.

binding energy per nucleon = ... J

2. Calculate the energy change that takes place in this reaction.

energy change = ... J

[3]

(iii) Use your answer in **(ii) part 2** to determine the energy release when 2.0 g of deuterium ($^{2}_{1}H$) reacts with 3.0 g of tritium ($^{3}_{1}H$).

energy = ... J [1]