1 Uranium-236 undergoes nuclear fission to produce barium-144, krypton-89 and three free neutrons.

What is the energy released in this process?

Nuclide	Binding energy per nucleon / MeV
$^{236}_{92}U$	7.5
$^{144}_{56}Ba$	8.3
$^{89}_{36}Kr$	8.6

A 84 MeV ⬭

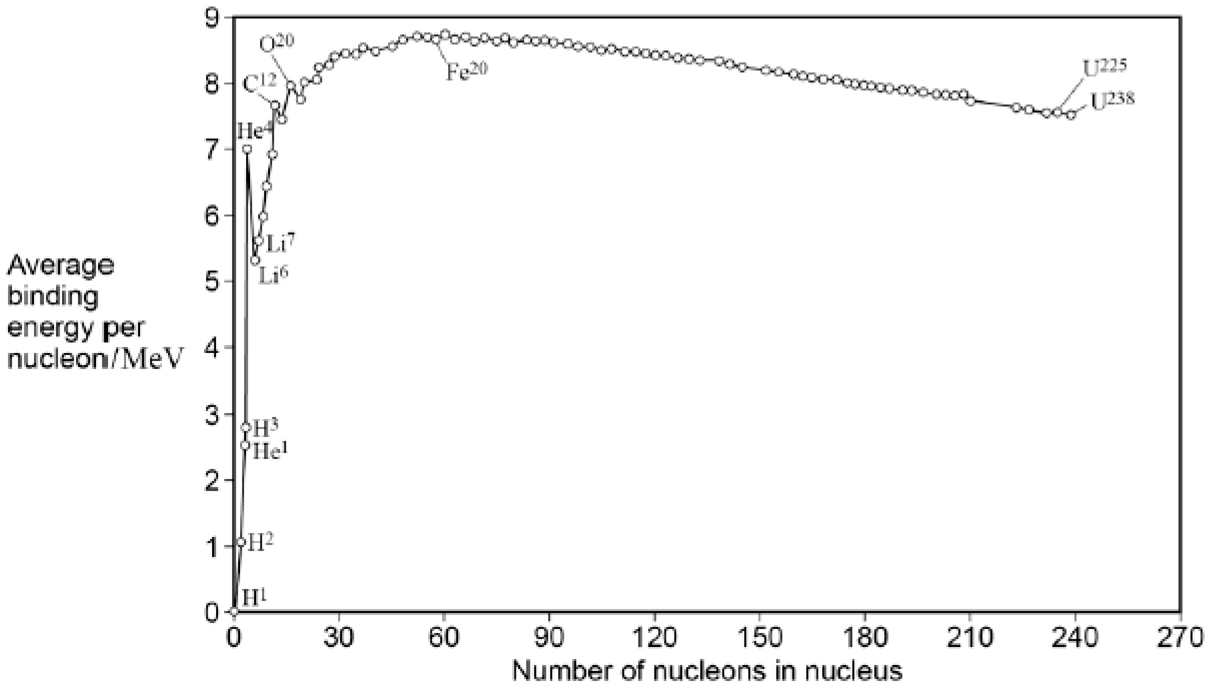
B 106 MeV ⬭

C 191 MeV ⬭

D 3730 MeV ⬭

(Total 1 mark)

2 The graph shows how the binding energy per nucleon varies with the nucleon number for stable nuclei.



What is the approximate total binding energy for a nucleus of ${}^{184}_{74}\mathrm{W}$?

A 1.28 pJ

B 94.7 pJ

C 103 pJ

D 230 pJ

(Total 1 mark)

3 The power output of a nuclear reactor is provided by nuclear fuel which decreases in mass at a rate of 4.0×10^{-6} kg hour^{-1}.

What is the maximum possible power output of the reactor?

A 28 kW

B 50 MW

C 100 MW

D 200 MW

(Total 1 mark)

4 In the reaction shown, a proton and a deuterium nucleus, ${}^{2}_{1}\mathrm{H}$, fuse together to form a helium nucleus, ${}^{3}_{2}\mathrm{He}$

$$ {}^{1}_{1}\mathrm{p} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He} + \mathrm{Q} $$

What is the value of Q, the energy released in this reaction?

mass of a proton = 1.00728 u

mass of a ${}^{2}_{1}\mathrm{H}$ nucleus = 2.01355 u

mass of a ${}^{3}_{2}\mathrm{He}$ nucleus = 3.01493 u

A 5.0 MeV

B 5.5 MeV

C 6.0 MeV

D 6.5 MeV

(Total 1 mark)

5 The reaction shown below occurs when a proton and a deuterium nucleus, $^{2}_{1}H$, fuse to form a helium nucleus, $^{3}_{2}He$.

$$^{1}_{1}P \quad + \quad ^{2}_{1}H \longrightarrow \; ^{3}_{2}He \quad + \quad Q$$

If the energy released, Q, is 5.49 MeV, what is the mass of the helium nucleus?

mass of $^{2}_{1}H$ nucleus = 2.01355 u
mass of proton = 1.00728 u
1u is equivalent to 931.3 Me V

A 0.00589 u

B 3.01494 u

C 3.02083 u

D 3.02323 u

(Total 1 mark)

6 The mass of the beryllium nucleus, $^{7}_{4}Be$, is 7.01473 u. What is the binding energy **per nucleon** of this nucleus?

Use the following data:

mass of proton = 1.00728 u
mass of neutron = 1.00867 u
1u = 931.3 MeV

A 1.6 MeV nucleon^{-1}

B 5.4 MeV nucleon^{-1}

C 9.4 MeV nucleon^{-1}

D 12.5 MeV nucleon^{-1}

(Total 1 mark)

7 The mass of the nuclear fuel in a nuclear reactor decreases at a rate of 1.2×10^{-5} kg per hour. Assuming 100% efficiency in the reactor what is the power output of the reactor?

A 100 MW

B 150 MW

C 200 MW

D 300 MW

(Total 1 mark)

8 The fusion of two deuterium nuclei produces a nuclide of helium plus a neutron and liberates 3.27 MeV of energy. How does the mass of the two deuterium nuclei compare with the combined mass of the helium nucleus and neutron?

A It is 5.8×10^{-30} kg greater before fusion.

B It is 5.8×10^{-30} kg greater after fusion.

C It is 5.8×10^{-36} kg greater before fusion.

D It is 5.8×10^{-36} kg greater after fusion.

(Total 1 mark)

9 What is the mass difference of the $^{7}_{3}$Li nucleus?

Use the following data:

mass of a proton = 1.00728 u
mass of a neutron = 1.00867 u
mass of $^{7}_{3}$Li nucleus = 7.01436 u

A 0.93912 u

B 0.04051 u

C 0.04077 u

D 0.04216 u

(Total 1 mark)

10 What is the binding energy of the nucleus $^{238}_{92}$U?

Use the following data:

mass of a proton =1.00728 u

mass of a neutron = 1.00867 u

mass of a $^{238}_{92}$U nucleus = 238.05076 u

1 u = 931.3 MeV

A 1685 MeV

B 1732 MeV

C 1755 MeV

D 1802 MeV

(Total 1 mark)

11 The nuclear fuel, which provides the power output in a nuclear reactor, decreases in mass at a rate of 6.0×10^{-6} kg per hour. What is the maximum possible power output of the reactor?

A 42 kW

B 75 MW

C 150 MW

D 300 MW

(Total 1 mark)

12 Nuclear binding energy is

A the energy required to overcome the electrostatic force between the protons in the nucleus

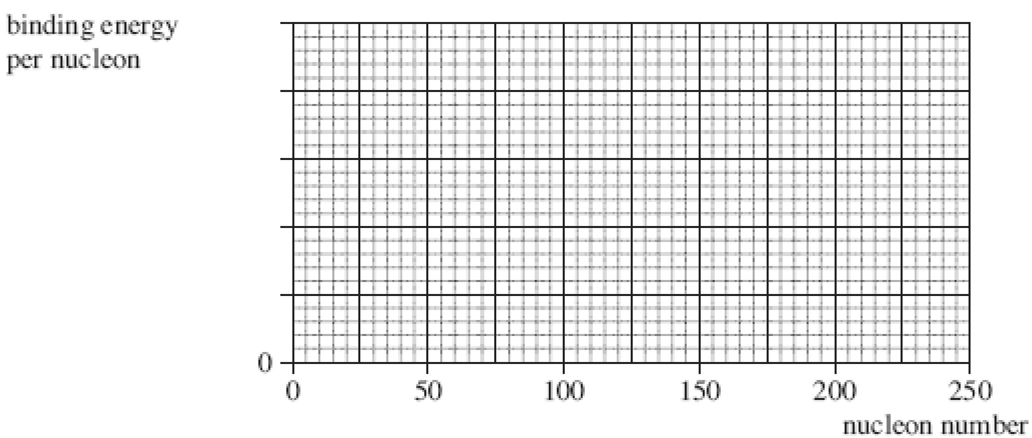
B energy equivalent of the mass of the protons in the nucleus

C the energy equivalent of the mass of all the nucleons in the nucleus

D the energy equivalent of the difference between the total mass of the individual nucleons and their mass when they are contained in the nucleus

(Total 1 mark)

13 (a) Sketch a graph of binding energy per nucleon against nucleon number for the naturally occurring nuclides on the axes given in the figure below. Add values and a unit to the binding energy per nucleon axis.



(4)

(b) Use the graph to explain how energy is released when some nuclides undergo fission and when other nuclides undergo fusion.

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(3)

(Total 7 marks)

14 (a) The mass of a nucleus ${}^{A}_{Z}X$ is *M*.

(i) If the mass of a proton is m_p, and the mass of a neutron is m_n, give an expression for the mass difference Δm of this nucleus.

Δm = ____

(ii) Give an expression for the binding energy per nucleon of this nucleus, taking the speed of light to be *c*.

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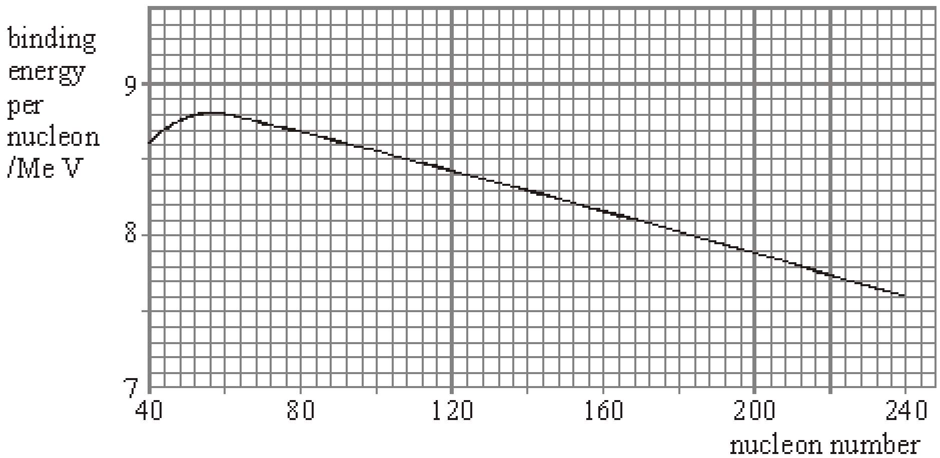
(2)

(b) The figure below shows an enlarged portion of a graph indicating how the binding energy per nucleon of various nuclides varies with their nucleon number.



(i) State the value of the nucleon number for the nuclides that are most likely to be stable. Give your reasoning.

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(ii) When fission of uranium 235 takes place, the nucleus splits into two roughly equal parts and approximately 200 Me V of energy is released. Use information from the figure above to justify this figure, explaining how you arrive at your answer.

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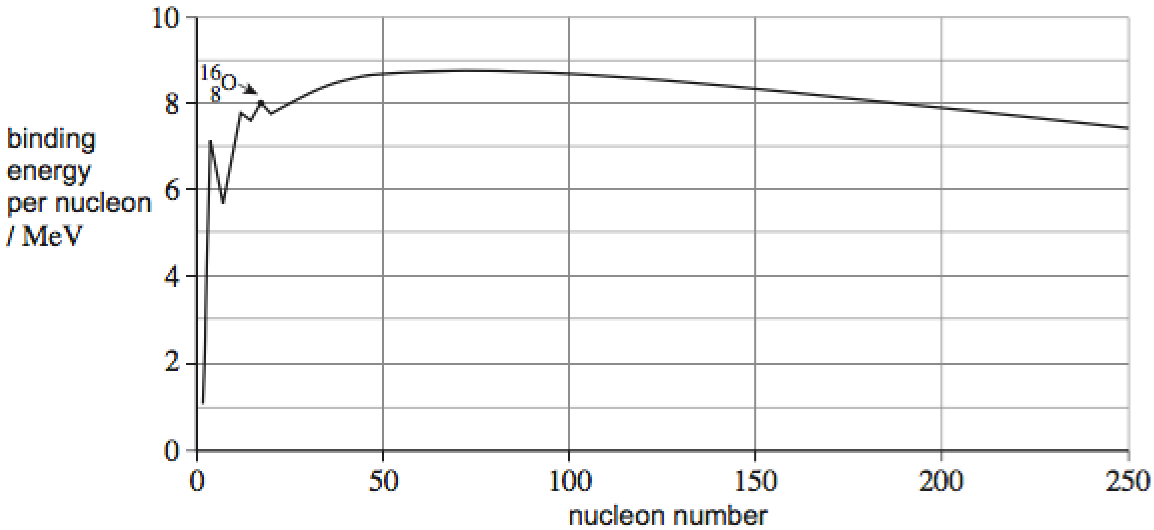
(5)

(Total 7 marks)

15 The diagram shows how the binding energy per nucleon varies with nucleon number.



(a) (i) Fission and fusion are two nuclear processes in which energy can be released. Explain why nuclei that undergo fission are restricted to a different part of the graph than those that undergo fusion.

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(2)

(ii) Explain, with reference to the diagram, why the energy released per nucleon from fusion is greater than that from fission.

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(2)

(b) (i) Calculate the mass difference, in kg, of the $^{16}_{8}O$ nucleus.

mass of $^{16}_{8}O$ nucleus = 15.991 u

mass difference = ____________________ kg

(2)

(ii) Using your answer to part **(b)(i)**, calculate the binding energy, in MeV, of an oxygen $^{16}_{8}O$ nucleus.

binding energy = ____________________ MeV

(1)

(iii) Explain how the binding energy of an oxygen $^{16}_{8}O$ nucleus can be calculated with information obtained from the diagram.

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(1)

(Total 8 marks)

16 Deuterium ($^{2}_{1}H$) and tritium ($^{3}_{1}H$) nuclei will fuse together, as illustrated in the equation below.

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{A}_{Z}X + \text{neutron}$$

(a) State the nucleon number and the proton number for the product of the reaction which has been written as X in the equation.

nucleon number ____________________

proton number ____________________

(2)

(b) The masses of the particles involved in the reaction are:

mass of $^{2}_{1}H$ = 3.34250×10^{-27} kg

mass of $^{3}_{1}H$ = 5.00573×10^{-27} kg

mass of $^{A}_{Z}X$ = 6.62609×10^{-27} kg

mass of neutron = 1.67438×10^{-27} kg

(i) Explain why energy is released during this reaction.

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(2)

(ii) Calculate the amount of energy released when a deuterium nucleus fuses with a tritium nucleus.

The speed of electromagnetic radiation, $c = 3.0 \times 10^{8}$ m s^{-1}

(3)

(Total 7 marks)

17 (a) Calculate the binding energy, in MeV, of a nucleus of $^{59}_{27}Co$.

nuclear mass of $^{59}_{27}Co$ = 58.93320 u

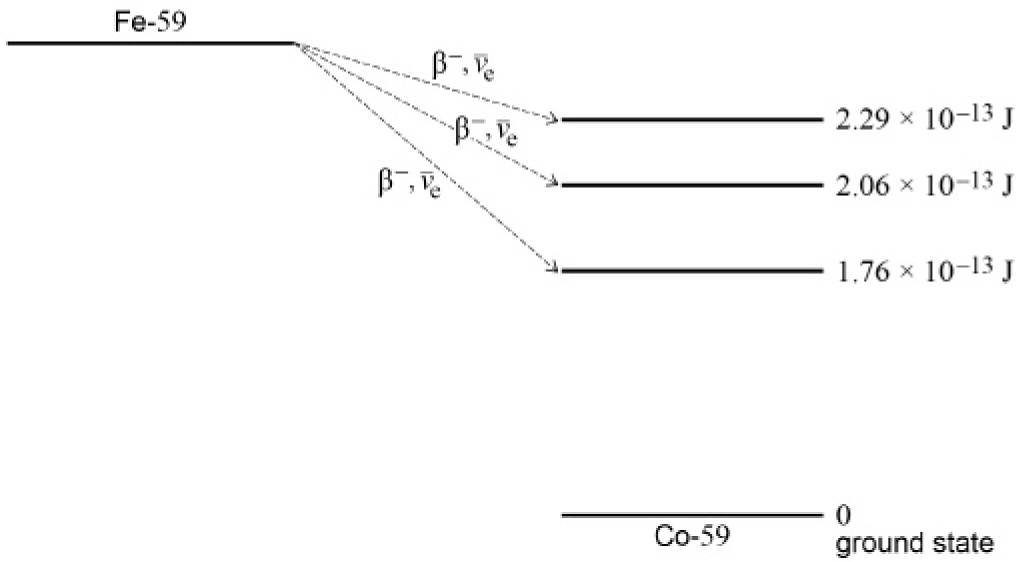
binding energy = ______________________ MeV

(3)

(b) A nucleus of iron Fe-59 decays into a stable nucleus of cobalt Co-59. It decays by β^- emission followed by the emission of γ-radiation as the Co-59 nucleus de-excites into its ground state.

The total energy released when the Fe-59 nucleus decays is 2.52×10^{-13} J.

The Fe-59 nucleus can decay to one of three excited states of the cobalt-59 nucleus as shown below. The energies of the excited states are shown relative to the ground state.



Calculate the maximum possible kinetic energy, in MeV, of the β^- particle emitted when the Fe-59 nucleus decays into an excited state that has energy above the ground state.

maximum kinetic energy = ____________________ MeV

(2)

(c) Following the production of excited states of $^{59}_{27}Co$, γ-radiation of discrete wavelengths is emitted.

State the maximum number of discrete wavelengths that could be emitted.

maximum number = ____________________

(1)

(d) Calculate the longest wavelength of the emitted γ-radiation.

Longest wavelength = ____________________ m

(3)

(Total 9 marks)

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

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(2)

(b) (i) When a $^{235}_{92}\mathrm{U}$ nucleus absorbs a slow-moving neutron and undergoes fission one possible pair of fission fragments is technetium $^{112}_{43}\mathrm{Tc}$ and indium $^{122}_{49}\mathrm{In}$.

Complete the following equation to represent this fission process.

$$^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{112}_{43}\mathrm{Tc} + {}^{122}_{49}\mathrm{In} + \ldots\ldots\ldots\ldots\ldots$$

(1)

(ii) Calculate the energy released, in MeV, when a single $^{235}_{92}\mathrm{U}$ nucleus undergoes fission in this way.

binding energy per nucleon of $^{235}_{92}\mathrm{U}$ = 7.59 MeV

binding energy per nucleon of $^{112}_{43}\mathrm{Tc}$ = 8.36 MeV

binding energy per nucleon of $^{122}_{49}\mathrm{In}$ = 8.51 MeV

energy released ____________________ MeV

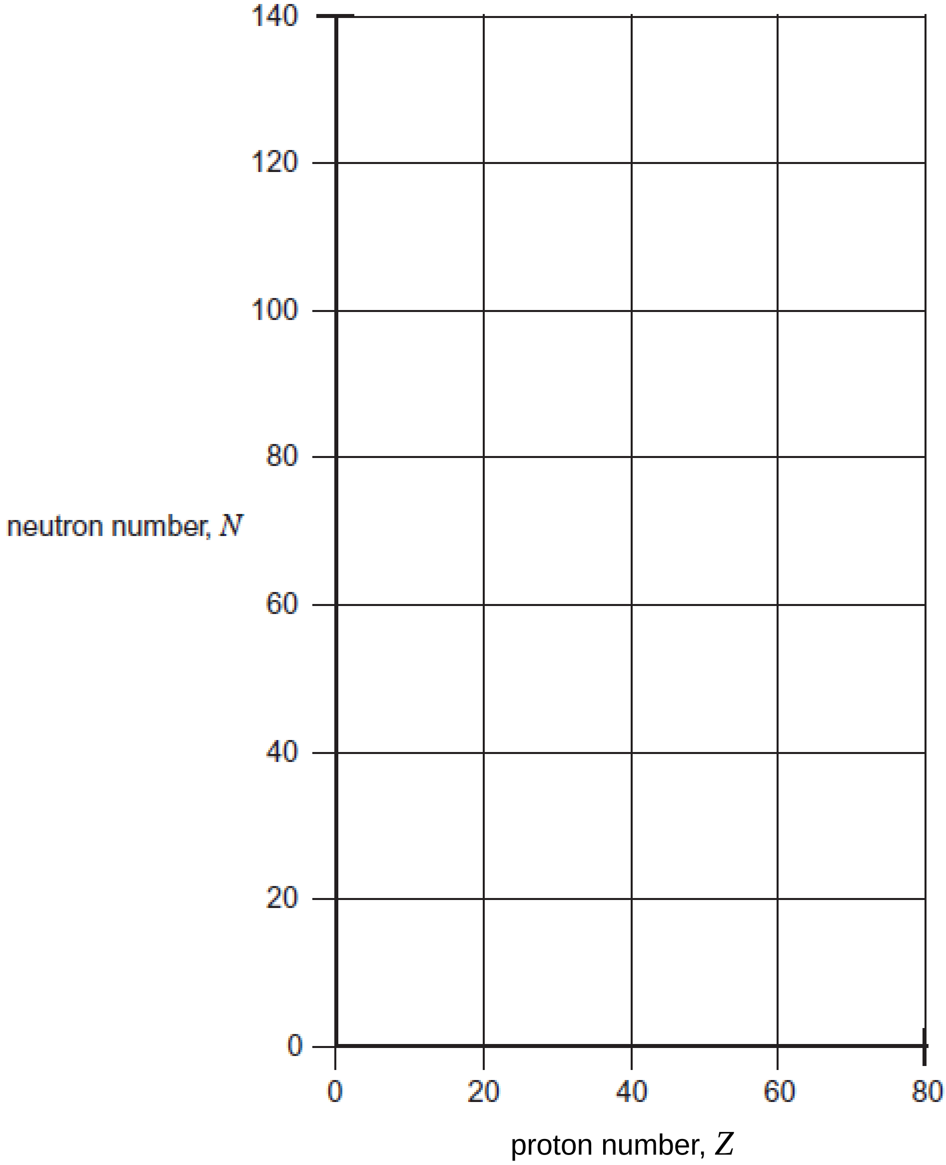
(3)

(iii) Calculate the loss of mass when a $^{235}_{92}\mathrm{U}$ nucleus undergoes fission in this way.

loss of mass ____________________ kg

(2)

(c) (i) On the figure below sketch a graph of neutron number, N, against proton number, Z, for stable nuclei.



(1)

(ii) With reference to the figure, explain why fission fragments are unstable and explain what type of radiation they are likely to emit initially.

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(3)

(Total 12 marks)

19 In a geothermal power station, water is pumped through pipes into an underground region of hot rocks. The thermal energy of the rocks heats the water and turns it to steam at high pressure. The steam then drives a turbine at the surface to produce electricity.

(a) Water at 21°C is pumped into the hot rocks and steam at 100°C is produced at a rate of 190 kg s^{-1}.

(i) Show that the energy per second transferred from the hot rocks to the power station in this process is at least 500 MW.

specific heat capacity of water = 4200 J kg^{-1} K^{-1}
specific latent heat of steam = 2.3×10^6 J kg^{-1}

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(ii) The hot rocks are estimated to have a volume of 4.0×10^6 m^3. Estimate the fall of temperature of these rocks in one day if thermal energy is removed from them at the rate calculated in part (i) without any thermal energy gain from deeper underground.

specific heat capacity of the rocks = 850 J kg^{-1} K^{-1}
density of the rocks = 3200 kg m^{-3}

(7)

(b) Geothermal energy originates as energy released in the radioactive decay of the uranium isotope $^{238}_{92}$U deep inside the Earth. Each nucleus that decays releases 4.2 MeV. Calculate the mass of $^{238}_{92}$U that would release energy at a rate of 500 MW.

half-life of $^{238}_{92}$U = 4.5×10^9 years

molar mass of $^{238}_{92}$U = 0.238 kg mol^{-1}

(5)
(Total 12 marks)

20 (a) (i) Define the atomic mass unit.

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(1)

(ii) State and explain how the mass of a $^{4}_{2}He$ nucleus is different from the total mass of its protons and neutrons when separated.

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(2)

(b) Explain why nuclei in a star have to be at a high temperature for fusion to take place.

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(3)

(c) (i) In massive stars, nuclei of hydrogen $^{1}_{1}H$ are processed into nuclei of helium $^{4}_{2}He$ through a series of interactions involving carbon, nitrogen and oxygen called the CNO cycle.

Complete the nuclear equations below that represent the last two reactions in the series.

$$^{\cdots\cdots}_{8}O \rightarrow \, ^{15}_{7}N + \,\ldots\ldots\ldots + \nu_e$$

$$^{15}_{7}N + \, ^{1}_{1}H \rightarrow \, ^{\cdots\cdots}_{6}C + \, ^{4}_{2}He$$

(3)

(ii) The whole series of reactions is summarised by the following equation.

$$4\,{}^{1}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + 2\mathrm{e}^{+} + 2\,\nu_{\mathrm{e}}$$

Calculate the energy, in Me V, that is released.

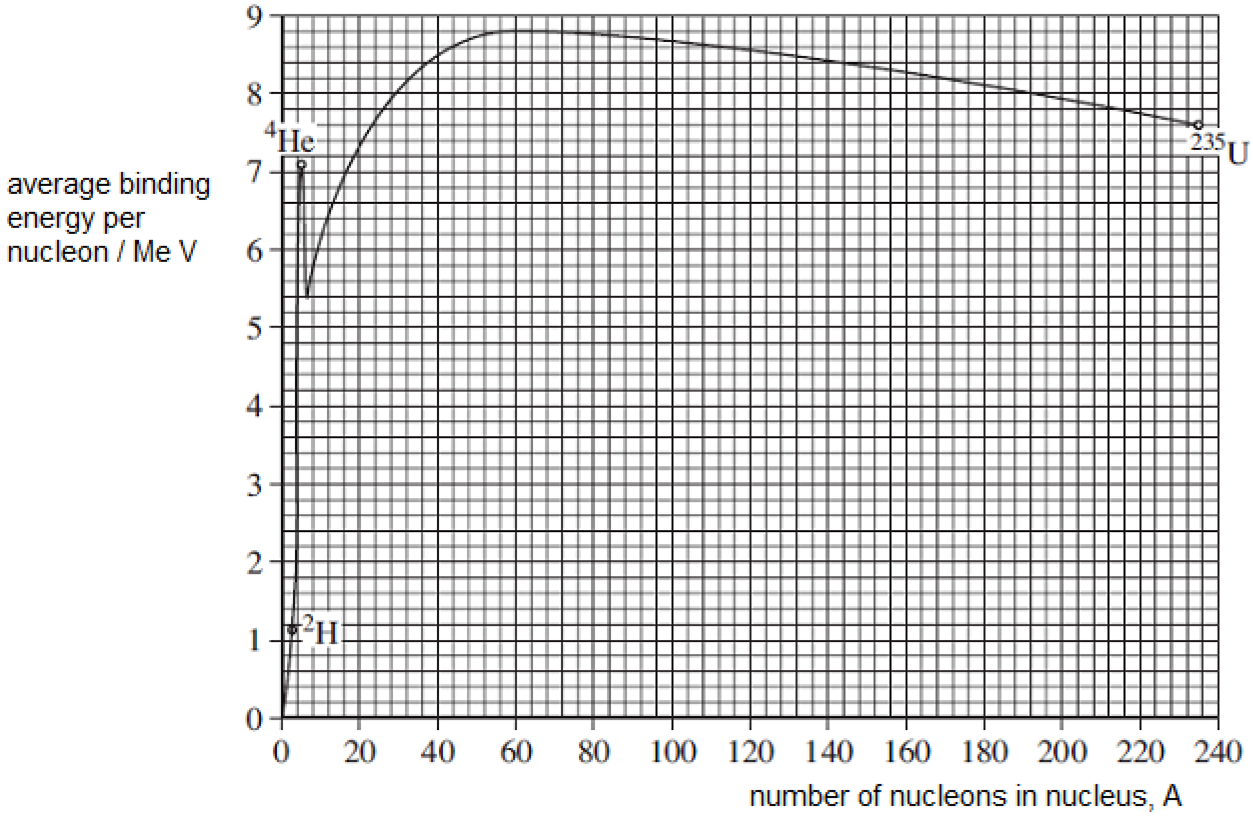
nuclear mass of ${}^{4}_{2}\mathrm{He}$ = 4.00150 u

energy ____________________ Me V

(3)

(Total 12 marks)

21 The figure below shows the variation in binding energy per nucleon with nucleon number.



(a) A uranium-235, ^{235}U, nucleus fissions into two approximately equally sized products. Use data from the graph to show that the energy released as a result of the fission is approximately 4×10^{-11} J.
Show on the graph how you have used the data.

(4)

(b) Using the data below, show that the energy available from the fusion of two hydrogen-2, ^{2}H, nuclei to make a helium-4, ^{4}He, nucleus is approximately 3.7×10^{-12} J.

mass of ^{2}H = 2.0135 u
mass of ^{4}He = 4.0026 u

(4)

(c) Compare the energy available from the complete fission of 1 kg of uranium-235 with the energy available from the fusion of 1 kg of hydrogen-2.

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(3)

(d) Fission and fusion reactions release different amounts of energy. Discuss other reasons why it would be preferable to use fusion rather than fission for the production of electricity, assuming that the technical problems associated with fusion could be overcome.

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(2)

(Total 13 marks)

22 In stars, helium-3 and helium-4 are formed by the fusion of hydrogen nuclei. As the temperature rises, a helium-3 nucleus and a helium-4 nucleus can fuse to produce beryllium-7 with the release of energy in the form of gamma radiation.

The table below shows the masses of these nuclei.

Nucleus	**Mass / u**
Helium-3	3.01493
Helium-4	4.00151
Beryllium-7	7.01473

(a) (i) Calculate the energy released, in J, when a helium-3 nucleus fuses with a helium-4 nucleus.

energy released ____________________ J

(4)

(ii) Assume that in each interaction the energy is released as a single gamma-ray photon.

Calculate the wavelength of the gamma radiation.

wavelength ____________________ m

(3)

(b) For a helium-3 nucleus and a helium-4 nucleus to fuse they need to be separated by no more than 3.5×10^{-15} m.

(i) Calculate the minimum total kinetic energy of the nuclei required for them to reach a separation of 3.5×10^{-15} m.

total kinetic energy ____________________ J

(3)

(ii) Calculate the temperature at which two nuclei with the average kinetic energy for that temperature would be able to fuse.
Assume that the two nuclei have equal kinetic energy.

temperature ____________________ K

(3)

(c) Scientists continue to try to produce a viable fusion reactor to generate energy on Earth using reactors like the Joint European Torus (JET). The method requires a plasma that has to be raised to a suitable temperature for fusion to take place.

(i) State **two** nuclei that are most likely to be used to form the plasma of a fusion reactor.

1. ____

2. ____

(2)

(ii) State **one** method which can be used to raise the temperature of the plasma to a suitable temperature.

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(1)
(Total 16 marks)

23 The Sun's energy is produced by the fusion of protons. Near the Sun's surface the protons have a mean kinetic energy of 0.75 eV which is too low for fusion to take place. The core, however, has a temperature of about 1.5×10^6 K and a pressure of about 1.0×10^{16} Pa. This core consists of a plasma of (mainly) protons. Within the core the density, pressure and temperature of the proton plasma are sufficiently high for nuclear fusion to occur.
The energy is thought to be produced mainly by a cycle called the hydrogen cycle. The overall effect in one cycle is that 4 protons fuse to form a helium nucleus. The total mass of hydrogen that fuses each second is 7.0×10^{11} kg of which about 5.0×10^9 kg per second is converted into energy that is radiated.

When answering the following questions assume, where necessary, that the plasma behaves like an ideal gas.

(a) (i) Use the mean value of the kinetic energy of protons near the Sun's surface to calculate the temperature near its surface.

temperature near the Sun's surface ____________________ K

(3)

(ii) Calculate the closest distance of approach for two protons near the Sun's surface.

closest distance of approach ____________________ m

(3)

(iii) Explain why fusion cannot occur near the surface.

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(3)

(b) (i) Calculate the number of protons in each cubic metre of the Sun's core.

number of protons ____________________

(3)

(ii) Calculate the density of the Sun's core.

density of the Sun's core ____________________ kg m $^{-3}$

(2)

(c) (i) Show that the data given in the passage in question (a) suggest that every second, about 4×10^{38} protons fuse to form helium nuclei.

(2)

(ii) The total binding energy of a helium nucleus is 4.5×10^{-12} J.
Determine with an appropriate calculation whether the mass that is converted into radiant energy, stated in the passage, is consistent with this value.

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(4)

(Total 20 marks)