

1

- (a) Explain what is meant by a **thermal** neutron.

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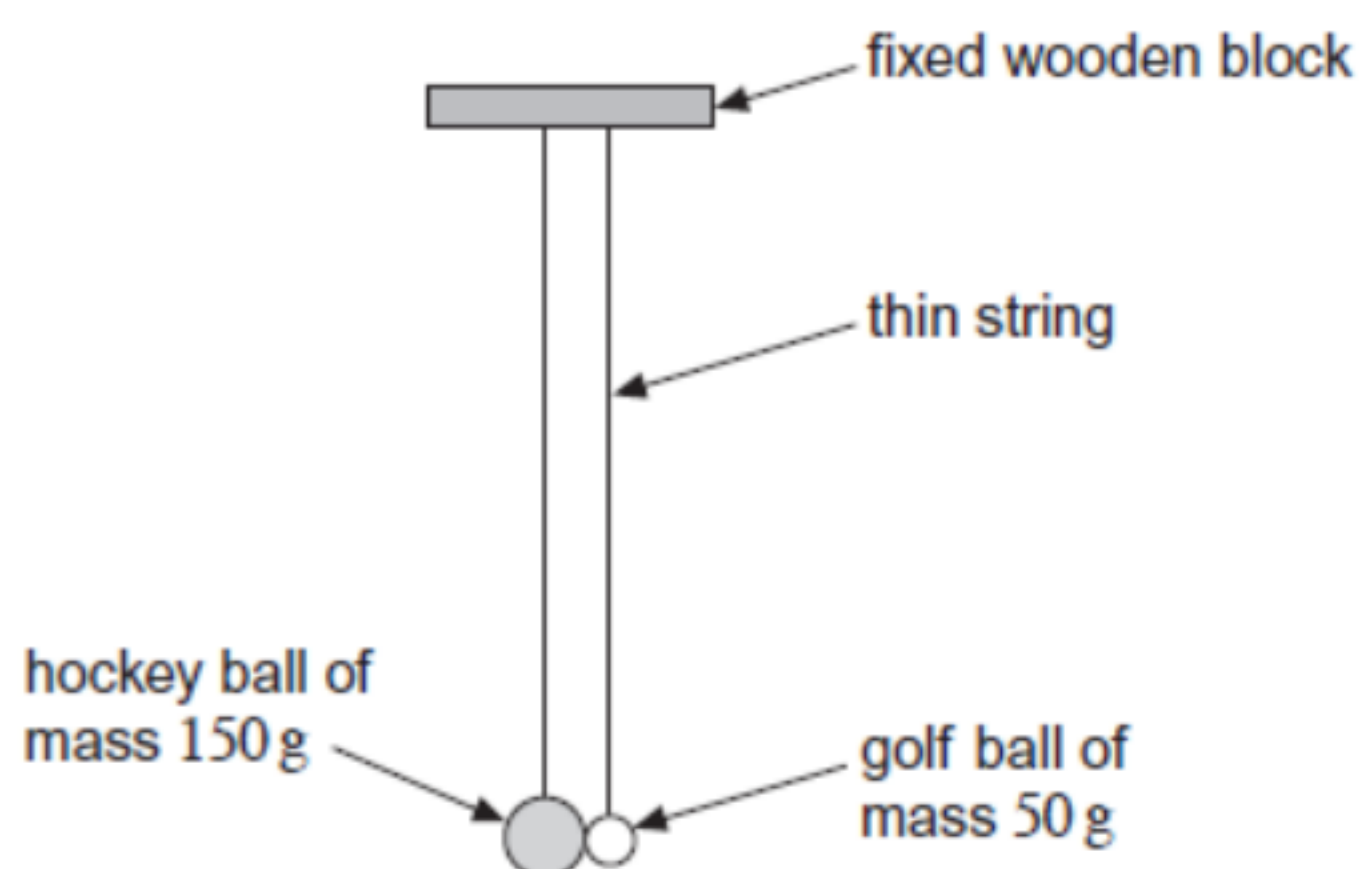
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(2)

- (b) A student sets up the arrangement, shown in the diagram below, to demonstrate the principle of moderation in a nuclear reactor.



A golf ball of mass 50 g is initially hanging vertically and just touching a hockey ball of mass 150 g. The golf ball is pulled up to the side and released. It has a speed of  $1.3 \text{ m s}^{-1}$  when it collides head-on with the hockey ball. After the collision the balls move in opposite directions with equal speeds of  $0.65 \text{ m s}^{-1}$ .

- (i) Calculate the height above its initial position from which the golf ball is released. Assume that there is no air resistance.

height \_\_\_\_\_ m

(2)

- (ii) Show that momentum is conserved in the collision and that the collision is perfectly elastic.

(4)

- (iii) Calculate the percentage of the kinetic energy of the golf ball transferred to the hockey ball during the collision.

percentage transferred \_\_\_\_\_ %

(2)

- (iv) Explain how this demonstration relates to the moderation process in a reactor and state **one** way in which the collisions in a reactor differ from the collision in the demonstration.

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(2)

- (v) Name the substance used as the moderator in a pressurised water reactor (PWR).

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(1)

(Total 13 marks)

2

A rod made from uranium-238 ( $^{238}_{92}\text{U}$ ) is placed in the core of a nuclear reactor where it absorbs free neutrons.

When a nucleus of uranium-238 absorbs a neutron it becomes unstable and decays to

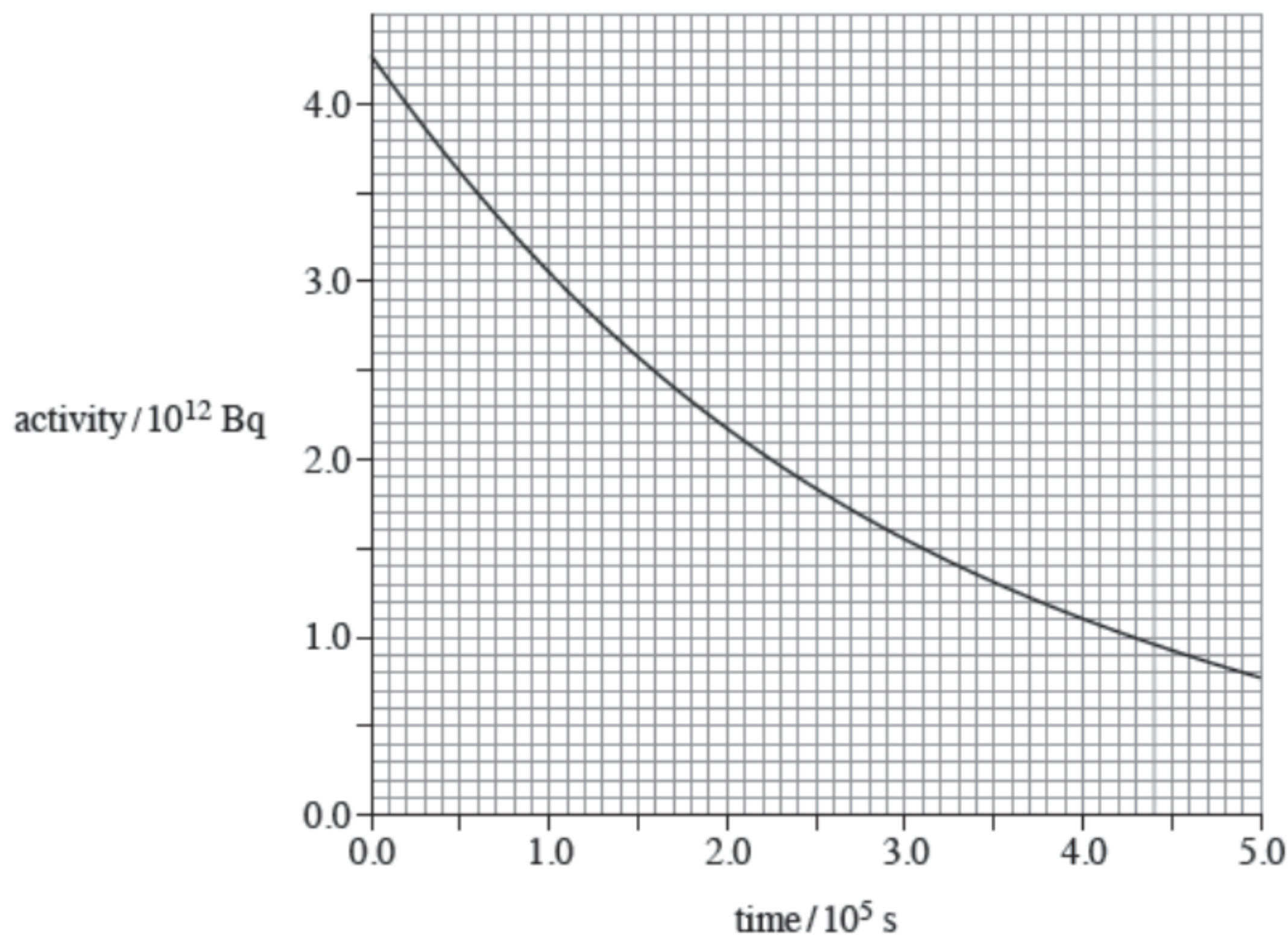
neptunium-239 ( $^{239}_{93}\text{Np}$ ), which in turn decays to plutonium-239 ( $^{239}_{94}\text{Pu}$ ).

- (a) Write down the nuclear equation that represents the decay of neptunium-239 into plutonium-239.

(2)

- (b) A sample of the rod is removed from the core and its radiation is monitored from time  $t = 0$  s.

The variation of the activity with time is shown in the graph.



- (i) Show that the decay constant of the sample is about  $3.4 \times 10^{-6} \text{ s}^{-1}$ .

(2)

- (ii) Assume that the activity shown in the graph comes only from the decay of neptunium.

Estimate the number of neptunium nuclei present in the sample at time  $t = 5.0 \times 10^5$  s.

number of nuclei \_\_\_\_\_

(1)

- (c) (i) A chain reaction is maintained in the core of a thermal nuclear reactor that is operating normally.

Explain what is meant by a chain reaction, naming the materials and particles involved.

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(2)

- (ii) Explain the purpose of a moderator in a thermal nuclear reactor.

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(2)

- (iii) Substantial shielding around the core protects nearby workers from the most hazardous radiations. Radiation from the core includes  $\alpha$  and  $\beta$  particles,  $\gamma$  rays, X-rays, neutrons and neutrinos.

Explain why the shielding becomes radioactive.

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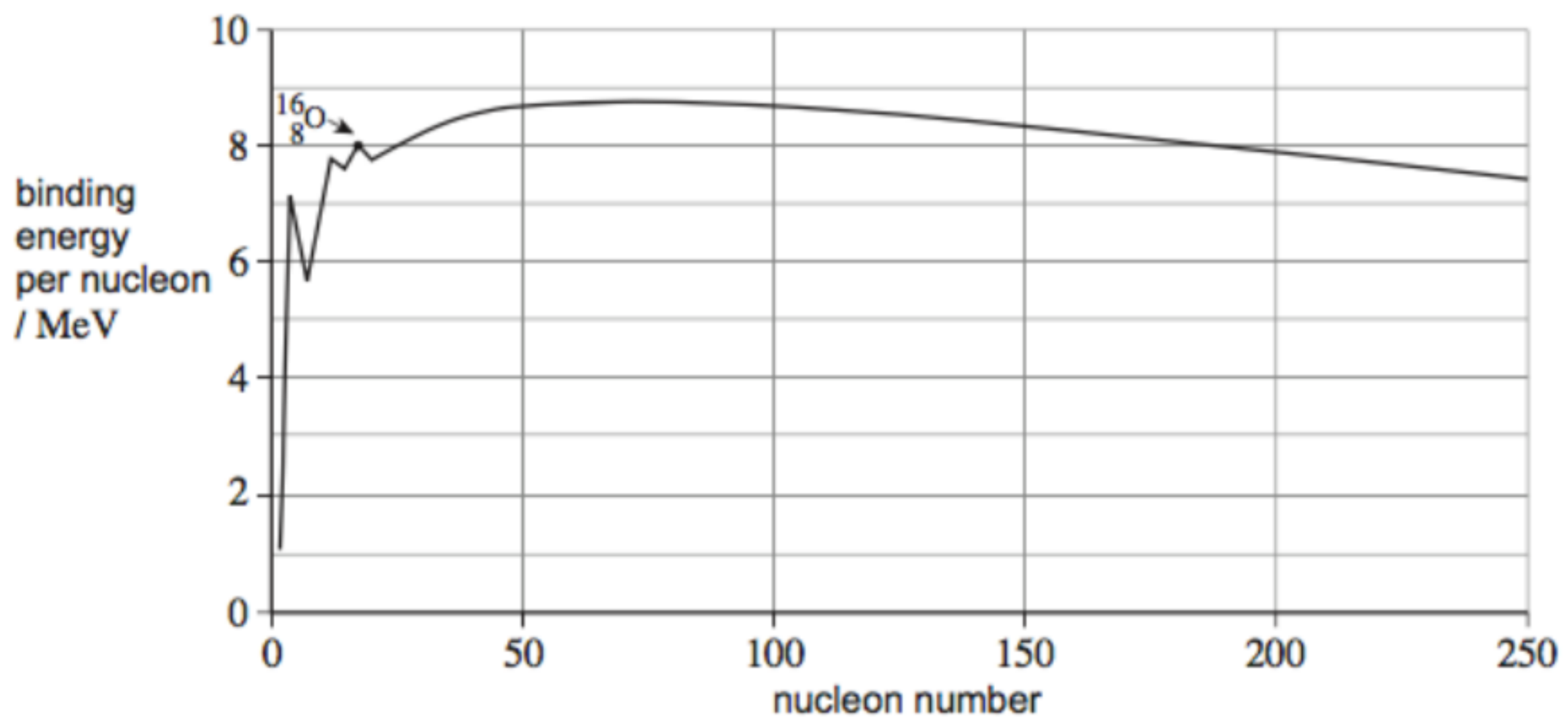
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(2)

(Total 11 marks)

3

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  $^{16}_8\text{O}$  nucleus.

mass of  $^{16}_8\text{O}$  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  $^{16}_8\text{O}$  nucleus.

binding energy = \_\_\_\_\_ MeV

**(1)**

- (iii) Explain how the binding energy of an oxygen  $^{16}_8\text{O}$  nucleus can be calculated with information obtained from the diagram.

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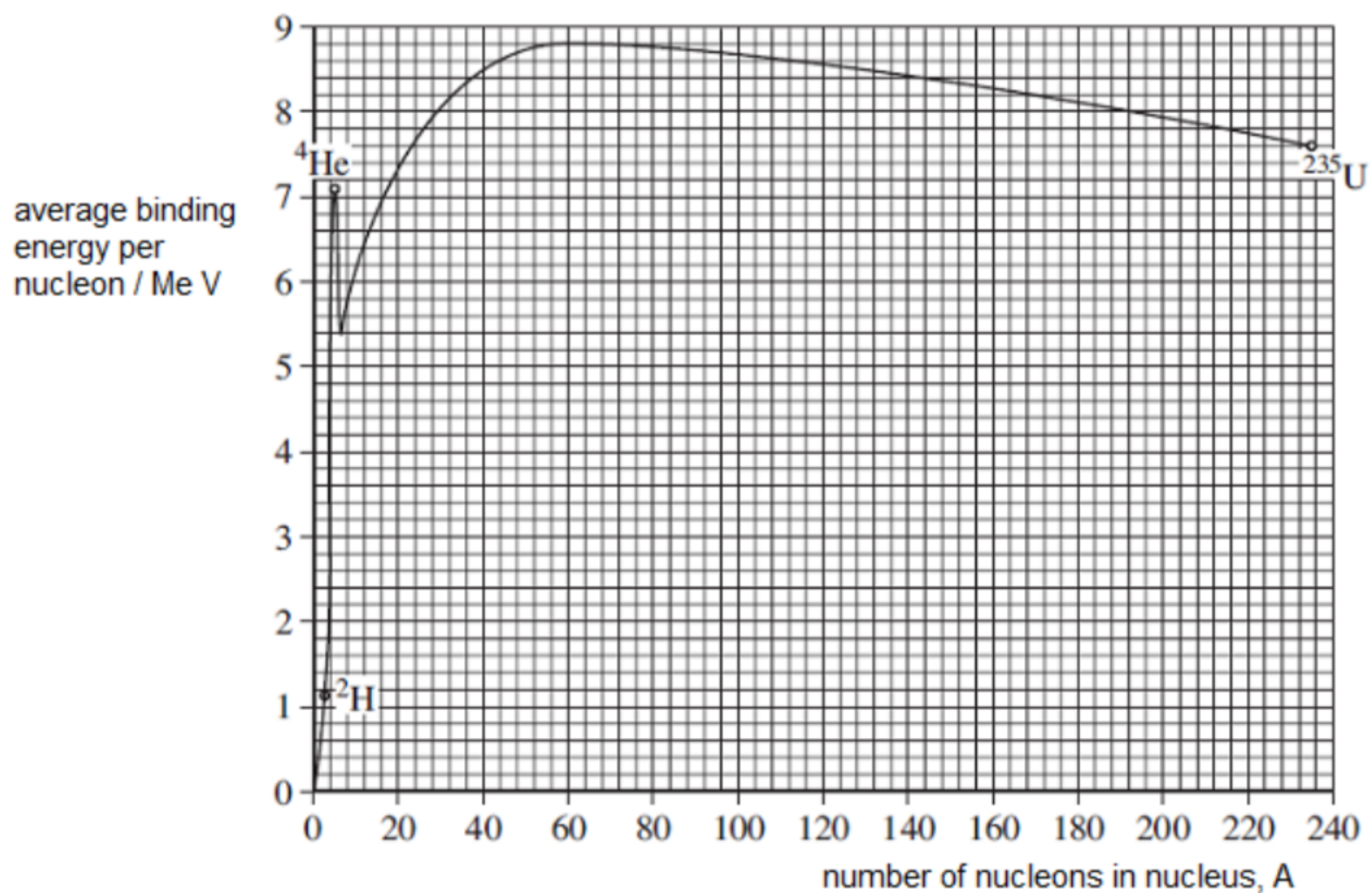
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**(1)**

**(Total 8 marks)**

4

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



- (a) A uranium-235,  ${}^{235}\text{U}$ , 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  $4 \times 10^{-11}\text{J}$ . Show on the graph how you have used the data.

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

mass of  $^2\text{H} = 2.0135 \text{ u}$

mass of  $^4\text{He} = 4.0026 \text{ u}$

(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)

5

- (a) Describe the changes made inside a nuclear reactor to reduce its power output and explain the process involved.

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(2)

- (b) State the main source of the highly radioactive waste from a nuclear reactor.

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(1)

- (c) In a nuclear reactor, neutrons are released with high energies. The first few collisions of a neutron with the moderator transfer sufficient energy to excite nuclei of the moderator.

- (i) Describe and explain the nature of the radiation that may be emitted from an excited nucleus of the moderator.

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(2)

- (ii) The subsequent collisions of a neutron with the moderator are elastic.

Describe what happens to the neutrons as a result of these subsequent collisions with the moderator.

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(2)

(Total 7 marks)

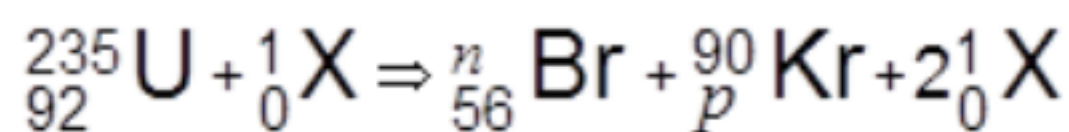
**6**

In a nuclear reactor the mean energy produced by each uranium-235 nucleus that undergoes induced fission is  $3.0 \times 10^{-11}$  J. In one pressurised water reactor, PWR, the fuel rods in the reactor contain  $2.0 \times 10^4$  kg of uranium-235 and 40% of the energy produced per second is converted to 500 MW of electrical output power. It is assumed that all the energy produced in the reactor core is removed by pressurised water in the coolant system. The pressure of the water is approximately 150 times greater than normal atmospheric pressure. The water enters the reactor at a temperature of  $275^\circ\text{C}$  and leaves at a temperature of  $315^\circ\text{C}$ . Under the operational conditions of the reactor the mean density of water in the coolant circuit is  $730 \text{ kg m}^{-3}$  and the specific heat capacity of water is approximately  $5000 \text{ J kg}^{-1} \text{ K}^{-1}$ .

normal atmospheric pressure =  $1.0 \times 10^5 \text{ Pa}$

molar mass of uranium-235 =  $0.235 \text{ kg}$

- (a) The equation below gives one induced fission reaction that takes place in a reactor.



- (i) State the name of the particle represented by **X**.

\_\_\_\_\_

(1)

- (ii) State the proton and nucleon numbers represented by  $p$  and  $n$ .

$p$  \_\_\_\_\_

$n$  \_\_\_\_\_

(2)

- (b) (i) Calculate the number of fission reactions that occur in the reactor each second.

number of fission reactions per second \_\_\_\_\_

(2)

- (ii) The reactor fuel rods contain  $2.0 \times 10^4$  kg of uranium-235. Assume that all this uranium-235 could be used.

Calculate the maximum time, in years, for which the reactor could operate.

time \_\_\_\_\_ years

(4)

- (iii) Suggest why it is not possible to use all the uranium-235 in the reactor fuel rods.

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(2)

- (c) Calculate the force exerted by the pressurised water on each square centimetre of the wall of the reactor.

force \_\_\_\_\_ N

(2)

- (d) Calculate, in  $\text{m}^3 \text{s}^{-1}$ , the flow rate of the water through the PWR reactor.  
You will need to use data from the passage at the beginning of the question.

flow rate \_\_\_\_\_  $\text{m}^3 \text{s}^{-1}$

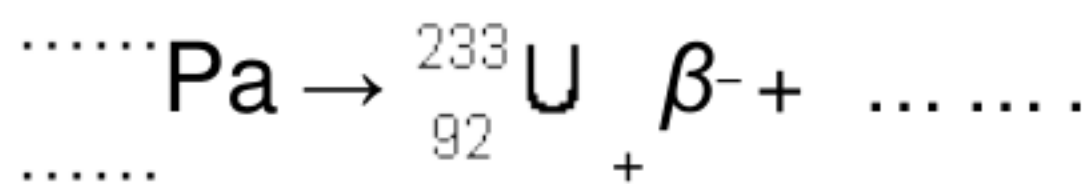
(4)

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- This image shows a blank sheet of white paper with horizontal ruling lines. The lines are evenly spaced and run across the width of the page. There are no margins, text, or other markings on the paper.

**(Total 21 marks)**

The fissile isotope of uranium,  ${}_{92}^{233}\text{U}$ , has been used in some nuclear reactors. It is normally produced by neutron irradiation of thorium-232. An irradiated thorium nucleus emits a  $\beta^-$  particle to become an isotope of protactinium.

(a) Complete the following equation to show the  $\beta^-$  decay of protactinium.



(2)

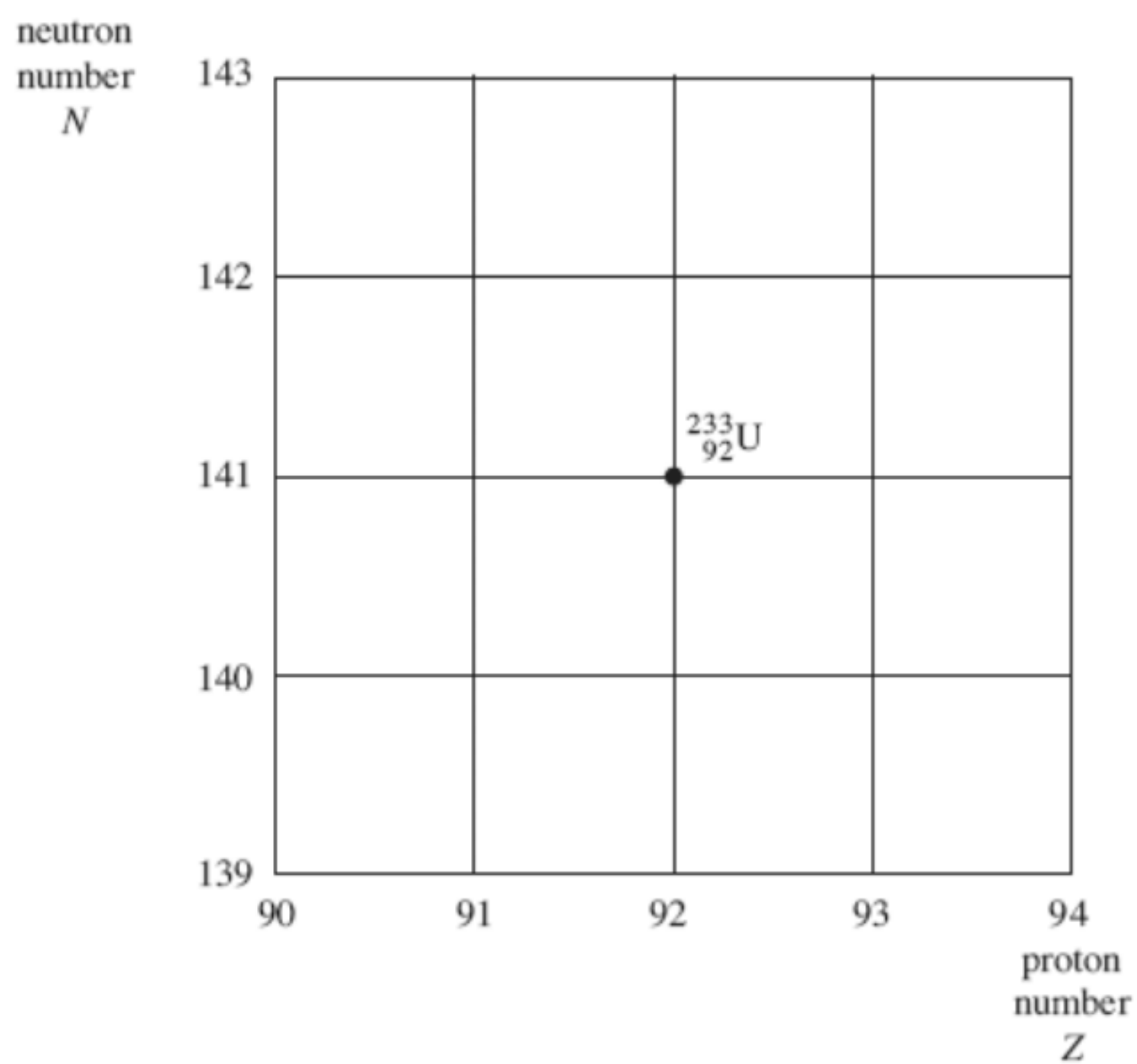
(b) Two other nuclei, **P** and **Q**, can also decay into  ${}_{92}^{233}\text{U}$ .

**P** decays by  $\beta^+$  decay to produce  ${}_{92}^{233}\text{U}$ .

**Q** decays by  $\alpha$  emission to produce  ${}_{92}^{233}\text{U}$ .

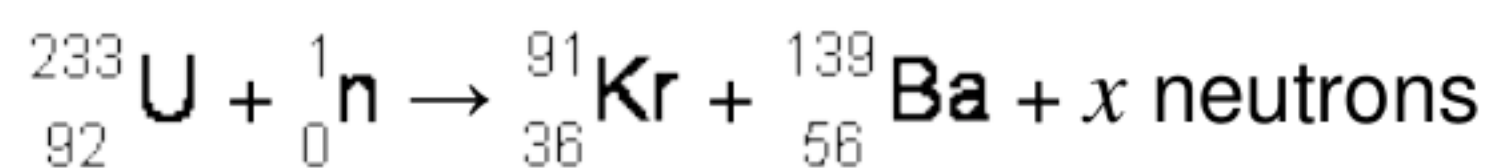
The figure below shows a grid of neutron number against proton number with the position of the  ${}_{92}^{233}\text{U}$  isotope shown.

On the grid label the positions of the nuclei **P** and **Q**.



(2)

- (c) A typical fission reaction in the reactor is represented by



- (i) Calculate the number of neutrons,  $x$ .

answer = \_\_\_\_\_ neutrons

(1)

- (ii) Calculate the energy released, in MeV, in the fission reaction above.

mass of neutron = 1.00867 u

mass of  ${}_{92}^{233}\text{U}$  nucleus = 232.98915 u

mass of  ${}_{36}^{91}\text{Kr}$  nucleus = 90.90368 u

mass of  ${}_{56}^{139}\text{Ba}$  nucleus = 138.87810 u

answer = \_\_\_\_\_ MeV

(3)

(Total 8 marks)

**8** For a nuclear reactor in which the fission rate is constant, which one of the following statements is correct?

- A** There is a critical mass of fuel in the reactor.
- B** For every fission event, there is, on average, one further fission event.
- C** A single neutron is released in every fission event.
- D** No neutrons escape from the reactor.

(Total 1 mark)

**9** Which line, **A** to **D**, in the table gives a combination of materials that is commonly used for moderating, controlling and shielding respectively in a nuclear reactor?

|          | <b>moderating</b> | <b>controlling</b> | <b>shielding</b> |
|----------|-------------------|--------------------|------------------|
| <b>A</b> | graphite          | carbon             | lead             |
| <b>B</b> | cadmium           | carbon             | concrete         |
| <b>C</b> | cadmium           | boron              | lead             |
| <b>D</b> | graphite          | boron              | concrete         |

(Total 1 mark)

**10** Which one of the following statements is **not** true about the control rods used in a nuclear reactor?

- A** They must absorb neutrons.
- B** They must slow down neutrons to thermal speeds.
- C** They must retain their shape at high temperatures.
- D** The length of rod in the reactor must be variable.

(Total 1 mark)

**11** Why is a moderator required in a thermal nuclear reactor?

- A** to prevent overheating of the nuclear core
- B** to absorb surplus uranium nuclei
- C** to shield the surroundings from gamma radiation
- D** to reduce the kinetic energy of fission neutrons

(Total 1 mark)

12

The sodium isotope  $^{24}_{11}\text{Na}$  is a radioactive isotope that can be produced by bombarding the aluminium isotope  $^{27}_{13}\text{Al}$  with neutrons. Which line, **A** to **D**, in the table correctly represents the production of  $^{24}_{11}\text{Na}$  from the aluminium isotope  $^{27}_{13}\text{Al}$  and its subsequent decay?

|          | production                                                                               | decay                                                                              |
|----------|------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|
| <b>A</b> | $^{27}_{13}\text{Al} + {}^1_0\text{n} \rightarrow ^{24}_{11}\text{Na} + {}^4_2\alpha$    | $^{24}_{11}\text{Na} \rightarrow ^{24}_{12}\text{Mg} + {}^0_{+1}\beta + \nu$       |
| <b>B</b> | $^{27}_{13}\text{Al} + {}^1_0\text{n} \rightarrow ^{24}_{11}\text{Na} + {}^4_2\alpha$    | $^{24}_{11}\text{Na} \rightarrow ^{24}_{12}\text{Mg} + {}^0_{-1}\beta + \bar{\nu}$ |
| <b>C</b> | $^{27}_{13}\text{Al} + {}^1_0\text{n} \rightarrow ^{24}_{11}\text{Na} + {}^3_2\text{He}$ | $^{24}_{11}\text{Na} \rightarrow ^{24}_{12}\text{Mg} + {}^0_{+1}\beta + \nu$       |
| <b>D</b> | $^{27}_{13}\text{Al} + {}^1_0\text{n} \rightarrow ^{24}_{11}\text{Na} + {}^3_2\text{He}$ | $^{24}_{11}\text{Na} \rightarrow ^{24}_{12}\text{Mg} + {}^0_{-1}\beta + \bar{\nu}$ |

(Total 1 mark)

13

A thermal nuclear reactor is shut down by inserting the control rods fully into the core. Which line, **A** to **D**, shows correctly the effect of this action on the fission neutrons in the reactor?

|          | number of fission neutrons | average kinetic energy of fission neutrons |
|----------|----------------------------|--------------------------------------------|
| <b>A</b> | reduced                    | reduced                                    |
| <b>B</b> | reduced                    | unchanged                                  |
| <b>C</b> | unchanged                  | reduced                                    |
| <b>D</b> | unchanged                  | unchanged                                  |

(Total 1 mark)

14

In a thermal reactor, induced fission is caused by the  $^{235}_{92}\text{U}$  nucleus capturing a neutron, undergoing fission and producing more neutrons. Which one of the following statements is true?

- A** To sustain the reaction a large number of neutrons is required per fission.
- B** The purpose of the moderator is to absorb all the heat produced.
- C** The neutrons required for induced fission of  $^{235}_{92}\text{U}$  should be slow neutrons.
- D** The purpose of the control rods is to slow down neutrons to thermal speeds.

(Total 1 mark)

**15**

Artificial radioactive nuclides are manufactured by placing naturally-occurring nuclides in a nuclear reactor. They are made radioactive in the reactor as a consequence of bombardment by

- A**  $\alpha$  particles.
- B**  $\beta$  particles.
- C** protons.
- D** neutrons.

(Total 1 mark)

**16**

- (a) In the reactor at a nuclear power station, uranium nuclei undergo *induced fission* with *thermal neutrons*. Explain what is meant by each of the terms in italics.

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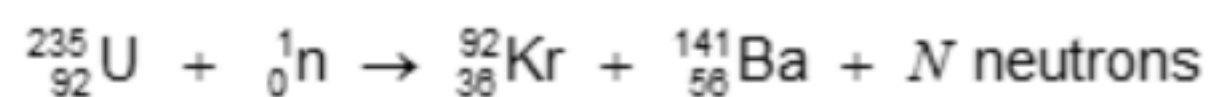
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(3)

- (b) A typical fission reaction in the reactor is represented by



- (i) Calculate  $N$ .

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- (ii) How do the neutrons produced by this reaction differ from the initial neutron that goes into the reaction?

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- (iii) Calculate the energy released in MeV when one uranium nucleus undergoes fission in this reaction. Use the following data.

|                                   |               |
|-----------------------------------|---------------|
| mass of neutron                   | = 1.00867 u   |
| mass of $^{235}\text{U}$ nucleus  | = 234.99333 u |
| mass of $^{92}\text{Kr}$ nucleus  | = 91.90645 u  |
| mass of $^{141}\text{Ba}$ nucleus | = 140.88354 u |
| 1 u is equivalent to 931 MeV      |               |

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(5)

(Total 8 marks)

17

The moderator in a nuclear reactor is sometimes made of graphite. What is the purpose of the graphite?

- A** to absorb all the heat produced
- B** to decrease the neutron speeds
- C** to absorb  $\alpha$  and  $\gamma$  radiations
- D** to prevent the reactor from going critical

(Total 1 mark)

18

The moderator in a nuclear reactor is sometimes made of graphite. What is the purpose of the graphite?

- A** to absorb all the heat produced
- B** to decrease the neutron speeds
- C** to absorb the  $\alpha$  and  $\gamma$  radiations
- D** to prevent the reactor from going critical

(Total 1 mark)

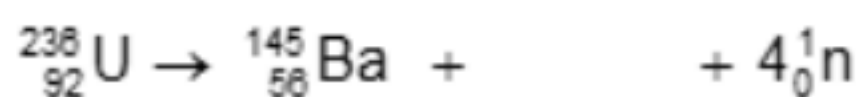
19

(a) The unstable uranium nucleus  $^{238}_{92}\text{U}$  is produced in a nuclear reactor.

- (i) Complete the equation which shows the formation of  $^{238}_{92}\text{U}$ .



- (ii)  $^{238}_{92}\text{U}$  can decay by nuclear fission in many different ways. Complete the equation which shows one possible decay channel.



(2)

- (b) Calculate the energy released, in MeV, in the fission reaction.

atomic mass of  $^{145}_{56}\text{Ba} = 144.92694 \text{ u}$

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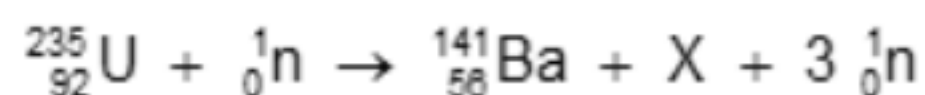
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(3)

(Total 5 marks)

20

- (a) Nuclear fission can occur when a neutron is absorbed by a nucleus of uranium-235. An incomplete equation for a typical fission reaction is given below.



- (i) State the nuclear composition of X.

proton number \_\_\_\_\_

neutron number \_\_\_\_\_

- (ii) Name the element of which X is an isotope.

\_\_\_\_\_

(3)

- (b) In a small nuclear power plant one fifth of the fission energy is converted into a useful output power of 10 MW. If the average energy released per fission is  $3.2 \times 10^{-11} \text{ J}$ , calculate the number of uranium-235 nuclei which will undergo fission per day.

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(3)

**21**

A space probe contains a small fission reactor, fuelled by plutonium, which is designed to produce an average of 300 W of useful power for 100 years. If the overall efficiency of the reactor is 10%, calculate the minimum mass of plutonium required.

energy released by the fission of one nucleus of  $^{239}_{94}\text{Pu} = 3.2 \times 10^{-11}\text{J}$

the Avogadro constant =  $6.0 \times 10^{23} \text{ mol}^{-1}$

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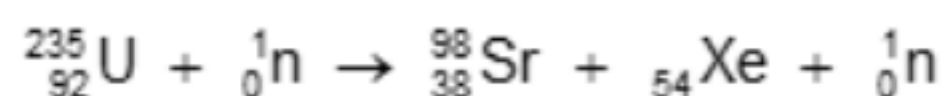
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(Total 7 marks)

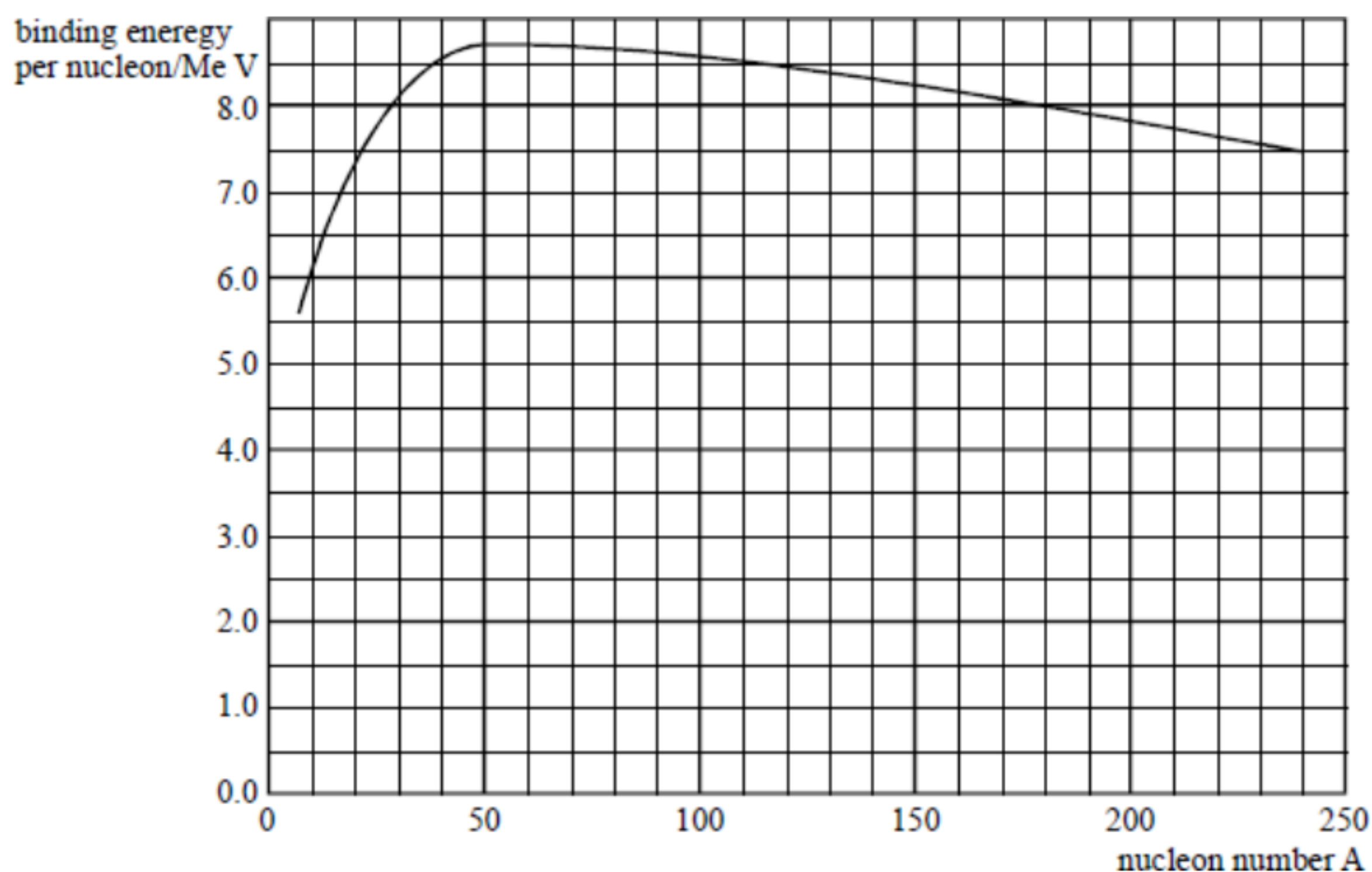
**22**

(a) (i) Complete the equation below which represents the induced fission of a nucleus of uranium  $^{235}_{92}\text{U}$ .



- (ii) The graph shows the binding energy per nucleon plotted against nucleon number A.

Mark on the graph the position of each of the three nuclei in the equation.



- (iii) Hence determine the energy released in the fission process represented by the equation.

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(6)

- (b) (i) Use your answer to part (a)(iii) to estimate the energy released when 1.0 kg of uranium, containing 3% by mass of  $^{235}_{92}\text{U}$ , undergoes fission.

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- (ii) Oil releases approximately 50 MJ of heat per kg when it is burned in air. State and explain **one** advantage and **one** disadvantage of using nuclear fuel to produce electricity.

advantage \_\_\_\_\_

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disadvantage \_\_\_\_\_

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(6)

(Total 12 marks)

23

Natural uranium consists of 99.3%  $^{238}_{92}\text{U}$  and 0.7%  $^{235}_{92}\text{U}$ . In many nuclear reactors, the fuel consists of enriched uranium enclosed in sealed metal containers.

- (a) (i) Explain what is meant by *enriched uranium*.

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- (ii) Why is enriched uranium rather than natural uranium used in many nuclear reactors?

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(2)

- (b) (i) By considering the neutrons involved in the fission process, explain how the rate of production of heat in a nuclear reactor is controlled.

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- (ii) Explain why all the fuel in a nuclear reactor is **not** placed in a single fuel rod.

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(5)

(Total 7 marks)

- (a) (i) Explain what is meant by the term *binding energy* for a nucleus.

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- (ii) Sketch on the axes a graph of the average binding energy per nucleon against nucleon number  $A$ , giving approximate values of the scale on each axis.



(5)

- (b) Use your graph to explain why energy is released when a neutron collides with a  ${}^{235}_{92}\text{U}$  nucleus causing fission.

(2)

- (c) Neutrons are released when nuclear fission occurs in  ${}^{235}_{92}\text{U}$ . Some of these neutrons induce further fission, others are absorbed without further fission and others escape from the surface of the material. The average number of neutrons released per fission is 2.5, of which at least one must produce further fission if a chain reaction is to be sustained.

Explain how a chain reaction can occur only if the piece of uranium has a certain minimum mass (the *critical mass*).

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(3)

(Total 10 marks)

## Mark schemes

1

(a) ANY 2 from

- Slow moving neutrons or low (kinetic) energy neutrons

B1

- (They are in) thermal equilibrium with the moderator /  
Are in thermal equilibrium with other material (at a  
temperature of about 300 K)

B1

- Have energies of order of 0.025 eV
- Have (range of) KE similar to that of a gas at 300 K or  
room temperature

2

(b) (i) Use of  $mgh = \frac{1}{2}mv^2$  by substitution or rearranges to make  
h the subject

*PE for use of equation of motion (constant acceleration)*

C1

0.086(1) (m) or 0.086(2) (m)

A1

2

- (ii) Correct equation for conservation of momentum

$$m_1 u_1 (+ m_2 u_2) = m_1 v_1 + m_2 v_2$$

**or** states momentum before = momentum after **or**  $p_{\text{before}} = p_{\text{after}}$

B1

(Correct clear Manipulation =)  $0.065 (+ 0) = - 0.0325 + 0.0975$

**or**  $-0.065 (+ 0) = 0.0325 - 0.0975$  must see signs

*Condone non-SI here:*

$$65 (+0) = - 32.5 + 97.5$$

B1

**States** initial kinetic energy = final kinetic energy **or**

**States** kinetic energy is conserved

*Allow equivalent on RHS where masses are summed in one KE term*

B1

(Correct clear Manipulation=)  $0.04225 = 0.0105625 + 0.0316875$

Or equivalent workings with numbers seen

**and**  $0.04225 = 0.04225$  / KE before = KE after

B1

4

- (iii) (Percentage / fraction remaining after 1 collision =)  $\frac{1}{4} = 25\%$   
**seen**

C1

**OR**

$$\% \text{ remaining} = 100 \times \frac{1}{2} m(1.3^2 - 0.65^2) / \frac{1}{2} m1.3^2$$

**or** hockey ball = 0.0317 **and** initial ke = 0.04225

**or** their  $KE_{\text{hb}} / 0.04225$  or their  $KE_{\text{hb}} / \text{their } KE_{\text{T}}$

75(%)

range 75 to 76

A1

2

(iv) **Demonstrates:**

Slowing down / loss of KE of golf ball is like neutrons slowed down / Neutrons can lose KE by elastic collisions also

B1

**Differs:**

Collisions in a reactor are not always / rarely head-on

**or**

KE loss is variable

**or**

Collisions are not always elastic

**or**

Ratio of mass of neutron to mass of nucleus is usually much smaller in a reactor

B1

2

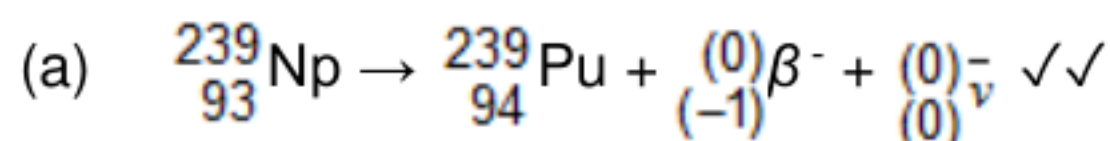
(v) Water

B1

1

[13]

2



*First mark for one anti-neutrino or one beta minus particle in any form e.g.  $e^{-}$ . If subscript and superscripts are given for these they must be correct but ignore the type of neutrino if indicated.*

*The second mark is for both particles and the rest of the equation. Ignore the full sequence if it is shown but the Np to Pu must be given separately for the mark.*

2

- (b) (i)  $T_{1/2} 2.0 \rightarrow 2.1 \times 10^5 \text{ s} \checkmark$   
 then substitute and calculate  
 $\lambda = \ln 2 / T_{1/2} \checkmark$

*$T_{1/2}$  may be determined from graph not starting at zero time.  
 Look for the correct power of 10 in the half-life – possible AE.*

Or

(substitute two points from the graph into  $A = A_0 e^{-\lambda t}$ )

e.g.  $0.77 \times 10^{12} = 4.25 \times 10^{12} \exp(-\lambda \times 5 \times 10^5) \checkmark$

then make  $\lambda$  the subject and calculate  $\checkmark$

(the rearrangement looks like

$$\lambda = [\ln (A_0 / A)] / t$$

$$\text{or } \lambda = - [\ln (A / A_0)] / t$$

*Allow the rare alternative of using the time constant of the decay*

$$A = A_0 \exp (-t / t_{tc})$$

*from graph  $t_{tc} = 2.9 \rightarrow 3.1 \times 10^5 \text{ s} \checkmark$*

$$\lambda = 1 / t_{tc} = 3.4 \times 10^{-6} \text{ s}^{-1} \checkmark$$

*No CE is allowed within this question.*

both alternatives give

$$\lambda = 3.3 \rightarrow 3.5 \times 10^{-6} \text{ s}^{-1} \checkmark$$

*For reference*

$$T_{1/2} = 2.0 \times 10^5 \text{ s gives}$$

$$\lambda = 3.5 \times 10^{-6} \text{ s}^{-1} \text{ and}$$

$$T_{1/2} = 2.1 \times 10^5 \text{ s gives}$$

$$\lambda = 3.3 \times 10^{-6} \text{ s}^{-1}.$$

2

- (ii) (using  $A = N\lambda$   
 $N = 0.77 \times 10^{12} / 3.4 \times 10^{-6} = 2.2(6) \times 10^{17}$  )  
 allow 2.2  $\rightarrow 2.4 \times 10^{17}$  nuclei  $\checkmark$

*A possible route is find  $N_0 = A_0 / \lambda$*

*then use  $N = N_0 e^{-\lambda t}$ .*

*Condone lone answer.*

1

- (c) (i) uranium (– 235 captures) a neutron (and splits into 2 smaller nuclei / fission fragments) releasing more neutrons  $\checkmark$

*First mark for uranium + neutron gives more neutrons.*

*Ignore which isotope of uranium is used.*

(at least one of) these neutrons go on to cause further / more splitting / fissioning (of uranium– 235)  $\checkmark$

*Second mark for released neutron causes more fission.*

*The word 'reaction' may replace 'fission' here provided 'fission / splitting of uranium' is given somewhere in the answer.*

2

- (ii) **Escalate if clip shows critical mass in the question.**  
 the moderator slows down / reduces the kinetic energy of neutrons ✓  
 so neutrons are absorbed / react / fission (efficiently) by the uranium / fuel ✓  
*owtte*  
**Possible escalation.**

2

- (iii) neutrons are absorbed / collide with (by the nuclei in the shielding) ✓  
*Second mark is only given if neutrons appear somewhere in the answer.*

converting the nuclei / atoms (of the shielding) into unstable isotopes (owtte)

*No neutrons = no marks.*

*Making it neutron rich implies making them unstable.*

2

[11]

3

- (a) (i) Fission occurs at  $A$  values above the peak / above  $A$  of about 56 and fusion occurs at  $A$  values below the peak / below  $A$  of about 56 ✓

Fission is the splitting of a nucleus (into two smaller ones) *and* fusion is the joining of two nuclei ✓

*First mark uses the graph so 'fission occurs in very large nuclei' does not gain a mark. (allow other interpretations that use the graph eg gradients)*

*2nd Mark splitting into 2 is not required for fission but if the answer implies something different like the separating of all the nucleons the mark may not be given.*

2

- (ii) Energy is released when the binding energy (per nucleon) is increased ✓  
 fusion energy is greater as the increase in  $BE(A)$  for fusion > increase in  $BE(A)$  for fission (owtte) ✓

*The last point can be given for a reference to the larger gradient at small values of  $A$  (fusion region) compared to the gradient at large values of  $A$  (fission region)*

2

- (b) (i)  $\Delta m = (8m_p + 8m_n) - M_{\text{oxygen}}$   
 mark for substituting data into the above equation in any workable consistent units

$$= 8(1.00867 + 1.00728) - 15.991 \checkmark$$

$$(\Delta m = 0.1366 \text{ u})$$

$$\Delta m = 0.1366 \times 1.661 \times 10^{-27} = 2.3 \times 10^{-28} \text{ (kg)} \checkmark$$

(range of answers  $2.2 - 2.3 \times 10^{-28} \text{ kg}$ )

*Substitution may take the following form*

$$8(1.673 \times 10^{-27}) + 8(1.675 \times 10^{-27}) - (15.991 \times 1.661 \times 10^{-27}) \checkmark$$

$$= 2.23 \times 10^{-28} \text{ (kg)} \checkmark$$

*Correct answer gains full marks.*

*Look out for a physics error in which u is not taken as  $1.661 \times 10^{-27} \text{ kg}$*

2

- (ii)  $E = m \times c^2 = 2.3 \times 10^{-28} \times (3.00 \times 10^8)^2 = 2.07 \times 10^{-11} \text{ J}$   
 $\text{BE} = 2.07 \times 10^{-11} / 1.6 \times 10^{-13} = 130 \text{ (MeV)} \checkmark (129 \text{ MeV})$   
 Or using  
 using  $\Delta m = 0.1366 \text{ u}$  (this must appear in b(i) for this approach)  
 $\text{BE} = 0.1366 \times 931.3 = 130 \text{ (MeV)} \checkmark (127 \text{ MeV})$

*CE is allowed but only if the calculation is shown*

*Note answer =  $b(i) \times 5.625 \times 10^{29}$*

*answer only is acceptable for one mark.*

*(factor may be 931 or 931.5)*

1

- (iii) read from the graph the BE/A for  $^{16}_8\text{O}$  and multiply by the number of nucleons (or 16)  
 $\checkmark$

Or show the calculation

$$\text{BE} = 8(\text{MeV}) \times 16(\text{nucleons}) = 130 \text{ (MeV)} \checkmark (128 \text{ MeV}) \checkmark$$

*There must be a reference to  $^{16}_8\text{O}$  position on the graph.*

*with the calculation allow  $\text{BE} = 8.1(\text{MeV}) \times 16(\text{nucleons}) = 130 \text{ (MeV)}$*

*A calculation may lead to an answer in joule*

1

[8]

4

- (a) Draws appropriate triangle on graph or other mark on graph at  $\sim 118$

**B1**

Change of approx 1 Me V per nucleon is multiplied by 235

**B1**

Multiplies by  $1.6 \times 10^{-13}$

**B1**

Quotes their answer of approx  $3.8 \times 10^{-11}$  to more than 2 sf

**B1**

4

- (b)  $(2 \times 2.0135) - 4.0026$  seen or 0.0244 (u)

**C1**

Multiplies u by  $1.7 \times 10^{-27}$

**C1**

$E = mc^2$  seen or multiplies by  $(3 \times 10^8)^2$

**C1**

$3.67 \times 10^{-12} \text{J}$

**A1**

4

- (c) Multiplies  $3.8 \times 10^{-11}$  or their (b) by  $6 \times 10^{23}$

**M1**

attempts to convert to energy per kg by multiplying by 1000 / 4 or 1000 / 235

**M1**

Compares  $5.5 \times 10^{14}$  (J) (Hydrogen) with  $9.6 \times 10^{13}$  (J) (Uranium) in some way eg by stating that the fusion reaction gives more energy (per kg) than the fission or very similar values – must be consequent on some correct analysis

**A1**

3

(d) Availability of fuel easier for fusion

B1

Doesn't produce radioactive fission products / no waste management problem

B1

2

[13]

5

(a) insert control rods (further) into the nuclear core / reactor ✓

*a change must be implied for 2 marks*

*marks by use of (further) or (more)*

*allow answers that discuss shut down as well as power reduction*

which will absorb (more) neutrons (reducing further fission reactions) ✓

*If a statement is made that is wrong but not asked for limit the score to 1 mark (e.g. wrong reference to moderator)*

2

(b) fission fragments / daughter products or spent / used fuel / uranium rods (allow) plutonium (produced from U-238) ✓

*not uranium on its own*

1

(c) (i) ✓ (electromagnetic radiation is emitted) ✓

*A reference to  $\alpha$  or  $\beta$  loses this first mark*

as the energy gaps are large (in a nucleus) as the nucleus de-excites down discrete energy levels to allow the nucleus to get to the ground level / state ✓  
mark for reason

*2<sup>nd</sup> mark must imply energy levels or states*

2

(ii) momentum / kinetic energy is transferred (to the moderator atoms)

or

a neutron slows down / loses kinetic energy (with each collision) ✓

(eventually) reaching speeds associated with thermal random motion or reaches speeds which can cause fission (owtte) ✓

2

[7]

6

(a) (i) neutron

B1

1

(ii)  $p = 36$

B1

$n = 144$

B1

2

(b) (i) total energy produced =  $\frac{500 \times 100}{40}$  MJ each second

C1

number of reaction =  $4.2 \times 10^{19}$  per second

A1

2

(ii) 1 kg contains  $(1000/235) \times 6.02 \times 10^{23}$  atoms of uranium

C1

total number of fissions =  $(1000/235) \times 6.02 \times 10^{23} \times 2 \times 10^4$   
 $(5.1 \times 10^{28})$

C1

time = total fissions available/number per second or  $1.2 \times 10^9$ s

C1

38.7(39) years

A1

4

(iii) too few neutrons produced to maintain the chain reaction

B1

probability of a neutron colliding with a uranium nucleus too low

B1

more absorption of neutrons in non-fission capture

B1

2

(c) pressure =  $150 \times 10^5$  (Pa) or  $F = PA$

C1

force on  $1 \text{ cm}^2 = 1500\text{N}$

A1

2

(d) energy removed each second

$$E = \frac{500 \times 100}{40} \text{ MJ} = 1.25 \times 10^9 \text{ J or } E = mc\Delta\theta$$

C1

$$1.25 \times 10^9 = m \times 5000 \times 40$$

C1

mass per second = 6250 kg

C1

volume per second =  $8.6(8.56) \text{ m}^3$

A1

4

(e) **control rods**

neutrons are absorbed

B1

by the nucleus of the boron/atoms

B1

**moderator**

neutrons are slowed down

B1

when colliding with the protons/hydrogen nucleus

B1

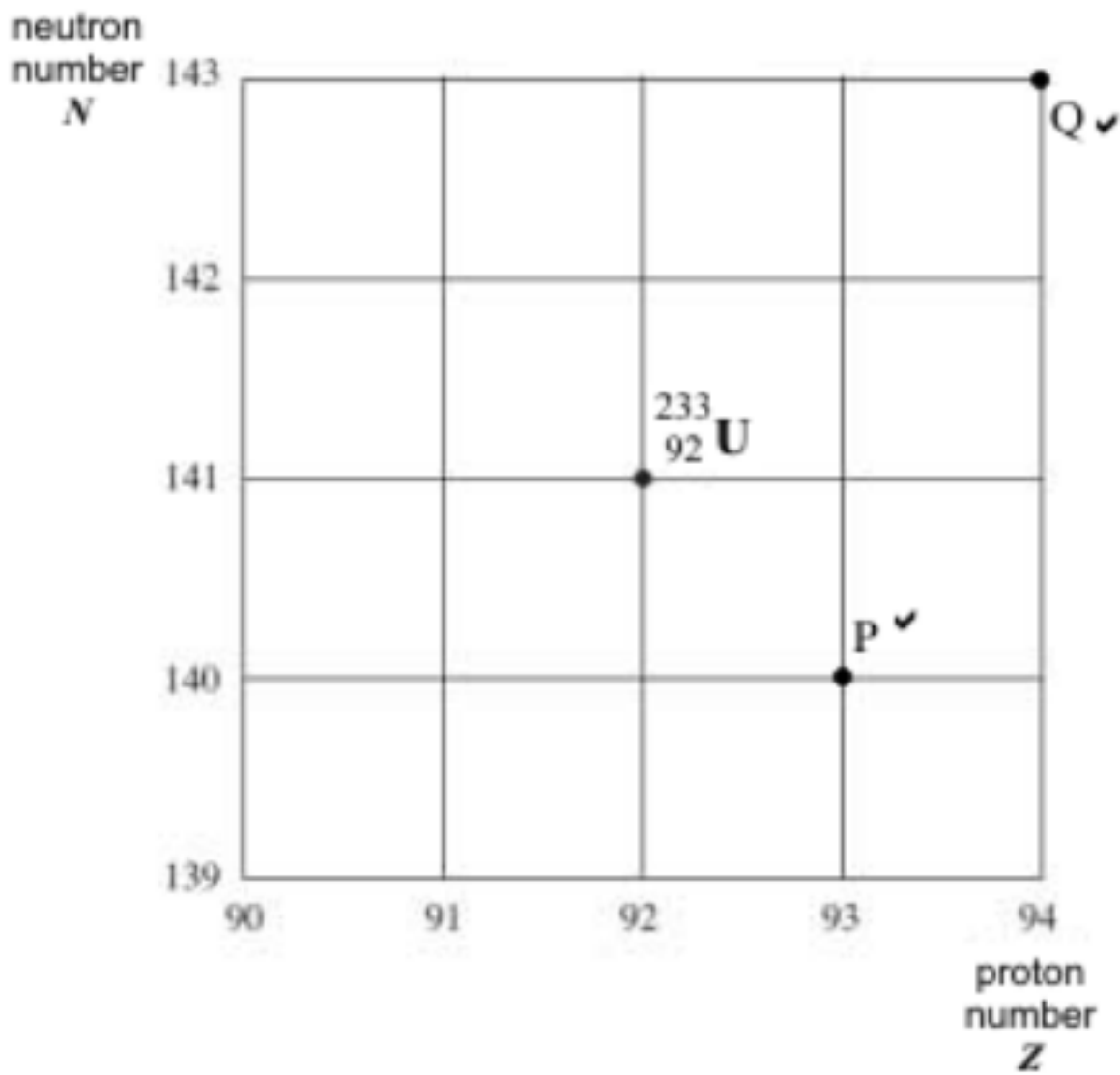
4

7

- (a)  ${}_{91}^{231}\text{Pa}$  ✓  
anti (electron) neutrino ✓

2

(b)



2

- (c) (i)  $x = 4$  ✓
- (ii) mass defect =  $[(232.98915 + 1.00867) - (90.90368 + 138.87810 + 4 \times 1.00867)] \text{ u}$  ✓  
 $= 0.18136 \text{ u}$  ✓

1

3

energy released  $(= 0.18136 \times 931) = 169 \text{ (MeV)}$  ✓

[8]

8

B

[1]

9

D

[1]

10

B

[1]

11

D

[1]

12

B

[1]

13

B

[1]

|    |     |                                                                                                                                                                                                                                                                                                                                                                                                                |     |
|----|-----|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----|
| 14 | C   |                                                                                                                                                                                                                                                                                                                                                                                                                | [1] |
| 15 | D   |                                                                                                                                                                                                                                                                                                                                                                                                                | [1] |
| 16 | (a) | induced fission: (large) <u>nucleus</u> splits unto two (smaller nuclei) (1)<br>brought about by bombardment or collision (1)<br>thermal neutrons have low energies or speeds (< 1 eV) (1)                                                                                                                                                                                                                     | 3   |
|    | (b) | (i) $N = 3$ (1)<br>(ii) released neutrons have high(er) energies or speeds (1)<br>(iii) $\Delta m = 234.99333 - (91.90645 + 140.88354) - (2 \times 1.00867)$ (1)<br>$= 0.186 \text{ u}$ (1)<br>(if last term in $\Delta m$ omitted or incorrect number of neutrons<br>used in calculation, treat answer as C.E.)<br>energy released = $0.186 \times 931 = 173 \text{ MeV}$ (1)<br>(allow C.E. for $\Delta m$ ) | 5   |
|    |     |                                                                                                                                                                                                                                                                                                                                                                                                                | [8] |
| 17 | B   |                                                                                                                                                                                                                                                                                                                                                                                                                | [1] |
| 18 | B   |                                                                                                                                                                                                                                                                                                                                                                                                                | [1] |
| 19 | (a) | (i) ${}_0^1\text{n} + {}_{92}^{235}\text{U} \rightarrow {}_{92}^{236}\text{U}$ (1)<br>(ii) ${}_{92}^{235}\text{U} \rightarrow {}_{56}^{145}\text{Ba} + {}_{36}^{87}\text{Kr} + 4{}_0^1\text{n}$ (1)                                                                                                                                                                                                            | (2) |
|    | (b) | ( $\Delta m = m_u - m_{\text{Ba}} - m_{\text{Kr}} - 4m_n$ , electron masses balance)<br>$\Delta m = 236.04573 - 144.92694 - 86.91340 - 4 \times 1.00867$ (1)<br>$= 0.17071 \text{ u}$ (1)<br>$Q (= 0.17071 \times 931.3 \text{ MeV}) = 159(\text{MeV})$ (1)                                                                                                                                                    | (3) |
|    |     |                                                                                                                                                                                                                                                                                                                                                                                                                | [5] |
| 20 | (a) | (i) proton number = 36 (1)<br>neutron number = 56 (1)<br>(ii) krypton (1)                                                                                                                                                                                                                                                                                                                                      | 3   |

(b) one-fifth efficiency so total output  $(= 10 \times \frac{100}{20} = 50 \text{ (MW)})$  (1)

energy in one day  $= 50 \times 10^6 \times 24 \times 3600 \text{ (J)}$  (1)  $(4.32 \times 10^{12} \text{ J})$

$$\text{fission atoms per day} = \frac{4.32 \times 10^{12}}{3.2 \times 10^{-11}} = 1.35 \times 10^{23} \text{ (1)}$$

3

[6]

21

100y  $= 100 \times 365 \times 24 \times 3600 (= 3.15 \times 10^9 \text{ s})$  (1)

energy needed  $= 3.15 \times 10^9 \times 300 \text{ (1)} \times 10 \text{ (1)} (= 9.46 \times 10^{12} \text{ J})$

$$\text{number of disintegrations} = \frac{9.46 \times 10^{12}}{3.2 \times 10^{-11}} (= 2.96 \times 10^{23}) \text{ (1)}$$

$$\text{number of moles needed} = \frac{2.96 \times 10^{23}}{6.02 \times 10^{23}} (= 0.49) \text{ (1)}$$

molar mass  $= 0.239 \text{ kg}$  (1)

mass needed  $= 0.49 \times 0.239 = 0.117 \text{ kg}$  (1)

[7]

22

(a) (i)  ${}_{92}^{235}\text{U} + {}_0^1\text{n} \rightarrow {}_{38}^{98}\text{Sr} + {}_{54}^{135}\text{Xe} + 3{}_0^1\text{n} (+Q)$  (1)

(ii) three correct positions to within  $\pm 2$  on x-axis (1) (1) (one mark if two correct)

(iii) *estimate of energy released:*

binding energy of U-235 nucleus  $= (235 \times 7.5) = 1763(\pm 15) \text{ (MeV)}$  (1)

binding energy of Sr-98  $= (98 \times 8.6) = 843(\pm 15) \text{ (MeV)}$  (1)

binding energy of Xe-135  $= (135 \times 8.4) = 1134(\pm 15) \text{ (MeV)}$  (1)

binding energy released  $= 1134 + 843 - 1763 = 214 \text{ MeV}$  (1)  
( $\pm 40 \text{ MeV}$ )

max 6

- (b) (i) 235g of U-235 releases  $6 \times 10^{23} \times 214 \times 1.6 \times 10^{-13} \text{ J} = 2.1 \times 10^{13} \text{ (J)}$  (1)  
 1.0 kg of uranium containing 3% U-235 contains 30g of U-235 (1)

energy from 1.0kg of uranium =  $\frac{2.1 \times 10^{13} \times 30}{235} = 2.6 \times 10^{12} \text{ J}$  [ $1.6 \times 10^{25} \text{ MeV}$ ]  
 (1)

- (ii) *advantage:*  
 less mass of fuel used (1) because more energy per kilogram (1)  
 [alternative: less harm to environment (1) because does not generate greenhouse gases (1)  
 or any statement (1) argued (1)]  
*disadvantage:*  
 hazardous waste (1) because fission products are radioactive (1)  
 [alternative: long term responsibility (1) because waste needs to be stored for many years (1)  
 or any statement (1) argued (1)]

max 6

[12]

23

- (a) (i) proportion of U-235 is greater than in natural uranium (1)  
 (ii) induced fission more probable with U-235 than with U-238 (1)

2

- (b) (i) for steady rate of fission, one neutron per fission required to go on to produce further fission (1)  
 each fission produces two or three neutrons on average (1)  
 some neutrons escape [or some absorbed by U-238 without fission] (1)  
 control rods absorb sufficient neutrons (to maintain steady rate of fission) (1)  
 (ii) neutrons need to pass through a moderator (1)  
 to slow them (in order to cause further fissions or prevent U-238 absorbing them) (1)  
 neutrons that leave the fuel rod (and pass through the moderator)  
 are unlikely to re-enter the same fuel rod (1)  
 makes it easier to replace the fuel in stages (1)

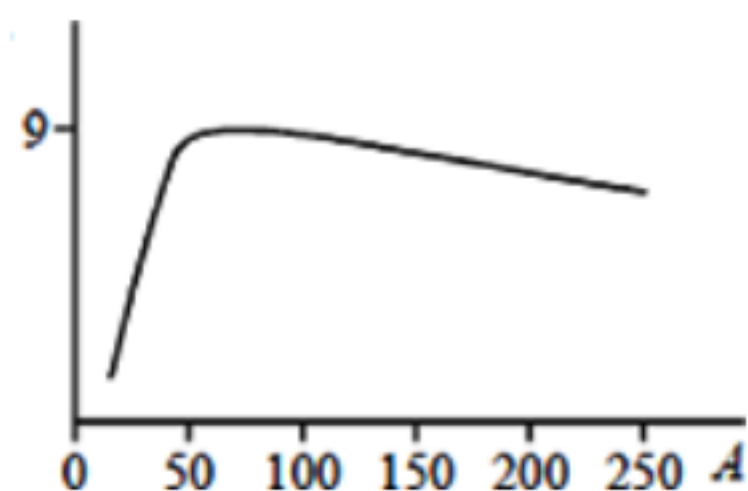
max 5

[7]

24

- (a) (i) binding energy is the work done on nucleons to separate nucleons completely [or the energy **released** by nucleons when nucleus is formed from separated nucleons] (1)

- (ii) average  
binding energy  
per nucleon



*curve:* correct shape, maximum at  $A$  between 40 – 60 (1)  
sharp rise from  $<50$  (binding energy)<sub>max</sub> (1)  
gradual fall to  $> 60\%$  (binding energy)<sub>max</sub>  
*scales:* binding energy per nucleon to 8 – 10 MeV (1)  
 $A$  to  $> 220$  (1)

(max 5)

- (b) uranium splits into two fragments (1)  
binding energy **per nucleon** rises (causing energy release) (1)

(2)

- (c) number of neutrons escaping is proportional to surface area (1)  
as mass increases a smaller fraction escapes (1)  
because surface/volume ratio decreases (1)  
hence fraction producing fission increases as mass increases (1)

(max 3)

[10]