IB · DP · Physics

3 hours 15 questions

Structured Questions

7.2 Nuclear Reactions

7.2.1 Atomic Mass Unit / 7.2.2 Mass Defect & Nuclear Binding Energy / 7.2.3 Nuclear Fission & Fusion / 7.2.4 Binding Energy per Nucleon Curve

Easy (5 questions)	/57
Medium (5 questions)	/57
Hard (5 questions)	/57
Total Marks	**/171**

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Easy Questions

1 (a) Define unified atomic mass unit.

(2 marks)

(b) The unified atomic mass unit (a.m.u) is roughly equal to the mass of one nucleon.

Calculate the mass of a nucleus of uranium−238. Give your answer to 3 significant figures.

You may take 1 a.m.u to be 1.66×10^{-27} kg.

(3 marks)

(c) Einstein's Theory of Relativity showed that mass could be converted into energy, and energy into mass. This is summarised in the equation:

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

Define the terms in the equation and give the units:

(i) *E* [1]

(ii) *m* [1]

(iii) *c* [1]

(3 marks)

(d) Calculate the energy (in J) released if all of the mass in the nucleus of uranium−238 were converted into energy.

(2 marks)

2 (a) Define:

(i) Binding energy.

[1]

(ii) Mass defect.

[1]

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(2 marks)

(b) The nuclear rest mass of oxygen−16 $\left({}^{16}_{8}\text{O}\right)$ is 15.994 914 u.

The mass defect, Δ*m*, equation describes the relationship between the proton number, *Z*, the number of neutrons, *N*, the proton rest mass, m_p, the neutron rest mass, m_n, and the nuclear rest mass, m_{total}.

$$\Delta m = Zm_p + Nm_n - m_{total}$$

Calculate the mass defect of oxygen−16. Give your answer to 6 d.p.

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(4 marks)

(c) The mass defect (from part (b)) can be used to calculate the binding energy.

Calculate the total binding energy for a nucleus of oxygen−16 in J

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(3 marks)

(d) Determine the binding energy per nucleon of oxygen−16 in J.

(2 marks)

3 (a) The binding energy per nucleon of Helium−4 $\left({}^{4}_{2}\text{He}\right)$ is 7.1 MeV.

Determine the energy required to completely separate the nucleons of the atom of helium. Give your answer in MeV.

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(2 marks)

(b) Match the processes with the correct definition by drawing a line:

Nuclear fusion	The splitting of a large atomic nucleus into smaller nuclei
Nuclear fission	The joining of two small nuclei to produce a larger nucleus

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(2 marks)

(c) Complete the following sentences using appropriate words:

Helium is formed inside main sequence stars due to the process of nuclear ________. For this process to occur, both nuclei must have high _______ energy. This high energy is because the protons inside the nuclei are ________ charged and a great deal of energy is needed to overcome the ________ force of repulsion.

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(3 marks)

(d) Complete the following sentences using appropriate words:

Nuclear ________ can be induced by firing ________ at a nucleus. When the nucleus is struck it splits into two or more ________ nuclei and more ________. This leads to a chain reaction.

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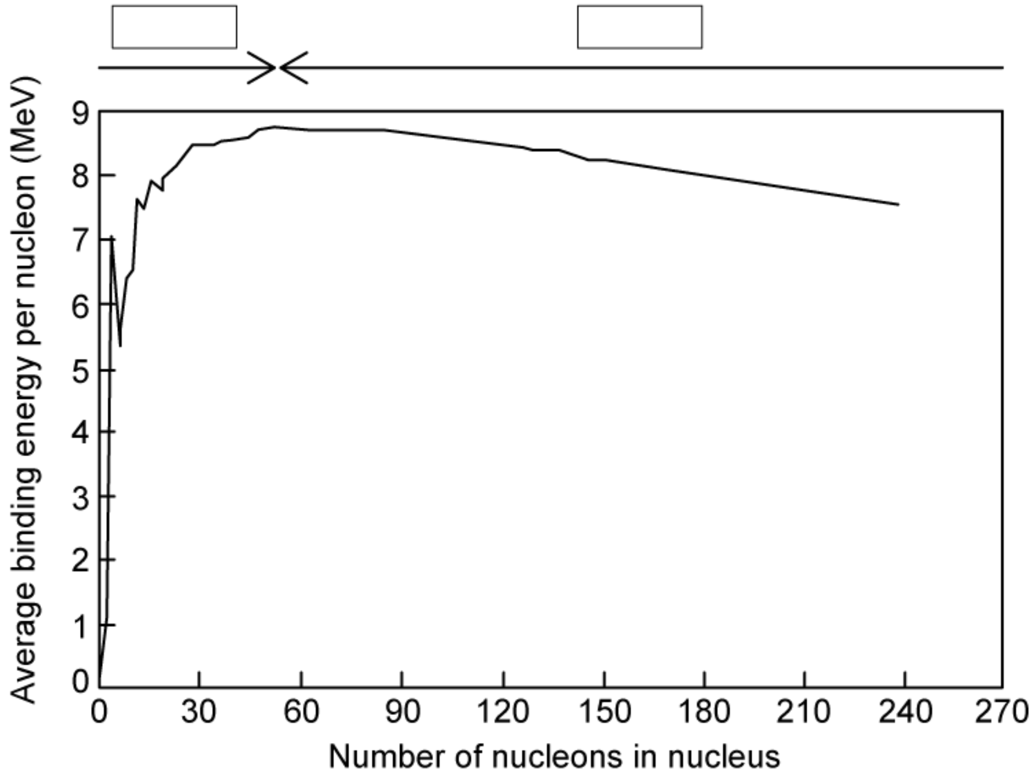
(2 marks)

4 (a) The chart shows the binding energy per nucleon for a number of nuclei.



Label the chart to show:

(i) Where fusion of these elements occurs to release energy

[1]

(ii) Where fission of these elements occurs to release energy

[1]

(ii) The location of Iron $\left({}^{56}_{26}\text{Fe}\right)$ by drawing an X

[1]

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(3 marks)

(b) In terms of the forces acting within the nucleus, explain why:

(i) Fusion occurs for nuclides with low nucleon numbers.

[2]

(i) Fission occurs for nuclides with high nucleon numbers.

[2]

(4 marks)

(c) In both fission and fusion, there is a mass defect between the original nuclei and the daughter nuclei.

Complete the sentences by circling the correct word.

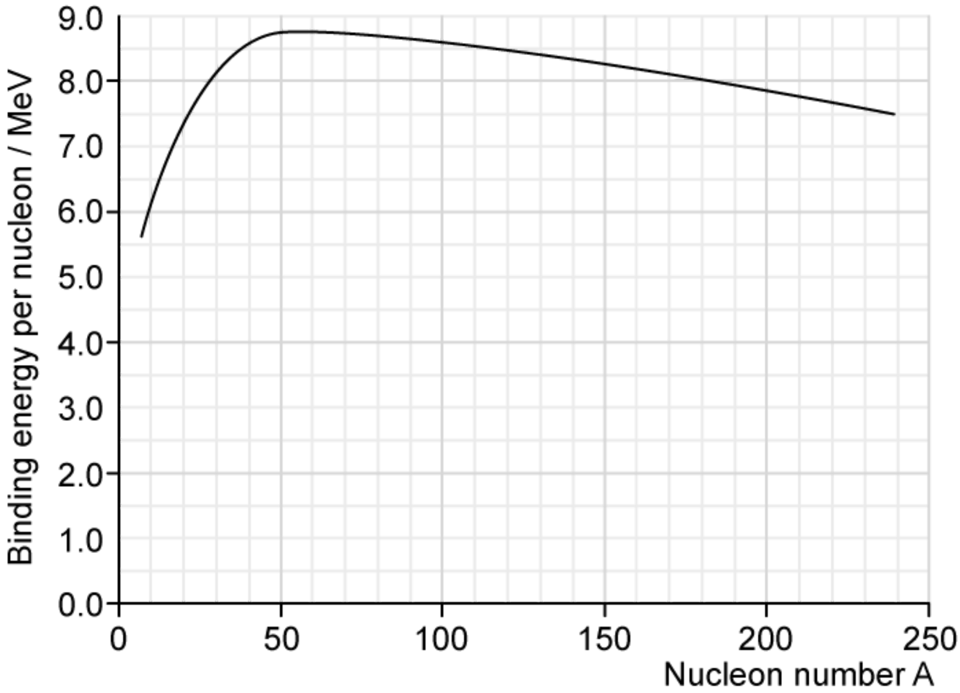
In fusion, the mass of the nucleus that is created is slightly **more / less** than the total mass of the original nuclei and the daughter nucleus is **more / less** stable.

In fission, an unstable nucleus is converted into more stable nuclei with a **larger / smaller** total mass. In both cases, this difference in mass, the mass defect, is equal to the binding energy that is released.

Fission / Fusion releases much more energy per kg than **fission / fusion**. The greater the increase in binding energy, the **more / less** energy is released.

(4 marks)

(d) The graph shows the binding energy per nucleon in MeV plotted against nucleon number, A.



Use the graph to find the binding energy of the following nuclei.

(i) Platinum−190.

[1]

(ii) Silicon−28.

[1]

(iii) Tellurium−120.

[1]

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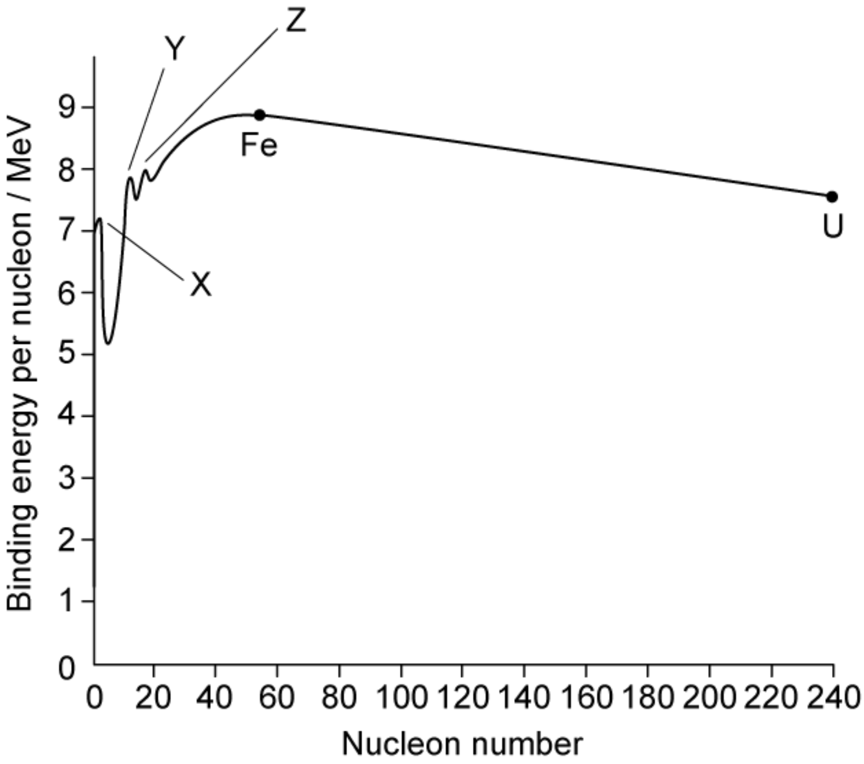
(3 marks)

5 (a) The graph below shows the binding energy per nucleon against the number of nucleons in the nucleus.



There are three nuclei, labelled X, Y and Z, which do not sit on the line of the graph.

Match up the labels to the correct element by drawing a line between the boxes

X	Oxygen
Y	Helium
Z	Carbon

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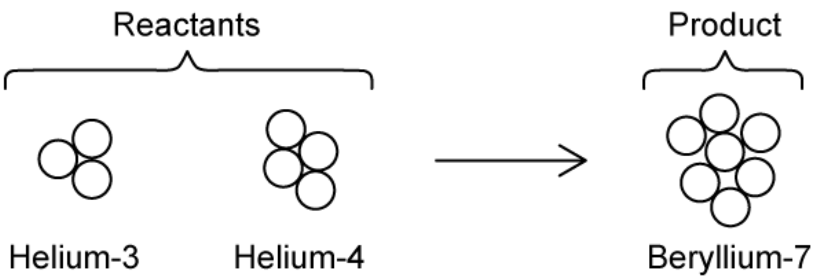
(3 marks)

(b) Helium can fuse together to form beryllium as shown in the reaction below:



State and explain which is larger, the mass of the reactants or the mass of the products.

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(3 marks)

(c) The table shows the mass of each reactant and daughter nucleus:

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

Using the information in the table:

(i) Calculate the mass of the reactants, m_R in atomic mass units.

[2]

(ii) Calculate the mass defect, Δm, between the reactants and the daughter nuclei in atomic mass units.

[3]

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(5 marks)

(d) Helium−3 and helium−4 fuse together to form beryllium−7.

The mass defect, Δ*m* for this fusion reaction is equal to 2.8×10^{-30} kg.

Calculate the energy released, Δ*E,* in the fusion of beryllium−7.

(2 marks)

Medium Questions

1 (a) A nuclear fission reaction occurs that has the following equation:

$$^{1}_{0}n + ^{235}_{92}U \rightarrow ^{90}_{38}Sr + ^{143}_{54}Xe + 3^{1}_{0}n$$

Given the following information, estimate the amount of energy released during the fission reaction:

- Binding energy per nucleon of Uranium 235: 7.59 MeV/nucleon
- Binding energy per nucleon of Strontium 90: 8.70 MeV/nucleon
- Binding energy per nucleon of Xenon-143: 8.20 MeV/nucleon

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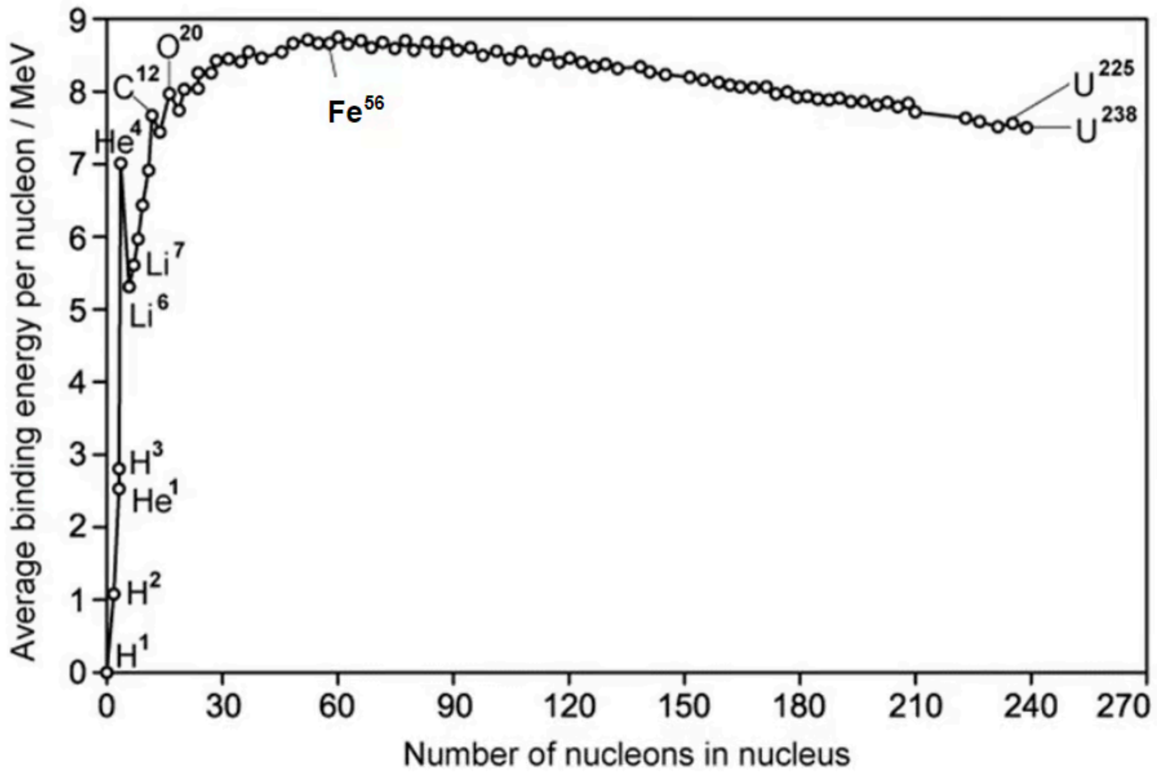
(2 marks)

(b) The binding energy per nucleon curve is shown:



With reference to the binding energy per nucleon curve:

(i) Explain why fission is possible

[2]

(ii) Identify the source of energy released during this process

[2]

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(4 marks)

(c) A Uranium-235 nucleus undergoes fission into two approximately equally sized products.

Use the data from the figure in part (b) 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.

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(5 marks)

(d) Under the right conditions, two hydrogen-2, ^{2}H, nuclei can fuse to make a helium-4, ^{4}He, nucleus.

Nuclei	Mass/ u
^{2}H	2.0135
^{4}He	4.0026

Using the data in the above table, calculate the energy available as a result of the fusion of two hydrogen-2 nuclei.

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(4 marks)

2 (a) This question is about nuclear physics.

(i) Define mass defect

(ii) Define binding energy

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(2 marks)

(b) If deuterium is combined using fusion, then the following reaction will occur:

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

The following data is given for this interaction:

- Binding energy per nucleon of deuterium $^{2}_{1}H$: 1.12 MeV/nucleon
- Binding energy per nucleon of tritium $^{3}_{1}H$: 2.82 MeV/nucleon

Estimate the energy released from this fusion reaction.

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(2 marks)

(c) In order for the fusion reaction in part (b) to actually take place, very high temperatures are needed such as those found within the core of a star. Suggest why this the case.

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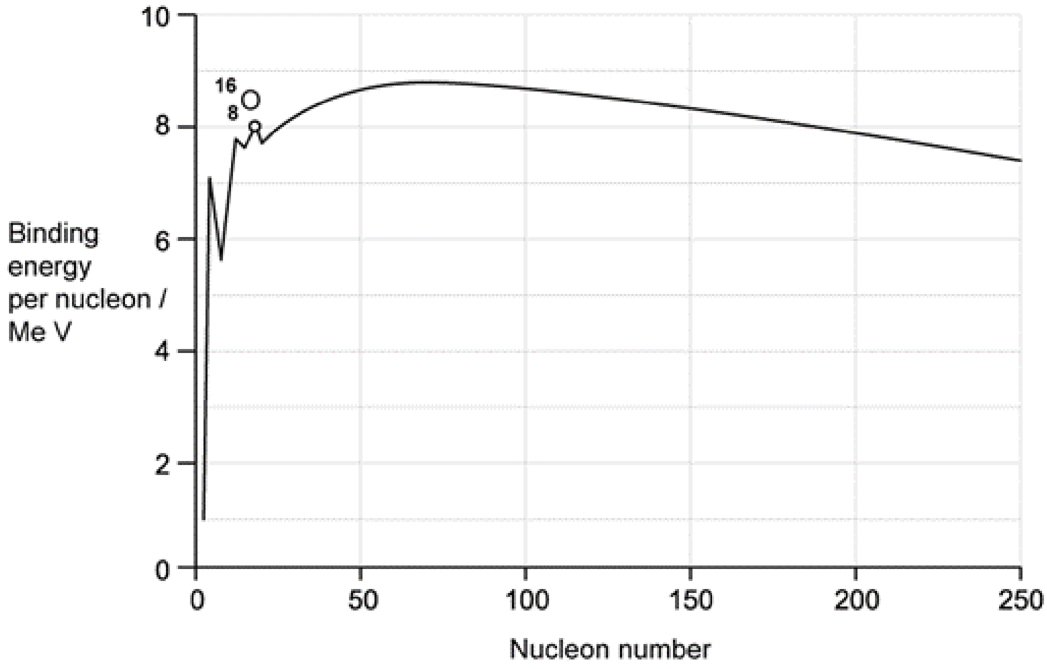
(2 marks)

(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 can be overcome.

(3 marks)

3 (a) The image below shows how the binding energy per nucleon varies with nucleon number.



Fission and fusion are two nuclear processes in which energy can be released.

(i) On the image, mark the element with the highest binding energy per nucleon.

[1]

(ii) Explain why nuclei that undergo fission are restricted to a different part of the graph than those that undergo fusion.

[2]

(3 marks)

(b) Explain with reference to the figure in part (a), why the energy released per nucleon from fusion is greater than that from fission.

(3 marks)

(c) Explain how the binding energy of an oxygen $^{16}_{8}O$ nucleus can be calculated with information obtained in the figure from part (a).

(2 marks)

(d) The mass of an $^{16}_{8}O$ nucleus is 15.991 u.

Calculate:

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

[2]

(ii) The binding energy, in MeV, of an oxygen $^{16}_{8}O$nucleus.

[1]

(3 marks)

4 (a) Bismuth-214 ($^{214}_{83}Bi$) decays into Polonium-214 ($^{214}_{84}Po$) by beta minus decay.

The binding energy per nucleon of Bismuth-214 is 7.774 MeV and the binding energy per nucleon of Polonium-214 is 7.785 MeV.

Beta-minus decay is described by the following equation:

$$^{214}_{83}Bi \rightarrow {}^{214}_{84}Po + \beta^- + \overline{v}_e$$

Show that the energy released in the β^- decay of bismuth is about 2.35 MeV and state where the energy comes from.

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(3 marks)

(b) If an additional neutron is accelerated into the Polonium-214 ($^{214}_{84}Po$) to produce the isotope Polonium-215 ($^{215}_{84}Po$), use the following information to deduce the binding energy per nucleon of this new isotope.

Mass of $^{215}_{84}Po$ nucleus = 3.571140 × 10^{-25} kg

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(5 marks)

(c) Polonium-215 ($^{215}_{84}Po$) is radioactive and decays by the producing alpha radiation, which is known to be a particularly stable.

Determine the binding energy of alpha radiation.

The following information is available:

- Mass of a Helium-4 nucleus: 4.001265 u

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(3 marks)

(d) A student claims that the amount of matter within a marble directly converted into energy would be enough to provide 1 year of current human energy consumption globally which is estimated to be 5.80×10^{18} J.

If the matter within marble is approximately 6.02×10^{23} u, determine if this statement is true, using the mass-energy equivalence.

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(2 marks)

5 (a) Explain why the mass of an alpha-particle (α) is less than the total mass of two individual protons and two individual neutrons.

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(2 marks)

(b) Show that the energy equivalence of 1.0 u is 931.5 MeV.

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(2 marks)

(c) Data for the masses of some nuclei are given below

Nuclei	Mass / u
Deuterium ($^{2}_{1}H$)	2.0141
Zirconium ($^{97}_{40}Zr$)	97.0980

Use the data to determine the binding energy of deuterium in MeV.

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(2 marks)

(d) Using the data given in part (c), determine the binding energy per nucleon of zirconium in MeV.

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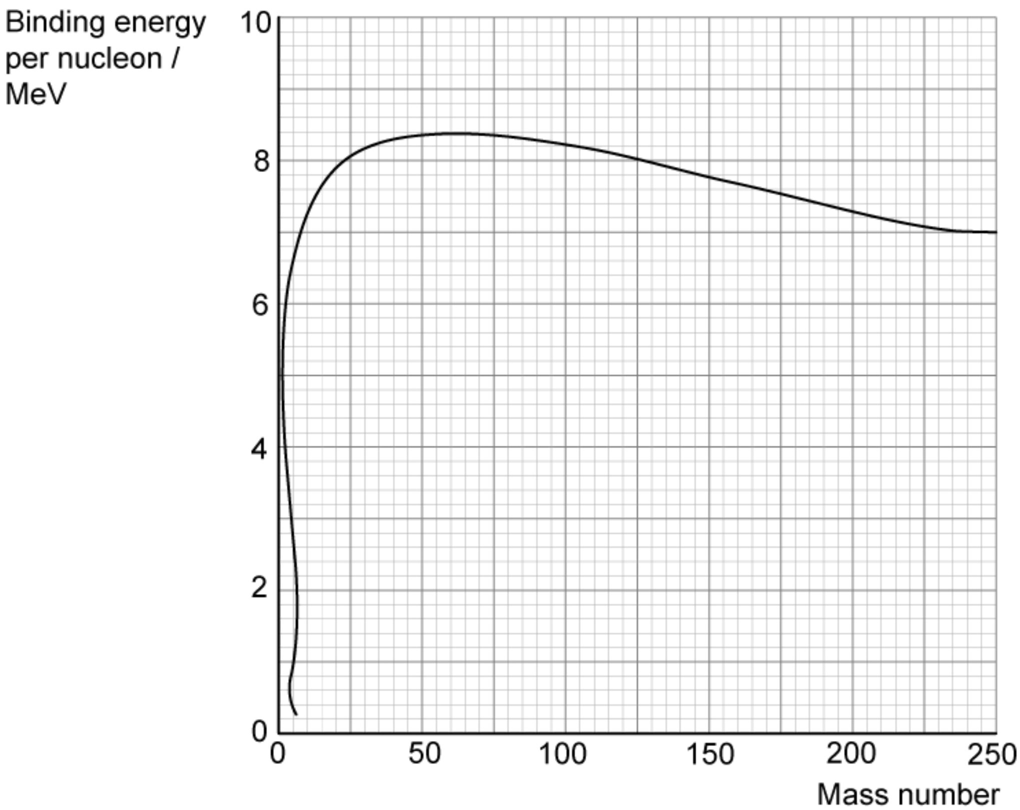
(3 marks)

Hard Questions

1 (a) During a particular fission process, a uranium–236 nucleus is bombarded with a slow-moving neutron creating a krypton–92 nucleus and a barium–141 nucleus, among other fission products.

The graph shows the relationship between the binding energy per nucleon and the mass number for various nuclides.



Calculate the energy released during this fission process.

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(3 marks)

(b) Identify the other fission products in this process and justify why they can be discounted from the calculation in part (a).

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(2 marks)

(c) A different fission process, involving uranium–235 is again triggered by the absorption of a slow−moving neutron and releases gamma ray photons. The process is described by the equation below:

$$^{235}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{138}_{52}\text{Te} + ^{98}_{40}\text{Zr} + \gamma$$

In this process, 90% of the energy released is carried away as kinetic energy of the two daughter nuclei.

The following data are available:

- Mass of $^{235}_{92}\text{U}$ = 235.0439 u
- Mass of $^{138}_{52}\text{Te}$ = 137.9603 u
- Mass of $^{98}_{40}\text{Zr}$ = 97.9197 u
- Mass of $^{1}_{0}\text{n}$ = 1.0087 u
- Wavelength of γ photons emitted = 2.5×10^{-12} m

Show that approximately 32 gamma ray photons are released in this process.

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(5 marks)

(d) Assuming the nuclei are initially at rest, show that the $^{98}_{40}\text{Zr}$ nucleus is emitted with a speed about 1.4 times larger than the $^{138}_{52}\text{Te}$ nucleus.

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(2 marks)

2 (a) When a uranium–235 nucleus undergoes fission, one of the possible reactions is:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{139}_{54}Xe + ^{95}_{38}Sr + 2^{1}_{0}n \left(+ \text{energy}\right)$$

The binding energy per nucleon, *E*, is given in the table below:

Nuclide	E/MeV
$^{235}_{92}U$	7.60
$^{139}_{54}Xe$	8.39
$^{95}_{38}Sr$	8.74

A 1500 MW nuclear reactor, operating at 27% efficiency, uses enriched fuel containing 2% uranium–235 and 98% uranium–238. The molar mass of uranium−235 is 0.235 kg/mol.

Estimate the total mass of original fuel required per year in the nuclear reactor.

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(5 marks)

(b) The average energy released by the various modes of fission of uranium–235 is 200 MeV.

Calculate the number of fission reactions per day in the nuclear reactor (assuming continuous production of power).

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(2 marks)

3 (a) In the research into nuclear fusion, scientists are working with 1.5 kg of Lithium. One of the most promising reactions is between deuterons, ${}^{2}_{1}\mathrm{H}$, and tritium nuclei, ${}^{3}_{1}\mathrm{H}$, in a gaseous plasma. Although deuterons can be relatively easily extracted from sea water, tritium is more difficult to produce. It can, however, be produced by bombarding lithium−6, ${}^{6}_{3}\mathrm{Li}$, with neutrons.

These reactions can be represented in the following nuclear equations:

$${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n} + (\mathrm{energy})$$

$${}^{6}_{3}\mathrm{Li} + \mathrm{X} \rightarrow {}^{3}_{1}\mathrm{H} + \mathrm{Y} + (\mathrm{energy})$$

The masses of the nuclei involved are given in the following table:

Nuclei	**Mass / u**
Neutron	1.008665
Deuteron	2.013553
Tritium	3.016049
Helium−4	4.002603
Lithium−6	6.015122

(i) Determine the nature of particles X and Y and hence complete the equation.

[1]

(ii) Calculate the maximum amount of energy, in MeV, released when 1.5 kg of lithium-6 is bombarded by neutrons.

[4]

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(5 marks)

(b) Suggest why the lithium-6 reaction could be thought to be self-sustaining once the deuteron-tritium reaction is underway.

(2 marks)

(c) Explain, in terms of the forces acting on nuclei, why the deuteron-tritium mixture must be very hot in order to achieve the fusion reaction.

(3 marks)

4 (a) *This is a synoptic question and will need knowledge from previous IB topics.*

Plasma is superheated matter. It is so hot that the electrons are stripped from their atoms, forming an ionised gas.

The Sun is made up of gas and plasma and can be thought of as a giant fusion reactor. At its core where fusion takes place, the plasma is (mainly) protons with a temperature of about 1.5×10^6 K.

Near the Sun's surface, however, protons have a mean kinetic energy of 0.75 eV, which is too low for fusion to take place.

Calculate the temperature of the Sun near its surface, stating any assumptions you make.

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(3 marks)

(b) By considering the distance of closest approach between two protons, explain why fusion does not occur near the Sun's surface.

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(4 marks)

(c) The energy produced by the Sun comes from a cycle of hydrogen fusion, during which the net effect is the fusion of 3 protons to a helium nucleus. One of the steps in the cycle is:

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

The amount of energy radiated away in this step is 5.49 MeV.

The following data are available:

- Mass of ${}^{2}_{1}\text{H}$ nucleus = 2.01355 u
- Mass of proton = 1.00728 u

(i) Calculate the mass of the helium nucleus, ${}^{3}_{2}\text{He}$ in standard units

[3]

(ii) State the nature of the energy released

[1]

(4 marks)

5 (a) One possible fission reaction of uranium-235 is

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + 2^{1}_{0}n$$

The following data are available:

- Mass of one atom of $^{235}_{92}U$ = 235u
- Binding energy per nucleon for $^{235}_{92}U$ = 7.59 MeV
- Binding energy per nucleon for $^{140}_{54}Xe$ = 8.29 MeV
- Binding energy per nucleon for $^{94}_{38}Sr$ = 8.59 MeV

Calculate the amount of energy released in the reaction.

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(4 marks)

(b) A nuclear power station uses the uranium-235 as fuel. The useful power output of the power station is 1.4 GW and it has an efficiency of 30%.

(i) Show that the specific energy of $^{235}_{92}U$ is about 7.5 × 10^{13} J kg^{-1}.

[3]

(ii) Determine the mass of $^{235}_{92}U$ which undergoes fission in one day.

[2]

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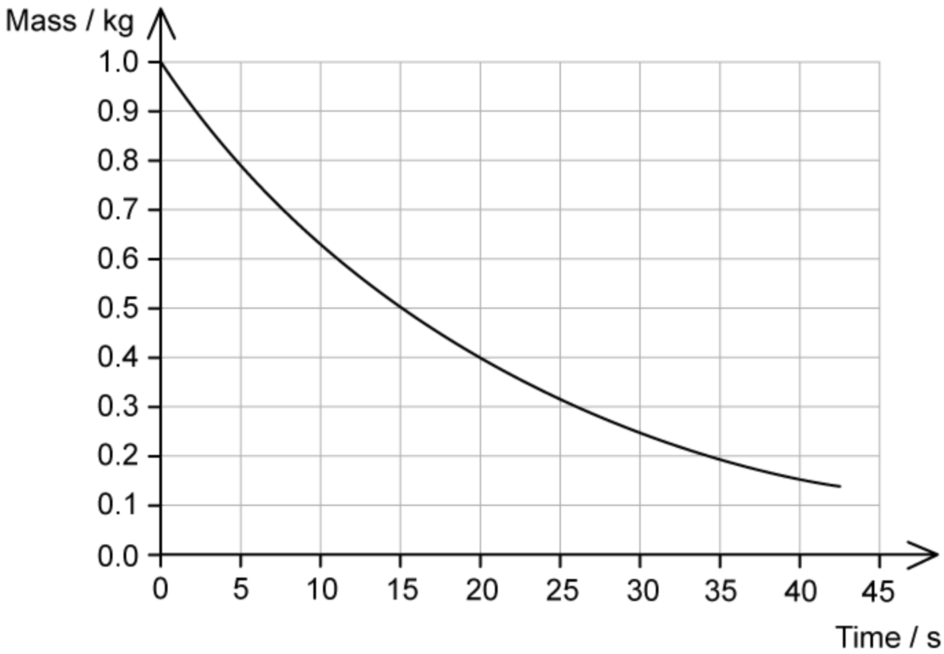
(5 marks)

(c) One of the waste products of the reaction is xenon−140, ${}^{140}_{54}\text{Xe}$. Xenon−140 is radioactive, decaying through β^- decay.

$$ {}^{140}_{54}\text{Xe} \rightarrow \text{Z} + \beta^- + \overline{\nu}_e $$

The graph shows the variation with time of the mass of 1kg of xenon−140 remaining in the sample.



(i) Calculate the proton and mass numbers of nuclide Z.

[1]

(ii) Calculate the mass of xenon−140 remaining in the sample after 2.5 minutes

[3]

(4 marks)

(d) An alternative nuclear fuel to the traditionally used uranium-235 is thorium-232. When thorium-232 is exposed to neutrons, it will undergo a series of nuclear reactions until it eventually emerges as an isotope of uranium-233, which will readily split and release energy the next time it absorbs a neutron.

Part of the thorium fuel cycle is shown below.

$$^{232}_{90}\text{Th} + ^{1}_{0}\text{n} \rightarrow ^{233}_{90}\text{Th} \rightarrow ^{233}_{91}\text{Pa} \rightarrow ^{233}_{92}\text{U}$$

Once the uranium-233 nucleus absorbs a neutron, it undergoes fission, releasing energy and two neutrons and forming the fission products Xenon and Strontium as in parts a-c. Any isotopes of uranium-233 which do not undergo fission decay through a chain ending with a stable nucleus of thallium-205 $\left(^{205}_{81}\text{Tl}\right)$.

Show that 12 particles, not including neutrons, are emitted during this combination of decay chains. Explain your reasoning.

(4 marks)