7.2 Nuclear Reactions

Question Paper

Course	DP IB Physics
Section	7. Atomic, Nuclear & Particle Physics
Topic	7.2 Nuclear Reactions
Difficulty	Hard

Time allowed: 70

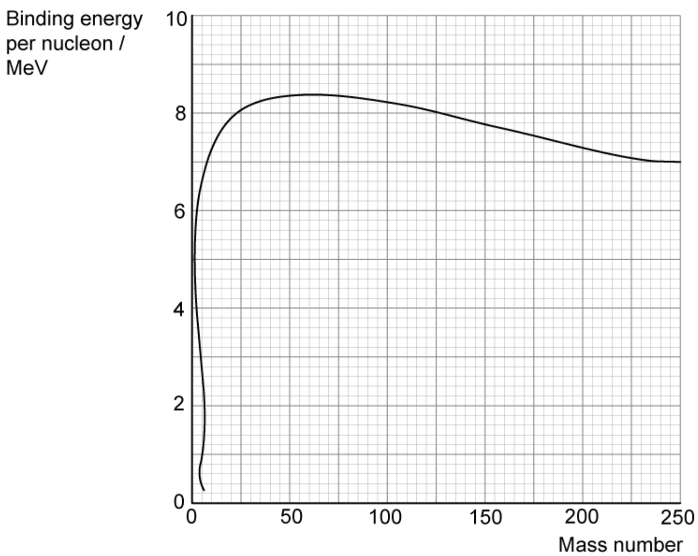
Score: /57

Percentage: /100

Question 1a

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.



(a)
Calculate the energy released during this fission process.

[3]

[3 marks]

Question 1b

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

[2]

[2 marks]

Question 1c

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:

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

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

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

[5]

[5 marks]

Question 1d

(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.

[2]

[2 marks]

Question 2a

When a uranium-235 nucleus undergoes fission, one of the possible reactions is:

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

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

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

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

[5]

[5 marks]

Question 2b

The average energy released by the various modes of fission of uranium-235 is 200 MeV.

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

[2]

[2 marks]

Question 3a

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:

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

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

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

(a)

(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]

[5 marks]

Question 3b

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

[2]

[2 marks]

Question 3c

(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]

[3 marks]

Question 4a

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.

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

[3]

[3 marks]

Question 4b

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

[4]

[4 marks]

Question 4c

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

(c)

(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]

Question 5a

One possible fission reaction of uranium-235 is

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

The following data are available:

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

(a)
Calculate the amount of energy released in the reaction.

[4]

[4 marks]

Question 5b

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%.

(b)

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

[3]

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

[2]

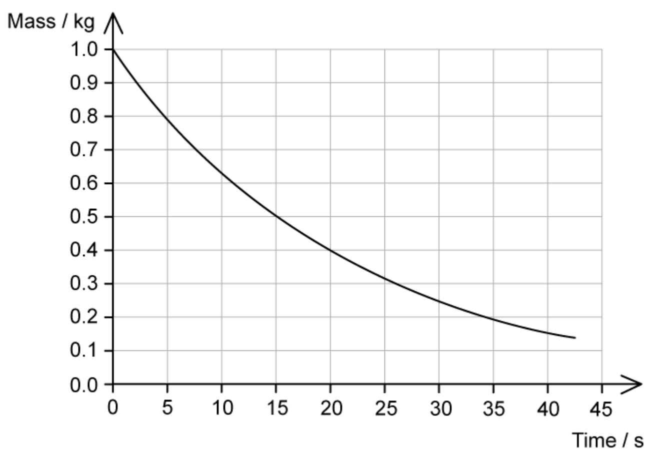
[5 marks]

Question 5c

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.



(c)

(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]

Question 5d

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 $\left(^{205}_{81}\text{Tl}\right)$.

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

[4]

[4 marks]