1)

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

This isotope of protactinium may undergo β^- decay to become ${}^{233}_{92}U$.

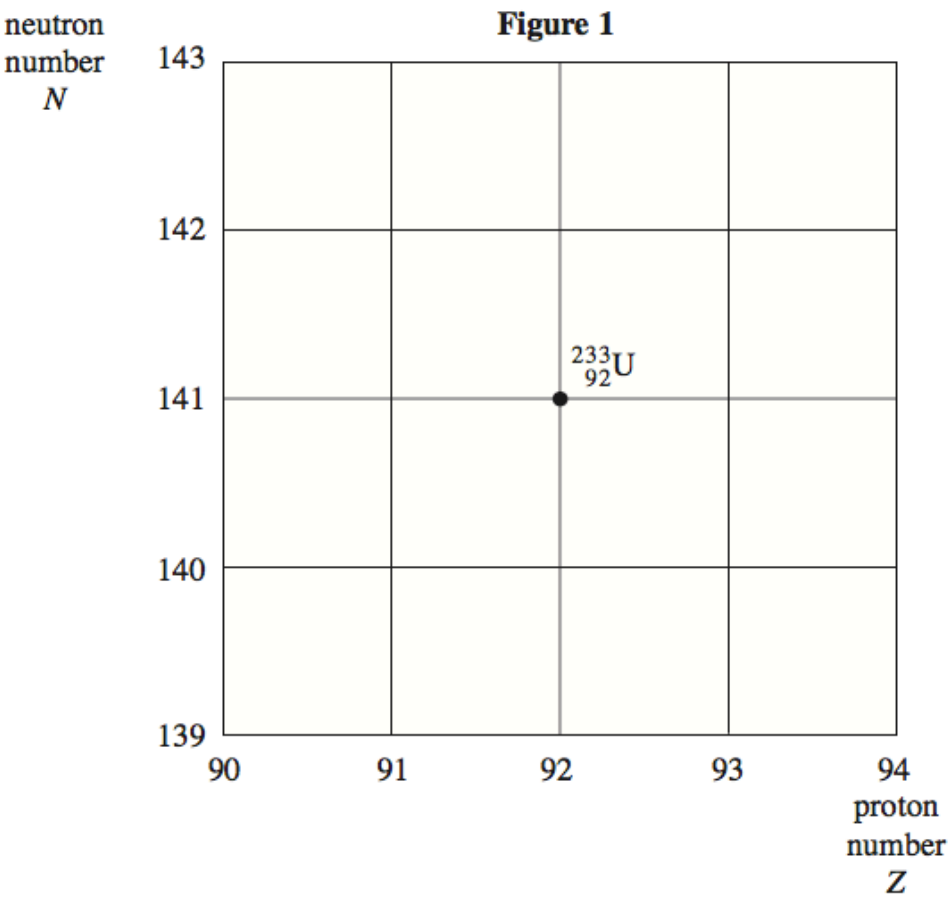
(a) Complete the following equation to show the β^- decay of protactinium.

$$^{\dots\dots}_{\dots\dots}Pa \rightarrow {}^{233}_{92}U + \beta^- + \dots\dots\dots$$

(2 marks)

(b) Two other nuclei, **P** and **Q**, can also decay into ${}^{233}_{92}U$.
P decays by β^+ decay to produce ${}^{233}_{92}U$.
Q decays by α emission to produce ${}^{233}_{92}U$.
Figure 1 shows a grid of neutron number against proton number with the position of the ${}^{233}_{92}U$ isotope shown.
On the grid label the positions of the nuclei **P** and **Q**.

Figure 1



(2 marks)

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

$$^{233}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{91}_{36}\text{Kr} + ^{139}_{56}\text{Ba} + x \text{ neutrons}$$

(c) (i) Calculate the number of neutrons, x.

answer = ...neutrons
(1 mark)

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

mass of neutron = 1.00867 u

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

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

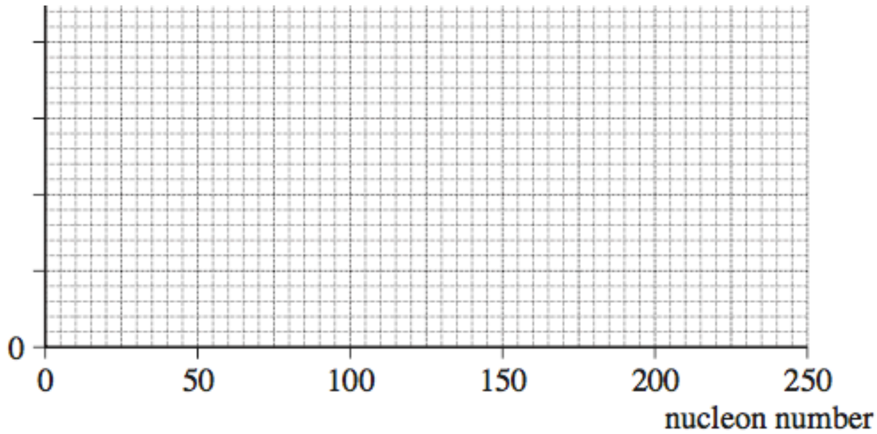
mass of $^{139}_{56}\text{Ba}$ nucleus = 138.87810 u

answer = ...MeV
(3 marks)

(b) (iii) Explain how the binding energy of an oxygen $^{16}_{8}O$ nucleus can be calculated with information obtained from **Figure 3**.

[1 mark]

per nucleon



(4 marks)

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

(3 marks)

2)

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

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(1 mark)

(a) (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 marks)

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

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(3 marks)

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 marks)

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

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

Calculate the energy, in MeV, that is released.

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

energy .... MeV

(3 marks)

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

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(2 marks)

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

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(1 mark)

(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.

(c) (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 marks)

(c) (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 marks)

4)

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

[2 marks]

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(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 mark]

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

(b) (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

[3 marks]

energy released .... MeV

5)

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

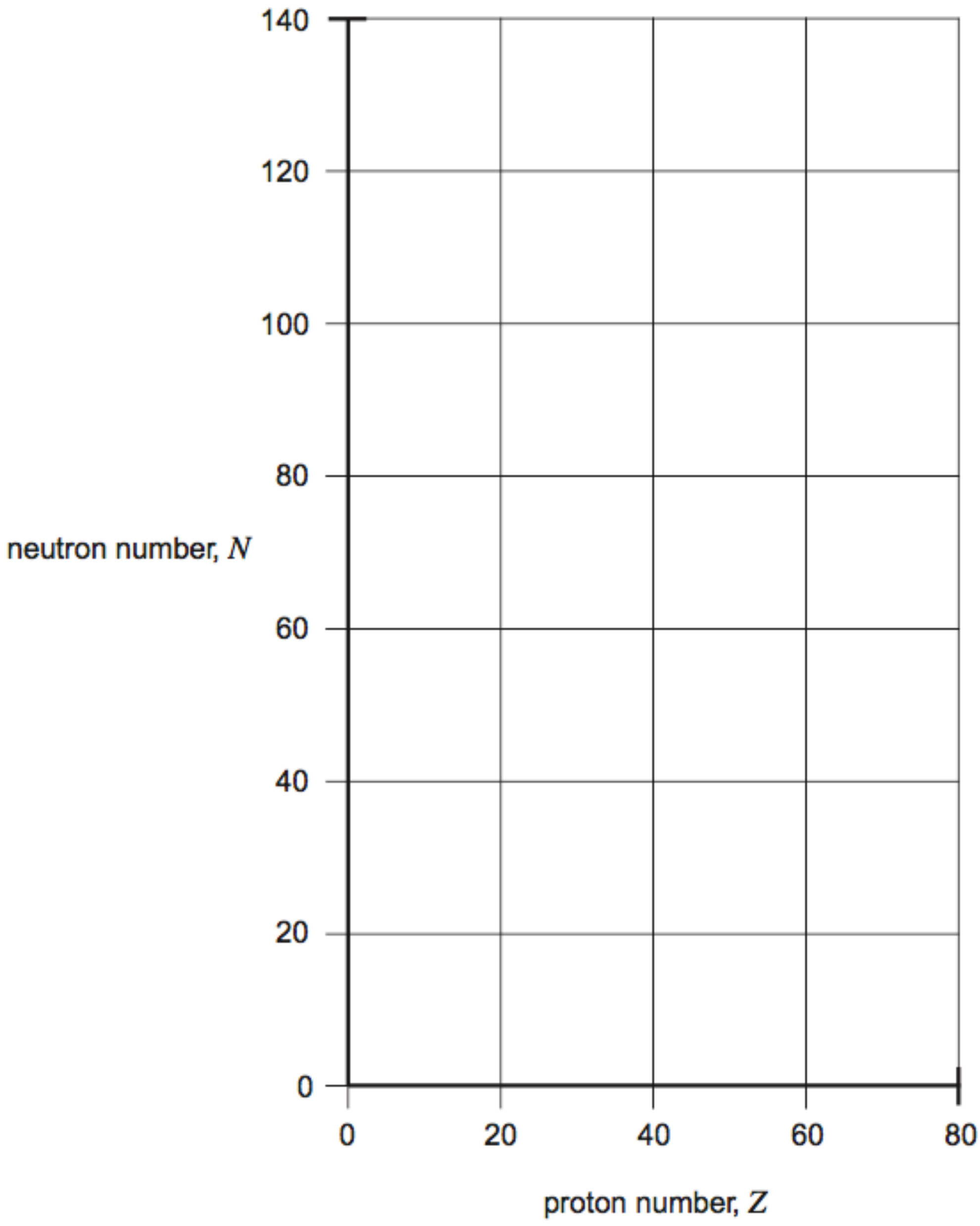
[2 marks]

loss of mass .... kg

(c) (i) On **Figure 1** sketch a graph of neutron number, N, against proton number, Z, for stable nuclei.

[1 mark]

Figure 1



(c) (ii) With reference to **Figure 1**, explain why fission fragments are unstable and explain what type of radiation they are likely to emit initially.

[3 marks]

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(a) In a thermal nuclear reactor, one fission reaction typically releases 2 or 3 neutrons. Describe and explain how a constant rate of fission is maintained in a reactor by considering what events or sequence of events may happen to the released neutrons.

The quality of your written communication will be assessed in this question.

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(7 marks)

6)

(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.

[2 marks]

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

[2 marks]

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(iii) Substantial shielding around the core protects nearby workers from the most hazardous radiations. Radiation from the core includes α and β particles, γ rays, X–rays, neutrons and neutrinos.

Explain why the shielding becomes radioactive.

[2 marks]

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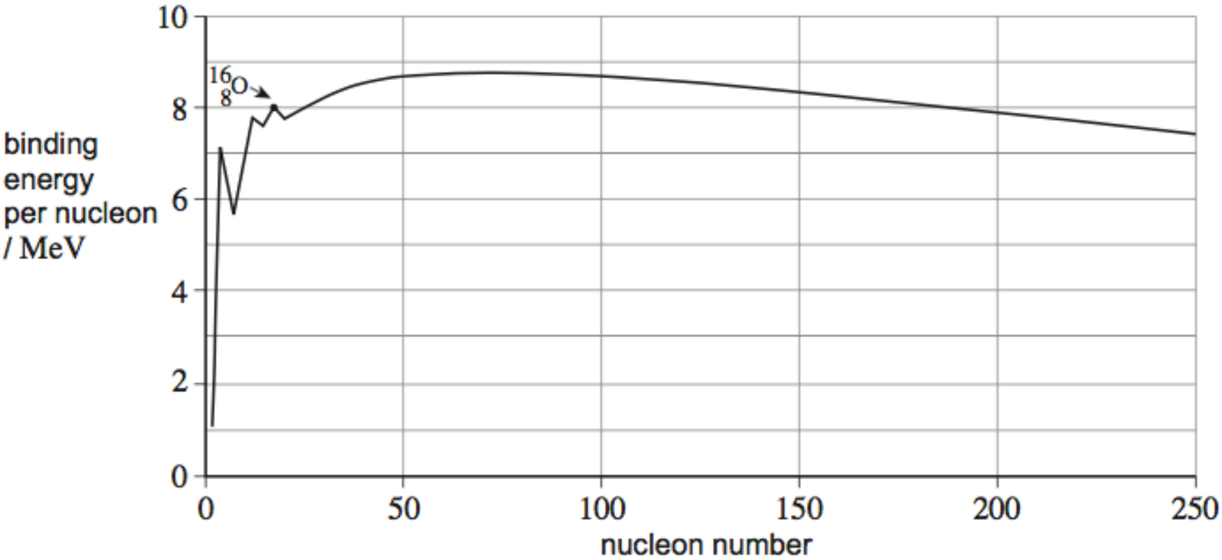
7)

Figure 3 shows how the binding energy per nucleon varies with nucleon number.

Figure 3



(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.

[2 marks]

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8)

(a) (ii) Explain, with reference to **Figure 3**, why the energy released per nucleon from fusion is greater than that from fission.

[2 marks]

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

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

[2 marks]

mass difference = ______________________________ kg

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

[1 mark]

binding energy = ___________________________ MeV