For Radioactivity only, (not nuclear radius and binding energy)
Questions to do, 1, 2, 3, 4a, 5, 7, 9, 10, 12 a and b

1)

The age of an ancient boat may be determined by comparing the radioactive decay of $^{14}_{6}C$ from living wood with that of wood taken from the ancient boat.
A sample of 3.00×10^{23} atoms of carbon is removed for investigation from a block of living wood. In living wood one in 10^{12} of the carbon atoms is of the radioactive isotope $^{14}_{6}C$, which has a *decay constant* of $3.84 \times 10^{-12}\,s^{-1}$.

(a) What is meant by the decay constant?

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(1 mark)

(b) Calculate the half-life of $^{14}_{6}C$ in years, giving your answer to an appropriate number of significant figures.

$$1\ \text{year} = 3.15 \times 10^{7}\,s$$

answer = ... years
(3 marks)

(c) Show that the rate of decay of the $^{14}_{6}C$ atoms in the living wood sample is 1.15 Bq.

(2 marks)

(d) A sample of 3.00×10^{23} atoms of carbon is removed from a piece of wood taken from the ancient boat. The rate of decay due to the $^{14}_{6}C$ atoms in this sample is 0.65 Bq. Calculate the age of the ancient boat in years.

answer = ... years

(3 marks)

(e) Give **two** reasons why it is difficult to obtain a reliable age of the ancient boat from the carbon dating described.

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(2 marks)

2)

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 $^{233}_{92}U$.

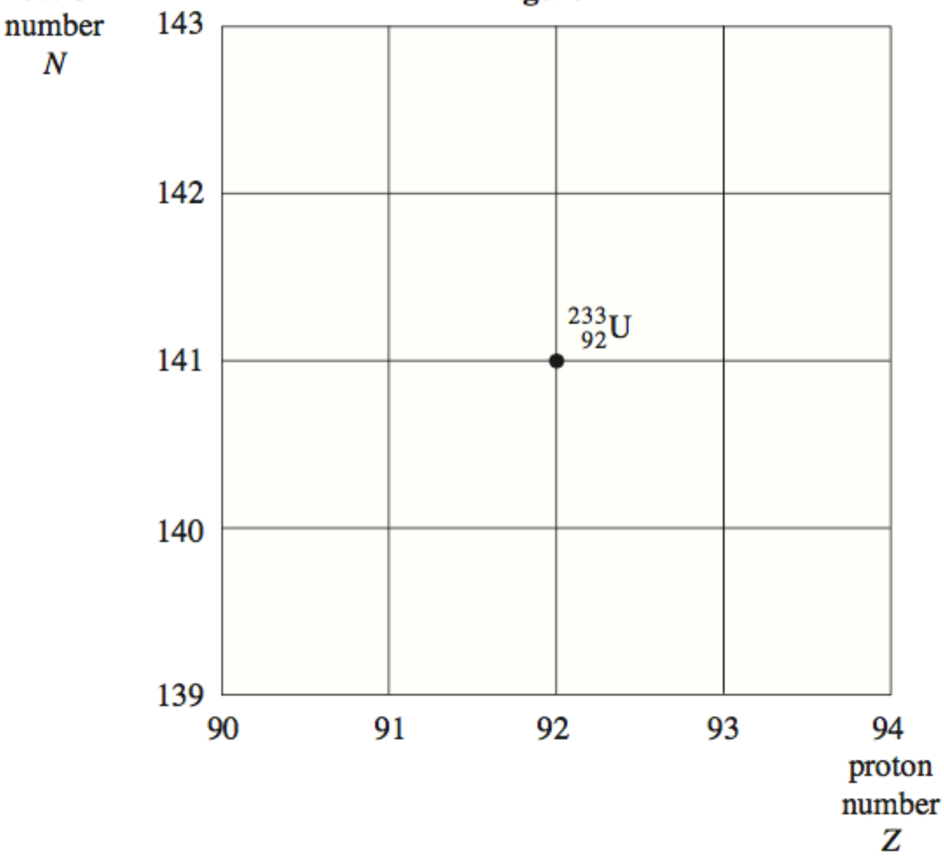
(a) Complete the following equation to show the β^- decay of protactinium.

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

(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)

3)

The first artificially produced isotope, phosphorus $^{30}_{15}\text{P}$, was formed by bombarding an aluminium isotope, $^{27}_{13}\text{Al}$, with an α particle.

(a) Complete the following nuclear equation by identifying the missing particle.

$$^{27}_{13}\text{Al} + \alpha \rightarrow {}^{30}_{15}\text{P} + \;\ldots\ldots\ldots$$

(1 mark)

(b) For the reaction to take place the α particle must come within a distance, *d*, from the centre of the aluminium nucleus.
Calculate *d* if the nuclear reaction occurs when the α particle is given an initial kinetic energy of at least 2.18×10^{-12} J.

The electrostatic potential energy between two point charges Q_1 and Q_2 is equal to $\frac{Q_1 Q_2}{4\pi\varepsilon_0 r}$ where r is the separation of the charges and ε_0 is the permittivity of free space.

answer = ...m

(3 marks)

4)

The isotope of uranium, $^{238}_{92}U$, decays into a stable isotope of lead, $^{206}_{82}Pb$, by means of a series of α and β^- decays.

(a) In this series of decays, α decay occurs 8 times and β^- decay occurs n times. Calculate n.

answer = ...

(1 mark)

(b) (i) Explain what is meant by the binding energy of a nucleus.

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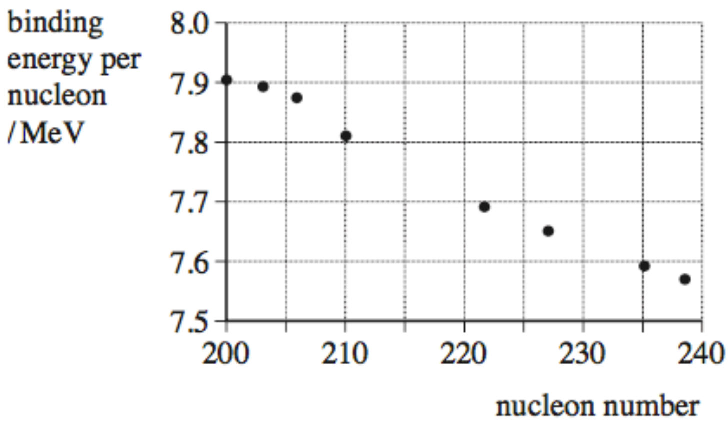
(2 marks)

(b) (ii) **Figure 2** shows the binding energy per nucleon for some stable nuclides.

Figure 2



Use **Figure 2** to estimate the binding energy, in MeV, of the $^{206}_{82}Pb$ nucleus.

answer = ... MeV

(1 mark)

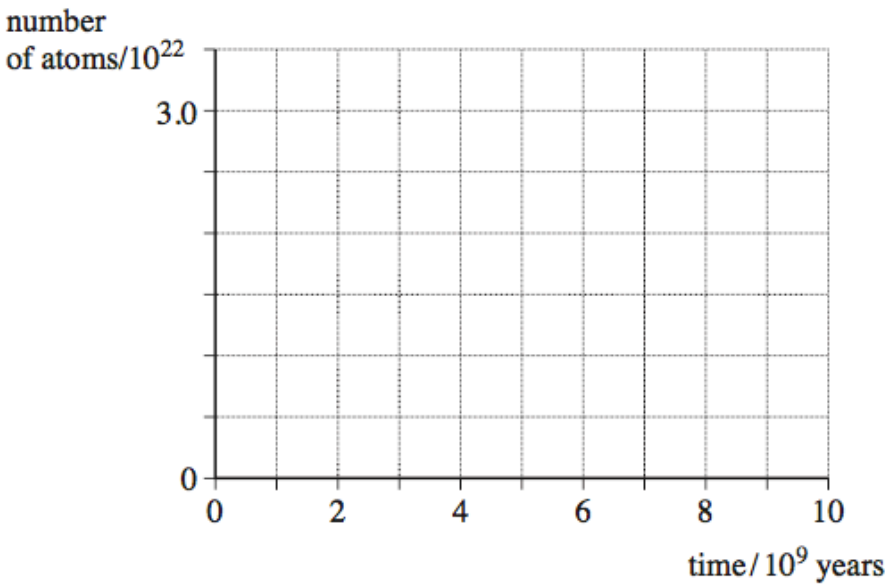
(c) The half-life of $^{238}_{92}U$ is 4.5×10^9 years, which is much larger than all the other half-lives of the decays in the series.

A rock sample when formed originally contained 3.0×10^{22} atoms of $^{238}_{92}U$ and no $^{206}_{82}Pb$ atoms.

At any given time most of the atoms are either $^{238}_{92}U$ or $^{206}_{82}Pb$ with a negligible number of atoms in other forms in the decay series.

(c) (i) Sketch on **Figure 3** graphs to show how the number of $^{238}_{92}U$ atoms and the number of $^{206}_{82}Pb$ atoms in the rock sample vary over a period of 1.0×10^{10} years from its formation.
Label your graphs U and Pb.

Figure 3



(2 marks)

(c) (ii) A certain time, *t*, after its formation the sample contained twice as many $^{238}_{92}U$ atoms as $^{206}_{82}Pb$ atoms.
Show that the number of $^{238}_{92}U$ atoms in the rock sample at time *t* was 2.0×10^{22}.

(1 mark)

(c) (iii) Calculate *t* in years.

answer = ... years
(3 marks)

5)

(a) In a radioactivity experiment, background radiation is taken into account when taking corrected count rate readings in a laboratory. One source of background radiation is the rocks on which the laboratory is built. Give **two** other sources of background radiation.

source 1 ....

source 2 ....

(1 mark)

(b) A γ ray detector with a cross-sectional area of $1.5 \times 10^{-3}\,\text{m}^2$ when facing the source is placed 0.18 m from the source.
A corrected count rate of 0.62 counts s^{-1} is recorded.

(b) (i) Assume the source emits γ rays uniformly in all directions.
Show that the ratio

$$\frac{\text{number of } \gamma \text{ photons incident on detector}}{\text{number of } \gamma \text{ photons produced by source}}$$

is about 4×10^{-3}.

(2 marks)

(b) (ii) The γ ray detector detects 1 in 400 of the γ photons incident on the facing surface of the detector.
Calculate the activity of the source. State an appropriate unit.

answer = ... unit ....

(3 marks)

(c) Calculate the corrected count rate when the detector is moved 0.10 m further from the source.

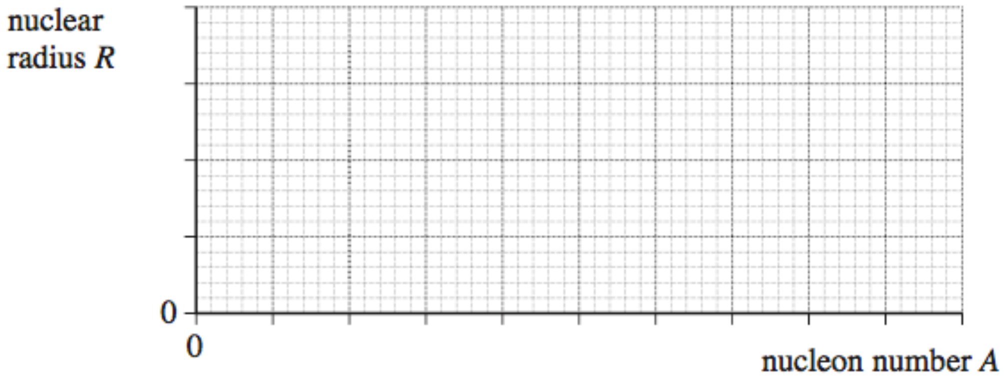
answer = ... counts s^{-1}

(3 marks)

6)

(a) On **Figure 4** sketch a graph to show how the radius, R, of a nucleus varies with its nucleon number, A.

Figure 4



(1 mark)

(b) (i) The radius of a gold-197 nucleus $^{197}_{79}\text{Au}$ is 6.87×10^{-15} m.
Show that the density of this nucleus is about 2.4×10^{17} kg m^{-3}.

(2 marks)

(b) (ii) Using the data from part b(i) calculate the radius of an aluminium-27 nucleus, $^{27}_{13}\text{Al}$.

answer = ... m

(2 marks)

(c) Nuclear radii have been investigated using α particles in Rutherford scattering experiments and by using electrons in diffraction experiments.
Make comparisons between these two methods of estimating the radius of a nucleus.
Detail of any apparatus used is not required.
For each method your answer should contain:

- the principles on which each experiment is based including a reference to an appropriate equation
- an explanation of what may limit the accuracy of each method
- a discussion of the advantages and disadvantages of each method

The quality of your written communication will be assessed in your answer.

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(6 marks)

7)

A radioactive source used in a school laboratory is thought to emit α particles and γ radiation. Describe an experiment that may be used to verify the types of radiation emitted by the source. The experiment described should allow you to determine how the intensity of radiation varies with distance in air or with the thickness of suitable absorbers.

Your answer should include:

- the apparatus you would use and any safety precautions you would take
- the measurements you would make
- how the measurements would be used to reach a final decision about the emitted radiation.

The quality of your written communication will be assessed in your answer.

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(6 marks)

8)

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

[2 marks]

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(b) (i) When a $^{235}_{92}\text{U}$ nucleus absorbs a slow-moving neutron and undergoes fission one possible pair of fission fragments is technetium $^{112}_{43}\text{Tc}$ and indium $^{122}_{49}\text{In}$.
Complete the following equation to represent this fission process.

[1 mark]

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

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

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

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

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

[3 marks]

energy released .... MeV

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

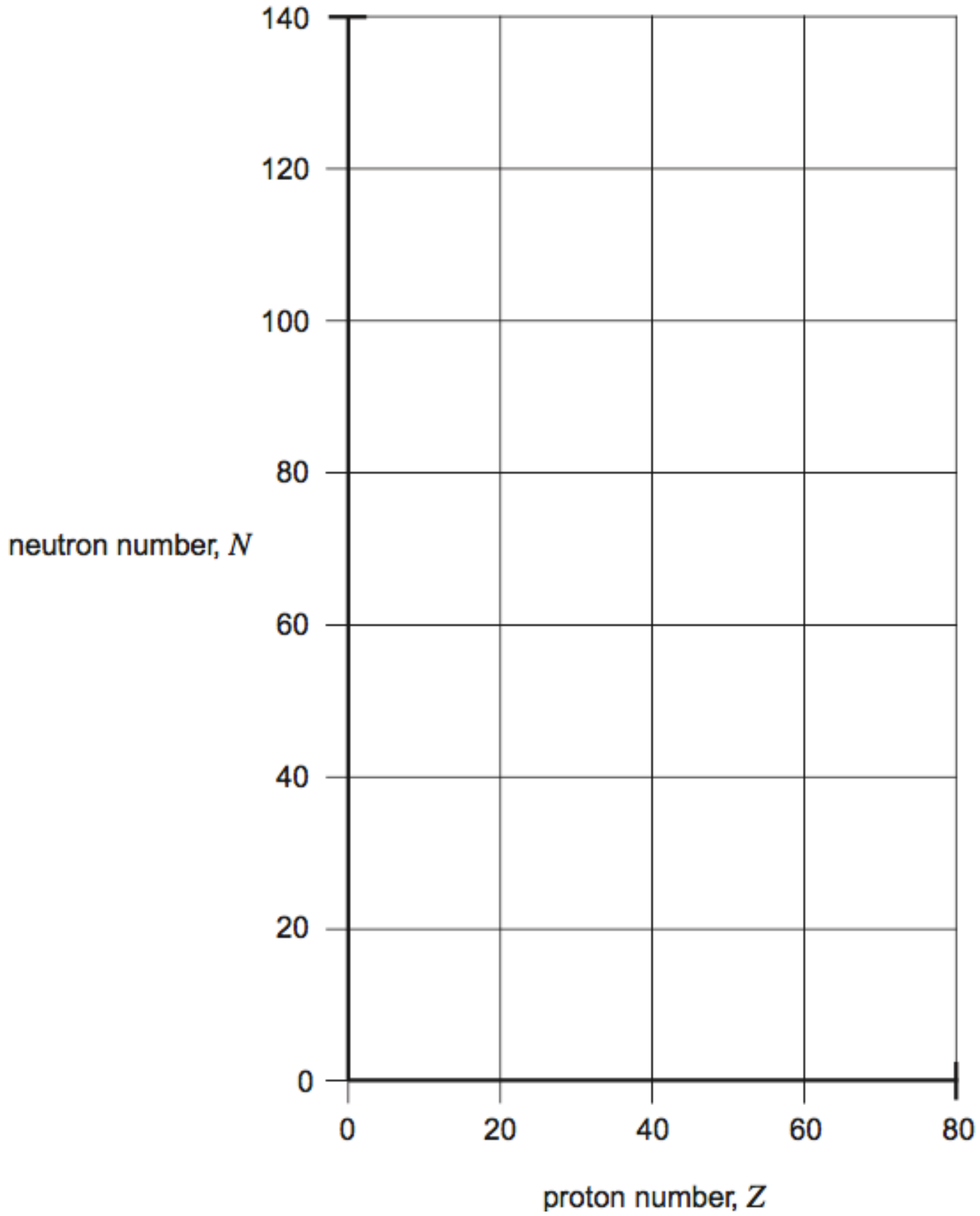
[2 marks]

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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9)

The carbon content of living trees includes a small proportion of carbon-14, which is a radioactive isotope. After a tree dies, the proportion of carbon-14 in it decreases due to radioactive decay.

(a) (i) The half-life of carbon-14 is 5740 years.
Calculate the radioactive decay constant in yr^{-1} of carbon-14.

[1 mark]

decay constant .... yr^{-1}

(a) (ii) A piece of wood taken from an axe handle found on an archaeological site has 0.375 times as many carbon-14 atoms as an equal mass of living wood.
Calculate the age of the axe handle in years.

[3 marks]

age .... yr

(b) Suggest why the method of carbon dating is likely to be unreliable if a sample is:

[2 marks]

(b) (i) less than 200 years old,

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(b) (ii) more than 60 000 years old.

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10)

(a) Which ionizing radiation produces the greatest number of ion pairs per mm in air?
Tick (✓) the correct answer.

[1 mark]

α particles	
β particles	
γ rays	
X-rays	

(b) (i) Complete **Table 1** below showing the typical maximum range in air for α and β particles.

[2 marks]

Table 1

Type of radiation	Typical range in air / m
α	
β	

(b) (ii) γ rays have a range of at least 1 km in air.
However, a γ ray detector placed 0.5 m from a γ ray source detects a noticeably smaller count-rate as it is moved a few centimetres further away from the source.

Explain this observation.

[1 mark]

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(c) Following an accident, a room is contaminated with dust containing americium which is an α-emitter.

Explain the most hazardous aspect of the presence of this dust to an unprotected human entering the room.

[2 marks]

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11)

(a) Scattering experiments are used to investigate the nuclei of gold atoms.
In one experiment, alpha particles, all of the same energy (monoenergetic), are incident on a foil made from a single isotope of gold.

(a) (i) State the main interaction when an alpha particle is scattered by a gold nucleus.

[1 mark]

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(a) (ii) The gold foil is replaced with another foil of the same size made from a mixture of isotopes of gold. Nothing else in the experiment is changed.

Explain whether or not the scattering distribution of the monoenergetic alpha particles remains the same.

[1 mark]

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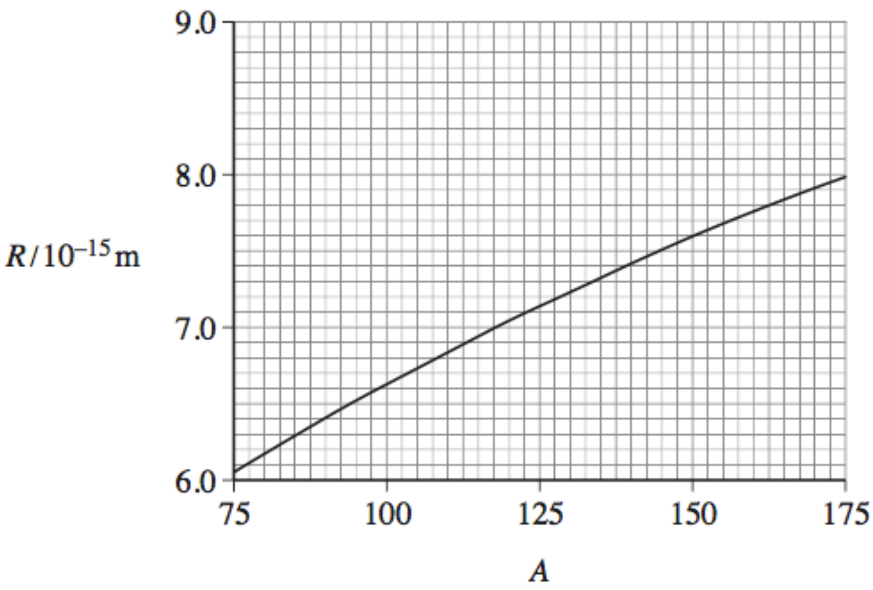
(b) Data from alpha-particle scattering experiments using elements other than gold allow scientists to relate the radius R, of a nucleus, to its nucleon number, A.
Figure 1 shows the relationship obtained from the data in a graphical form, which obeys the relationship $R = r_0 A^{\frac{1}{3}}$.

Figure 1



(b) (i) Use information from **Figure 1** to show that r_0 is about 1.4×10^{-15} m.

[1 mark]

(b) (ii) Show that the radius of a $^{51}_{23}\text{V}$ nucleus is about 5×10^{-15} m.

[2 marks]

(c) Calculate the density of a $^{51}_{23}\text{V}$ nucleus.

State an appropriate unit for your answer.

[3 marks]

density .... unit ....

12)

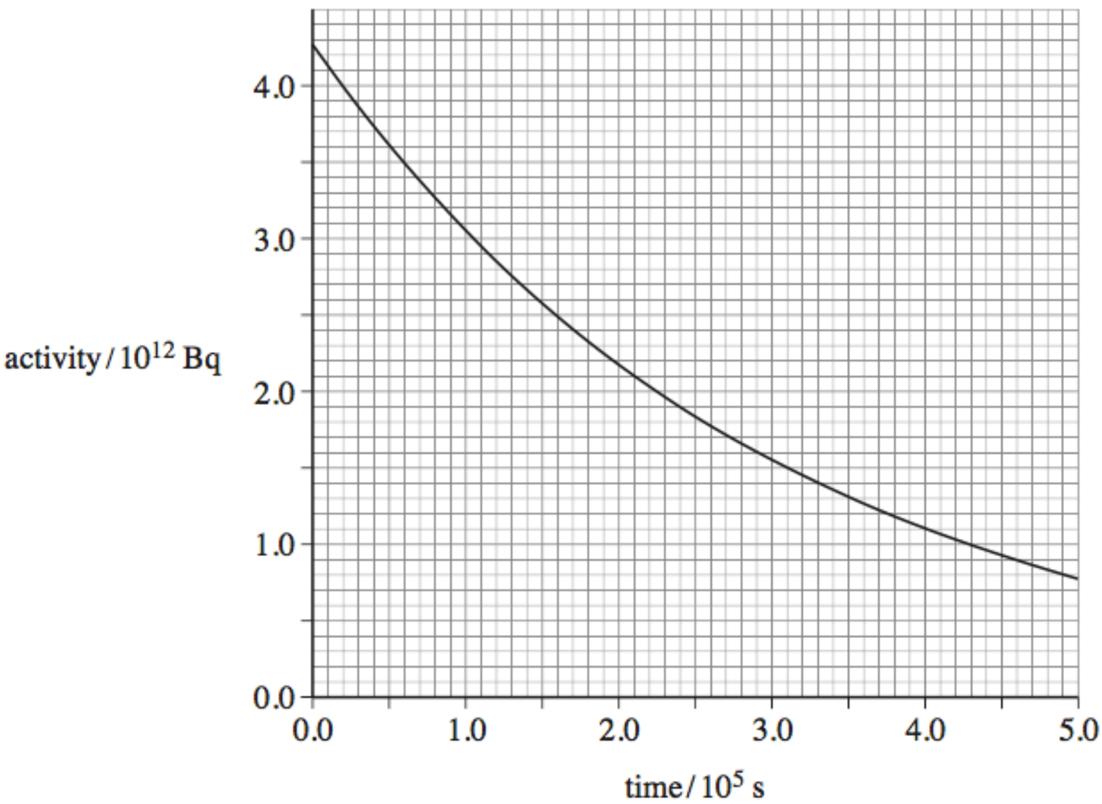
A rod made from uranium-238 ($^{238}_{92}U$) is placed in the core of a nuclear reactor where it absorbs free neutrons.
When a nucleus of uranium-238 absorbs a neutron it becomes unstable and decays to neptunium-239 ($^{239}_{93}Np$), which in turn decays to plutonium-239 ($^{239}_{94}Pu$).

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

[2 marks]

(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 **Figure 2**.

Figure 2



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

[2 marks]

(b) (ii) Assume that the activity shown in **Figure 2** 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.

[1 mark]

number of nuclei ....

(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.

[2 marks]

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

[2 marks]

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(c) (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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