A-Level Physics

Radioactive Decay

Question Paper

Time available: 58 minutes
Marks available: 52 marks

1. A thermal nuclear reactor uses enriched uranium as its fuel.
This is fuel in which the ratio of U-235 to U-238 has been artificially increased from that found in naturally-occurring ore.

(a) Describe what happens when neutrons interact with U-235 and U-238 nuclei in a thermal nuclear reactor.

(3)

(b) The amounts of U-235 and U-238 in the ore decrease due to radioactive decay at different rates.

A sample of uranium ore today contains 993 g of U-238
The mass of U-238 in this sample was greater 2.00×10^9 years ago.

Show that the mass of U-238 in this sample at that time was about 1.4 kg.

decay constant of U-238 = 1.54×10^{-10} year^{-1}

(2)

(c) A thermal nuclear reactor requires a minimum of 3.0% of its uranium mass to be U-235

The ratio of U-235 to U-238 in the ore has changed over time.
2.00×10^9 years ago, the sample in part (b) contained 52 g of U-235

Deduce whether the sample had a high enough U-235 content to be used in a reactor 2.00×10^9 years ago.

_____

_____

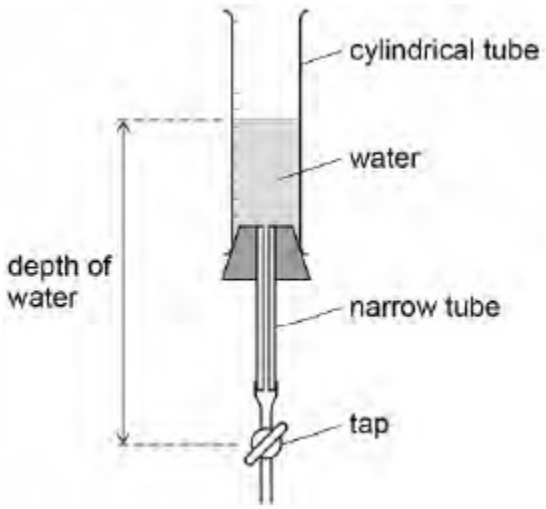
_____

(1)

(Total 6 marks)

2. **Figure 1** shows how radioactive decay of one nuclide can be modelled by draining water through a tap from a cylindrical tube.

Figure 1

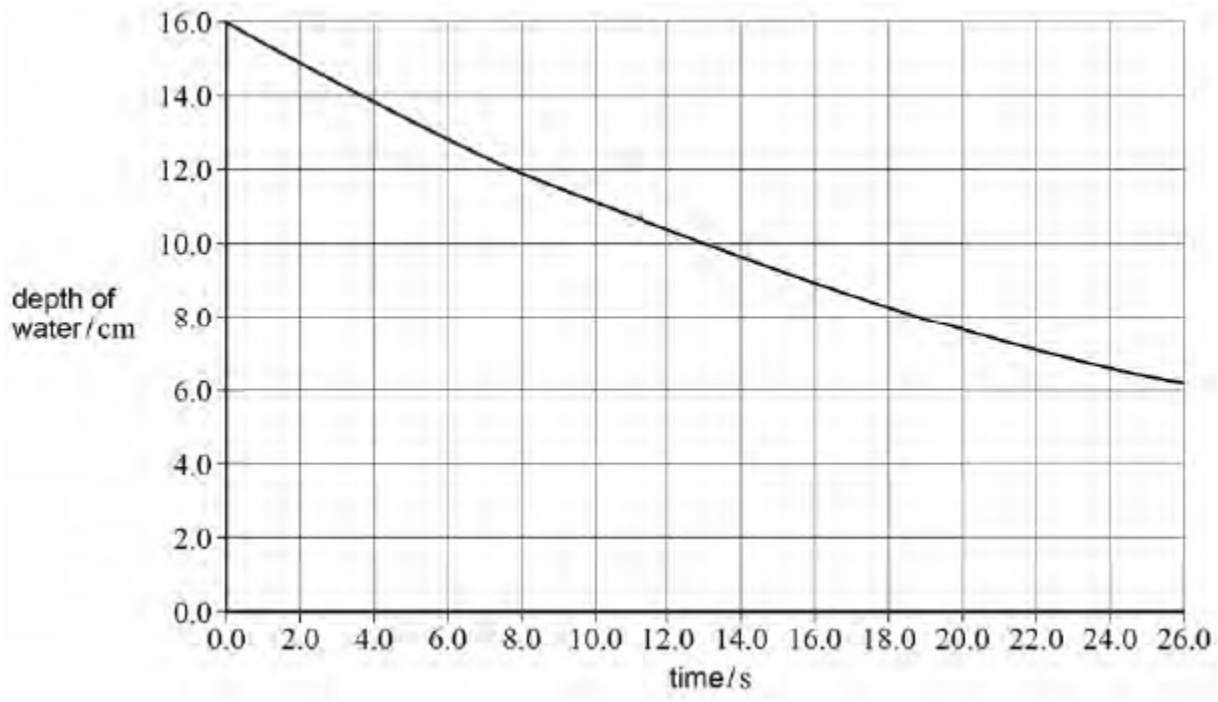


The water flow-rate is proportional to the pressure of the water. The pressure of the water is proportional to the depth of the water. Therefore the rate at which the depth decreases is proportional to the depth of the water.

Before the tap is opened the depth is 16.0 cm

The tap is opened and the depth is measured at regular intervals. These data are plotted on the graph in **Figure 2**.

Figure 2



(a) Determine the predicted depth of water when the time is 57 s

depth = _____ cm

(1)

(b) Suggest how the apparatus in **Figure 1** may be changed to represent a radioactive sample of the same nuclide with a greater number of nuclei.

_____

_____

(1)

(c) Suggest how the apparatus in **Figure 1** may be changed to represent a radioactive sample of a nuclide with a smaller decay constant.

_____

_____

(1)

(d) The age of the Moon has been estimated from rock samples containing rubidium (Rb) and strontium (Sr), brought back from Moon landings.

$^{87}_{37}Rb$ decays to $^{87}_{38}Sr$ with a radioactive decay constant of 1.42×10^{-11} year^{-1}

Calculate, in years, the half-life of $^{87}_{37}Rb$

half-life = _____ years

(1)

(e) A sample of Moon rock contains 1.23 mg of $^{87}_{37}Rb$.

Calculate the mass, in g, of $^{87}_{37}Rb$ that the rock sample contained when it was formed 4.47×10^{9} years ago.

Give your answer to an appropriate number of significant figures.

mass = _____ g

(3)

(f) Calculate the activity of a sample of $^{87}_{37}Rb$ of mass 1.23 mg

Give an appropriate unit for your answer.

activity = _____ unit _____

(3)

(Total 10 marks)

3. 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)

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

_____

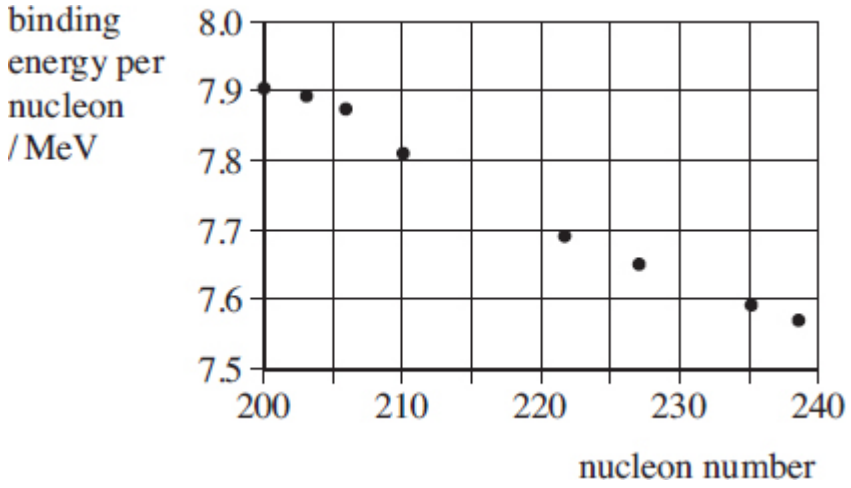
_____

_____

(2)

(ii) **Figure 1** shows the binding energy per nucleon for some stable nuclides.

Figure 1



Use **Figure 1** to estimate the binding energy, in MeV, of the $^{206}_{82}Pb$ nucleus.

answer = _____ MeV

(1)

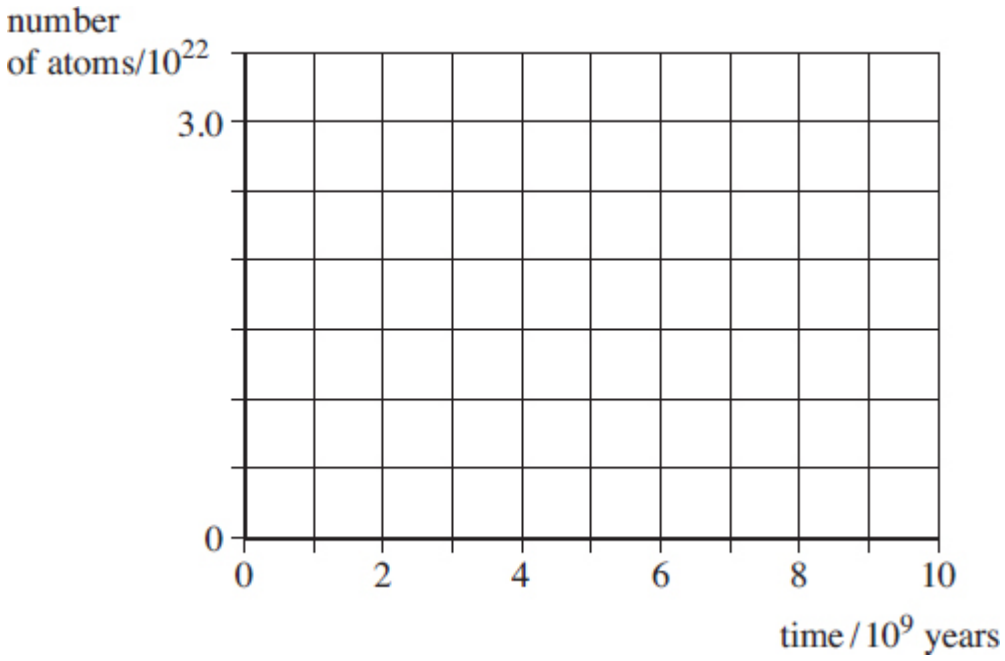
(c) The half-life of $^{238}_{92}U$ is 4.5×10^9 years, which is much larger than all the other half-lives of the decays in the series.

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.

(i) Sketch on **Figure 2** 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 2



(2)

(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)

(ii) Calculate *t* in years.

answer = _____ years

(3)

(Total 10 marks)

4. Complete the following equation showing the β^+ decay of carbon-11.

$$^{11}_{6}\mathrm{C} \rightarrow {}^{\cdots\cdots}_{\cdots\cdots}\mathrm{B} + {}^{\cdots\cdots}_{\cdots\cdots}\beta^+ + {}^{\cdots\cdots}_{\cdots\cdots}\ \cdots\cdots$$

(Total 3 marks)

5. A nuclide of manganese $\left({}^{52}_{25}\mathrm{Mn}\right)$ undergoes beta$^+$ decay to form a nuclide of chromium (Cr).

(a) Complete the equation for this decay process.

$$^{52}_{25}\mathrm{Mn} \rightarrow {}^{\cdots\cdots}_{24}\mathrm{Cr} + {}^{\cdots\cdots\cdots}_{\cdots\cdots\cdots}\beta^+ + {}^{\cdots\cdots\cdots}_{\cdots\cdots\cdots}$$

(2)

(b) State the name of the exchange particle involved in this beta$^+$ decay.

_____

(1)

(Total 3 marks)

6.

Radioisotope thermoelectric generators (RTGs) are electrical generators powered by radioactive decay. As a radioisotope decays some of the energy released is converted into electricity by means of devices called thermocouples. In this way RTGs have been used as power sources in satellites, space probes and heart pacemakers.

The Cassini space probe was launched in 1997. It carried three RTGs each containing 11 kg of a nuclear fuel, plutonium oxide (a compound having two oxygen atoms combined with every plutonium-238 atom). In 1997, when the probe was launched, the power released from one gram of plutonium oxide was 500 mW.

Plutonium-238 $^{238}_{94}Pu$ is an alpha emitter, decaying into uranium(U).
The half-life of the decay is 87.7 years.

mass of one mol of plutonium-238 = 238 g
mass of one mol of oxygen atoms = 16 g

(a) State and explain why environmentalists might have been concerned by the use of such a large quantity of plutonium-238.

_____

_____

_____

_____

_____

(2)

(b) State and explain whether the activity of a given number of atoms of plutonium is affected when they are in the form of plutonium oxide.

_____

_____

_____

(2)

(c) (i) Calculate the decay constant, in s^{-1}, for plutonium-238.

_____

_____

_____

_____

decay constant _____ s^{-1}

(2)

(ii) Calculate the number of plutonium-238 atoms in the total mass of the plutonium oxide in the Cassini probe at the beginning of its mission.

number of plutonium-238 atoms _____

(5)

(iii) Calculate the initial activity of the plutonium-238 in the Cassini probe.
Give a suitable unit for your answer.

initial activity of plutonium-238 _____ unit _____

(3)

(d) (i) Write a nuclear equation for the $\left({}^{238}_{94}\mathrm{Pu}\right)$ decay.

(2)

(ii) Assume the power released by the RTGs' fuel originated as the kinetic energy of the alpha particles emitted in the decay of $\left({}^{238}_{94}\mathrm{Pu}\right)$.

Calculate the maximum kinetic energy of each alpha particle.

kinetic energy of alpha particle _____ J

(4)

(Total 20 marks)