(b) In order to fuse, the centres of the protons must reach a separation of 2.1×10^{-15} m or less. Calculate the minimum initial kinetic energy of **each** proton for fusion to occur.
The total potential energy E_P of **two** charges Q_1 and Q_2 at separation r is given by

$$E_P = \frac{Q_1 Q_2}{4\pi\varepsilon_0 r}.$$

kinetic energy = ... J [2]

(c) Using the equation

$$E_K = 2.07 \times 10^{-23}\, T$$

calculate the temperature T of a plasma such that the kinetic energy of the protons is equal to your answer to **(b)**.

temperature = ... K [1]

(d) Proton fusion occurs at a temperature of about 1.5×10^{7} K. Suggest why this fusion can occur at a much lower temperature than your answer to **(c)**.

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....[2]

(e) Two series of fusion reactions in the Sun are particularly important. One is the **hydrogen cycle** which consists of the following reactions. The energy outputs from each reaction are shown.

$$2\,({}^{1}_{1}H) \rightarrow {}^{2}_{1}H + {}^{0}_{1}e + {}^{0}_{0}\nu + 2.3 \times 10^{-13}\,J$$

$${}^{2}_{1}H + {}^{1}_{1}H \rightarrow {}^{3}_{2}He + 8.8 \times 10^{-13}\,J$$

$$2\,({}^{3}_{2}He) \rightarrow {}^{4}_{2}He + 2\,({}^{1}_{1}H) + 20.6 \times 10^{-13}\,J$$

The hydrogen cycle of reactions may be summarised in the equation

$$4\,({}^{1}_{1}H) \rightarrow {}^{4}_{2}He + 2\,({}^{0}_{1}e) + 2\,({}^{0}_{0}\nu) + E$$

(i) Calculate the value of E, the total energy output for this reaction.

E = ... J [2]

(ii) Suggest why the amount of heat generated inside the Sun by the hydrogen cycle of reactions is less than would be expected from your answer to **(i)**.

....

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....[1]

(f) Another series of reactions which occurs in the Sun is the **carbon cycle**. This involves the fusion of protons with carbon and nitrogen nuclei. It happens to a greater extent inside stars hotter than the Sun. Suggest why these reactions require higher temperatures than the hydrogen cycle.

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....[2]

[Total: 13]

45

This question is about the ways in which a gold isotope might undergo spontaneous decay.

Data.

name	symbol	mass/u
gold-192	$^{192}_{79}Au$	191.92147
platinum-192	$^{192}_{78}Pt$	191.91824
mercury-192	$^{192}_{80}Hg$	191.92141
electron	$^{0}_{-1}e$	0.00055

A student suggests that $^{192}_{79}Au$ should undergo either β^+ or β^- decay.

(a) Write nuclear equations for each of these suggested reactions.

β^+

β^-

[2]

(b) Deduce whether either of these reactions can take place.

[5]

(c) Calculate the maximum kinetic energy, in joule, of any emitted β particle.

energy = ... J [4]

[Total: 11]

46

(a) With particular reference to **two** kinds of hadron, discuss the stability or otherwise of hadrons.

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....[5]

(b) Tritium-3 (^3_1H) decays to helium-3 (^3_2He) with the emission of a β^- particle.

(i) Name the force responsible for this decay process.

....[1]

(ii) Write a nuclear equation to represent this process.

[1]

(iii) Write a quark equation, in its simplest form, to represent this process.

[2]

[Total: 9]

47

The radioactive nickel nuclide $^{63}_{28}Ni$ decays by beta-particle emission with a half-life of 120 years.

(a) A copper nucleus is produced as the result of this decay. State the number of nucleons in the copper nucleus which are

protons ....

neutrons ....[2]

(b) Show that the decay constant of the nickel nuclide is $1.8 \times 10^{-10}\,s^{-1}$.

1 year = 3.2×10^{7} s

[1]

(c) A student designs an electronic clock, powered by the decay of nuclei of $^{63}_{28}Ni$. One plate of a capacitor of capacitance 1.2×10^{-12} F is to be coated with this isotope. As a result of this decay, the capacitor becomes charged. The capacitor is connected across the terminals of a small neon lamp. See Fig. 4.1. When the capacitor is charged to 90 V, the neon gas inside the lamp becomes conducting, causing it to emit a brief flash of light and discharging the capacitor. The charging starts again. Fig. 4.2 is a graph showing how the voltage *V* across the capacitor varies with time.

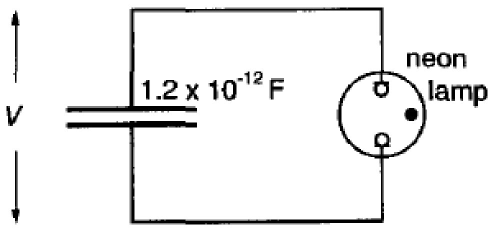

Fig. 4.1

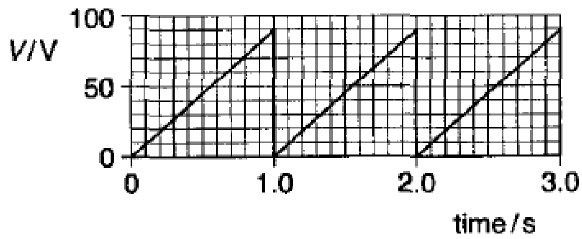

Fig. 4.2

(i) Show that the maximum charge stored on the capacitor is 1.1×10^{-10} C.

[2]

(ii) When a nickel atom emits a beta-particle, a positive charge of 1.6×10^{-19} C is added to the capacitor plate. Show that the number of nickel nuclei that must decay to produce 1.1×10^{-10} C is about 7×10^{8}.

[2]

(iii) The neon lamp is to flash once every 1.0 s. Using your answer to **(b)**, calculate the number of nickel atoms needed in the coating on the plate.

number = ... [3]

(iv) State, giving a reason, whether or not you would expect the clock to be accurate to within 1% one year after manufacture.

....

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....[1]

[Total: 11]

48

In this question, four marks are available for the quality of written communication.

This question is about helium nuclei.

(a) Describe the nature of alpha-particles and the main features of alpha-particle decay. Describe **one** experiment where alpha-particles have been used to learn about atomic structure. Explain how the experiment led to the discovery of the nucleus. A space has been left for you to draw suitable diagram(s), if you wish to illustrate your answer.

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....[7]

(b) A method of producing helium nuclei is shown by the following nuclear equation.

$$4\,^{1}_{1}H \rightarrow \,^{4}_{2}He + 2\,^{0}_{1}e$$

Describe this process of fusion giving as much detail as you can.
Compare the energy release in this process with the energy released in alpha-particle decay.

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....[5]

Quality of Written Communication [4]

[Total: 16]

49

The radioactive radium nuclide $^{226}_{88}Ra$ decays by alpha-particle emission to an isotope of radon Rn with a half-life of 1600 years.

(a) State the number of

(i) neutrons in a radium nucleus ....[1]

(ii) protons in the radon nucleus resulting from the decay ....[1]

(b) The historic unit of radioactivity is called the curie and is defined as the number of disintegrations per second from 1.0 g of $^{226}_{88}Ra$. Show that

(i) the decay constant of the radium nuclide is $1.4 \times 10^{-11}\,s^{-1}$

1 year = 3.16×10^{7} s

[1]

(ii) 1 curie equals 3.7×10^{10} Bq.

[3]

(c) Use the data below to show that the energy release in the decay of a single nucleus of $^{226}_{88}Ra$ by alpha-particle emission is 7.9×10^{-13} J.

nuclear mass of Ra-226 = 226.0254 u
nuclear mass of Rn-222 = 222.0175 u
nuclear mass of He = 4.0026 u

[3]

(d) Estimate the time it would take a freshly made sample of radium of mass 1.0 g to increase its temperature by 1.0 °C. Assume that 80% of the energy of the alpha-particles is absorbed within the sample so that this is the energy which is heating the sample. Use data from **(b)** and **(c)**.

specific heat capacity of radium = $110\,J\,kg^{-1}\,K^{-1}$

time = ... s [4]

[Total: 13]

50

This question is about the composition of nuclei.

In the equation $r = r_0A^{1/3}$, $r_0 = 1.41 \times 10^{-15}$ m.

(a) **(i)** State the meaning of

r ....

r_0 ....

A .... [2]

(ii) On Fig. 1.1, sketch a graph to show how r varies with A.

[1]

Fig. 1.1

(b) **(i)** Calculate the radius of the iron-56 ($^{56}_{26}Fe$) nucleus. Give your answer to 3 significant figures.

radius = ... m [2]

(ii) The density of the nucleus of $^{56}_{26}Fe$ is 1.44×10^{17} kg m^{-3}.

Show that the mass of a $^{56}_{26}Fe$ nucleus is 9.45×10^{-26} kg.

[2]

(c) The $^{56}_{26}Fe$ nucleus is composed of protons and neutrons.

proton mass = 1.673×10^{-27} kg

neutron mass = 1.675×10^{-27} kg

(i) State the number of protons and neutrons in the $^{56}_{26}Fe$ nucleus.

protons ....

neutrons .... [1]

(ii) Calculate the total mass of these protons and neutrons.

mass = ... kg [1]

(d) Use your answers to **(b)(ii)** and **(c)(ii)** to find the difference in mass between the $^{56}_{26}Fe$ nucleus and the total mass of the protons and neutrons of which the nucleus is made.

[1]

(e) Use your answer to **(d)** to calculate the binding energy of the $^{56}_{26}Fe$ nucleus.

binding energy = ... J [2]

[Total: 12]

51

This question is about nuclear fission.

When a uranium-235 ($^{235}_{92}U$) nucleus absorbs a neutron, it becomes uranium-236 ($^{236}_{92}U$) which may undergo fission.

(a) In order to increase the probability of neutron-induced fission, neutrons from a fission reaction are slowed down before they collide with another $^{235}_{92}U$ nucleus. This is achieved by causing the neutrons to collide elastically with other nuclei. Explain why these other nuclei should have a mass which is similar to the neutron mass.

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.... [2]

(b) The fission of $^{236}_{92}U$ can produce many different pairs of nuclei.

Fig. 2.1 shows 3 possible pairs of product nuclei and their relative yields.

nucleus 1	nucleus 2	relative yield
zirconium-100 ($^{100}_{40}Zr$)	tellurium-135 ($^{135}_{52}Te$)	6.4%
selenium-83 ($^{83}_{34}Se$)	cerium-152 ($^{152}_{58}Ce$)	0.40%
rhodium-110 ($^{110}_{45}Rh$)	silver-121 ($^{121}_{47}Ag$)	0.020%

Fig. 2.1

(i) Write an equation to show the fission reaction which produces $^{110}_{45}Rh$ and $^{121}_{47}Ag$.

[2]

(ii) Use Fig. 2.1 to plot 6 points on Fig. 2.2.

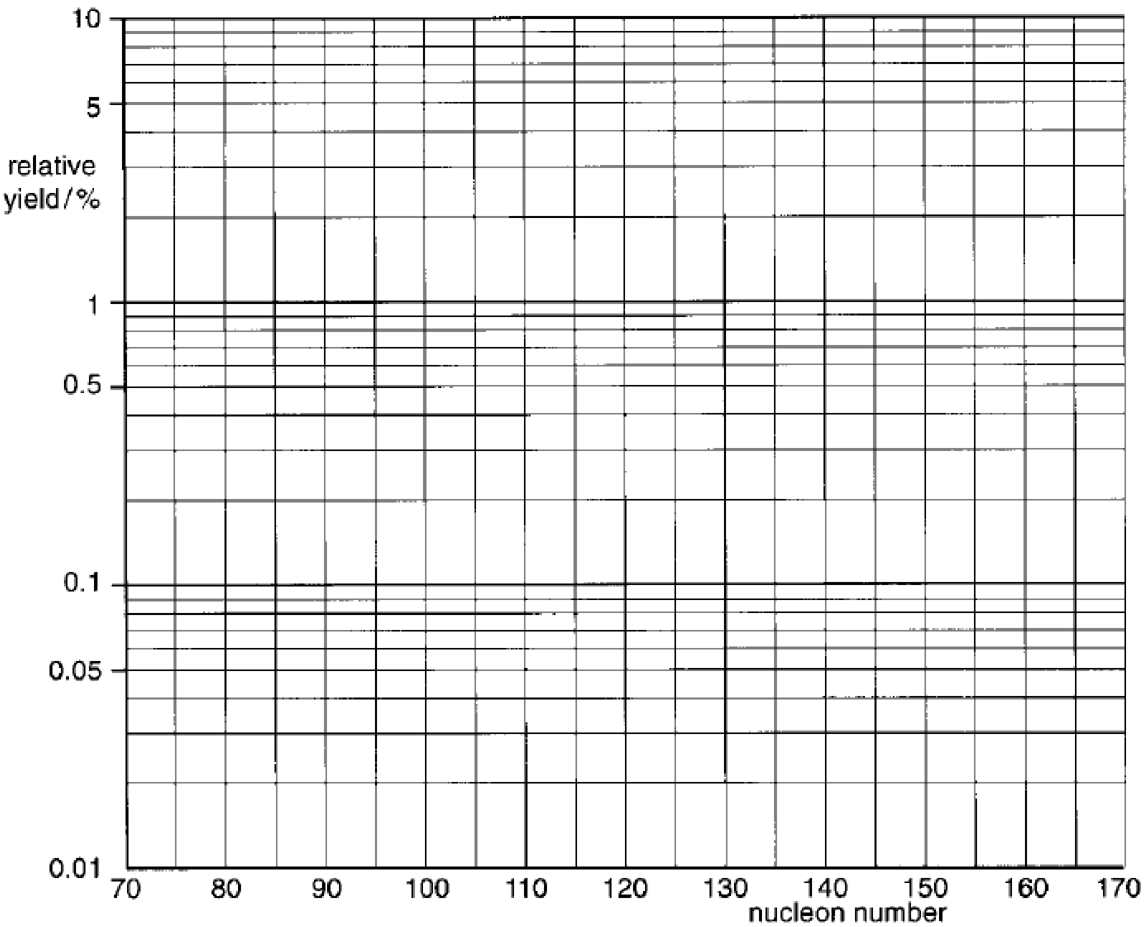

Fig. 2.2

[2]

(iii) On Fig. 2.2, sketch a graph to show how the relative yield varies with nucleon number for **all** the possible fission products. [2]

(iv) Use your graph on Fig. 2.2 to estimate the relative yield of the fission reaction in which a $^{236}_{92}U$ nucleus divides into **equal** parts.

....

.... [1]

(c) **(i)** All the product nuclei in Fig. 2.1 are β^- emitters.

Write an equation for the β^- decay of $^{121}_{47}Ag$. Use 'X' to represent any new nuclide formed.

[2]

(ii) State the **change** in the number of protons and neutrons which result from a β^- decay.

protons ....

neutrons .... [1]

[Total: 12]

52

(a) Describe briefly the quark model of hadrons.

- Illustrate your answer by referring to the composition of **one** hadron.
- Include in your answer the names of **all** the known quarks.
- Give as much information as you can about **one** particular quark.

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(b) A proton (p^+) can interact with a π^- particle according to the equation

$$p^+ + \pi^- \longrightarrow n^0 + \pi^0 + \pi^- + \mathbf{X}.$$

The charge, baryon number and strangeness of the π^- and π^0 particles are shown in Fig. 3.1.

	charge	baryon number	strangeness
π^-	−1	0	0
π^0	0	0	0

Fig. 3.1

(i) Assuming that strangeness is conserved in this reaction, find the charge, baryon number and strangeness of particle **X**.

charge ....

....

baryon number ....

....

strangeness ....

.... [3]

(ii) Suggest what particle **X** is.

....

.... [1]

[Total: 9]

53 This question is about obtaining energy from fusion reactions.

(a) Describe briefly the nature of a plasma.

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.... [1]

(b) Explain how it is possible for a plasma to be confined by a magnetic field.

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.... [3]

(c) Energy may be generated by fusing deuterium nuclei in the reaction

$$^{2}_{1}H + ^{2}_{1}H \longrightarrow ^{3}_{2}He + ^{1}_{0}n + \text{energy}$$ **reaction 1**

The values of binding energy per nucleon for $^{2}_{1}H$ and $^{3}_{2}He$ are given in Fig. 4.1.

nuclide	binding energy per nucleon / MeV
$^{2}_{1}H$	1.11
$^{3}_{2}He$	2.57

Fig. 4.1

(i) Calculate the energy in joule released in **reaction 1**.

energy = ... J [3]

(ii) Energy may also be generated by the fusion of deuterium and tritium in the reaction

$${}^{2}_{1}H + {}^{3}_{1}H \longrightarrow {}^{4}_{2}He + {}^{1}_{0}n + \text{energy}$$ **reaction 2**

The amount of energy generated in **reaction 2** is 2.82×10^{-12} J. State why this shows that **reaction 2** is more suitable than **reaction 1** for generating energy.

....

.... [1]

(d) The energy generated in **reaction 2** is shared between the helium-4 nucleus and the neutron.

Calculate what percentage of the energy released is gained by the neutron. Assume that the initial momentum of the products is zero.

percentage = ... % [5]

54 Neptunium-239 ($^{239}_{93}Np$) is formed in a fission reactor. This nuclide decays to form plutonium-239 ($^{239}_{94}Pu$), thus:

$$^{239}_{93}Np \longrightarrow {}^{239}_{94}Pu + {}^{0}_{-1}e + {}^{0}_{0}\bar{\nu}$$

The half-lives are: $^{239}_{93}Np$: 2.36 days; $^{239}_{94}Pu$: 24 100 years.

A sample consisting of 3.00 x 10^{20} atoms of $^{239}_{93}Np$ is isolated and the number of $^{239}_{93}Np$ nuclei is monitored. This number of nuclei is plotted against time to give the graph labelled Np in Fig. 6.1.

The number of nuclei of $^{239}_{94}Pu$ is also monitored to give the graph labelled Pu.

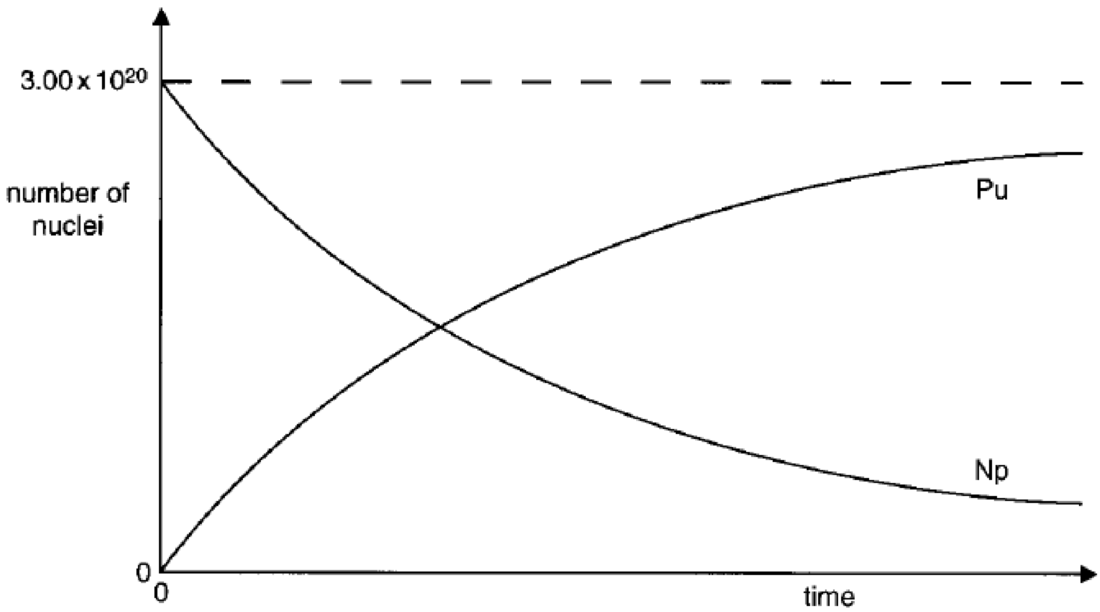

Fig. 6.1

(a) Explain in words the shapes of these graphs.

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.... [3]

(b) Calculate the time taken in days for the number of $^{239}_{94}Pu$ nuclei to reach 2.70×10^{20}.

time = ... days [4]

[Total: 7]

55

This question is about the decay of an isotope of bismuth, $^{212}_{83}Bi$.

(a)

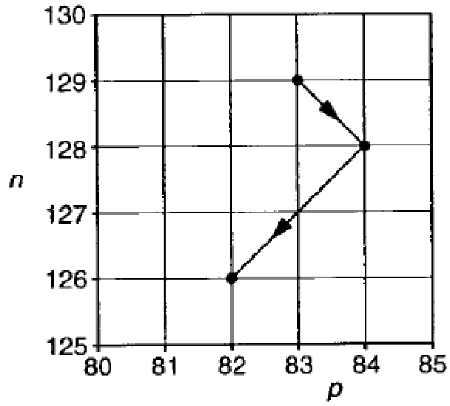

Fig. 6.1

Fig. 6.1 shows a small region of the chart of neutron number *n* against proton number *p*. An isotope of bismuth, Bi, decays to an isotope of lead, Pb, in two stages along the path shown by the two arrows on Fig. 6.1.
Complete the nuclear equations which describe these two decays.

(i) $^{212}_{83}Bi \rightarrow {}^{---}_{84}Po + $ ------ [2]

(ii) $^{---}_{84}Po \rightarrow {}^{---}_{82}Pb + $ ------ [2]

(b) Imagine that you are given a sample of $^{212}_{83}Bi$ mounted on a stand. You are asked to verify experimentally that the two decays in **(a)(i)** and **(ii)** occur. Outline briefly the experiment that you would perform.

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....[4]

(c) The decay constant for $^{212}_{83}Bi$ is 0.0115 min^{-1}.

(i) Show that the initial activity of a sample containing 1.00×10^{-9} g of the isotope is about 3×10^{10} min^{-1}.

[3]

(ii) Calculate the half-life of the isotope.

half-life = ...min [1]

(iii) Assume that only one decay in a million is detected in an experiment to measure the half-life. Draw a graph on the axes of Fig. 6.2 of the count rate against time that you would expect to observe. [1]

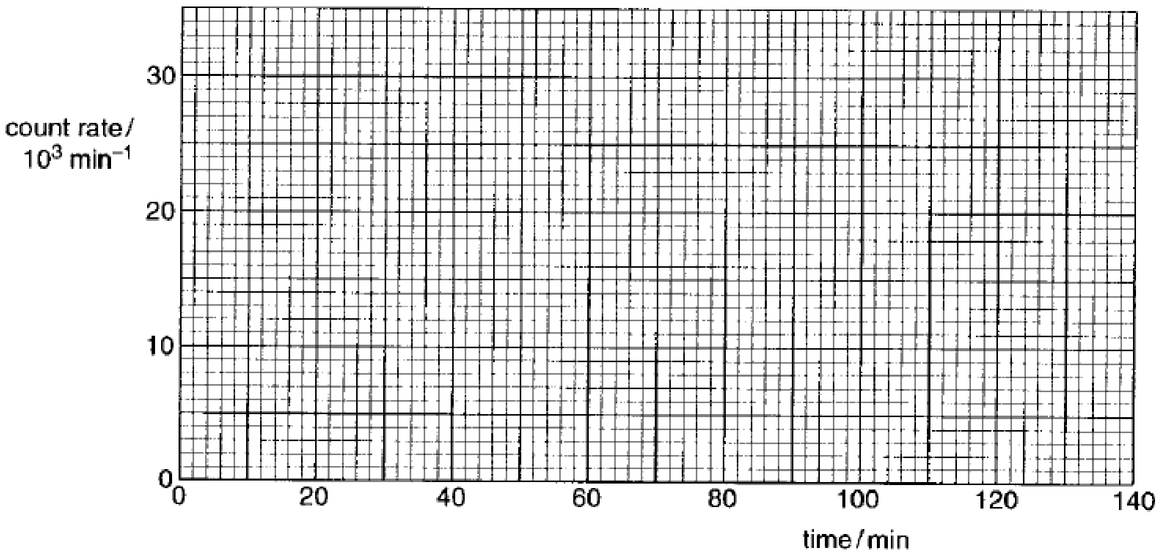

Fig.6.2

[Total: 13]

56

This question is about the strong interaction within the nucleus.

(a) **(i)** On Fig. 1.1, sketch a graph to show the variation with nucleon separation of the strong interaction between two neutrons.

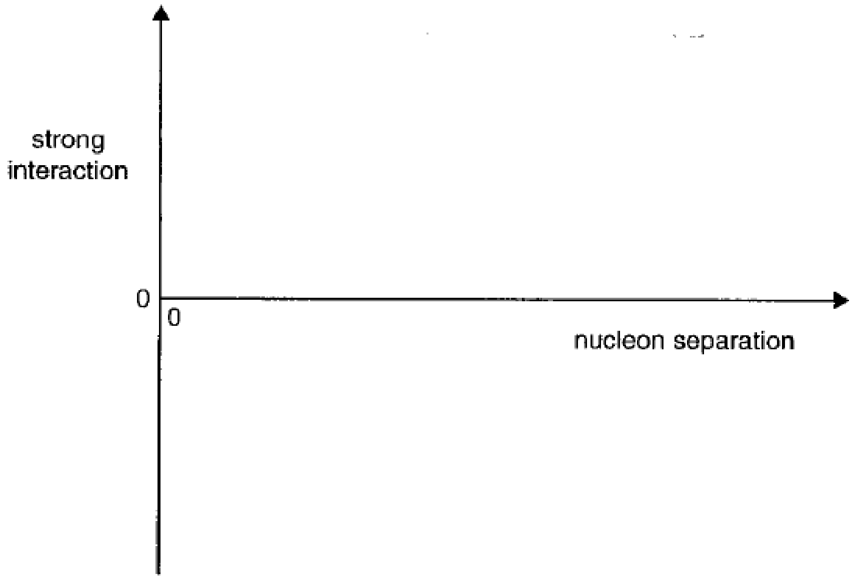

Fig. 1.1 [2]

(ii) Mark on Fig. 1.1 the parts of the graph where the force is attractive and where it is repulsive. [1]

(iii) Mark on Fig.1.1 the equilibrium separation of two neutrons. Label this point X. [1]

(b) By considering small displacements on either side of X, explain why two neutrons are stable at this separation.

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.... [3]

(c) Explain what is meant by the statement that the strong interaction is a short-range force and explain what this implies about the densities of nuclei of various sizes.

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.... [3]

[Total: 10]

57 A fuel rod inside a nuclear reactor contains uranium-238. When a $^{238}_{92}U$ nucleus is exposed to free neutrons it can absorb a neutron. The resulting nucleus decays, first to neptunium-239 $^{239}_{93}Np$ (**decay 1**) and then to plutonium-239 $^{239}_{94}Pu$ (**decay 2**).

(a) Write nuclear equations for these two decay reactions.

decay 1 ....

decay 2 .... [2]

(b) In the fuel rod, $^{239}_{93}Np$ nuclei are produced at a constant rate of $1.80 \times 10^7 s^{-1}$.

On Fig. 2.1, draw a graph to show how the number of $^{239}_{93}Np$ nuclei **produced** varies with time. Label this graph X. Assume that initially there are no $^{239}_{93}Np$ nuclei. [1]

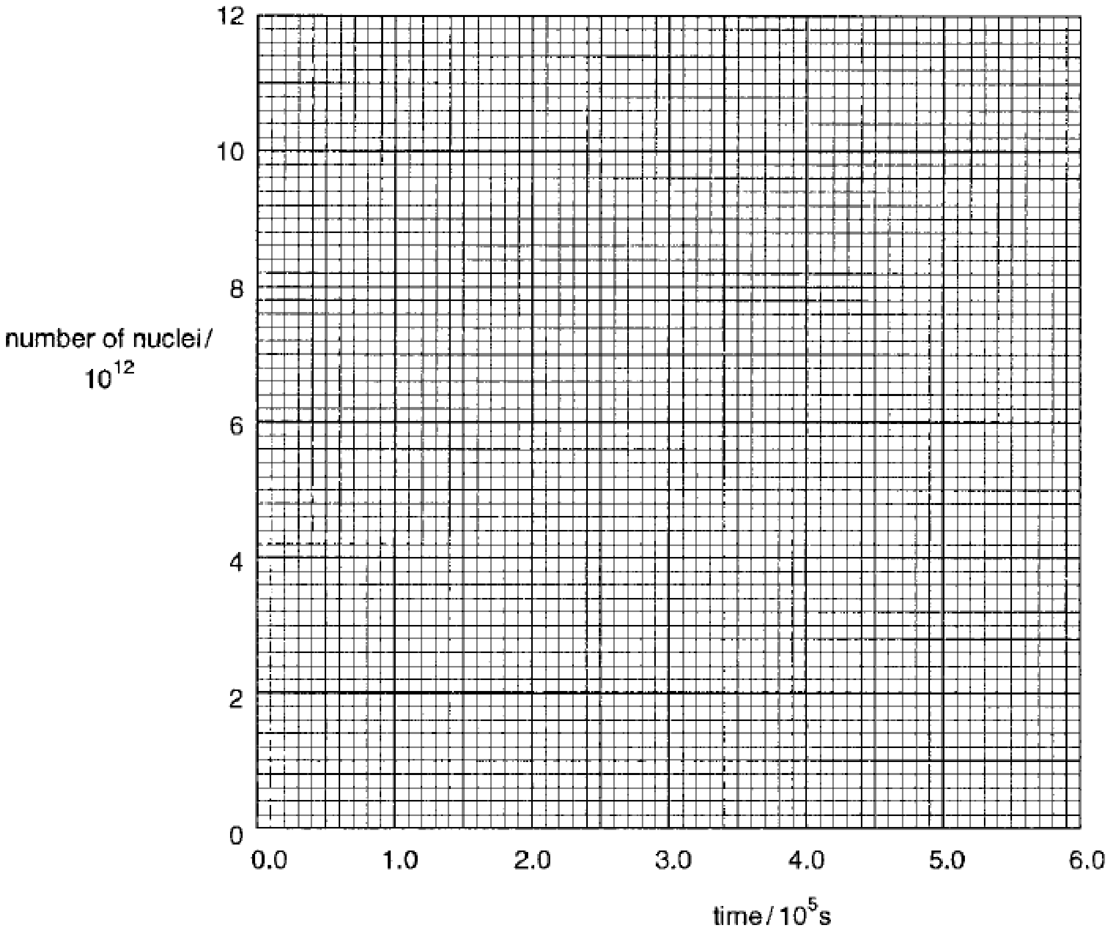

Fig. 2.1

(c) **(i)** State and explain, without calculation, how the number of $^{239}_{93}Np$ nuclei **decaying** per second varies with time.

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.... [2]

(ii) State why the number of $^{239}_{93}Np$ nuclei **present** eventually becomes constant.

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.... [1]