23. Nuclear Physics

23.2 Radioactive decay

Paper 4

Question Paper

1 **(a)** Define half-life of a radioactive isotope.

.....

.....

..... [1]

(b) Radioactive isotope X decays to isotope Y.

A sample contains only nuclei of X at time $t = 0$. Fig. 9.1 shows the variation with t of the numbers of nuclei of X and of Y as the sample decays.

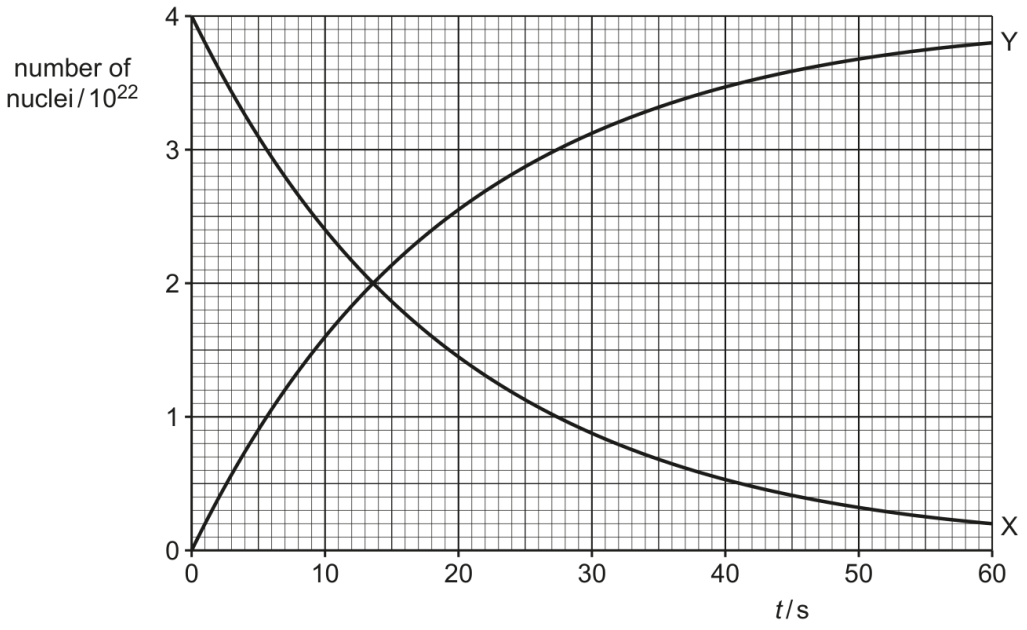


Fig. 9.1

(i) State the name of the quantity represented by the magnitude of the gradient of line X in Fig. 9.1.

..... [1]

(ii) State **three** conclusions about X or Y that may be drawn from Fig. 9.1. The conclusions may be qualitative or quantitative. Use the space below for any working that you need.

1 .....

.....

2 .....

.....

3 .....

.....

[3]

(c) The mass of radioactive isotope X in the sample in **(b)** is 7.3×10^{-4} kg at time $t = 0$.

Determine the nucleon number of isotope X.

nucleon number = ... [3]

2 Fluorine-18 ($^{18}_{9}F$) decays by beta-plus (β^+) emission with a half-life of 110 minutes.

(a) (ii) Show that the decay constant of fluorine-18 is $1.05 \times 10^{-4}\,s^{-1}$.

[1]

(iii) Determine the activity of 2.1×10^{-12} kg of fluorine-18.

activity = ... Bq [3]

3 **(a)** Radioactive decay is both random and spontaneous.

(i) State what is meant by random.

.....

..... [1]

(ii) State what is meant by spontaneous.

.....

..... [1]

(iii) State **one** piece of evidence for the random nature of decay.

.....

..... [1]

4 Carbon-11 is radioactive and decays by β^+ emission to form boron-11. Carbon-11 has a half-life of 20 minutes. Boron-11 is stable.

(a) Define half-life.

.....

..... [1]

(b) A sample contains N_0 nuclei of carbon-11 and no other nuclei at time $t = 0$.

On Fig. 9.1, sketch the variation with t of the number of nuclei of **boron-11** in the sample.

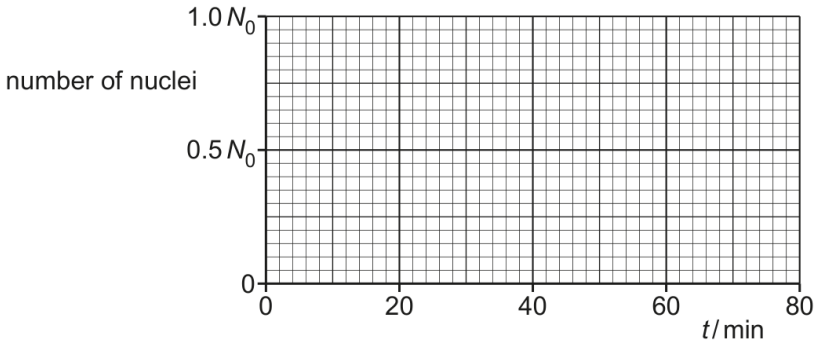


Fig. 9.1

[3]

(c) **(i)** Explain, with reference to the random nature of radioactive decay, why the activity of the carbon-11 sample in **(b)** decreases with time.

.....

.....

..... [2]

(ii) State, with reasons, whether a radiation detector placed near to the sample of carbon-11 indicates a measured count rate from the sample that is less than, the same as or greater than the activity of the sample.

.....

.....

.....

.....

..... [3]

5 Fluorine-18 ($^{18}_{9}F$) is a radioactive nuclide that is used as a tracer in positron emission tomography (PET scanning). Fluorine-18 decays to a nuclide of oxygen (O) according to

$$^{18}_{9}F \longrightarrow {}^{Q}_{P}X + {}^{R}_{8}O.$$

(c) The half-life of fluorine-18 is T.
A patient is injected with amount of substance n of fluorine-18.

(i) Determine an expression for the initial value R_0 of the rate R of production of gamma-ray photons by the tracer, in terms of n, T and the Avogadro constant N_A.

R_0 = ... [3]

(ii) On Fig. 9.1, sketch the variation with time t of R.

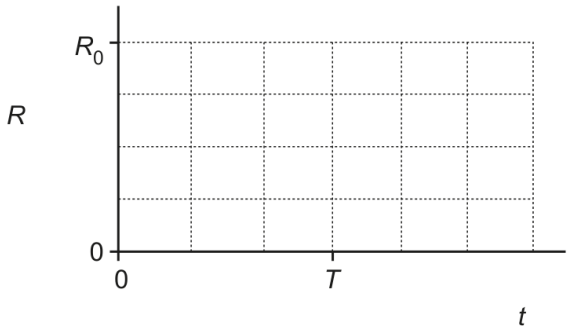


Fig. 9.1

[2]

6 **(a)** State what is meant by radioactive decay.

.....

.....

..... [2]

(b) A radioactive sample consists of an isotope X of half-life T that decays to form a stable product. Only X and the stable product are present in the sample.

At time $t = 0$, the sample has an activity of A_0 and contains N_0 nuclei of X.

(i) On Fig. 10.1, sketch the variation with t of the number N of nuclei of X present in the sample. Your line should extend from time $t = 0$ to time $t = 3T$.

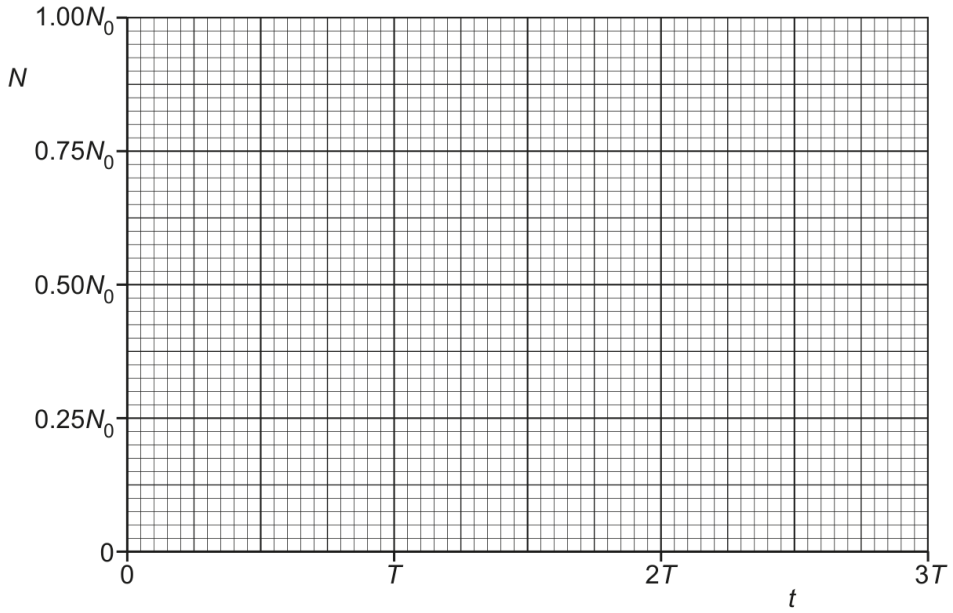


Fig. 10.1

[3]

(ii) On Fig. 10.2, sketch the variation with N of the activity A of the sample for values of N between $N = 0$ and $N = N_0$.

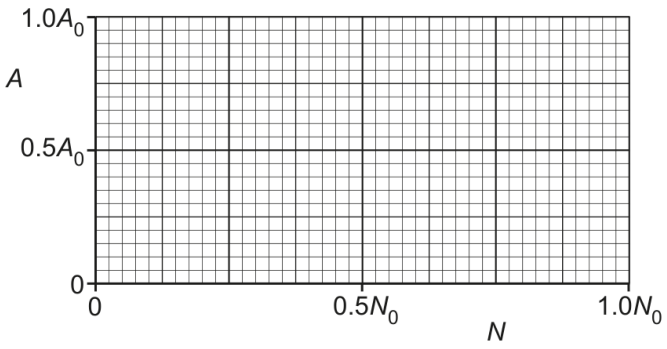


Fig. 10.2

[2]

(c) State the name of the quantity represented by the gradient of your line in:

(i) Fig. 10.1

..... [1]

(ii) Fig. 10.2.

..... [1]

(d) For the sample in **(b)**, calculate the fraction $\frac{N}{N_0}$ at time $t = 1.70T$.

$\frac{N}{N_0}$ = ... [2]

7 Carbon-15 ($^{15}_{6}C$) is an isotope of carbon that undergoes radioactive decay to nitrogen-15 ($^{15}_{7}N$), which is a stable isotope of nitrogen.

Radioactive decay is both a random and a spontaneous process.

(a) State what is meant by:

(i) random

.....

..... [1]

(ii) spontaneous.

.....

..... [1]

(b) A small sample of carbon-15 decays. The mass M of carbon-15 in the sample decreases with time t.

Fig. 10.1 shows the variation with t of the value of ln (M/10^{-16} g).

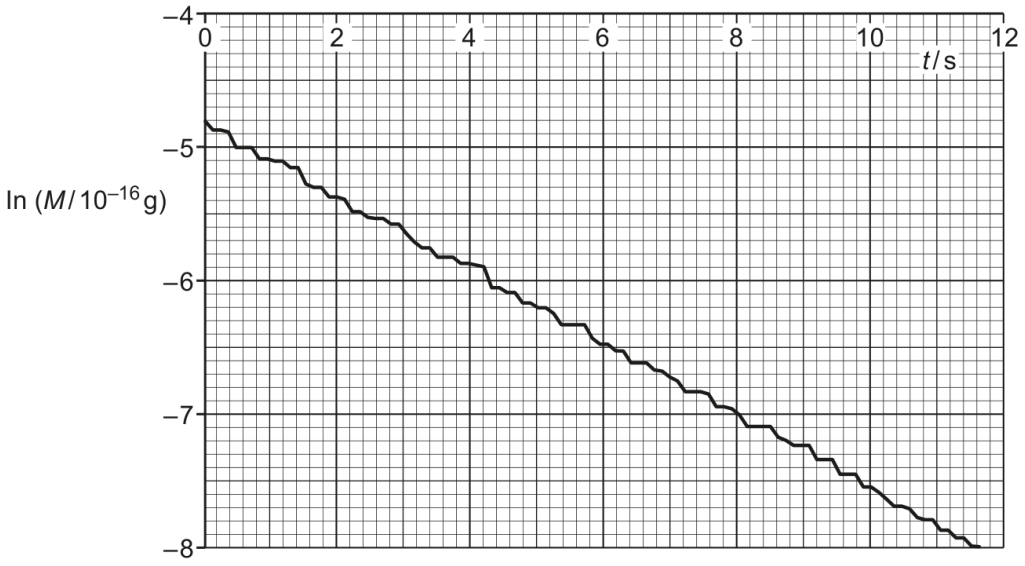


Fig. 10.1

(i) State how Fig. 10.1 demonstrates that radioactive decay is random.

.....

..... [1]

(ii) On Fig. 10.1, draw the straight line of best fit. [1]

(iii) Show that the decay constant λ of carbon-15 is given by the magnitude of the gradient of your line in **(b)(ii)**.

[1]

(iv) Use your line in **(b)(ii)** to determine λ. Give a unit with your answer.

λ = ... unit ..... [2]

(v) Use your answer in **(b)(iv)** to calculate the half-life of carbon-15.

half-life = ... s [1]

8 **(c)** A radioactive isotope decays with a half-life of 15 s to form a stable product.

A fresh sample of the radioactive isotope at time $t = 0$ contains N_0 nuclei and no nuclei of the stable product.

On Fig. 6.3, sketch the variation with t of the number n of nuclei of the stable product for time $t = 0$ to time $t = 45$ s.

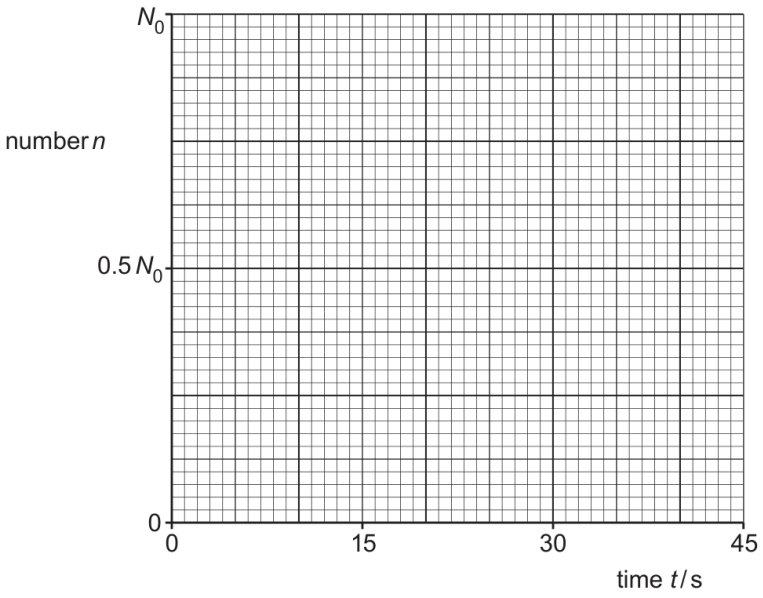


Fig. 6.3

[3]

9 **(c)** A pure sample of a radioactive isotope contains N_0 nuclei. The half-life of the isotope is $T_{\frac{1}{2}}$. The product of the radioactive decay is stable.

The variation with time t of the number N of nuclei of the radioactive isotope is shown in Fig. 5.3.

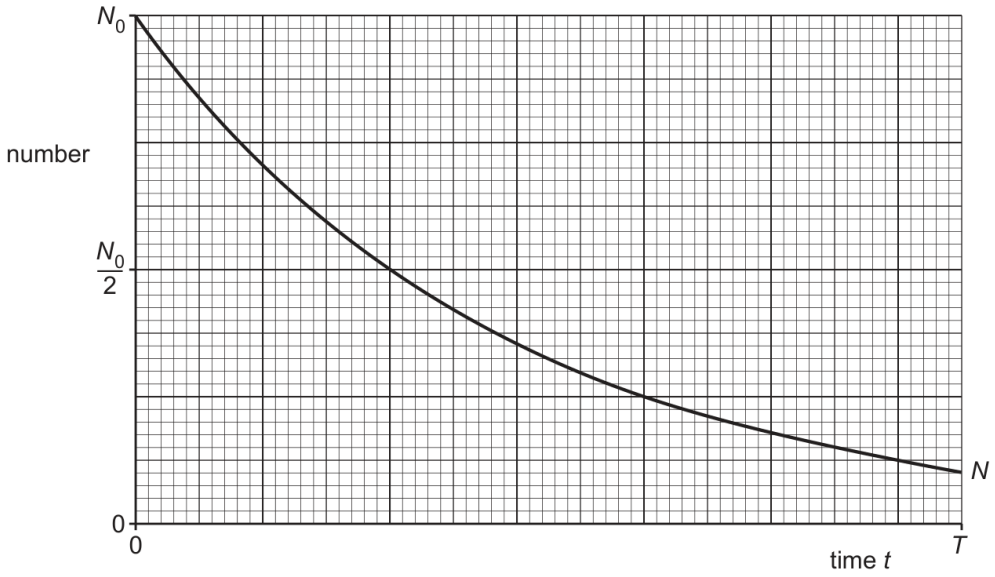


Fig. 5.3

On Fig. 5.3:

- label, on the time axis, the time $t = 1.0T_{\frac{1}{2}}$ and the time $t = 2.0T_{\frac{1}{2}}$
- sketch the variation with time t of the number of nuclei of the decay product for time $t = 0$ to time $t = T$.

[3]

10 **(a)** Define radioactive *decay constant*.

.....

.....

..... [2]

(b) A sample of radioactive iodine-131 ($^{131}_{53}\mathrm{I}$) of mass 5.87×10^{-10} kg has an activity of 2.92×10^{9} Bq.

Determine the decay constant of iodine-131.

decay constant = ... s^{-1} [3]

(c) Suggest **two** reasons why a detector placed near to the sample in **(b)** would record a count rate much less than 2.92×10^{9} counts per second.

1. .....

.....

2. .....

.....

[2]

11 **(a)** Radioactive decay is both random and spontaneous.

State what is meant by:

(i) *random*

.....

..... [1]

(ii) *spontaneous*.

.....

..... [1]

(b) A sample of radioactive material contains atoms of an unstable nuclide X. The activity of the sample due to the atoms of X is A. The variation with time t of ln A is shown in Fig. 12.1.

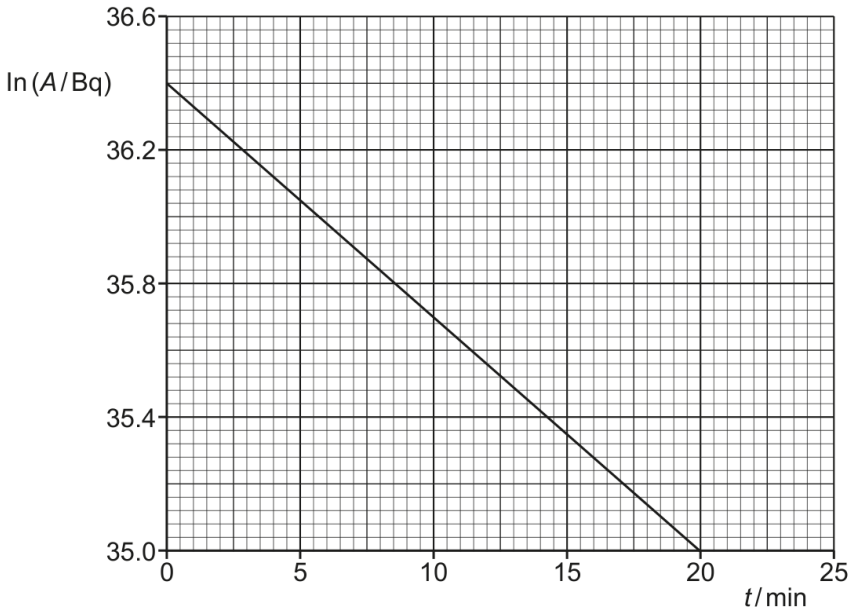


Fig. 12.1

(i) Use Fig. 12.1 to determine the half-life, in minutes, of nuclide X.

half-life = ... min [3]

(ii) At time $t = 0$, the mass of the atoms of X in the sample is 5.66×10^{-7} kg.

Determine the nucleon number of X.

nucleon number = ... [3]

12 **(a)** The decay of a sample of a radioactive isotope is said to be random and spontaneous.

Explain what is meant by the decay being:

(i) *random*

.....

..... [1]

(ii) *spontaneous*.

.....

..... [1]

(b) A radioactive isotope X has a half-life of 1.4 hours.

Initially, a pure sample of this isotope X has an activity of 3.6×10^5 Bq.

Determine the activity of the isotope X in the sample after a time of 2.0 hours.

activity = ... Bq [3]

(c) The variation with time t of the actual activity A of the sample in **(b)** is shown in Fig. 12.1.

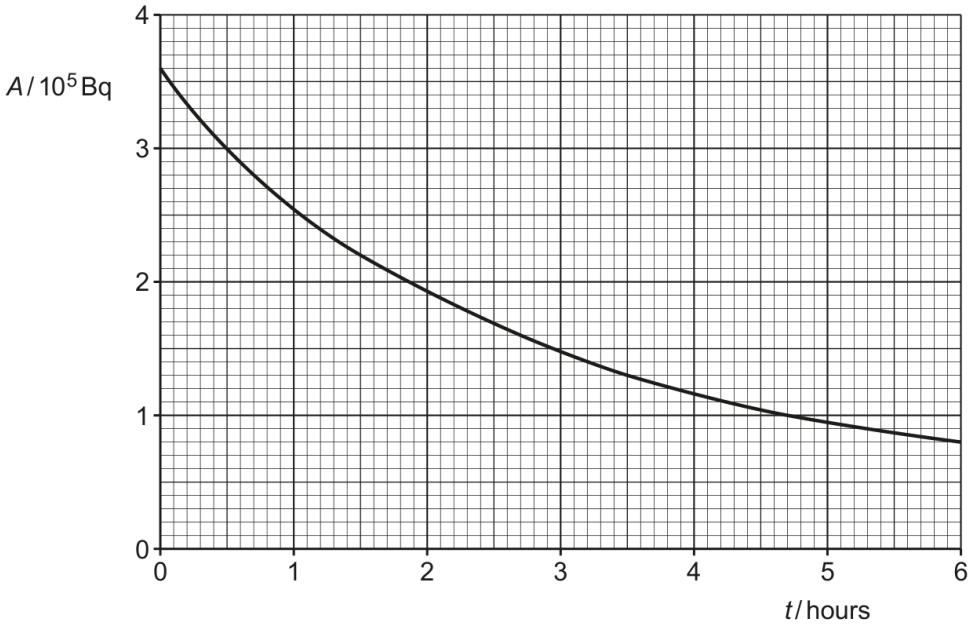


Fig. 12.1

(i) The initial activity of isotope X in the sample is 3.6×10^5 Bq.

Use information from **(b)** to sketch, on the axes of Fig. 12.1, the variation with time t of the activity of a pure sample of isotope X. [1]

(ii) Suggest an explanation for any difference between the actual activity of the sample shown in Fig. 12.1 and the curve you have drawn for the activity of isotope X.

.....

.....

..... [2]

13 Iodine-131 ($^{131}_{53}\mathrm{I}$) is a radioactive isotope with a decay constant of $9.9 \times 10^{-7}\,\mathrm{s}^{-1}$.

(a) State what is meant by:

(i) *radioactive*

.....

.....

..... [2]

(ii) *decay constant.*

.....

.....

..... [2]

(b) Some water becomes contaminated with iodine-131.
The activity of the iodine-131 in 1.0 kg of water is 560 Bq.

Determine the number of iodine-131 atoms in 1.0 kg of water.

number = ... [2]

(c) Regulations require that the activity of iodine-131 in 1.0 kg of water is to be less than 170 Bq.

Calculate the time, in days, for the activity of the contaminated water in **(b)** to be reduced to 170 Bq.

time = ... days [3]

14 (a) A sample of a radioactive isotope contains N nuclei of the isotope at time T.
At time $(T + \Delta T)$, the sample contains $(N - \Delta N)$ nuclei of the isotope. The time interval ΔT is short.

Use the symbols N, ΔN, T and ΔT to give expressions for:

(i) the average activity of the sample during the time ΔT

..... [1]

(ii) the probability of decay of a nucleus in the time ΔT

..... [1]

(iii) the decay constant λ of the isotope.

..... [1]

15 (c) The nuclide lanthanum-141 ($^{141}_{57}$La) has a half-life of 3.9 hours.

Initially, a radioactive source contains only lanthanum-141. The initial activity of the source is A_0.

(i) Calculate the time for the activity of the lanthanum-141 to be reduced to $0.40A_0$.

time = ... hours [3]

(ii) Suggest why the total activity of the radioactive source measured at the time calculated in **(i)** may be greater than $0.40A_0$.

.....

.....[1]

16 Radon-222 ($^{222}_{86}$Ra) is a radioactive gas that decays randomly with a decay constant of 7.55×10^{-3} hour^{-1}.

(a) State what is meant by:

(i) *random* decay

.....

..... [1]

(ii) *decay constant*.

.....

.....

..... [2]

(b) The activity of radon gas in a sample of 4.80×10^{-3} m^3 of air taken from a building is 0.600 Bq.

There are 2.52×10^{25} air molecules in a volume of 1.00 m^3 of air.

Calculate, for 1.00 m^3 of the air, the ratio

$$\frac{\text{number of air molecules}}{\text{number of radon atoms}}.$$

ratio = ... [5]

17 **(a)** State what is meant by *radioactive decay*.

.....

.....

.....

.....[2]

(b) The variation with time t of the number N of technetium-101 nuclei in a sample of radioactive material is shown in Fig. 13.1.

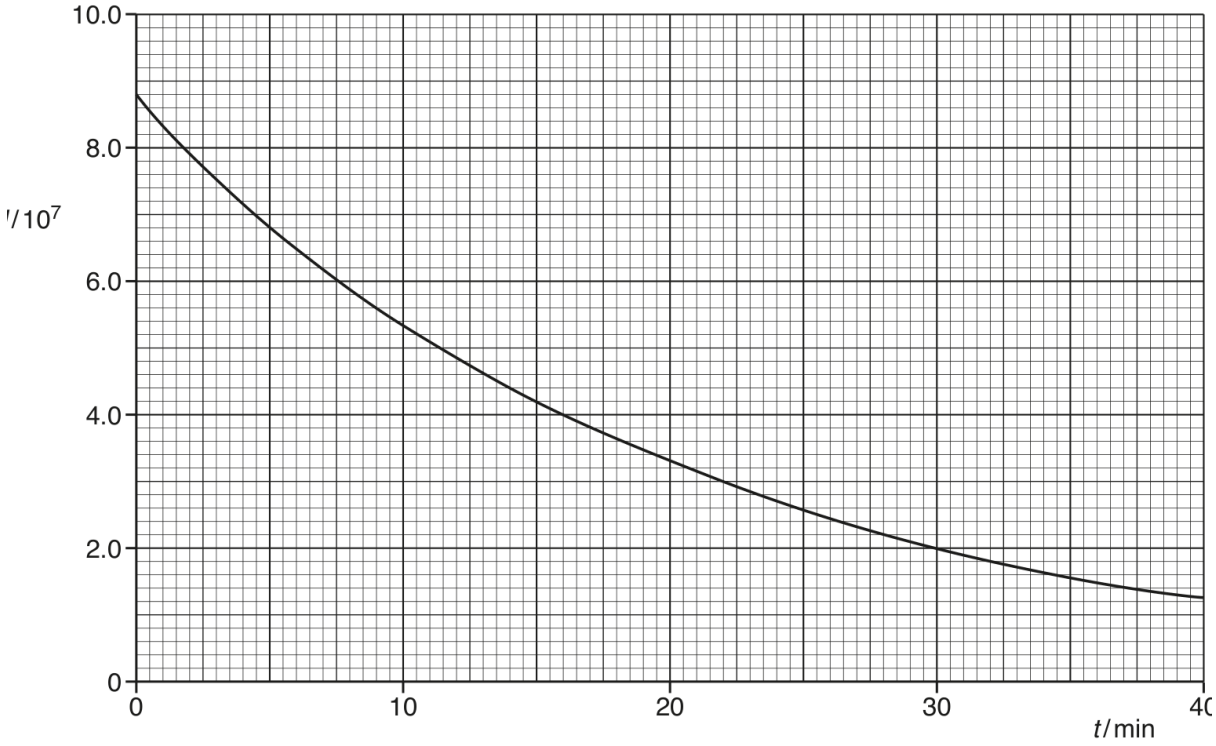


Fig. 13.1

(i) Use Fig. 13.1 to determine the activity, in Bq, of the sample of technetium-101 at time $t = 14.0$ minutes. Show your working.

activity = ... Bq [4]

(ii) Without calculating the half-life of technetium-101, use your answer in **(i)** to determine the decay constant λ of technetium-101.

λ = ... s^{-1} [2]

18 (a) State what is meant by *radioactive decay*.

.....

.....

.....

.....[2]

(b) An unstable nuclide P has decay constant λ_P and decays to form a nuclide D.
This nuclide D is unstable and decays with decay constant λ_D to form a stable nuclide S. The decay chain is illustrated in Fig. 12.1.

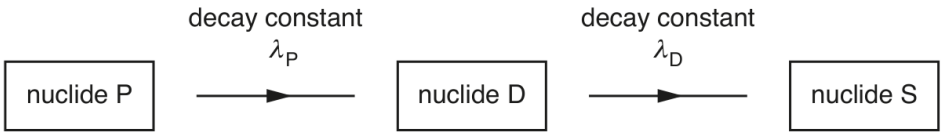


Fig. 12.1

The symbols P, D and S are not the nuclide symbols.

Initially, a radioactive sample contains only nuclide P.

The variation with time *t* of the number of nuclei of each of the three nuclides in the sample is shown in Fig. 12.2.

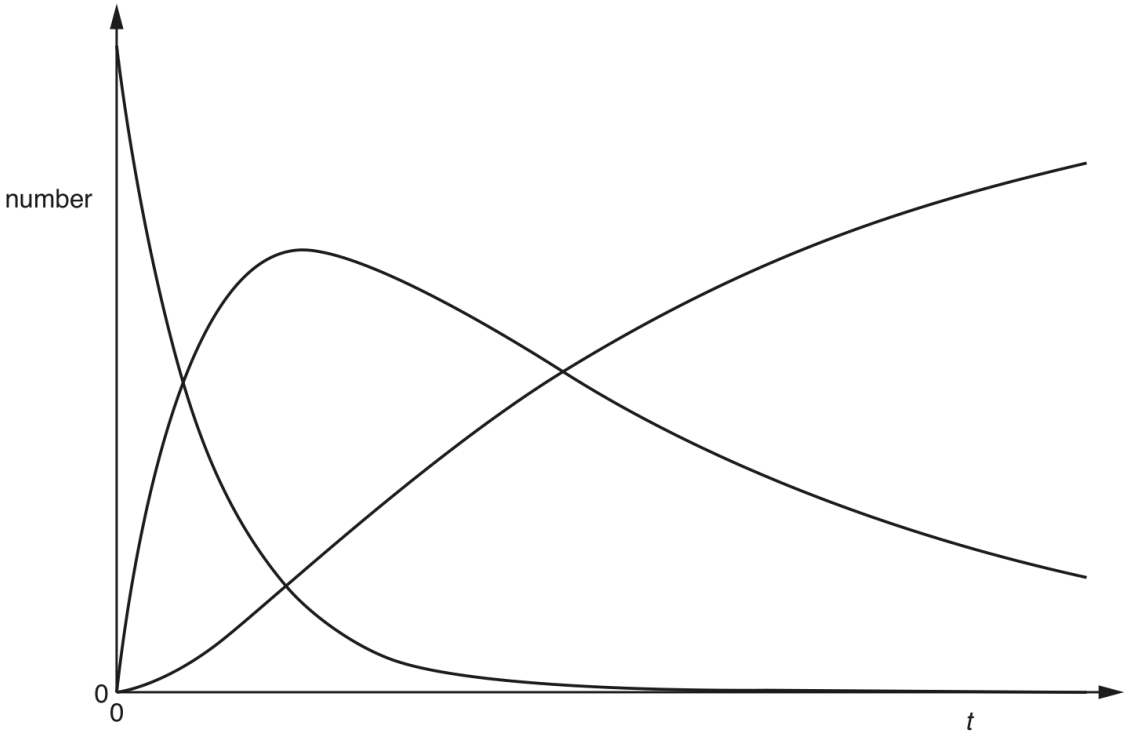


Fig. 12.2

(i) On Fig. 12.2, use the symbols P, D and S to identify the curve for each of the three nuclides. [2]

(ii) The half-life of nuclide P is 60.0 minutes.

Calculate the decay constant λ_P, in s^{-1}, of this nuclide.

λ_P = ... s^{-1} [2]

(c) In the decay chain shown in Fig. 12.1, λ_P is approximately equal to $5\lambda_D$.

The decay chain of a different nuclide E is illustrated in Fig. 12.3.

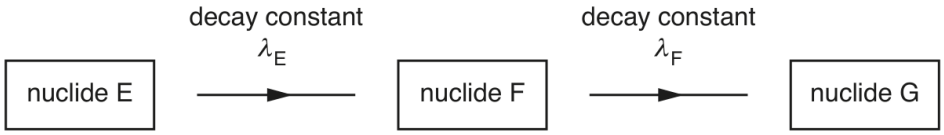


Fig. 12.3

The decay constant λ_F of nuclide F is very much larger than the decay constant λ_E of nuclide E.

By reference to the half-life of nuclide F, explain why the number of nuclei of nuclide F in the sample is always small.

.....

.....

.....[2]

19 **(a)** State what is meant by *radioactive decay*.

.....

.....

.....

.....[3]

(b) The variation with time t of the number N of undecayed nuclei in a sample of a radioactive isotope is shown in Fig. 12.1.

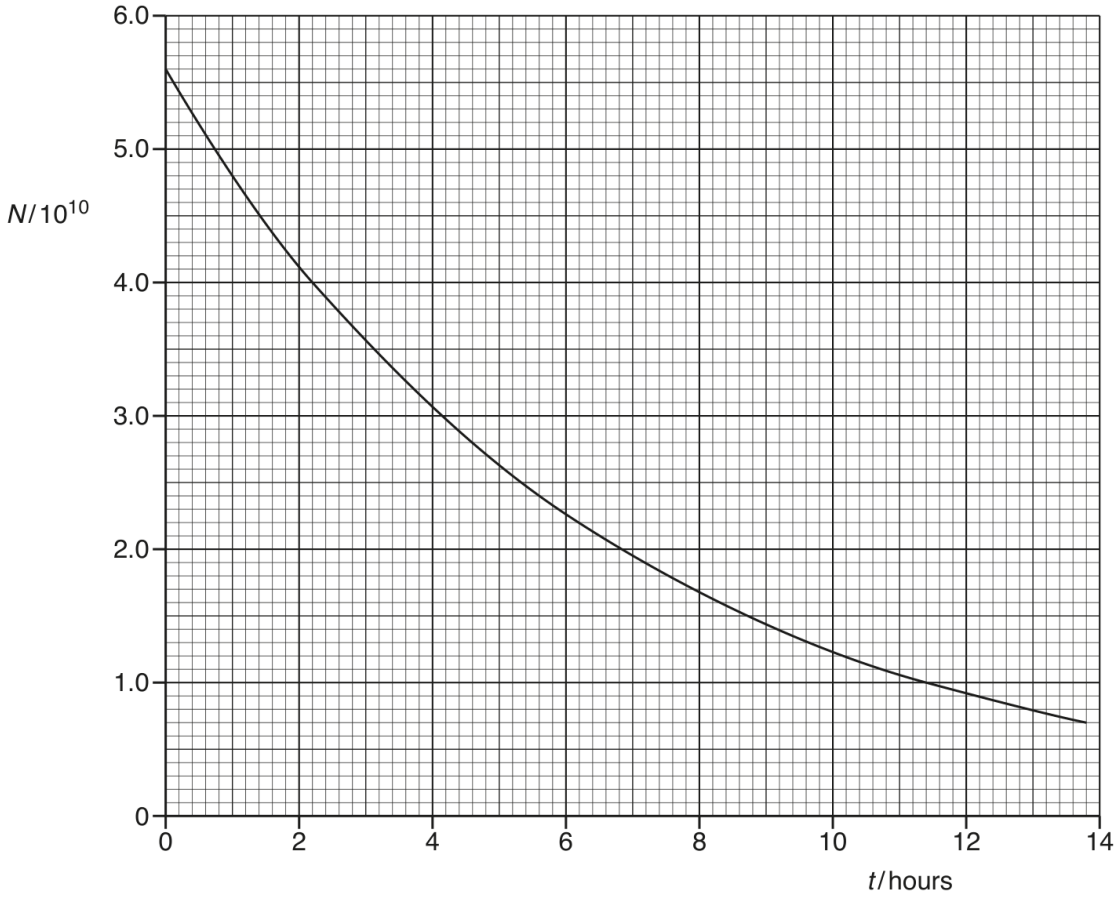


Fig. 12.1

(i) Use the gradient of the line in Fig. 12.1 to determine the activity, in Bq, of the sample at time $t = 4.0$ hours. Show your working.

activity = ... Bq [3]

(ii) Use your answer in **(i)** to show that the decay constant λ of the isotope is approximately $4 \times 10^{-5}\,s^{-1}$.

[2]

(c) A sample of a different radioactive isotope has an initial activity of 4.6×10^{3} Bq. The sample must be stored safely until its activity is reduced to 1.0×10^{3} Bq.

The decay constant of the isotope is $5.5 \times 10^{-7}\,s^{-1}$. The decay products are not radioactive.

Calculate the minimum time, in days, for which the sample must be stored.

time = ... days [3]