NUCLEAR PHYSICS

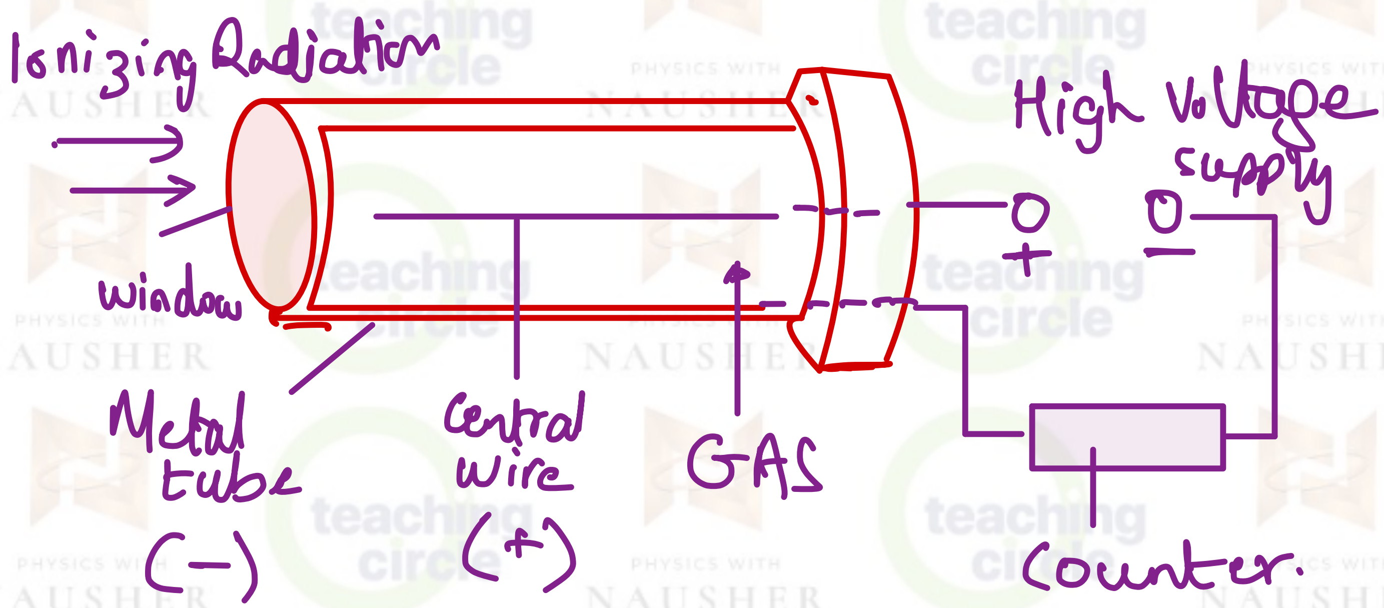
Radioactive Decay

The spontaneous emission of ionizing radiation from an unstable nucleus.

- The random nature of radioactive decay can be demonstrated by observing the count rate of a Geiger-Muller (GM) tube.

- When a GM tube is placed near a radioactive source, the counts are found to be irregular and cannot be predicted.
- Each count represents a decay of an unstable nucleus.
- These fluctuations in count rate on GM tube provide evidence for the randomness of radioactive decay

https://www.youtube.com/watch?v=LGU4mBTPIKw



GM Tube

Characteristics of Radioactive Decay

- Radioactive decay is both spontaneous and random
- A spontaneous process is defined as:-

A process which cannot be influenced by environmental factors.

Not knowing which nucleus will decay.

- This means radioactive decay cannot be affected by environmental factors such as -
  - Temperature
  - Pressure
  - Chemical conditions

- A random process is defined as:-

A process in which we cannot predict when a particular nucleus will decay.

- The probability of decay per unit time remains the same, but the number of undecayed nuclei decreases, leading to fewer decays over time.

- Each radioactive element has a unique probability of decay per unit time.

Imagine you have 100 radioactive atoms:

- Each atom has a 10% chance of decaying during the next minute (constant probability).

First minute:

- Since there are 100 atoms, and each has a 10% chance of decaying, you would expect about 10 atoms to decay in the first minute.
- After 10 decays, 90 atoms are left.

Second minute:

- Now, only 90 atoms are left, and each still has the same 10% chance of decaying.
- So, this time, you would expect about 9 atoms to decay (10% of 90).
- After this, 81 atoms remain.

Third minute:

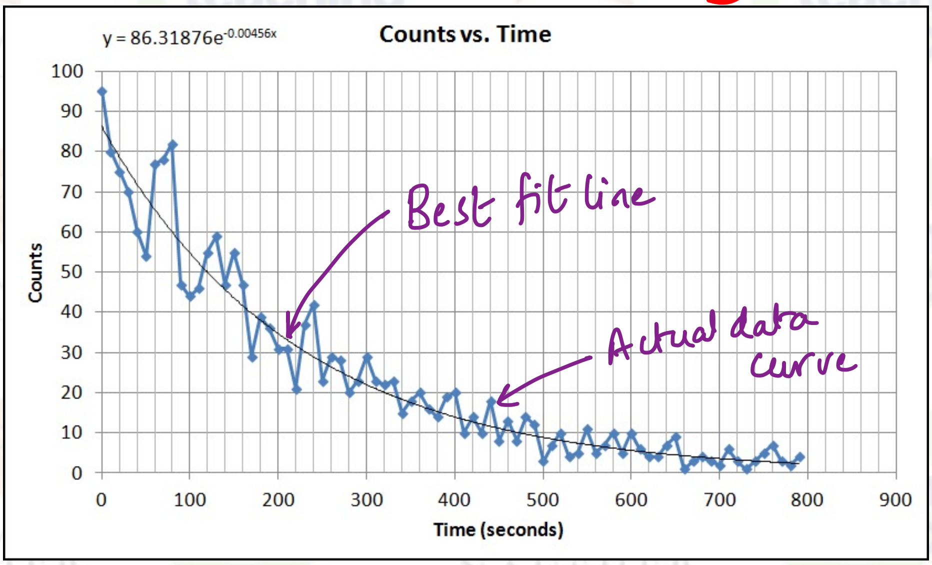
- With 81 atoms remaining, each again has a 10% chance of decaying.
- This means about 8 atoms decay in the third minute.
- After this, 73 atoms are left.

What's happening?

- The probability of decay per atom remains constant (10% chance per minute), but the total number of undecayed atoms decreases after each minute. As a result, fewer atoms are available to decay in the next minute, so the number of decays per minute drops.

This is why the overall decay rate slows down over time, even though each individual atom's chance of decaying stays the same. This pattern follows exponential decay.

Graph of Radioactive Decay



The fluctuations show the randomness of radioactive decay.

Activity and The Decay Constant

- Since radioactive decay is spontaneous and random, it is useful to consider the average number of nuclei which are expected to decay per unit time.
  - This is known as the **average decay rate**.

- As a result, each radioactive element can be assigned a **decay constant**

Decay constant

Probability of decay of a nucleus per unit time.

Symbol: λ

unit: s^{-1}, min^{-1}, yr^{-1}

Formula:

probability of decay

$$\lambda = -\frac{\frac{\Delta N}{N}}{t}$$

time

e.g $\frac{8}{80}$, $\frac{9}{90}$, $\frac{10}{100}$ ← $\frac{\Delta N \text{ (decayed number)}}{N \text{ (remaining)}}$

Time of each decay was 1 minute.

$$\frac{\frac{8}{80}}{1}, \frac{\frac{9}{90}}{1}, \frac{\frac{10}{100}}{1}$$

$= 0.1 \text{min}^{-1}$ ← Decay constant

This means 10% of the remaining nuclei decay each minute.

Note: for calculations always convert to s^{-1}

e.g $\lambda = 0.1386 \text{ year}^{-1}$

Explain what this means.

Note:

A higher decay constant means the substance is more radioactive because it decays more quickly.

Q. If the substance is very radioactive, should it take

A. long time to decay

B. short time to decay.

Activity

The number of decays per unit time

Symbol: A

Formula: $A = \dfrac{\Delta N}{\Delta t}$

unit: s^{-1} $\longrightarrow$ also equivalent to Bq (Becquerels)

Note: An activity of 1 Bq is equal to 1 decay per second.

Q. Does Activity remain constant over a period of time as a sample decays or does it stay the same?

Relationship between Activity and Decay constant

remaining activity

$$\lambda = \frac{\frac{\Delta N}{N}}{\Delta t} \Longrightarrow \lambda = \frac{\Delta N}{N \Delta t} \Longrightarrow \boxed{\lambda = \frac{A}{N}}$$

remaining nuclei

Hence $\boxed{A = -N\lambda}$

Note:

The greater the decay constant, the greater the activity of the sample

The activity depends on the number of undecayed nuclei remaining in the sample.

The minus sign indicates that the number of nuclei remaining decreases with time - however, for calculations it can be omitted.

Half Life

The time taken for the initial number of nuclei to reduce by half.

Symbol: H.L , t_{HL}

unit: s, min, year.

Formula: $\lambda = \frac{\ln 2}{H.L}$

- When a time equal to one half life passes, the activity also halves.
- What about decay constant? → Change → Constant
- If H.L ↑, λ ___ , A ___ , is the substance unstable stable

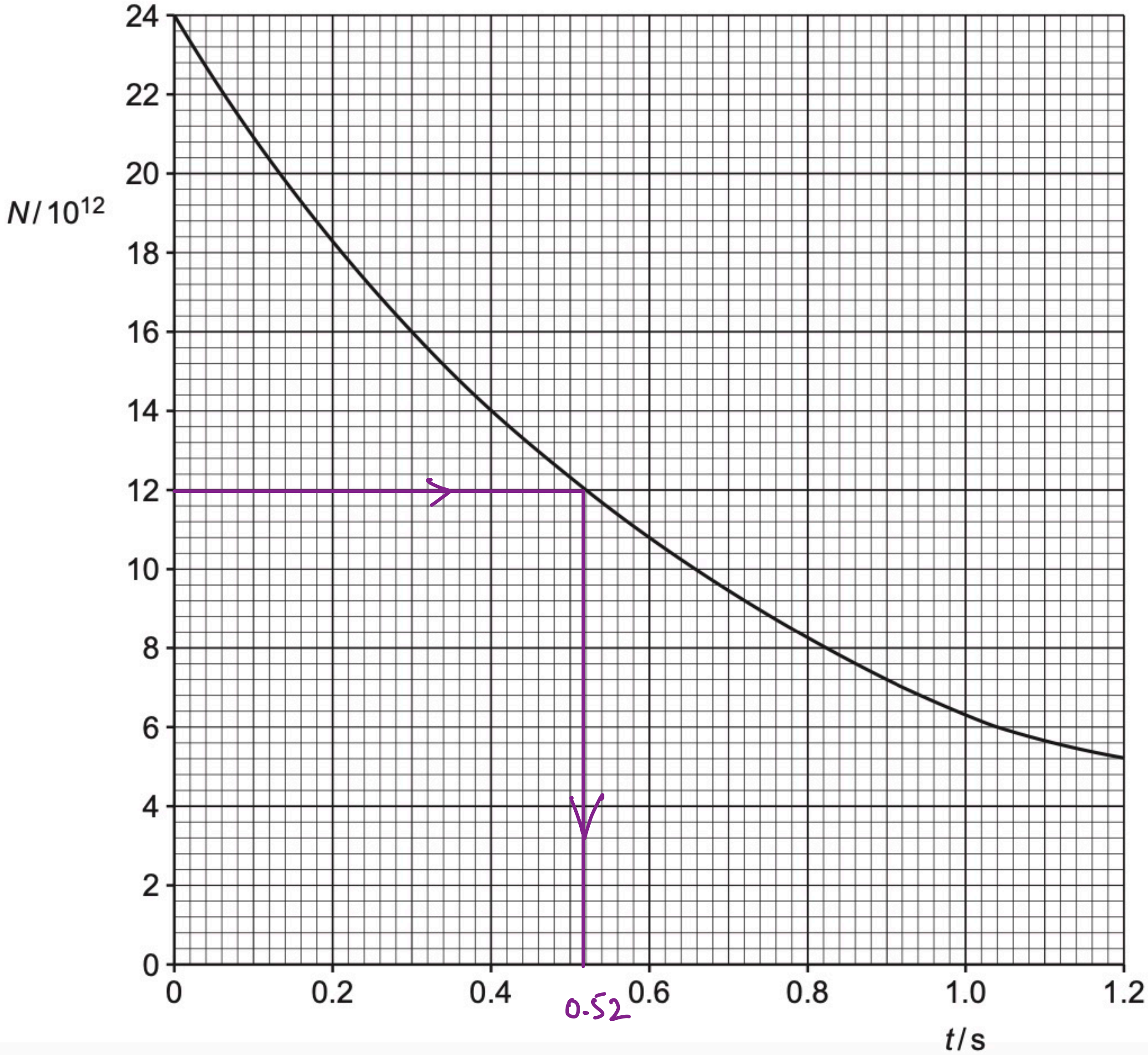
Polonium-211 ($^{211}_{84}Po$) decays by alpha emission to form a stable isotope of lead (Pb).

(a) Complete the equation for this decay.

$$^{211}_{84}Po \rightarrow \; ^{207}_{82}Pb + \; ^{4}_{2}\alpha$$

[2]

(b) The variation with time t of the number of unstable nuclei N in a sample of polonium-211 is shown in Fig. 9.1.



At time $t = 0$, the sample contains only polonium-211.

(i) Use Fig. 9.1 to determine the decay constant λ of polonium-211. Give a unit with your answer.

H.L = 0.52 s

$$\lambda = \frac{\ln 2}{HL} = \frac{0.693}{0.52}$$

λ = 1.33 unit s^{-1} [2]

(ii) Use your answer in **(b)(i)** to calculate the activity at time $t = 0$ of the sample of polonium-211.

$A = N\lambda$

$= 24 \times 10^{22} \times 1.33$

activity = 3.2×10^{23} Bq [1]

(iii) On Fig. 9.1, sketch a line to show the variation with t of the number of lead nuclei in the sample. [2]

Done on next page.

(c) Each decay releases an alpha particle with energy 6900 keV.

(i) Calculate, in J, the total amount of energy given to alpha particles that are emitted between time $t = 0.30$ s and time $t = 0.90$ s.

$t = 0.30$ s — 16×10^{12} atoms

$t = 0.90$ s — 7.2×10^{12} atoms

1 mole of Po atoms form 1 mol of α-particles

8.8×10^{12} atoms of Po decay $\longrightarrow$ 8.8×10^{12} atoms of α- formed.

1 decay releases = 6900 keV

8.8×10^{12} decays release = $6900 \times 8.8 \times 10^{12} = 6.072 \times 10^{16}$ keV

$1\text{ keV} = 1.6 \times 10^{-16}$ J

energy = 9.8 J [3]

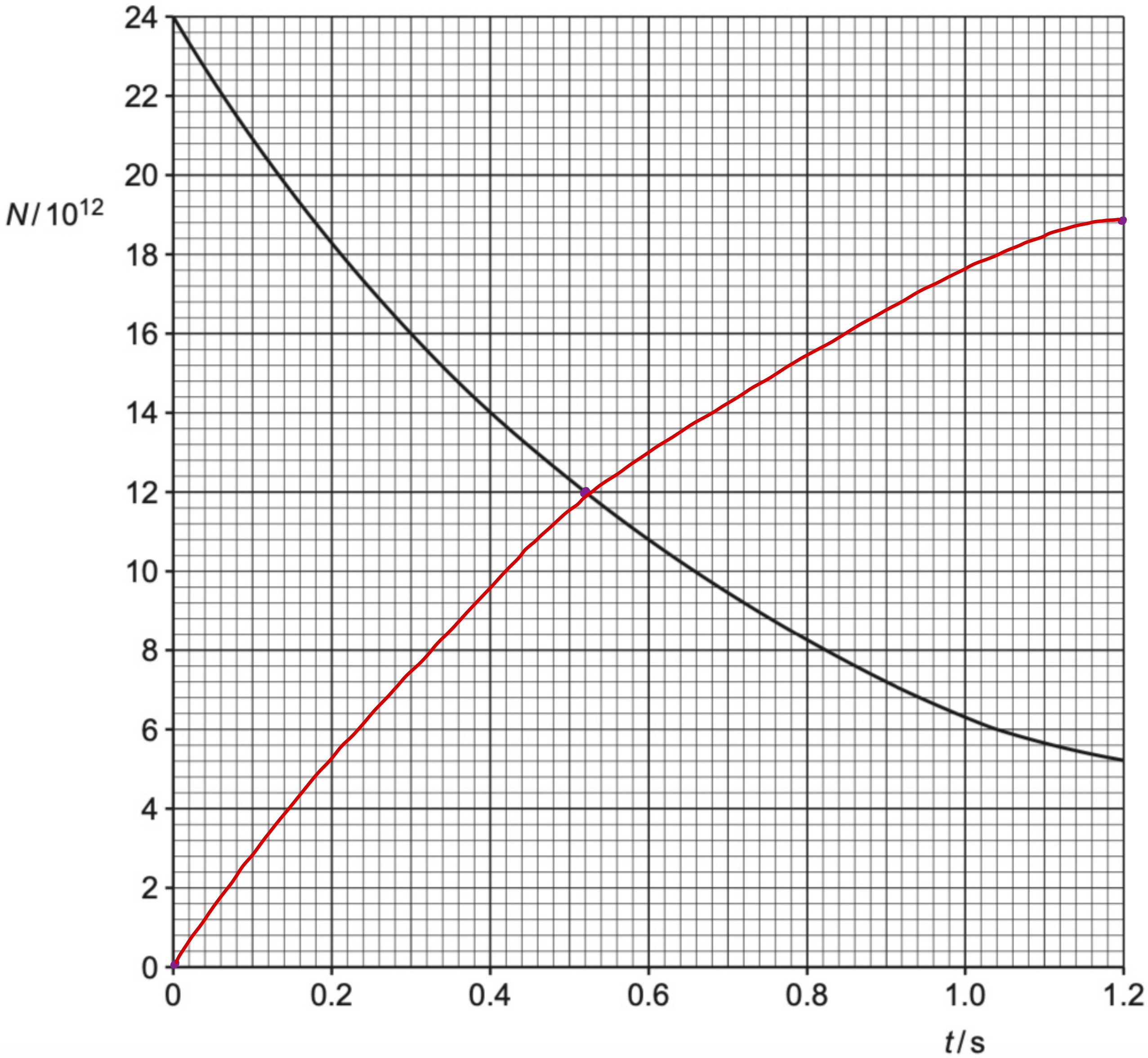
(ii) Suggest why the total amount of energy released by the decay process between time $t = 0.30$ s and time $t = 0.90$ s is greater than your answer in **(c)(i)**.

Lead nuclei will have kinetic energy

[1]

Note: Remember recoil

(b) The variation with time t of the number of unstable nuclei N in a sample of polonium-211 is shown in Fig. 9.1.



Initial # = 24×10^{12}
Final # = 5.2×10^{12}] Po

Difference = 18.8×10^{12}] Pb

Note: Total # of nuclei remain constant.

Uranium-234 is radioactive and emits α-particles at what appears to be a constant rate.

A sample of Uranium-234 of mass 2.65 µg is found to have an activity of 604 Bq. $\rightarrow s^{-1}$

(a) Calculate, for this sample of Uranium-234,

(i) the number of nuclei,

$$\text{no. of moles} = \frac{\text{mass in gram}}{A} = \frac{2.65\times10^{-6}}{234} = 1.13\times10^{-10}$$

1 mole — 6.02×10^{23} particles

1.13×10^{-10} moles — 6.8×10^{15}

number = 6.8×10^{15} [2]

(ii) the decay constant,

$$A = N\lambda$$

$$604\ s^{-1} = 6.8\times10^{15}\cdot\lambda$$

$$\lambda = 8.9\times10^{-14}$$

decay constant = 8.9×10^{-14} s^{-1} [2]

(iii) the half-life in years.

$$H.L = \frac{\ln 2}{\lambda} = \frac{\ln 2}{8.9\times10^{-14}} = 7.8\times10^{12}\ s$$

1 year = $365\times24\times3600\ s$

$x = 7.8\times10^{12}$

half-life = 250 000 years [2]

$x = 247451.9$ years

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

the time taken for the initial number of nuclei to half.

.... [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.

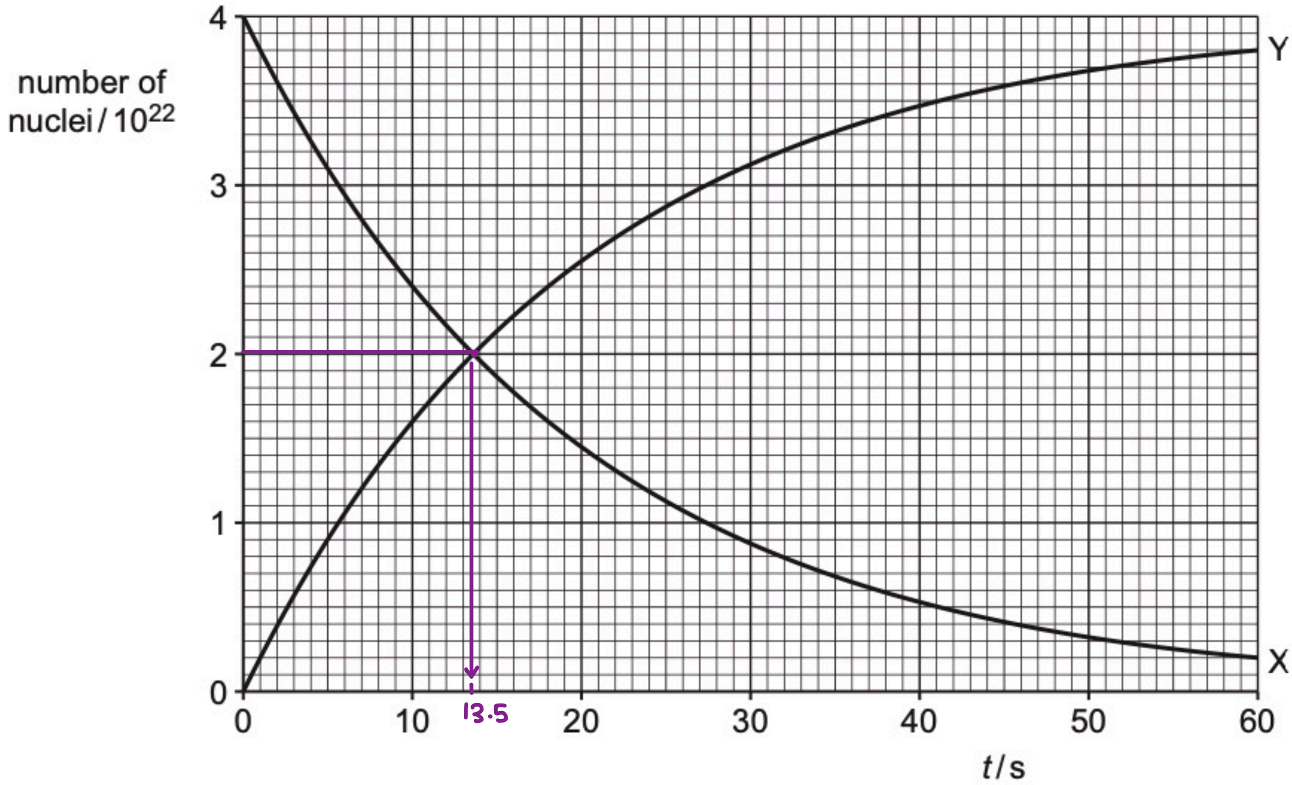


Fig. 9.1

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

activity [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.

$$\text{Decay constant} = \frac{\ln 2}{H.L} = \frac{\ln 2}{13.5}$$

1 The total # of nuclei remain constant.

2 The half life is 13.5s

3 Decay constant = 0.051 s^{-1}

[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.

initial number of nuclei in X $= 4.0 \times 10^{22}$

initial mass of X $= 7.3 \times 10^{-4}$ kg $= 0.73$g

1 mol — 6×10^{23} nuclei

x — 4×10^{22} nuclei

nucleon number = 11 [3]

[Total: 8]

$6 \times 10^{23} x = 4 \times 10^{22}$

$x = 0.0667$ moles

$$\text{no. of moles} = \frac{\text{mass}}{A}$$

$$A = \frac{0.73}{0.0667} = 10.95$$

The isotope phosphorus-33 ($^{33}_{15}P$) undergoes β-decay to form sulfur-33 ($^{33}_{16}S$), which is stable.
The half-life of phosphorus-33 is 24.8 days.

(a) **(i)** Define radioactive *half-life*.

....

....

.... [2]

(ii) Show that the decay constant of phosphorus-33 is $3.23 \times 10^{-7}\,s^{-1}$.

[1]

(b) A pure sample of phosphorus-33 has an initial activity of 3.7×10^{6} Bq.

Calculate

(i) the initial number of phosphorus-33 nuclei in the sample,

number = ... [2]

(ii) the number of phosphorus-33 nuclei remaining in the sample after 30 days.

number = ... [2]

similar concept to the first question

(c) After 30 days, the sample in **(b)** will contain phosphorus-33 and sulfur-33 nuclei.
Use your answers in **(b)** to calculate the ratio

$$\frac{\text{number of phosphorus-33 nuclei after 30 days}}{\text{number of sulfur-33 nuclei after 30 days}}.$$

ratio = ... [2]

A radioactive source is formed from a lead isotope. The source has 3.20×10^{18} lead nuclei. The average energy released during each decay is 9.12×10^{-20} J.

The half-life of the lead isotope is 10.6 hours.

What is the initial power of the source?

A 8.60×10^{-21} W

B 5.30×10^{-6} W

C 7.65×10^{-6} W

D 1.91×10^{-2} W

The half-life of carbon-14 is 5700 years.

A sample of pure carbon-14 has an activity of 6.2 MBq.

How many atoms of carbon-14 does the sample contain?

A 5.1×10^{4} **B** 5.1×10^{10} **C** 1.6×10^{12} **D** 1.6×10^{18}