Chapter 14
Radioactivity

Worksheet

Intermediate level

1 **a** Give the name of each of the following ionising radiations:

    i $^4_2$He   **ii** $^{\ 0}_{-1}$e   **iii**   [3]

  b Which radiation is the most ionising?   [1]

  c What is wrong with the statement below written by a student in his notes?

    Beta-particles emitted from a radioactive material are the orbiting electrons of the atoms.   [1]

2 State two of the properties of   -radiation.   [2]

3 **a** In each case below, write a nuclear decay equation.

    i An isotope of polonium $^{210}_{84}$Po emits an   -particle and changes into an isotope of lead (Pb).   [2]

    ii An isotope of strontium $^{90}_{38}$Sr emits a   -particle and changes into an isotope of yttrium (Y).   [2]

  b Explain why the nucleon number in your answer to **a ii** does not change.   [2]

4 During the transformation of the isotope of thorium $^{232}_{90}$Th into an isotope of radon (Rn), a total of three   -particles and two   -particles are emitted. Determine the nucleon number and proton number of the isotope of radon.   [4]

5 **a** Define the half-life of a radioactive isotope.   [1]

  b The half-life of a particular isotope is 20 minutes. In a radioactive sample, there are N_0 nuclei of this isotope. Determine the number of nuclei of the isotope left in the sample after a time of:

    i 20 minutes;   [1]

    ii 1.0 hour.   [2]

6 The activity of an   -source is 540 Bq. The kinetic energy of each   -particle is 8.6×10^{-14} J. The isotope in the source has a very long half-life.

  a How many   -particles are emitted by the source in:

    i 1 second?   [1]

    ii 1 hour?   [1]

  b Determine the total energy released by the source in a time of 1 second.   [3]

  c What is the power released by the source?   [1]

Higher level

7 The half-life of the isotope radon-220 is 52 s. Determine:

   a   the decay constant in s^{-1}; [3]

   b   the activity of a sample containing 6.0×10^{10} nuclei of the isotope of radon-220. [3]

8 The activity of a radioactive source containing 8.0×10^{14} undecayed nuclei is 5.0×10^9 Bq. Determine:

   a   the decay constant in s^{-1}; [3]

   b   the half-life of the nucleus; [3]

   c   the number of undecayed nuclei left after 40 hours. [3]

9 **a**   Define the decay constant of a nucleus. [1]

   b   The isotope of thorium $^{227}_{90}$Th has a half-life of 18 days. A particular radioactive source contains 4.0×10^{12} nuclei of the isotope $^{227}_{90}$Th. Determine:

      i   the decay constant for the thorium isotope $^{227}_{90}$Th in s^{-1}; [3]

      ii   the initial activity of the source; [3]

      iii   the activity of the source after 36 days. [2]

10 A sample of rock is known to contain $1.0\,\mu g$ of the radioactive radium isotope $^{226}_{88}$Ra. The half-life of this particular isotope is 1600 years. The molar mass of radium-226 is 226 g. Determine:

   a   the number of nuclei of the isotope $^{226}_{88}$Ra in the rock sample; [2]

   **b**   the activity from decay of the radium-226 in the sample. [3]

Extension

11 Some astronomers believe that our Solar System was formed 5.0×10^9 y ago. Assuming that all uranium-238 nuclei were formed before this time, determine the fraction of uranium-238 nuclei left on the Earth today. The isotope of uranium $^{238}_{92}$U has a half-life of 4.5×10^9 y. [4]

12 A student records the initial count rate from a radioactive sample as 340 counts per second. The count rate after 26 minutes is 210 counts per second. Determine the half-life of each nuclide within the radioactive sample. [7]

Total: $\overline{67}$ Score: %

Worked examples

Example 1

The graph shows the number N of undecayed nuclei left in a radioactive source after a time t.
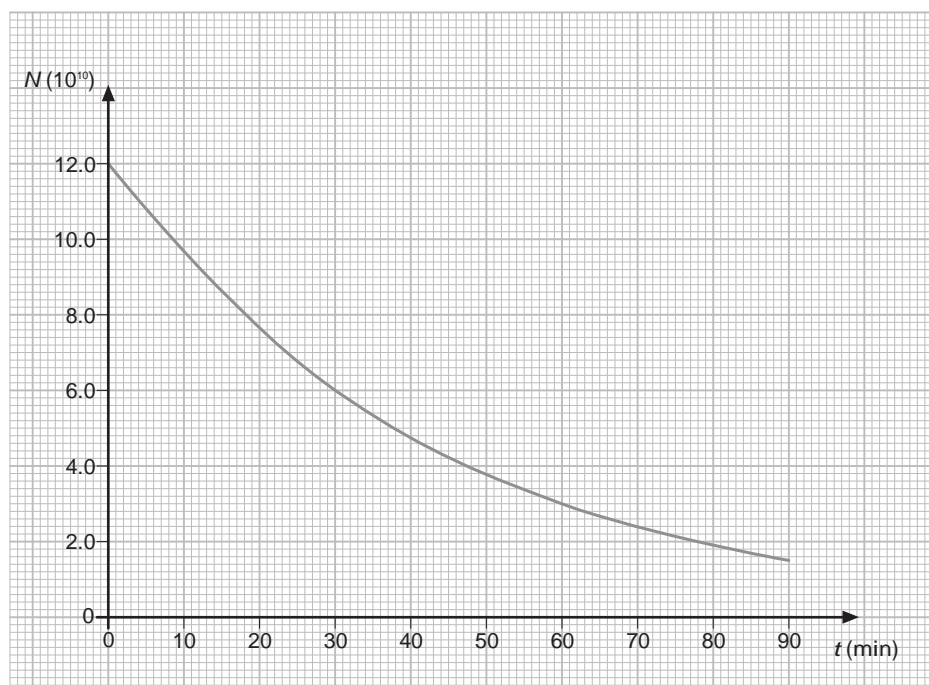
Determine the decay constant in s^{-1} of the nuclide in the source.

From the graph, the half-life $t_{1/2}$ is 30 minutes.

> *In a time equal to one half-life, the number of undecayed nuclei left in the source is halved.*

The decay constant λ is given by the relation:

$$t_{1/2} = \frac{0.693}{\lambda}$$

Hence:

$$\lambda = \frac{0.693}{t_{1/2}}$$

$$\lambda = \frac{0.693}{30 \times 60}$$

> *In order to get the answer for the decay constant in s^{-1}, the half-life must be converted into seconds.*

$$\lambda = 3.85 \times 10^{-4}\,s^{-1} \approx 3.9 \times 10^{-4}\,s^{-1}$$

Example 2

The isotope of argon $^{39}_{18}Ar$ has a decay constant of $8.3 \times 10^{-11}\,s^{-1}$. A sample of rock contains 4.5×10^{12} nuclei of the isotope $^{39}_{18}Ar$ trapped within it. Determine the number of nuclei of $^{39}_{18}Ar$ left in the rock after a time of 270 years.

The number N of undecayed nuclei left after a time t is given by the relation:

$$N = N_0\, e^{-\lambda t}$$

where N_0 is the original number of nuclei. Therefore:

$$N = 4.5 \times 10^{12}\, e^{-(8.3 \times 10^{-11} \times 270 \times 365 \times 24 \times 3600)}$$

$$N \approx 2.2 \times 10^{12}$$

> *The time t must be converted from years into seconds.*

> **Tip**
>
> The number of nuclei left is almost half the original number of nuclei. Hence, the half-life of the isotope $^{39}_{18}Ar$ must be about 270 years.

Practical 1

## *The absorption of ®-radiation by aluminium*

Safety

It is vital that Local Authority regulations on the use of sealed radioactive sources are adhered to when carrying out the experiment. Always keep the source at a safe distance by using long tweezers. Never point the source at the eyes or sensitive organs. Teachers and technicians should follow their school and departmental safety policies and should ensure that the employer's risk assessment has been carried out before undertaking any practical work.

Apparatus

- GM tube
- scaler
- micrometer
- strontium-90 source in a holder

- long tweezers
- aluminium plates
- stopwatch

Introduction

The absorption of different radiations by materials is described in detail on page 142 of *Physics 2*. In this experiment you will estimate the thickness of aluminium needed to stop half of the -particles emitted by a -source. The experimental arrangement is shown below.
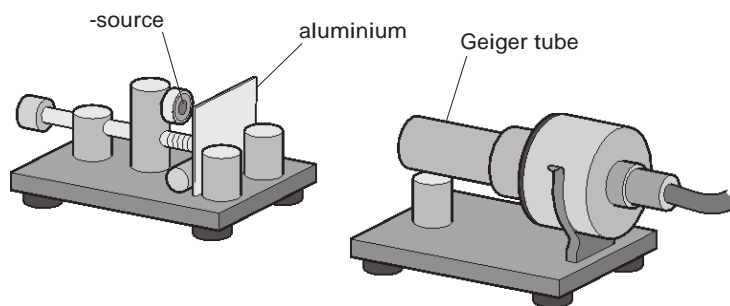
Procedure

1 Use a micrometer to measure the thickness *x* of each aluminium sheet to be used in this experiment.

2 Measure the average background count per minute.

3 Insert the thinnest sheet between the GM tube and the source (see diagram above).

4 Measure the count for a time of 1 minute.

5 Calculate the 'corrected count' for this thickness of aluminium sheet:

corrected count = count – background count

6 Repeat the measurement and determine the corrected count for different thicknesses of aluminium sheet. You may use a combination of plates to get different thicknesses.

7 Record your results in a table.

x (mm)	Count (min^{-1})	Corrected count (min^{-1})

8 Plot a graph of corrected count against thickness of aluminium.

9 Determine the thickness of aluminium for which the count is halved. This is known as the **half-thickness** of aluminium.

10 It is suggested that the count should decay exponentially with the thickness *x* of the aluminium. Do your results support this?

Practical 2

Simulating the decay of radioactive nuclei using dice

Apparatus

- about 500 dice (small wooden cubes with one face coloured black)
- storage trays (optional)

Introduction

Radioactive decay curves are discussed on page 146 of *Physics 2*. In this 'experiment', you will use dice to represent the radioactive nuclei in a sample. The probability of decay of each die is $\frac{1}{6}$. Hence, the decay constant λ must be '$\frac{1}{6}$ per throw'. According to the equation:

$$t_{1/2} = \frac{0.693}{\lambda}$$

the half-life $t_{1/2}$ of each die will be:

$$t_{1/2} = \frac{0.693}{(1/6)} \, 4 \quad \text{throws}$$

Procedure

1 Count the total number of dice N_0.

2 Share the total number of dice amongst all the students in the group.

3 Roll all the dice once in the tray.

4 Remove all the dice that show 'black' because they have 'decayed'.

5 Determine the total number N of 'undecayed' dice left after the first throw.

6 Repeat the procedure above for another 10 throws.

7 Record your results in a table.

Number of throws, n	N
0	
1	
2	
3	
4	
etc.	

8 Plot a graph of N against the number of throws n.

9 Use the graph to determine the 'half-life'.

10 The graph should show an exponential decay. Does the graph decay exponentially?

11 How will your graph change if each die used had more than six faces?

Guidance for teachers

This is an ideal 'experiment' for communicating some of the key ideas of radioactive decay. You have the chance to discuss how this experiment relates to real radioactive nuclei. It also helps students appreciate the **random** nature of the decay process and the importance of half-life.

End-of-chapter test

Answer all questions.

1 **a** What are α-particles? [1]

   b $^{14}_{6}$C is an isotope of carbon that emits a β-particle and changes into an isotope of nitrogen (N). Write a nuclear decay equation for this decay. [2]

2 A radioactive source emits α-radiation. The kinetic energy of each α-particle is 8.0×10^{-13} J and the source has an activity of 4.0×10^9 Bq.

   a How many α-particles are emitted from the source in a time of 1 second? [1]

   b How much energy is released by the source in a time of 1 second? [2]

3 **a** Define the activity of a radioactive source. [1]

   b The isotope of iodine $^{131}_{53}$I is used in hospitals as a 'tracer' to check the function of the kidneys. Iodine-131 emits β-radiation and γ-radiation. The half-life of iodine-131 is 8.1 days.

   i State one of the dangers of having a β-emitter in the human body. [1]

   ii What fraction f of undecayed nuclei of iodine-131 is left in a patient after a time equal to two half-lives of the isotope? [2]

4 The isotope of polonium $^{210}_{84}$Po has a half-life of 140 days. A radioactive source has 6.0×10^{10} nuclei of the isotope $^{210}_{84}$Po. Determine:

   a the decay constant for polonium $^{210}_{84}$Po in s^{-1} ; [3]

   b the initial activity of the source; [3]

   c the number of nuclei of $^{210}_{84}$Po left after 50 days. [3]

Total: $\overline{19}$ Score: %

Marking scheme

Worksheet

1 **a** **i** Alpha-particle (2 neutrons and 2 protons). [1]

    ii Electron. [1]

    ii Gamma-radiation of very short wavelength (high-energy photon). [1]

  b Alpha-radiation is the most ionising radiation. [1]

  c A β-particle is an electron emitted from **within** the radioactive nucleus. It is not an orbiting electron. [1]

2 Any **two** from: [2]

- Travels at the speed of light ($3.0 \times 10^8 \, \text{m s}^{-1}$).
- Has no charge.
- Is not affected by electric (or magnetic) fields.
- Is a very weak ionising radiation.
- Requires several centimetres of lead to be stopped.
- Obeys an inverse square law with distance as it spreads out from a source.

3 **a** **i** $^{210}_{84}\text{Po} \rightarrow \, ^{4}_{2}\text{He} + \, ^{206}_{82}\text{Pb}$ [2]

    ii $^{90}_{38}\text{Sr} \rightarrow \, ^{0}_{-1}\text{e} + \, ^{90}_{39}\text{Y}$ [2]

  b One of the neutrons within the nucleus of $^{90}_{38}\text{Sr}$ changes into a proton, an electron and a neutrino ($^{1}_{0}\text{n} \rightarrow \, ^{1}_{1}\text{p} + \, ^{0}_{-1}\text{e} + \bar{\nu}$). [1]

    The loss of a neutron and the gain of a proton implies the same total number of nucleons. [1]

4 The loss of a single α-particle reduces the nucleon number by 4 and reduces the proton number by 2. [1]

The loss of a single β-particle increases the proton number by 1 but the nucleon number is unchanged. [1]

Hence for the radon nucleus, we have:

$A = 232 - (3 \times 4) = 220$ [1]

$Z = 90 - (3 \times 2) + (2 \times 1) = 86$ [1]

(The nucleus of radon is $^{220}_{86}\text{Rn}$.)

5 **a** The half-life of a radioactive isotope is the **mean** time taken for the number of nuclei of the isotope to decrease to half the initial number. [1]

  b **i** 20 minutes is 1 half-life, so number of nuclei left $= \dfrac{N_0}{2}$ [1]

    ii 1.0 hour is 3 half-lives. [1]

      number of nuclei left $= \left(\dfrac{1}{2}\right)^3 N_0 = \dfrac{N_0}{8}$ [1]

6　**a**　**i**　Activity is equal to the number of emissions per second. Hence, there are 540 α-particles emitted in 1 second.　[1]

　　　ii　Number of α-particles emitted in $1\,\mathrm{h} = 540 \times 3600 = 1.9 \times 10^6$　[1]

　　b　Energy released in 1 s
　　　　= number of α-particles emitted in 1 s $\times$ energy of each α-particle　[1]

　　　energy released in $1\,\mathrm{s} = 540 \times 8.6 \times 10^{-14}$　[1]

　　　energy released in $1\,\mathrm{s} = 4.64 \times 10^{-11}\,\mathrm{J} \approx 4.6 \times 10^{-11}\,\mathrm{J}$　[1]

　　c　Power = energy released per second.

　　　Hence, power $= 4.6 \times 10^{-11}\,\mathrm{J\,s^{-1}} = 4.6 \times 10^{-11}\,\mathrm{W}$　[1]

7　**a**　$t_{1/2} = \dfrac{0.693}{\lambda}$　so　$\lambda = \dfrac{0.693}{t_{1/2}}$　[1]

　　　$\lambda = \dfrac{0.693}{52}$　[1];　$\lambda = 1.333 \times 10^{-2}\,\mathrm{s^{-1}} \approx 1.3 \times 10^{-2}\,\mathrm{s^{-1}}$　[1]

　　b　$A = \lambda N$　[1]

　　　$A = \dfrac{0.693}{52} \times 6.0 \times 10^{10}$　[1];　$A \approx 8.0 \times 10^8\,\mathrm{Bq}$　[1]

8　**a**　$A = \lambda N$　so　$\lambda = \dfrac{A}{N}$　[1]

　　　$\lambda = \dfrac{5.0 \times 10^9}{8.0 \times 10^{14}}$　[1];　$\lambda = 6.25 \times 10^{-6}\,\mathrm{s^{-1}} \approx 6.3 \times 10^{-6}\,\mathrm{s^{-1}}$　[1]

　　b　$t_{1/2} = \dfrac{0.693}{\lambda}$　[1]

　　　$t_{1/2} = \dfrac{0.693}{6.25 \times 10^{-6}}$　[1];　$t_{1/2} = 1.11 \times 10^5\,\mathrm{s} \approx 1.1 \times 10^5\,\mathrm{s}$　[1]

　　c　$N = N_0\, e^{-\lambda t}$　[1]

　　　$N = 8.0 \times 10^{14}\, e^{-(6.25 \times 10^{-6} \times 40 \times 3600)}$　[1]

　　　$N = 3.25 \times 10^{14} \approx 3.3 \times 10^{14}$　[1]

9　**a**　The decay constant is the probability that an individual nucleus will decay in 1 second.　[1]

　　b　**i**　$t_{1/2} = \dfrac{0.693}{\lambda}$　so　$\lambda = \dfrac{0.693}{t_{1/2}}$　[1]

　　　　$\lambda = \dfrac{0.693}{18 \times 24 \times 3600}$　[1];　$\lambda = 4.46 \times 10^{-7}\,\mathrm{s^{-1}} \approx 4.5 \times 10^{-7}\,\mathrm{s^{-1}}$　[1]

　　　ii　$A = \lambda N$　[1]

　　　　$A = 4.46 \times 10^{-7} \times 4.0 \times 10^{12}$　[1]

　　　　$A = 1.78 \times 10^6\,\mathrm{Bq} \approx 1.8 \times 10^6\,\mathrm{Bq}$　[1]

　　　iii　36 days is equal to 2 half-lives.　[1]

　　　　activity $= \left(\dfrac{1}{2}\right)^2 \times 1.78 \times 10^6 = 4.45 \times 10^5\,\mathrm{Bq} \approx 4.5 \times 10^5\,\mathrm{Bq}$　[1]

10 a Number of nuclei = number of moles $\times N_A$

number of nuclei $= \dfrac{1.0 \times 10^{-6}}{226} \times 6.02 \times 10^{23}$ [1]

number of nuclei $= 2.66 \times 10^{15} \approx 2.7 \times 10^{15}$ [1]

b $A = \lambda N$ [1]

$A = \left(\dfrac{0.693}{t_{1/2}}\right) N = \dfrac{0.693 \times 2.66 \times 10^{15}}{1600 \times 365 \times 24 \times 3600}$ [1]

$A \approx 3.7 \times 10^4 \, \text{Bq}$ [1]

11 $N = N_0 \, e^{-\lambda t}$ and $\lambda = \dfrac{0.693}{t_{1/2}}$ [1]

fraction left $= \dfrac{N}{N_0} = e^{-\lambda t} = e^{-(0.693 t/t_{1/2})}$ [1]

fraction left $= e^{-(0.693 \times 5.0 \times 10^9/4.5 \times 10^9)}$ [1]

fraction left $= 0.463 \approx 0.46$ [1]

12 Count rate $(R) \propto$ activity (A) [1]

$R = R_0 \, e^{-\lambda t}$ [1]

$210 = 340 \, e^{-(\lambda \times 26 \times 60)}$ [1]

$\ln\left(\dfrac{210}{340}\right) = -1560 \lambda$ [1]

$\lambda = -\ln\left(\dfrac{210}{340}\right)/1560 = 3.09 \times 10^{-4} \, \text{s}^{-1}$ [1]

$t_{1/2} = \dfrac{0.693}{\lambda}$ [1]

$t_{1/2} = \dfrac{0.693}{3.09 \times 10^{-4}} = 2.24 \times 10^3 \, \text{s} \approx 2.2 \times 10^3 \, \text{s} \quad (37 \, \text{min})$ [1]

Marking scheme

End-of-chapter test

1 **a** Beta-particles are electrons emitted from radioactive nuclei. [1]

    b $^{14}_{6}\text{C} \rightarrow \ ^{0}_{-1}\text{e} + \ ^{14}_{7}\text{N}$ [2]

2 **a** Activity is equal to the number of disintegrations (or emissions) per second.
Hence, there are 4.0×10^9 α-particles emitted in 1 second. [1]

    b Energy released in 1 s
= number of α-particles emitted in 1 s × energy of each α-particle [1]

    energy released in $1\,\text{s} = 4.0 \times 10^9 \times 8.0 \times 10^{-13} = 3.2 \times 10^{-3}\,\text{J}$ [1]

    (This value is the power of the source in J s^{-1}.)

3 **a** The activity of a source is the number of nuclei that disintegrate per second. [1]

    b **i** Intense γ-radiation destroys human cells. [1]

       ii Number of undecayed nuclei left $= \frac{1}{2} \times$ initial number of nuclei [1]

$$f = \left(\frac{1}{2}\right)^2 = \frac{1}{4} \ [1]$$

4 **a** $t_{1/2} = \dfrac{0.693}{\lambda}$ so $\lambda = \dfrac{0.693}{t_{1/2}}$ [1]

$$\lambda = \frac{0.693}{140 \times 24 \times 3600} \ [1]$$

$$= 5.73 \times 10^{-8}\,\text{s}^{-1} \approx 5.7 \times 10^{-8}\,\text{s}^{-1} \ [1]$$

    b $A = \lambda N$ [1]

    $A = 5.73 \times 10^{-8} \times 6.0 \times 10^{10}$ [1]

    $A = 3.44 \times 10^3\,\text{Bq} \approx 3.4 \times 10^3\,\text{Bq}$ [1]

    c $N = N_0\,e^{-\lambda t}$ [1]

    $N = 6.0 \times 10^{10}\,e^{-(5.73 \times 10^{-8} \times 50 \times 24 \times 3600)}$ [1]

    $N \approx 4.7 \times 10^{10}$ [1]