3 Radioactive decay

This unit will help you to learn more about the changes in the structure of atomic nuclei that happen during radioactive decay. It will also help you to learn about the patterns that occur during the random decay.

In the exam, you will be asked to answer questions such as the one below.

Exam-style question

1 A research scientist measured the count rate produced by a radiation detector for two different radioactive isotopes of the same element over a period of time.

The results are shown in Figure 1.

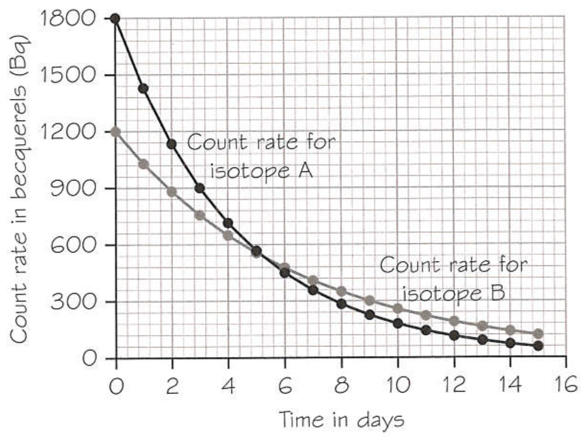


Figure 1

(a) Explain how an element can have different isotopes. **(2 marks)**

....

....

(b) State which isotope was most active at the start of the experiment. **(1 mark)**

....

(c) State which isotope had the longest half-life. **(1 mark)**

....

(d) Use the graph to determine the half-life of isotope B. **(1 mark)**

....

A sample of a different radioactive isotope (iodine-53) is known to decay by β^- (beta minus) particle emission.

(e) Complete the decay equation to show the three missing values.

$$^{131}_{53}I \rightarrow {}^{\dots}_{\dots}Xe + {}^{0}_{\dots}e$$

(3 marks)

You will already have done some work on atomic structure, radioactivity and radioactive decay. Before starting the **skills boosts**, rate your confidence in each area. Colour in the bars.

1. **How do I describe the changes that happen during nuclear decay?**
2. **How do I write decay equations?**
3. **How can I use a half-life graph to analyse radioactive decay?**

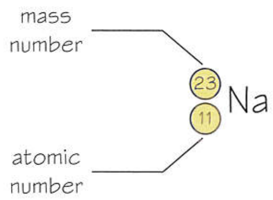
Get started

Atoms are the building blocks of all molecules and materials. Each atom is built from only three types of subatomic particles, **protons**, **neutrons** and **electrons**, in different numbers and arrangements.

1 Circle the correct answers in the table to leave the correct charges and locations of protons, neutrons and electrons.

Component	Electric charge	Location
proton	positive / negative / neutral	in the nucleus / in orbit around the nucleus
neutron	positive / negative / neutral	in the nucleus / in orbit around the nucleus
electron	positive / negative / neutral	in the nucleus / in orbit around the nucleus

Nuclear notation is used to describe a nucleus. This notation contains the element symbol, the atomic number (proton number) and the mass number (nucleon number):



2 Complete these statements about the use of nuclear notation. Use words from the box. Each word can be used once or more than once.

atomic number | mass number | protons | neutrons | electrons | nucleus

a The atomic number is the number of .... in the nucleus.

b The mass number is the total number of .... and .... in the nucleus.

c The number of neutrons is equal to the .... minus the ....

d In an atom, the number of .... is equal to the number of protons in the

....

All carbon atoms have 6 protons but the number of neutrons can vary. We say that there are different **isotopes** of carbon. There are also different isotopes of every other element.

3 Here are three different isotopes of chlorine: ${}^{35}_{17}Cl$ ${}^{36}_{17}Cl$ ${}^{37}_{17}Cl$

a Write a sentence to describe what is **the same** for these isotopes. Answer in terms of subatomic particles.

....

b Write a sentence to describe what is **different** about these isotopes. Answer in terms of subatomic particles.

Try to use the terms protons and neutrons in your descriptions.

....

....

4 Use the information in question 2 to complete this table for some isotopes of atoms.

Isotope and chemical symbol	Protons (from atomic number)	Neutrons (mass number – atomic number)	Electrons (same as protons)	Atomic notation
carbon-14, C	6	14 – 6 = 8	6	${}^{14}_{6}C$
carbon-12, C	6	6		
uranium-238, U		146		
				${}^{17}_{8}O$

1 How do I describe the changes that happen during nuclear decay?

Some atomic nuclei are unstable. They decay to form more stable nuclei over time. When unstable nuclei decay, they emit radiation in the form of alpha particles, β^- (beta minus) particles, β^+ particles (positrons), gamma rays or neutrons.

1 Each alpha particle consists of two protons and two neutrons joined together. As this is the same as a helium nucleus, the symbol 'He' is used.

a Which of these subatomic particles in the alpha particle has a charge? ....

b How many protons are in an alpha particle? ....

c Complete this symbol for an alpha particle using nuclear notation: $^{\cdots}_{\cdots}\text{He}$

Find the atomic number for an alpha particle from the number of protons and the mass number from the number of particles.

2 Each β^- (beta minus) particle consists of a high-speed electron ejected from the nucleus as a neutron decays into a proton.

a What type of electric charge do electrons carry? ....

b The mass of an electron is so small compared with a proton that it is written as 0. The atomic number is written as −1. Use this information to complete the symbol for a β^- particle.

$^{\cdots}_{\cdots}e$

The total number of protons and neutrons stays the same when a nucleus emits a β^- particle, but it has one less proton than before. So, to balance equations, the mass number is written as 0 and the atomic number as −1.

3 Each β^+ particle (positron) consists of a high-speed positron ejected from the nucleus as a proton decays into a neutron.

a What type of electric charge do positrons carry? ....

b Complete the symbol for a positron. $^{\cdots}_{\cdots}e$

The total number of protons and neutrons stays the same when a nucleus emits a β^+ particle, but it has one more proton than before. So, to balance equations, the mass number is written as 0 and the atomic number as +1.

4 Complete this table to show the properties of the four most common types of radiation.

Radiation	α (alpha)	β^- (beta minus)	β^+ (positron)	γ (gamma)
Symbol for radiation in equations	$^{4}_{2}\text{He}$			
Radiation consists of	two protons and	a fast-moving .... ejected from the	a fast-moving .... ejected from the	.... emitted from the nucleus

Physics

2 How do I write decay equations?

A **decay equation** shows the changes to the nucleus, and the type of radiation emitted, during radioactive decay. For example, a radon nucleus decays to form a polonium nucleus when it emits an alpha particle. The process is shown by this decay equation:

$$^{219}_{86}Rn \rightarrow {}^{215}_{84}Po + {}^{4}_{2}He$$

The symbol → used in the equation means 'decays into'.

In all radioactive decays, mass number and charge are 'conserved' – they do not change overall. The total mass number and total charge are the same on each side of the arrow.

1. What is the symbol for an alpha particle? ....

2. Circle the mass numbers for radon and the alpha particle in the equation above.

Look at the top number on each symbol in the nuclear equation.

The total mass number on the left has to be the same as the total mass number on the right.

3. Show how the equation shows this. .... = 215 + ...

The bottom number for a nucleus in a nuclear equation shows the atomic number or number of protons. This is also the charge on the nucleus, because each proton has a charge of +1. It is also the charge on the particle being emitted.

The total charge on the left has to be the same as the total charge on the right.

4. Show how the equation shows this. ....

5. Complete these decay equations.

$^{222}_{88}Ra \rightarrow {}^{\dots}_{86}Rn + {}^{4}_{2}He$	$^{208}_{84}Po \rightarrow {}^{204}_{\dots}Pb + {}^{4}_{2}He$

Make sure the top and bottom numbers balance on the left and right.

The β^- (beta minus) particle consists of a high-speed electron ejected from the nucleus. It is formed when a neutron decays into a proton. When a β^- particle is ejected:

- the mass number stays the same
- the proton number increases by 1.

For example, a silver nucleus decays to form a mercury nucleus by emitting a β^- particle:

$$^{201}_{79}Au \rightarrow {}^{201}_{80}Hg + {}^{0}_{-1}e$$

6. Show how charge is conserved in the nuclear equation.

79 = ...

Look at the bottom number on each symbol in the nuclear equation.

7. Complete these decay equations.

$^{6}_{2}He \rightarrow {}^{6}_{3}Li + {}^{\dots}_{-1}e$	$^{14}_{6}C \rightarrow {}^{14}_{\dots}N + {}^{0}_{-1}e$

You don't need to know the symbols for chemical elements. They will be given in the exam.

8. Use what you have learned to complete the following table showing decay equations

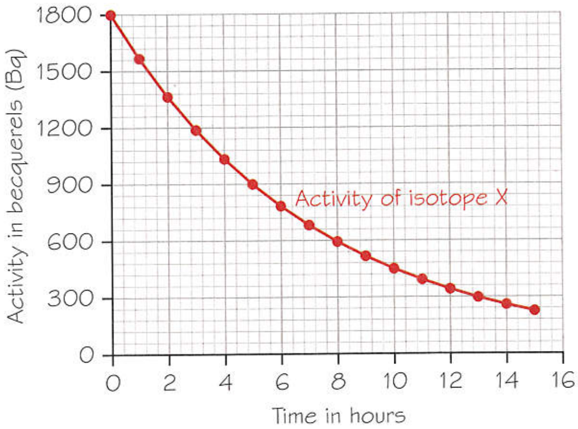
Decay type	Equation	Decay type	Equation
alpha	$^{185}_{79}Au \rightarrow {}^{\dots}_{\dots}Ir + {}^{4}_{2}He$		$^{\dots}_{\dots}Pa \rightarrow {}^{227}_{89}Ac + {}^{4}_{2}He$
	$^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{\dots}_{\dots}\dots$	beta	$^{8}_{3}Li \rightarrow {}^{\dots}_{\dots}\dots + {}^{0}_{-1}e$

Skills boost

3 How can I use a half-life graph to analyse radioactive decay?

Radioactive decay is a **random** process. We cannot predict when a particular nucleus will decay. However, when there is a large number of nuclei, we can predict a **pattern** to the decay and work out how many nuclei will be left after a certain time.

The **activity** of a sample is the number of decays that happen per second. Activity is measured in a unit called the becquerel (Bq). This activity falls in a specific pattern giving a **decay curve** shape.



1 The graph shows how the activity of isotope X changes over time.

a What is the initial activity of the sample? Tick ✓ the correct box.

Draw lines on the graph to help you read the values accurately.

☐ 180 Bq ☐ 1200 Bq ☐ 1800 Bq ☐ 2000 Bq

b How long does it take for the activity of the sample to halve? Tick ✓ the correct box.

☐ 0 hours ☐ 2.5 hours ☐ 5 hours ☐ 10 hours

Use the graph to find the time taken for the activity to fall to half of your answer in part a.

c How much longer does it take for the activity to halve again (1/4 of the original activity)? Tick ✓ the correct box.

☐ 0 hours ☐ 2.5 hours ☐ 5 hours ☐ 10 hours

2 We can use the symbol → to represent one half-life passing.

What fraction of the original activity will there be after a total time of 20 hours? ✎ ....

5 hours → 5 hours → 5 hours → 5 hours →

$1 \rightarrow \frac{1}{2} \rightarrow \frac{1}{2} \text{ of } \frac{1}{2} = \frac{1}{4} \rightarrow \frac{1}{2} \text{ of } \frac{1}{4} = \frac{1}{8} \rightarrow \frac{1}{2} \text{ of } \frac{1}{8} = \frac{1}{16}$

Look for the pattern in the decay. Don't try to extend the graph.

The **half-life** of a radioactive sample is the time it takes for the activity of that sample to fall to half of its original value. The activity (and so the count rate) falls by half every half-life.

3 Complete ✎ the table to show the pattern in decay for isotope X in question 1.

Time in hours	0		5		10		
Activity in Bq	1800	→		→		→	
Fraction remaining	$\frac{1}{1}$	1st half-life	$\frac{1}{2}$	2nd half-life		3rd half-life	

Physics

Sample response

When describing the structure of the nucleus and nuclear decay, remember that:

- The nuclear model of the atom was developed because of the results of an alpha particle scattering experiment which could not be explained by earlier models.
- The changes that happen in radioactive decay should be shown in carefully balanced nuclear decay equations.
- The half-life of an isotope is the time taken for half of the atoms to decay.
- Half-life is often determined using a graph of activity over time.

Here are some exam-style questions. Use the student answers to these questions to improve your understanding of radioactive decay.

Exam-style question

1 A radioactive isotope has an initial activity of 16 000 Bq and a half-life of 30 minutes. What will the activity of the sample be after 2 hours? **(2 marks)**

0 min → 30 min → 60 → 90 → 120 is 5 half-lives. $16\,000 \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = 500$ *Bq.*

The unit 'Bq' stands for becquerel. This is the number of decays each second.

Using arrows is a way to work out how many half-lives have passed.

1 What does the → represent in the student's answer? ....

2 The student's answer for the half-life is incorrect. The student counted the numbers (5) and so thought that five half-lives had passed.

a How many half-lives have really passed? Explain how you can tell. ....

b Rewrite the answer but put in activities instead of times to reach the correct answer.

....

Exam-style question

2 The isotope strontium-90 decays through β^- (beta minus) particle emission. Complete the decay equation for the decay of strontium-90. **(3 marks)**

$^{90}_{38}Sr \rightarrow$ $^{90}_{37}Y$ + $^{0}_{1}e$

3 a Circle Ⓐ the parts of the equation in the student's answer that are correct.

b Write the correct decay equation.

....

Be extra careful with β^- decay. What happens to the atomic number?

Your turn!

It is now time to use what you have learned to answer the exam-style question from page 129. Remember to read the question thoroughly, looking for information that may help you. Make good use of your knowledge from other areas of physics.

Exam-style question

1 A research scientist measured the count rate produced by a radiation detector for two different radioactive isotopes of the same element over a period of time.

The results are shown in Figure 1.

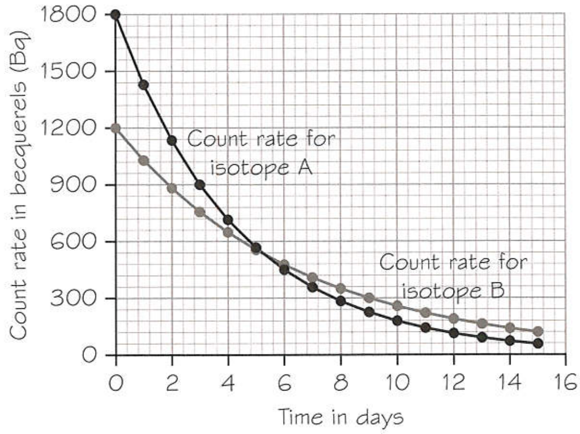


Figure 1

(a) Explain how an element can have different isotopes. **(2 marks)**

....

....

....

....

There are 2 marks here so make sure you mention one similarity and one difference between the isotopes.

(b) State which isotope was most active at the start of the experiment. **(1 mark)**

....

Use the graph. Will a more active source produce a high or low count rate?

(c) State which isotope had the longest half-life. **(1 mark)**

....

You will need to look to see which isotope's count rate halves first. Be careful as the isotopes don't start with the same level of activity.

(d) Use the graph to determine the half-life of isotope B. **(1 mark)**

....

A sample of a different radioactive isotope (iodine-53) is known to decay by β^- (beta minus) particle emission.

(e) Complete the decay equation to show the three missing values.

$$^{131}_{53}I \rightarrow \,^{\dots}_{\dots}Xe + \,^{0}_{\dots}e$$ **(3 marks)**

Watch out for the atomic number again here.

Physics

Get back on track

Need more practice?

Exam questions may ask about different parts of a topic, or parts of more than one topic. Questions about atomic structure and radioactive decay could occur as:

- questions about that topic only
- part of a question on radioactive decay and safety
- part of a question about an experiment or investigation.

Have a go at this exam-style question.

Exam-style question

1 A research team used a mixture of isotopes as the source of alpha particles. One of these sources was the isotope radium-226.

(a) Complete the nuclear decay equation to show the alpha decay of radium-226. **(3 marks)**

$$^{226}_{88}\text{Ra} \rightarrow ^{\ldots\ldots}_{\ldots\ldots}\text{Rn} + ^{\ldots\ldots}_{\ldots\ldots}\text{He}$$

Look back at the rules for alpha decay in Skills boost 2 if you need to.

(b) The alpha particle source used in the experiment also contained small amounts of the isotope bismuth-214. This has a half-life of 20 minutes.

(i) Define the term half-life. **(1 mark)**

....

....

(ii) Determine the fraction of the original sample of bismuth-214 that will remain after 1 hour. **(1 mark)**

....

Use the → method to step through the half-lives $1 \rightarrow \frac{1}{2} \rightarrow$ etc.

Boost your grade

To boost your grade, make sure you can describe the three main types of radioactive decay and explain the changes to the nucleus using equations. Make sure you can also explain why scientists changed their model of the nucleus due to the results of the alpha particle scattering experiment and the changes to the nuclear model since then.

How confident do you feel about each of these **skills**? Colour in the bars.

1 How do I describe the changes that happen during nuclear decay?

2 How do I write a decay equation?

3 How can I use a half-life graph to analyse radioactive decay?