Science 9–10

Chapter 10 — Chemical sciences A: atoms, isotopes and the periodic table

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Contents

How the model of the atom changed: electrons, protons, neutrons and the evidence for each

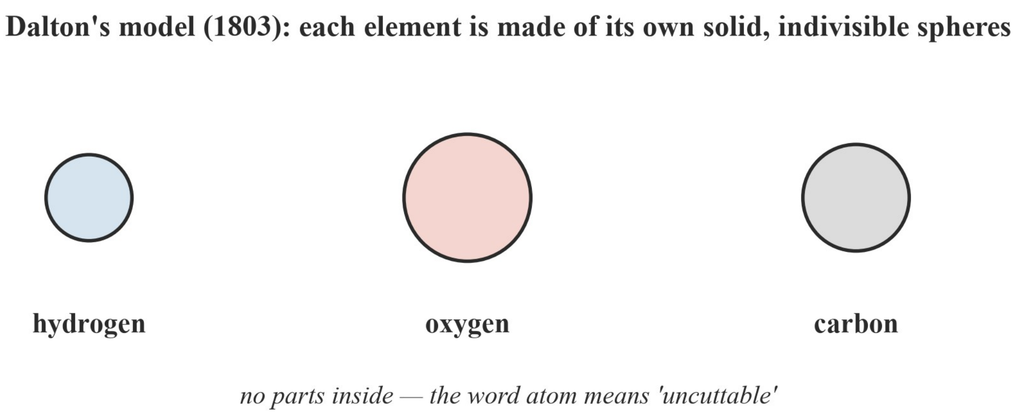
Chapter 10 — Chemical sciences A: atoms, isotopes and the periodic table (Science, Levels 9 and 10)

Subtopic 10A · VC2 Science Understanding — Chemical sciences

CD code: `VC2S10U06` † (split delivery: this subtopic is the accountable owner of the first clause — the changing model of the atom and the discovery of its particles; partner subtopic 10B delivers the second clause — isotopes, natural radioactive decay and half-life) **Content description (verbatim):** "the model of the atom changed following the discovery of electrons, protons and neutrons; natural radioactive decay results in a change from unstable to stable atoms" **Elaboration ids drawn on:** `VC2S10U06.E01` — "comparing the masses and charges of protons, neutrons and electrons, and examining how the discovery of these particles resulted from experimental evidence and answered questions related to properties and behaviours of atoms" (the only elaboration drawn on, per TOC §3) **Elaboration withheld:** `VC2S10U06.E05` is reserved under the TOC's D10 ICIP decision and is not taught in this book **Achievement standard (extract served):** "They explain how ideas about the structure of the atom have changed over time" Subtopics 10A and 10B in this chapter deliver the split CD `VC2S10U06`: the changing model of the atom and its particles (10A), and isotopes, natural radioactive decay and half-life (10B).

Theory

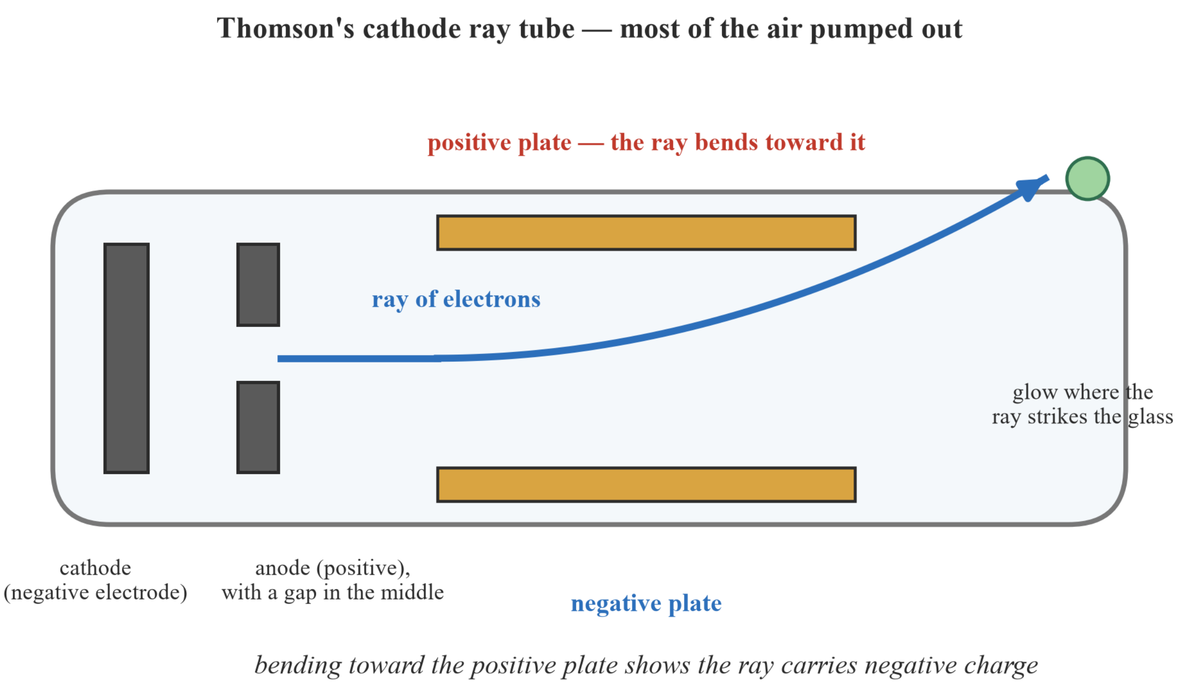
The starting picture: solid spheres. In Levels 7 and 8 you met the **atom** — the smallest particle of an element that keeps the properties of that element — and you used element symbols and formulas built from atoms. The picture of the atom you were using is the one John Dalton proposed in 1803: each element is made of its own kind of solid, indivisible sphere, with no parts inside (the word *atom* comes from a Greek word meaning 'uncuttable').



Dalton's solid-sphere model: hydrogen, oxygen and carbon atoms drawn as plain spheres with no parts inside

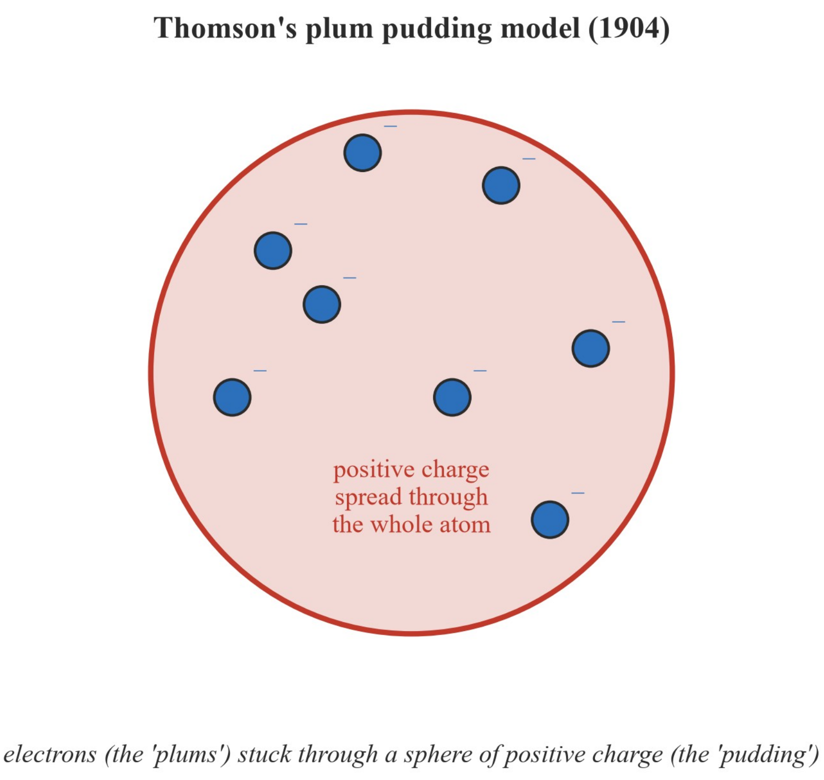
For most of the 1800s this model did everything chemists needed. Then, at the end of the century, experiments with electricity in partly emptied glass tubes produced a result the solid-sphere model could not explain.

The electron (Thomson, 1897). J.J. Thomson passed electricity through a tube with most of the air pumped out. A ray travelled from the negative **electrode** (a terminal called the **cathode**) to the positive one, and where the ray struck the far glass, the glass glowed. Thomson put charged plates around the ray's path and watched the ray bend *toward* the positive plate. Opposite charges attract, so the ray must carry **negative** charge. The ray behaved the same way no matter which metal the cathode was made of, so Thomson concluded that these negatively charged particles — later named **electrons** — come from *inside the atoms of every element*. He also measured how much the ray bent for a given push, and found the electron must be far lighter than the lightest atom, hydrogen.



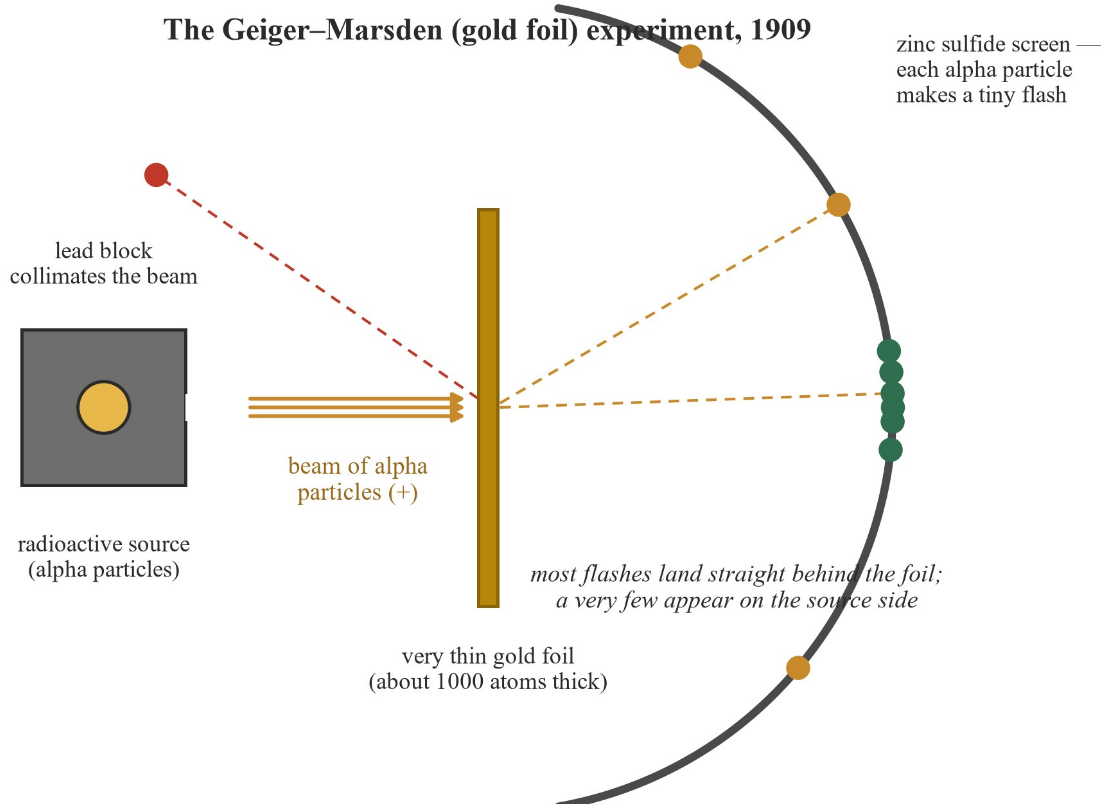
Thomson's cathode ray tube: the ray leaves the cathode, passes through a gap in the anode, and bends toward the positive plate, showing it carries negative charge

That was a shock: atoms were supposed to be uncuttable, yet every atom clearly contains small negative parts. An atom with negative pieces inside must also contain positive charge somewhere, because whole atoms are electrically **neutral** — they carry no overall charge. In 1904 Thomson proposed the **plum pudding model**: a sphere of spread-out positive charge with the electrons stuck through it like plums in a pudding.



Thomson's plum pudding model: electrons embedded in a sphere of spread-out positive charge

The gold foil experiment (Geiger and Marsden, 1909). Under the plum pudding model, the positive charge is spread out through the whole atom, so a fast, heavy, positively charged **alpha particle** (a particle shot out by some radioactive materials, defined here as a fast, positively charged particle given off by certain unstable substances) fired at an atom should punch through with only a tiny bend. Hans Geiger and Ernest Marsden, working in Rutherford's laboratory, tested this by firing a beam of alpha particles at a very thin gold foil, watching for the tiny flashes each particle makes when it hits a **zinc sulfide screen** (a screen coated with a substance that glows with a tiny flash where an alpha particle strikes it).

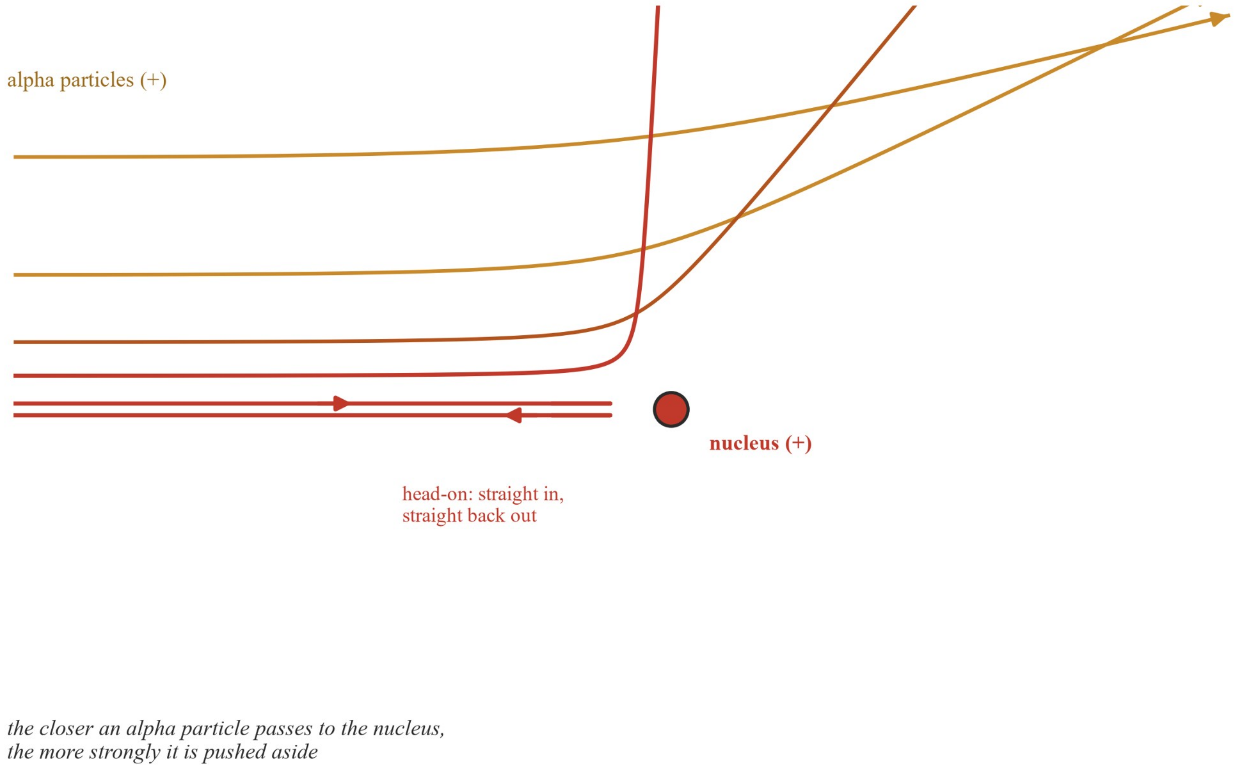


The Geiger–Marsden experiment: a beam of alpha particles at thin gold foil, with flashes on a screen mostly straight behind the foil and a very few on the source side

Most particles did go straight through, as expected. But some were pushed through large angles, and a very few — roughly one in 8000 — came straight back toward the source. Rutherford later said it was as astonishing as firing a shell at tissue paper and having it bounce back. Something in the atom was far more concentrated and far heavier than plum pudding allowed.

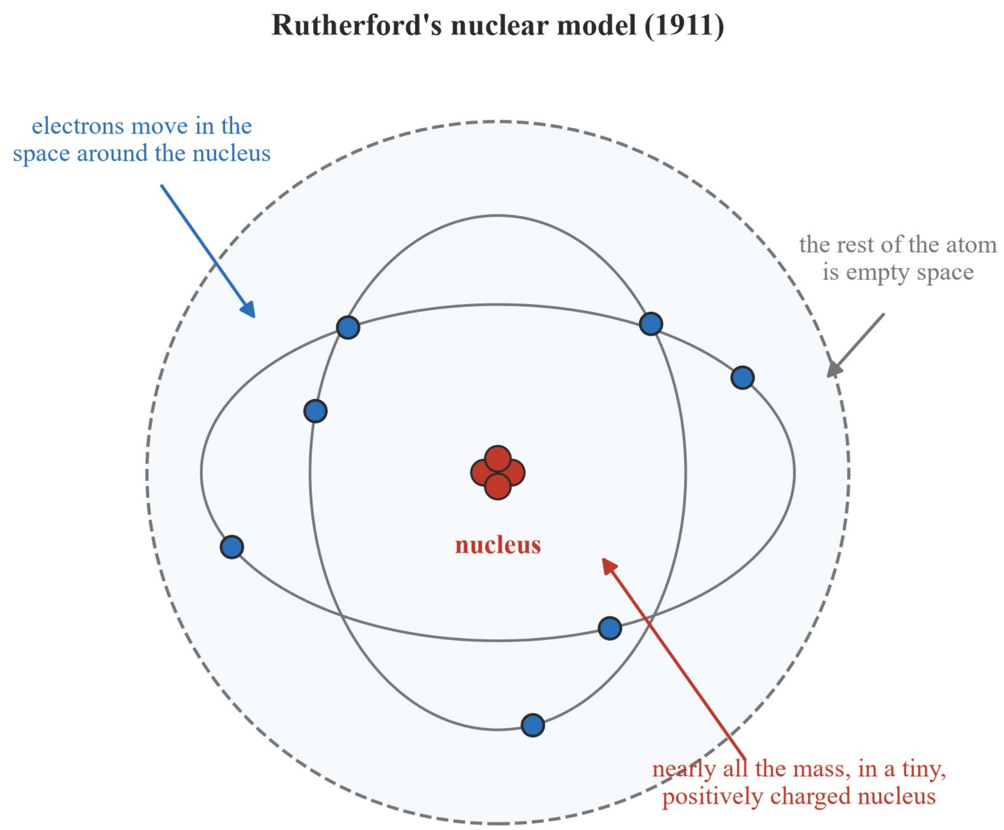
The nuclear model (Rutherford, 1911). Rutherford worked out what kind of atom would produce those paths. A positive alpha particle only swings through a large angle when almost all of the atom's mass and all of its positive charge sit together in one tiny lump, so that an alpha particle coming close to that lump feels one very strong push. The closer the pass, the bigger the bend, and a head-on approach bounces straight back.

Rutherford scattering — paths computed for a repulsive inverse-square force

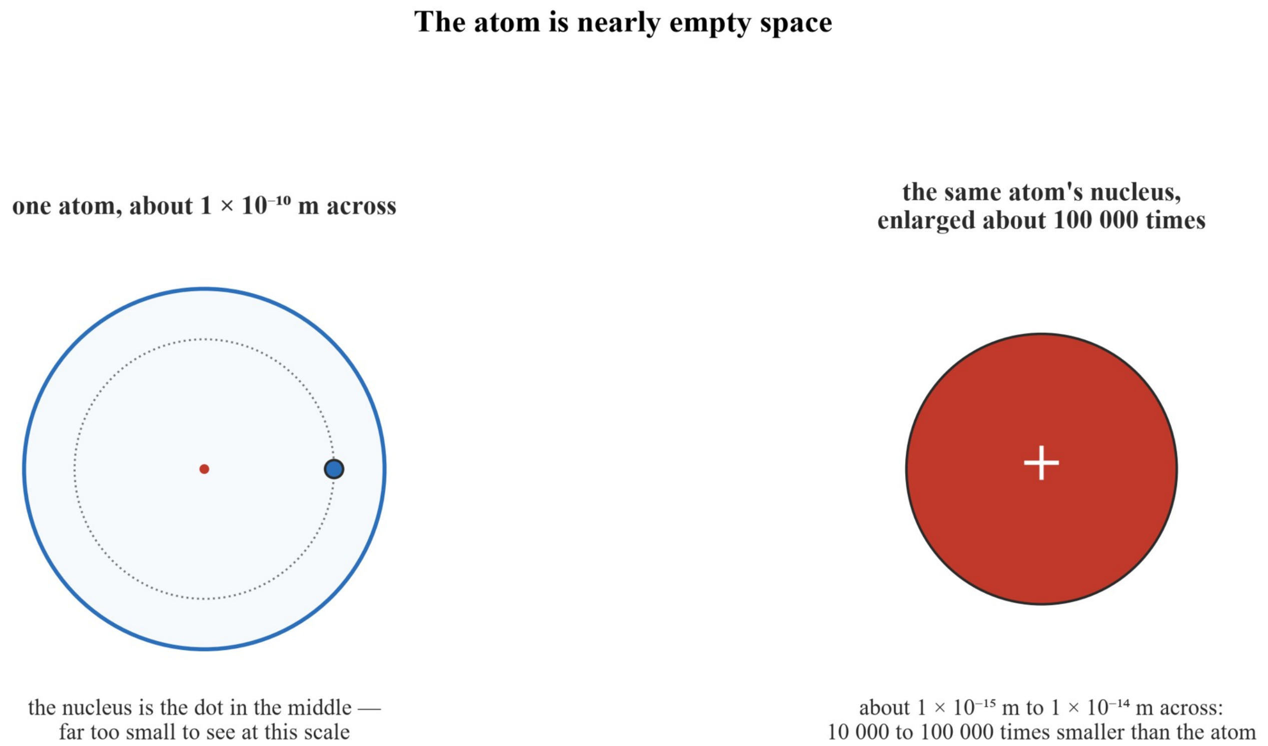


Computed alpha-particle paths in a repulsive inverse-square field: small bends for distant passes, large bends for close passes, and a straight-in straight-back bounce for a head-on approach

So Rutherford's **nuclear model** replaced the pudding: nearly all the mass and all the positive charge sit in a tiny **nucleus** (the dense, positively charged centre of the atom), while the electrons move in the space around it — and the rest of the atom is empty. How empty? If an atom were the size of a sports oval, the nucleus would be a marble at the centre spot.



Rutherford's nuclear model: a tiny positive nucleus holding nearly all the mass, with electrons moving in the mostly empty space around it

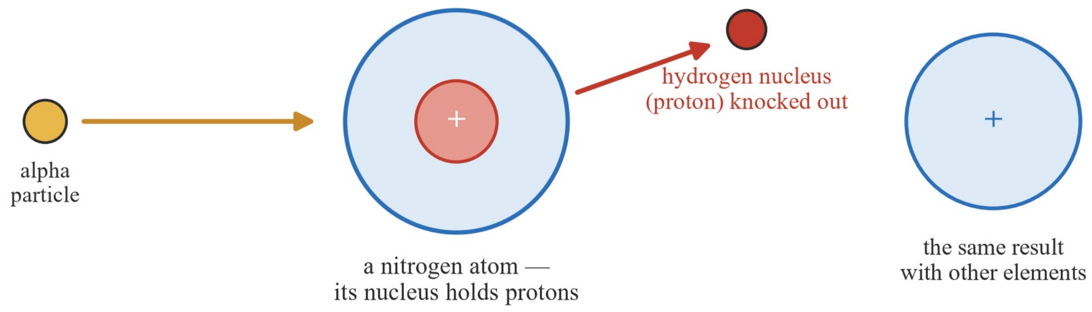


The atom is nearly empty space: the nucleus is 10 000 to 100 000 times smaller than the atom

The proton (Rutherford, 1919). The nucleus raised the next question: what is it made of? Rutherford fired alpha particles into nitrogen gas and detected hydrogen nuclei coming out. The same result appeared with other elements.

Since hydrogen nuclei were being knocked *out of* other kinds of nuclei, they must be one of the nucleus's building blocks. Rutherford named this particle the **proton**: charge +1, and a mass about 1836 times the electron's mass.

Rutherford (1919): alpha particles fired into nitrogen knocked out hydrogen nuclei

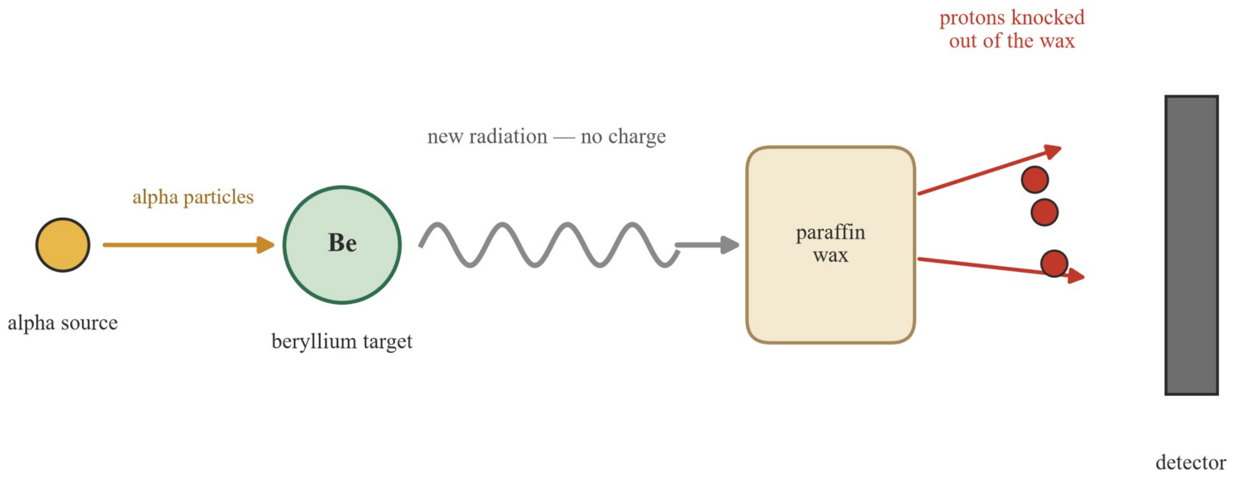


the hydrogen nucleus must live inside the nuclei of other atoms — Rutherford named it the proton

Rutherford's 1919 experiment: alpha particles fired into nitrogen knock hydrogen nuclei (protons) out of its nucleus

The neutron (Chadwick, 1932). Protons alone could not finish the picture. A helium nucleus carries only twice the charge of a hydrogen nucleus, yet has about four times the mass — there was extra mass in nuclei that no proton could account for, because adding protons would have added charge too. In 1932 James Chadwick fired alpha particles at beryllium and found that the target gave off a new kind of radiation. It travelled in straight lines, was not bent by charged plates, and knocked protons out of paraffin wax. Working from the speeds of those knocked-out protons, Chadwick showed that the radiation must be a particle with about the mass of a proton and no charge at all: the **neutron**. The extra mass in nuclei was explained.

Chadwick's experiment (1932): neutral radiation knocks protons out of paraffin wax



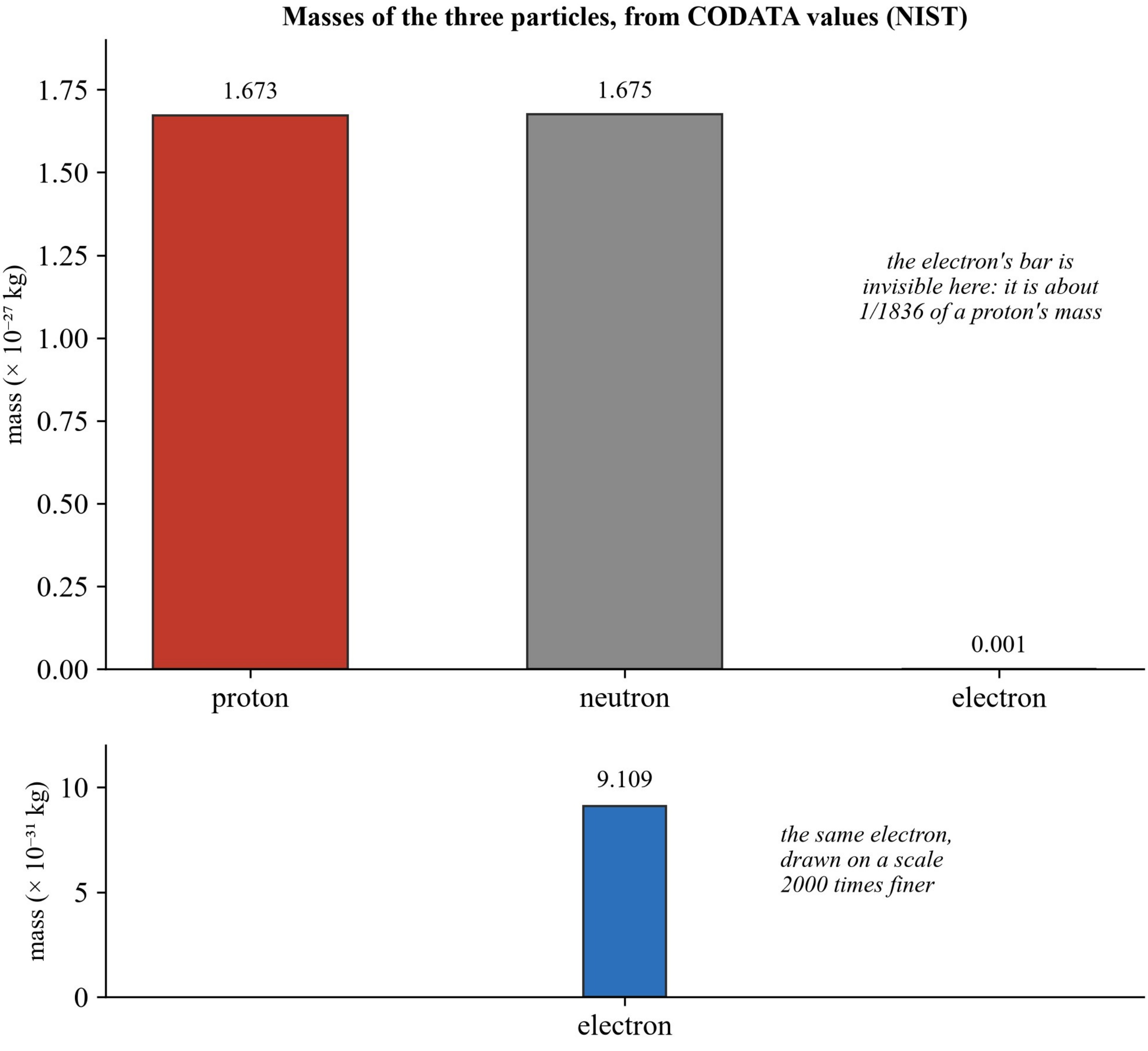
only a particle with about the mass of a proton and no charge could deliver the blow — the neutron

Chadwick's experiment: alpha particles strike beryllium, giving off neutral radiation that knocks protons out of paraffin wax and on to a detector

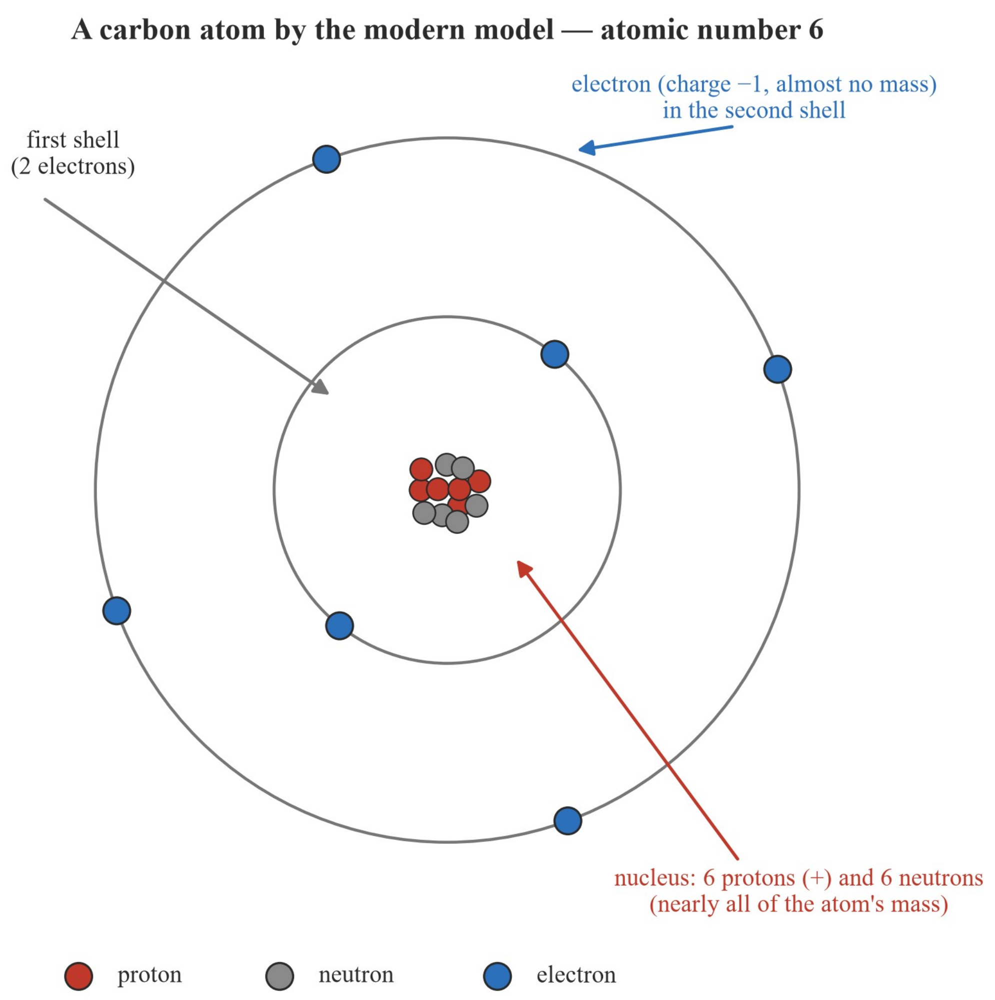
Comparing the three particles. With all three particles found, the atom's parts can be lined up side by side (masses are the CODATA recommended values published by NIST):

particle	charge	mass	where it sits
proton	+1	1.673×10^{-27} kg	in the nucleus
neutron	0	1.675×10^{-27} kg	in the nucleus
electron	−1	9.109×10^{-31} kg	in the space around the nucleus

An electron is about 1/1836 of the mass of a proton — so light that an atom's mass is essentially all in its nucleus, while its size and its chemistry belong to its electrons. A **carbon** atom, for example, has 6 protons and 6 neutrons packed in its nucleus and 6 electrons around it. The number of protons in a nucleus is the **atomic number**: carbon's is 6, and because a neutral carbon atom also has 6 electrons, its +6 and −6 charges cancel to zero.

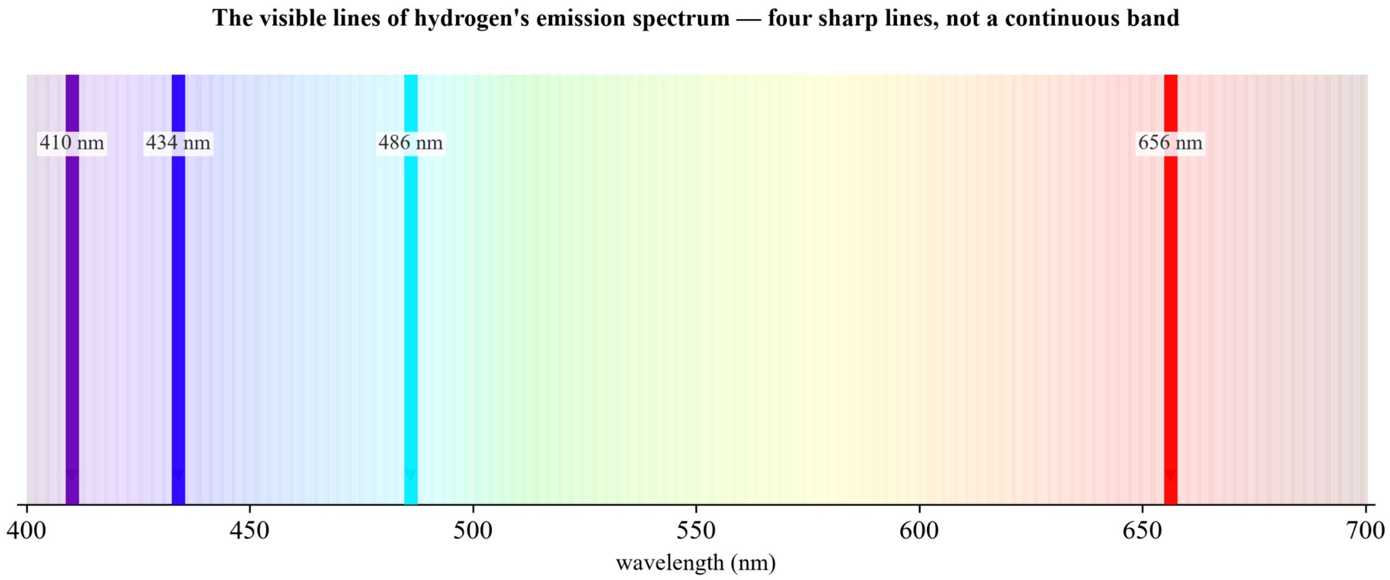


The masses of proton, neutron and electron compared: the electron's mass is about 1/1836 of a proton's, visible only when the mass scale is made 2000 times smaller



A carbon atom by the modern model: a nucleus of 6 protons and 6 neutrons, with 6 electrons arranged 2 in the first shell and 4 in the second

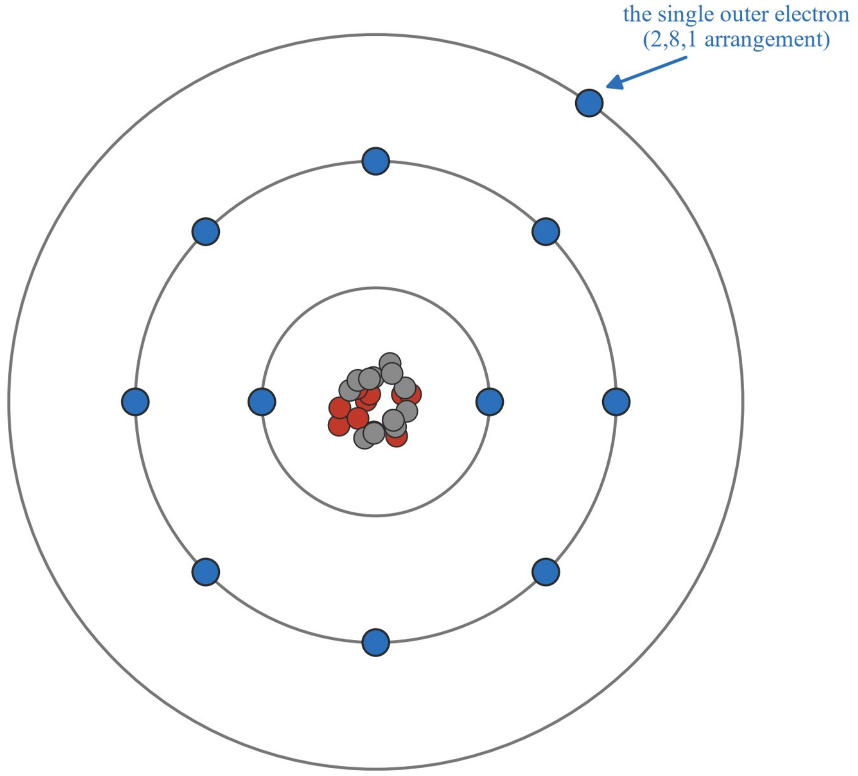
Bohr's shells (1913). One more question closed the loop of this subtopic. When atoms of an element are given extra energy — for example in a hot flame — they give the energy back as light, and if that light is split into its colours, each element shows its own pattern of sharp bright lines, its **emission spectrum**. Hydrogen's visible spectrum is not a rainbow but just four sharp lines.



Hydrogen's emission spectrum in visible light: four sharp lines at 656 nm, 486 nm, 434 nm and 410 nm, not a continuous band

A continuous spread of colours would mean electrons could hold any amount of energy. Sharp lines mean electrons can only hold certain fixed amounts. In 1913 Niels Bohr proposed that electrons circle the nucleus only in fixed **shells**, each shell holding a set number of electrons (2 in the first, 8 in the next for the first twenty elements) and a fixed amount of energy. Light is given out when an electron drops from a higher shell to a lower one, and the fixed shells explain the fixed lines. Sodium, with 11 electrons, arranges them 2,8,1.

Bohr model of a sodium atom: electrons only in fixed shells

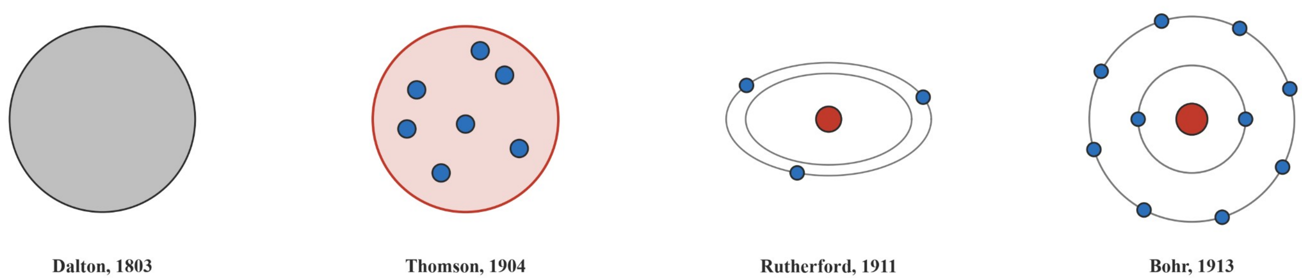


shells hold fixed numbers of electrons: 2, then 8, then 8 (for the first twenty elements)

Bohr model of a sodium atom: 11 protons and 12 neutrons in the nucleus and 11 electrons arranged 2,8,1 in fixed shells

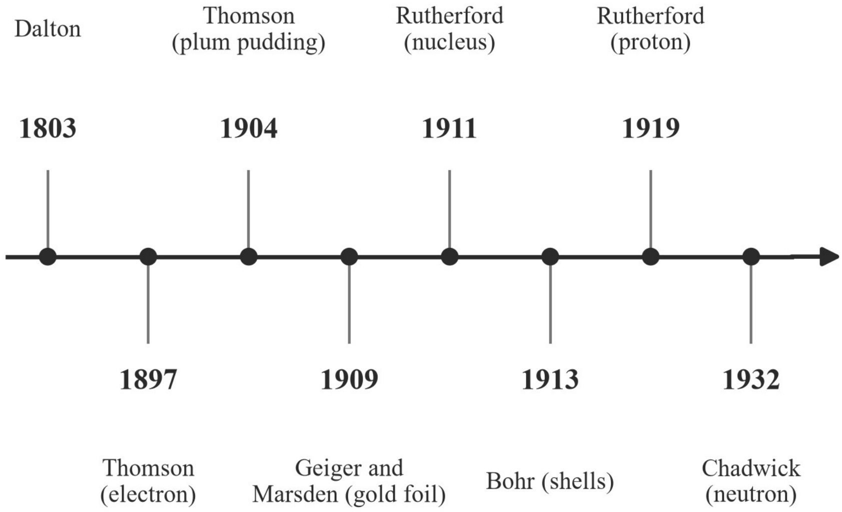
The pattern across a century. Step back and the story has a shape: every change to the model was forced by a result the old model could not explain.

Four models of the atom, in the order the evidence demanded them



Four models of the atom in the order the evidence demanded them: Dalton's sphere, Thomson's plum pudding, Rutherford's nuclear atom, Bohr's shells

The model of the atom changed step by step, each step driven by new evidence



Timeline 1803 to 1932: Dalton, Thomson's electron, Thomson's plum pudding, Geiger and Marsden's gold foil, Rutherford's nucleus, Bohr's shells, Rutherford's proton, Chadwick's neutron

The model of the atom is not a picture someone invented; it is an argument from evidence, and when the evidence changed, the model changed with it. The picture you will use from here on — a nucleus of protons and neutrons, electrons in shells around it, and the atomic number fixing the element — is the one this evidence built. (What nuclei with the *same* proton count but different neutron counts are called, and why some nuclei give off particles of their own, belongs to Subtopic 10B.)

Activities

Activity 1 — Evidence and model card sort (elaboration `VC2S10U06.E01`). In pairs, sort two card sets. Set A (models): Dalton's sphere, plum pudding, nuclear model, Bohr model. Set B (evidence): *cathode rays bend toward a positive plate and are identical from every metal*; *most alpha particles pass straight through gold foil*; *a very few alpha particles bounce straight back*; *hydrogen gives four sharp light lines, not a rainbow*; *knocking hydrogen nuclei out of nitrogen*. For each evidence card, write down (a) which model it supports, (b) which older model it breaks, and (c) in one sentence, why. Compare your sort with another pair and settle any disagreements by pointing at the observation a model fails to explain.

Activity 2 — Map a hidden object (Rutherford's logic). Work in pairs behind a screen. One partner fixes a small solid object (for example a wooden block or a drink bottle) under a sheet of cardboard taped flat over a tray, so the other partner cannot see it. The second partner rolls a marble across the tray from several different starting points and records, for each roll, the direction the marble leaves the tray. From the pattern of straight, bent and bounced-back marbles, draw a map of the hidden object's position and rough outline, then lift the cardboard and check. In your book, answer: which part of this activity plays the role of the alpha particle, the nucleus and the gold foil? Why could you not map the object from a single roll? Why do most marbles pass straight through, and what would a tray with *no* object look like in your records? (Safety: marbles on the floor are a slip hazard — keep all rolls inside the tray and collect stray marbles at once.)

Activity 3 — A scale model of the atom. A typical atom is about 1×10^{-10} m across; a typical nucleus is between 1×10^{-15} m and 1×10^{-14} m across. (a) Show that the nucleus is between 10 000 and 100 000 times smaller than the atom. (b) Choose a 1 cm marble to stand for the nucleus. Calculate the diameter of the model atom at both ratios (10 000 times and 100 000 times), giving your answers in metres. (c) Your school oval is about 150 m long. At each ratio, is the model atom smaller than, about the size of, or bigger than the oval? (d) Write one sentence stating where the mass of the real atom sits and what fills most of the rest of its volume.

Worked examples

Example 1 — scaffolded

The gold foil experiment gave three observations. Match each one to what it shows about the atom.

Step 1 — most alpha particles pass straight through. A particle that meets nothing solid and no strong push keeps going straight. So most of the atom's volume must be **empty space** — the nucleus and electrons take up very little of it.

Step 2 — some alpha particles bend through large angles. Alpha particles are positive, and like charges repel. A large bend needs a strong push, and a strong push needs the atom's positive charge gathered together rather than spread out. So the positive charge is **concentrated in one small region**.

Step 3 — a very few bounce straight back. To reverse a fast, heavy alpha particle, the small positive region must also hold **nearly all the atom's mass**, so the alpha particle hits something much heavier than itself. Conclusion: a tiny, dense, positive **nucleus** — Rutherford's nuclear model.

Example 2 — scaffolded

Compare the three particles of the atom, using the table in the Theory section.

Step 1 — charges. Proton +1, electron −1, neutron 0. A neutral atom needs equal numbers of protons and electrons so the charges cancel.

Step 2 — masses. Proton 1.673×10^{-27} kg and neutron 1.675×10^{-27} kg are almost equal; the electron's 9.109×10^{-31} kg is about 1/1836 of a proton's mass. So the **nucleus carries essentially all of an atom's mass**.

Step 3 — apply to carbon. Carbon's nucleus has 6 protons (+6) and 6 neutrons (0). A neutral carbon atom has 6 electrons (−6), and +6 with −6 cancels to zero. The atomic number 6 counts the protons.

Example 3 — unscaffolded

Explain why the plum pudding model could not explain alpha particles bouncing straight back from gold foil.

Example 4 — unscaffolded

An oxygen atom has 8 protons, 8 neutrons and 8 electrons. (a) Write its electron arrangement in shells. (b) Say where almost all of its mass sits. (c) Explain why the atom has no overall charge.

Practice questions

Scaffolded questions

Question 1 The timeline of the atomic model runs 1803 to 1932. (a) Which scientist proposed the solid-sphere model? (b) Which two particles were found first and last on the timeline, and in which years? (c) Whose 1911 idea placed the positive charge in a tiny nucleus?

Question 2 In Thomson's tube, the ray bent toward the positive plate. (a) What does that bending show about the charge the ray carries? (b) What name was later given to the particles in the ray? (c) Thomson got the same ray from every metal he tried. What did he conclude from that?

Question 3 Describe the plum pudding model. (a) Where does the positive charge sit in this model? (b) Where do the electrons sit?

Question 4 Match each gold foil observation to its conclusion. (a) Most alpha particles pass straight through the foil. (b) A very few alpha particles bounce back toward the source. Conclusions to choose from: *the atom is mostly empty space*; *the atom's mass and positive charge sit in a tiny nucleus*.

Question 5 Complete the particle table from memory, then check it against the Theory section.

particle	charge	mass compared with a proton	where it sits
proton	?	1	?
neutron	?	about 1	?
electron	?	about 1/1836	?

Question 6 A sodium atom arranges its 11 electrons 2,8,1. (a) How many electrons sit in sodium's outer shell? (b) How many shells are occupied? (c) How many protons does a neutral sodium atom have, and how do you know?

Unscaffolded questions

Question 7 Before Thomson, atoms were thought to have no parts inside. Which single observation from the cathode ray experiments showed that atoms *do* have parts?

Question 8 If the plum pudding model had been correct, what should have happened to a beam of alpha particles fired at thin gold foil?

Question 9 Rutherford concluded from the gold foil experiment that the atom is mostly empty space. Which observation forced that conclusion?

Question 10 Look at the figure of computed alpha-particle paths. Explain why a particle passing far from the nucleus shows almost no bend, while one passing close bends through a large angle.

Question 11 Chadwick's new radiation knocked protons out of paraffin wax, yet was not bent by charged plates. Explain why these two facts together point to a particle that (a) carries no charge and (b) is about as heavy as a proton.

Question 12 A neutral carbon atom has atomic number 6. (a) How many protons and how many electrons does it have? (b) Where is almost all of its mass? (c) Explain, using the charges of its particles, why the atom is neutral.

Question 13 Hydrogen gas given extra energy glows with four sharp visible lines rather than a full rainbow of colours. Explain how this observation supports Bohr's idea of fixed shells.

Question 14 A neutral atom has the arrangement 2,8,3. (a) How many electrons does it have, and so what is its atomic number? (b) How many of its electrons sit in the outer shell?

Question 15 An atom is about 1×10^{-10} m across and its nucleus about 1×10^{-14} m across. How many times smaller than the atom is this nucleus? If the nucleus were blown up to the size of a 1 cm marble, how wide would the atom be?

Question 16 "The model of the atom changed because the evidence changed." Choose **two** steps from the timeline (for example: electron, nucleus, neutron, shells) and for each explain (a) the observation the old model could not explain, and (b) how the new model explained it.

Answers

Question 1 (a) Dalton; (b) electron (1897) and neutron (1932); (c) Rutherford. **Question 2** (a) negative charge; (b) electrons; (c) electrons come from inside the atoms of every element. **Question 3** (a) spread through the whole atom; (b) stuck through the positive sphere like plums in a pudding. **Question 4** (a) mostly empty space; (b) tiny nucleus holding the mass and positive charge. **Question 5** proton +1, in the nucleus; neutron 0, in the nucleus; electron −1, in the space around the nucleus. **Question 6** (a) 1; (b) 3; (c) 11 — a neutral atom has as many protons as electrons (2 + 8 + 1). **Question 7** see solution. **Question 8** see solution. **Question 9** most alpha particles passed straight through. **Question 10** see solution. **Question 11** see solution. **Question 12** (a) 6 and 6; (b) in the nucleus; (c) see solution. **Question 13** see solution. **Question 14** (a) 13 electrons, atomic number 13; (b) 3. **Question 15** 10 000 times; 100 m. **Question 16** see solution.

Fully-worked solutions

Question 1 (a) John **Dalton** (1803) proposed that each element is made of its own solid, indivisible spheres. (b) First the **electron**, found by Thomson in **1897**; last the **neutron**, found by Chadwick in **1932**. (c) **Rutherford**, whose nuclear model (1911) gathered all the positive charge and nearly all the mass into a tiny nucleus.

Question 2 (a) The ray bends toward the positive plate, and opposite charges attract, so the ray carries **negative** charge. (b) The particles were later named **electrons**. (c) The same ray from every metal means electrons come from **inside the atoms of every element** — they are a part of all atoms, not of one special metal.

Question 3 (a) The positive charge is **spread out through the whole atom** as one positive sphere. (b) The electrons are **stuck through that sphere**, like plums in a pudding, so their negative charge balances the positive sphere.

Question 4 (a) *Most alpha particles pass straight through* → **the atom is mostly empty space**: most particles meet nothing strong enough to bend them. (b) *A very few bounce back* → **the atom's mass and positive charge sit in a tiny nucleus**: only a small, dense, positive lump can push a fast alpha particle straight back.

Question 5 Proton: charge **+1**, mass 1 (relative to itself), sits **in the nucleus**. Neutron: charge **0**, mass **about 1**, sits **in the nucleus**. Electron: charge **−1**, mass **about 1/1836**, sits **in the space around the nucleus** (in shells in the Bohr model).

Question 6 (a) The arrangement 2,8,1 puts **1** electron in the outer shell. (b) **3** shells are occupied (2, then 8, then 1). (c) A neutral atom has equal numbers of protons and electrons. The electrons number 2 + 8 + 1 = **11**, so sodium has **11 protons** (atomic number 11).

Question 7 Cathode rays carry negative charge and are far lighter than the lightest atom, yet they come *out of* atoms whenever any metal is used. A negative particle coming out of an atom is direct evidence that the atom **has parts inside** — it cannot be a solid sphere with no parts.

Question 8 In the plum pudding model the positive charge is spread out through the whole atom, so no single region can push strongly on an alpha particle. The beam should have passed through with **only very tiny bends** — no large angles and certainly no bounce-backs.

Question 9 **Most alpha particles passed straight through the foil.** A particle only bends when something pushes it; passing straight through means most of each atom's volume holds nothing massive or strongly charged — the atom is mostly empty space.

Question 10 The push on a positive alpha particle comes from the positive nucleus, and it grows rapidly stronger as the gap shrinks. A **distant pass** feels only a weak push, too small to change the path much, so the particle goes nearly straight on. A **close pass** feels a much stronger push for long enough to swing the path through a large angle, and a **head-on approach** is stopped and thrown straight back. The spread of bends is exactly what a tiny positive nucleus predicts.

Question 11 (a) Charged plates bend moving charged particles. The radiation was **not bent**, so it carries **no charge**. (b) When the radiation struck the wax it **knocked protons out at speed**. Only a particle with about the proton's own mass can shove a proton that hard in a collision (a light particle, like an electron, would bounce off without moving it much). So the radiation is a neutral particle of roughly proton mass — the **neutron**.

Question 12 (a) Atomic number 6 means **6 protons**; a neutral atom matches that with **6 electrons**. (b) Almost all the mass sits in the **nucleus** (protons and neutrons), because each electron is only about 1/1836 of a proton's mass. (c) The 6 protons contribute +6 and the 6 electrons −6; the neutrons add 0. So +6 with −6 cancels, and the atom carries **no overall charge**.

Question 13 If electrons could hold any amount of energy, the light given out would spread smoothly through all colours — a rainbow. Sharp lines mean only certain fixed amounts of energy are given out, which is exactly what **fixed shells** produce: an electron can only drop between set shells, so only set amounts of energy (set colours) appear. Four sharp lines are the fingerprint of fixed shells.

Question 14 (a) The arrangement 2,8,3 holds 2 + 8 + 3 = **13 electrons**; a neutral atom has 13 protons, so the **atomic number is 13** (the element is aluminium). (b) **3** electrons sit in the outer shell.

Question 15 (1×10^{-10} m) ÷ (1×10^{-14} m) = **10 000**, so this nucleus is 10 000 times smaller than the atom. Blown up the same 10 000 times, a 1 cm nucleus gives an atom 1 cm × 10 000 = 10 000 cm = **100 m** across — about two-thirds of a 150 m oval.

Question 16 Two steps, chosen from these four. *The electron (1897):* (a) cathode rays bending toward a positive plate showed negative particles lighter than any atom coming out of every metal — the solid-sphere model had no parts to give up; (b) Thomson's model put electrons inside a positive sphere, so atoms had structure. *The nucleus (1911):* (a) a very few alpha particles bouncing straight back could not happen in plum pudding, whose spread-out charge gives only tiny pushes; (b) Rutherford gathered the mass and positive charge into a tiny nucleus, whose strong close-range push explains the bounce-backs. *The neutron (1932):* (a) nuclei held more mass than their protons accounted for (helium: twice the charge of hydrogen but about four times the mass); (b) Chadwick's neutral particle of proton-like mass supplied the extra mass without extra charge. *The shells (1913):* (a) hydrogen's light comes out as sharp lines, not a continuous band, which a free-choice of energies cannot explain; (b) Bohr's fixed shells allow only set energy drops, giving exactly the set lines observed.

Sources

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Where this leads: the nucleus-and-shells picture built here is the starting point for Subtopic 10B (isotopes, natural radioactive decay and half-life) and Subtopic 10C (shells and the periodic table). At VCE, the atomic model returns in Chemistry Unit 1, Area of Study 1 ('How do the chemical structures of materials explain their properties and reactions?') and in Physics Unit 1, Area of Study 2, reference-only for this book; VCE adds the quantum refinements of the shell model and the energy accounting of nuclear changes, which are VCE-only and not taught here (TOC D9).

The habit this subtopic builds — that a scientific model stands only as long as it explains the evidence — is the habit VCE science assesses throughout.

Isotopes, natural radioactive decay and half-life — from unstable to stable atoms

Chapter 10 — Chemical sciences A: atoms, isotopes and the periodic table (Science, Levels 9 and 10)

Subtopic 10B · VC2 Science Understanding — Chemical sciences

CD code: `VC2S10U06` (split delivery †; this subtopic is the partner, not the accountable owner) **Content description (verbatim):** "the model of the atom changed following the discovery of electrons, protons and neutrons; natural radioactive decay results in a change from unstable to stable atoms" **This subtopic's limb (TOC §4 clause split):** isotopes, natural radioactive decay, half-life. The accountable owner `10A` delivers the other limb: the changing model of the atom and its subatomic particles. **Elaboration ids drawn on:** `VC2S10U06.E02` · `VC2S10U06.E03` · `VC2S10U06.E04` · `VC2S10U06.E06` (`VC2S10U06.E01` is drawn on by Subtopic 10A; `VC2S10U06.E05` is withheld under the TOC's D10 ICIP decision and is not taught here.) **Achievement standard (extract served):** "They explain how ideas about the structure of the atom have changed over time, and model natural radioactive decay to illustrate how stable atoms are formed." Subtopic 10B is assessed against the second clause — modelling natural radioactive decay to show how stable atoms are formed; the first clause is served by Subtopic 10A. **Maths interlock (D11):** `VC2M9M02` — scientific notation and very large and very small measurements and timescales, used here for half-life timescales; the ratio and percentage reasoning of `VC2M9M05` is re-used here for remaining fractions (taught in Subtopic 4B).

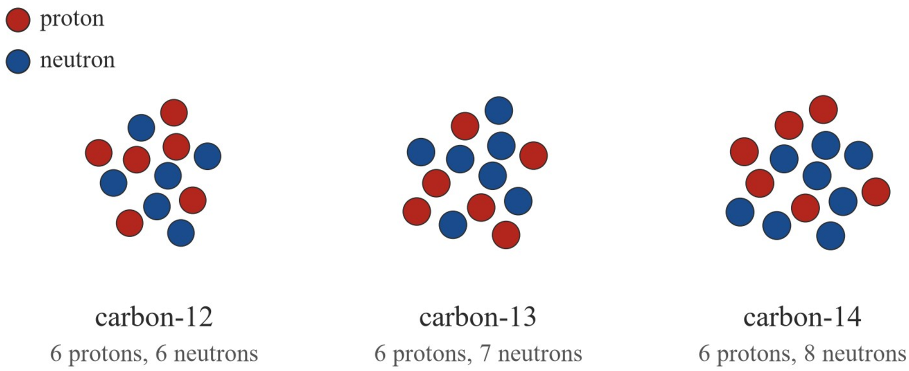
Theory

From unstable to stable. In Subtopic 10A you met the modern picture of the atom: a tiny, dense **nucleus** made of protons and neutrons, with electrons moving around it. The number of protons is the atom's **atomic number**, and it decides which element the atom is. The total number of protons and neutrons together is called the **mass number**. For most atoms of most elements, the nucleus holds together perfectly well, forever. Such atoms are **stable**. But some nuclei do not hold together forever. Given enough time, each of them changes by itself — it throws out a piece of itself, or a burst of energy, and becomes a different, more stable nucleus. That spontaneous change is called **radioactive decay**, and it is the subject of this subtopic: where unstable atoms come from, what they throw out, how fast they change, and how that change is put to work in medicine and industry.

The key words of this subtopic, each defined where it first appears: **isotope**, **radioisotope**, **radioactive decay**, **radiation**, **alpha particle**, **beta particle**, **gamma ray**, **ionising radiation**, **half-life**, **count rate**, **background radiation** and **tracer**.

Isotopes — the same element, with different neutron numbers (elaboration `VC2S10U06.E02`). Every atom of a given element has the same number of protons: every carbon atom has 6 protons, every uranium atom has 92. But the number of **neutrons** in the nucleus of a given element can vary. Atoms of the same element that differ in their number of neutrons are called **isotopes** of that element. An **isotope** is one of two or more forms of an element whose atoms have the same number of protons but different numbers of neutrons — and therefore different mass numbers.

Carbon has three well-known isotopes:



Three atomic nuclei side by side: carbon-12 with 6 protons and 6 neutrons, carbon-13 with 6 protons and 7 neutrons, and carbon-14 with 6 protons and 8 neutrons.

Isotope	Protons	Neutrons	Mass number	In brief
carbon-12	6	6	12	stable; about 99% of all natural carbon
carbon-13	6	7	13	stable; about 1% of all natural carbon
carbon-14	6	8	14	unstable; a tiny trace of all natural carbon

Isotopes are named by writing the element's name followed by the mass number: carbon-12, carbon-13, carbon-14 (also written C-12, C-13, C-14). In this book isotopes are always written in words in that form.

Because isotopes of an element have the same number of protons, a neutral atom of each has the same number of electrons, arranged in the same shells (Subtopic 10C). Chemical behaviour depends on those electrons, so **the isotopes of an element behave almost exactly the same way in chemical reactions**. Carbon-12 and carbon-14 both burn in oxygen to form carbon dioxide, for instance. What differs between isotopes is the mass of the atom — and, for some isotopes, the stability of the nucleus.

Stable and unstable nuclei (elaboration `VC2S10U06.E02`). Most naturally occurring isotopes are stable: carbon-12 and carbon-13 last forever. But **naturally occurring isotopes of some elements are unstable**. An unstable nucleus has a balance of protons and neutrons that cannot hold permanently. Sooner or later it changes, of its own accord, into a more stable arrangement. An unstable isotope is called a **radioisotope** (or radioactive isotope), and the change it undergoes is **radioactive decay**.

Three things about radioactive decay are worth fixing in your mind now, because they shape everything that follows:

- **It is spontaneous.** Heating the sample, cooling it, dissolving it in acid or combining it with another element makes no difference. The decay comes from inside the nucleus and cannot be sped up, slowed down or switched off by anything we do in a school laboratory.
- **It is random.** No one can say which atom in a sample will decay next, or when a particular atom will decay. Each unstable nucleus has the same chance of decaying in the next second as every other nucleus of the same isotope.
- **It releases energy.** Every decay gives out energy, carried away by what is emitted. That energy is what makes radiation detectable — and useful.

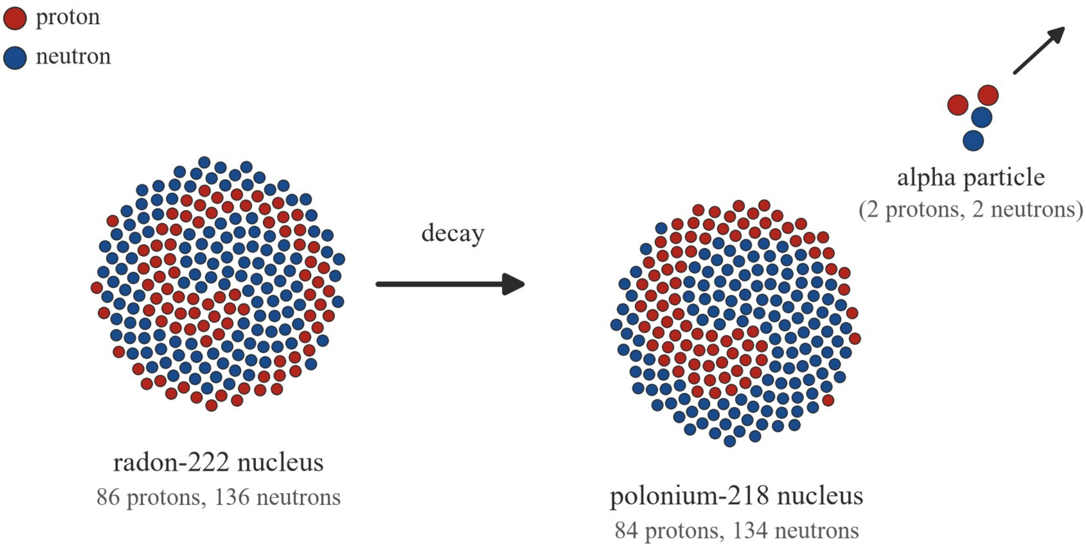
Unstable nuclei occur naturally all around us. Uranium-238 and thorium-232 are present in tiny amounts in rocks and soil, and have been decaying slowly since Earth formed. Radon-222 is a radioactive gas released as those elements decay; it seeps out of the ground into the air. Carbon-14 is continually made high in the atmosphere when radiation from space strikes nitrogen atoms, and a trace of it enters every living thing. Potassium-40, another natural radioisotope, is present in small amounts in food and in your own body. Decay that happens without any human cause is called **natural radioactive decay** — the change from unstable to stable atoms named in the content description of this subtopic. Radioisotopes can also be made on purpose in nuclear reactors, and Australia's ANSTO organisation makes medical radioisotopes at its OPAL reactor at Lucas Heights, New South Wales (you will meet these under *Uses* below). Source: ANSTO, Medical radioisotopes, ansto.gov.au, retrieved 2026-08-18.

Radiation — what unstable nuclei give out. The general name for what a decaying nucleus gives out is **radiation**: energy travelling outward through space or matter. In this subtopic, *radiation* means the particles and rays released by decaying nuclei. There are three common types, given Greek-letter names: **alpha**, **beta** and **gamma**. Each corresponds to a different way for an unstable nucleus to move toward stability.

Alpha decay (elaboration `VC2S10U06.E03`). An **alpha particle** is a cluster of **2 protons and 2 neutrons** bound together — identical to the nucleus of a helium atom. Some heavy unstable nuclei get rid of an alpha particle all in one piece. When a nucleus emits an alpha particle, it loses 2 protons and 2 neutrons. Losing protons changes the atomic number, so **the atom becomes a different element**.

The gas radon-222, found in tiny amounts in air above uranium-bearing rock, decays this way. A radon-222 nucleus has 86 protons and 136 neutrons (mass number 222). It emits an alpha particle, and what remains has 84 protons and 134 neutrons — the element with 84 protons is polonium, so the result is polonium-218:

radon-222 → polonium-218 + alpha particle



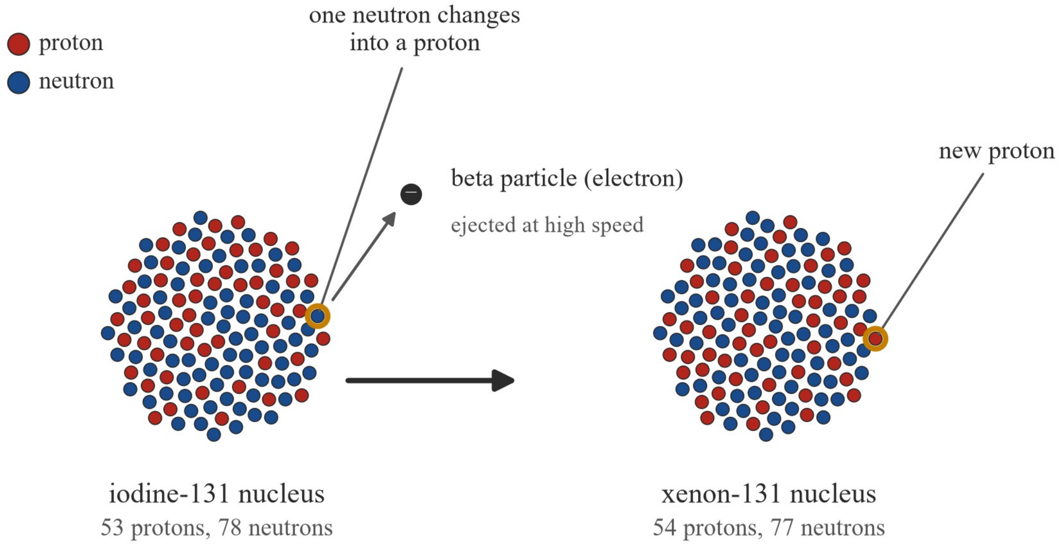
Model of alpha decay: a radon-222 nucleus with 86 protons and 136 neutrons emits an alpha particle of 2 protons and 2 neutrons, leaving a polonium-218 nucleus with 84 protons and 134 neutrons.

Notice the bookkeeping: 84 + 2 = 86 protons and 134 + 2 = 136 neutrons, so nothing is lost — the nucleus has simply split its particles between two products. At this level we describe decays in words and particle counts like these; the symbol equations used for the same process belong to VCE Physics and are not taught here (TOC D9).

Beta decay (elaboration `VC2S10U06.E03`). A **beta particle** is a fast-moving **electron** thrown out of the nucleus. The electron does not sit inside the nucleus waiting; it is created at the moment of decay, when **one of the nucleus's neutrons changes into a proton**. The new proton stays in the nucleus; the electron is ejected at high speed.

Because a neutron has become a proton, the nucleus gains one proton and loses one neutron. The mass number stays the same (the total count of protons and neutrons is unchanged), but the atomic number rises by one — again, a different element forms. Iodine-131, used in medicine, decays this way. An iodine-131 nucleus has 53 protons and 78 neutrons; one neutron changes into a proton, an electron is emitted, and the result has 54 protons and 77 neutrons — xenon-131, a stable atom:

iodine-131 → xenon-131 + beta particle

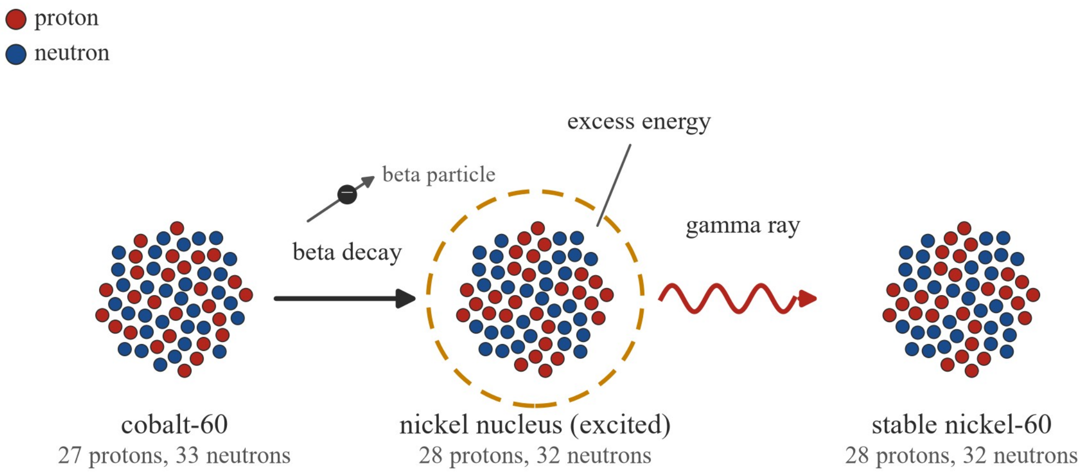


Model of beta decay: inside an iodine-131 nucleus with 53 protons and 78 neutrons, one neutron changes into a proton and a beta particle (electron) is ejected, leaving a xenon-131 nucleus with 54 protons and 77 neutrons.

Gamma emission (elaboration `VC2S10U06.E03`). A **gamma ray** is not a particle at all but a burst of energy — a very high-energy electromagnetic wave, like light or X-rays but far more energetic. A nucleus emits a gamma ray when it has excess energy to get rid of but no particles to throw out. **No protons or neutrons are lost in gamma emission, so the element does not change** — the nucleus simply settles into a more stable, lower-energy state.

Cobalt-60, a widely used gamma source, shows the two ideas together. A cobalt-60 nucleus (27 protons, 33 neutrons) first undergoes beta decay, becoming a nickel nucleus (28 protons, 32 neutrons). That new nickel nucleus is left with excess energy, which it promptly releases as gamma rays, becoming stable nickel-60. In everyday shorthand, cobalt-60 is called a gamma source, and that is how it is used in hospitals and industry:

> cobalt-60 → nickel-60 + beta particle, then gamma rays are emitted as the nickel nucleus settles to a stable state



Model of gamma emission in two steps: a cobalt-60 nucleus with 27 protons and 33 neutrons emits a beta particle to become a nickel nucleus with 28 protons and 32 neutrons, which then releases its excess energy as a gamma ray, becoming stable nickel-60.

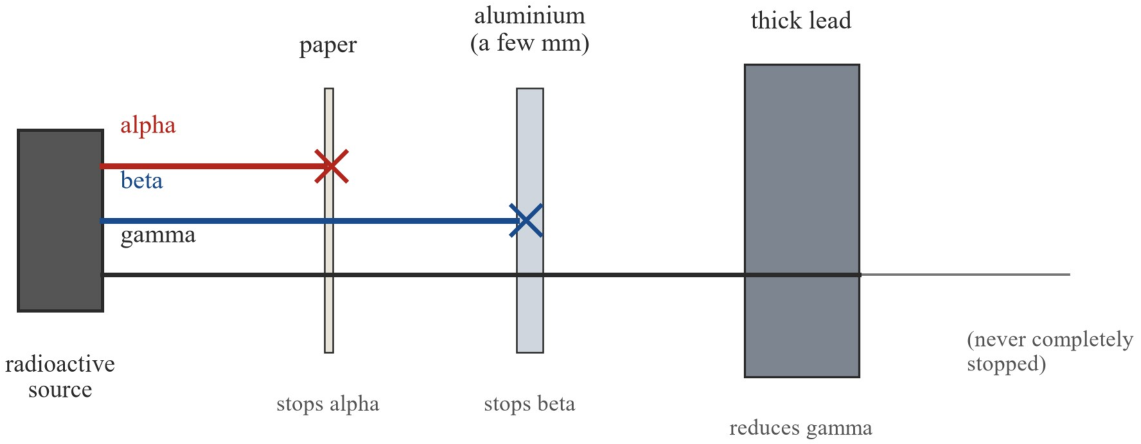
The three types are summarised here:

Type	What it is	Charge	What happens in the nucleus
alpha particle	2 protons + 2 neutrons	positive	loses 2 protons and 2 neutrons; new element forms
beta particle	a fast electron	negative	one neutron changes into a proton; new element forms
gamma ray	high-energy electromagnetic wave	none	excess energy released; no particles lost; element unchanged

In each case the products are more stable than the nucleus that decayed. Natural radioactive decay is a change from unstable to stable atoms, step by step, and every step gives out energy.

How far they penetrate. The three radiations behave very differently when they meet matter, and those differences decide how each is used and how each is handled.

- **Alpha** radiation is the least penetrating. A sheet of paper, a few centimetres of air, or the outer layer of dead skin is enough to stop it.
- **Beta** radiation passes through paper but is stopped by a few millimetres of a light metal such as aluminium.
- **Gamma** radiation passes through paper and aluminium; only thick lead or concrete reduces it a great deal (gamma rays are never completely stopped — thick shielding cuts the amount right down).



Penetration of the three radiations: alpha is stopped by a sheet of paper, beta passes through paper but is stopped by a few millimetres of aluminium, and gamma passes through both but is reduced by thick lead.

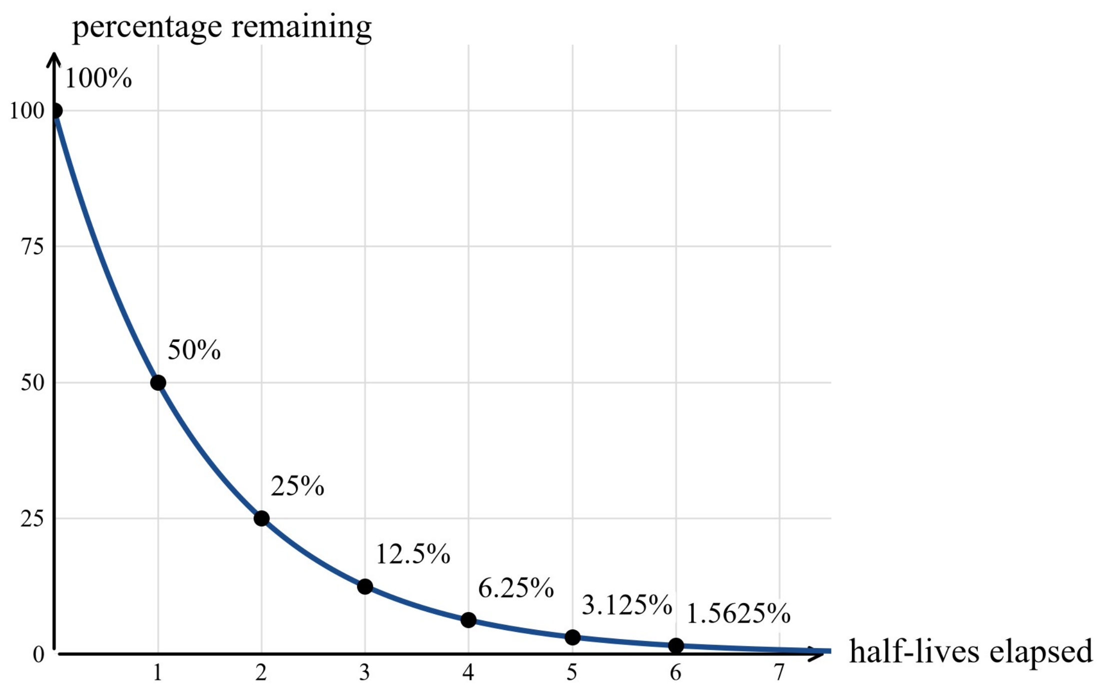
All three are forms of **ionising radiation**. *Ionising radiation* means radiation carrying enough energy to knock electrons out of the atoms it passes through, leaving charged atoms (ions) behind. That is why radiation must be treated with respect in the laboratory: the same ability to ionise atoms that makes radiation useful in medicine can damage living cells if the dose is too large. Alpha radiation is the most ionising of the three — it does the most damage to the material it hits — but because it cannot penetrate skin, an outside alpha source is the least hazardous. Swallowed or inhaled, though, an alpha source sits against living tissue with no dead skin to shield it, which is why alpha emitters are the most dangerous inside the body. Gamma radiation is the least ionising per centimetre of its path but the most penetrating, so it is the main outside hazard and the type used when radiation must reach through something — into the body, or through a metal weld.

Half-life — the clock inside a sample (elaboration `VC2S10U06.E04`). You cannot predict when one atom will decay. But a sample contains a huge number of atoms, and large numbers turn randomness into a pattern. Imagine rolling a die for every atom in a sample: you cannot say which atom will "come up six" on the next roll, but you can say with confidence that about one-sixth of them will. Unstable nuclei behave the same way, except each isotope has its own fixed chance of decaying in any given time.

That fixed chance gives every radioisotope a characteristic timescale called its **half-life**. The **half-life** of a radioisotope is the time taken for half of the nuclei in a sample to decay. Equivalently, it is the time for the count rate from the sample — the rate at which decays are detected (see *Measuring decay* below) — to fall to half its value.

After one half-life, half of the original nuclei remain undecayed. After a second half-life, half of that half remains — one quarter of the original. After a third, one eighth, and so on. The amount is **halved** every half-life; it is never all gone at once.

Half-lives elapsed	Fraction remaining	Percentage remaining
0	1	100%
1	1/2	50%
2	1/4	25%
3	1/8	12.5%
4	1/16	6.25%
5	1/32	3.125%



Decay curve showing the percentage of undecayed nuclei falling from 100% to 50% after one half-life, 25% after two, 12.5% after three, 6.25% after four, 3.125% after five and 1.5625% after six.

Two useful facts follow directly from the definition:

- **Number of half-lives = elapsed time ÷ half-life.**
- **Remaining amount = starting amount halved once for each half-life.**

The worked examples below show both in action.

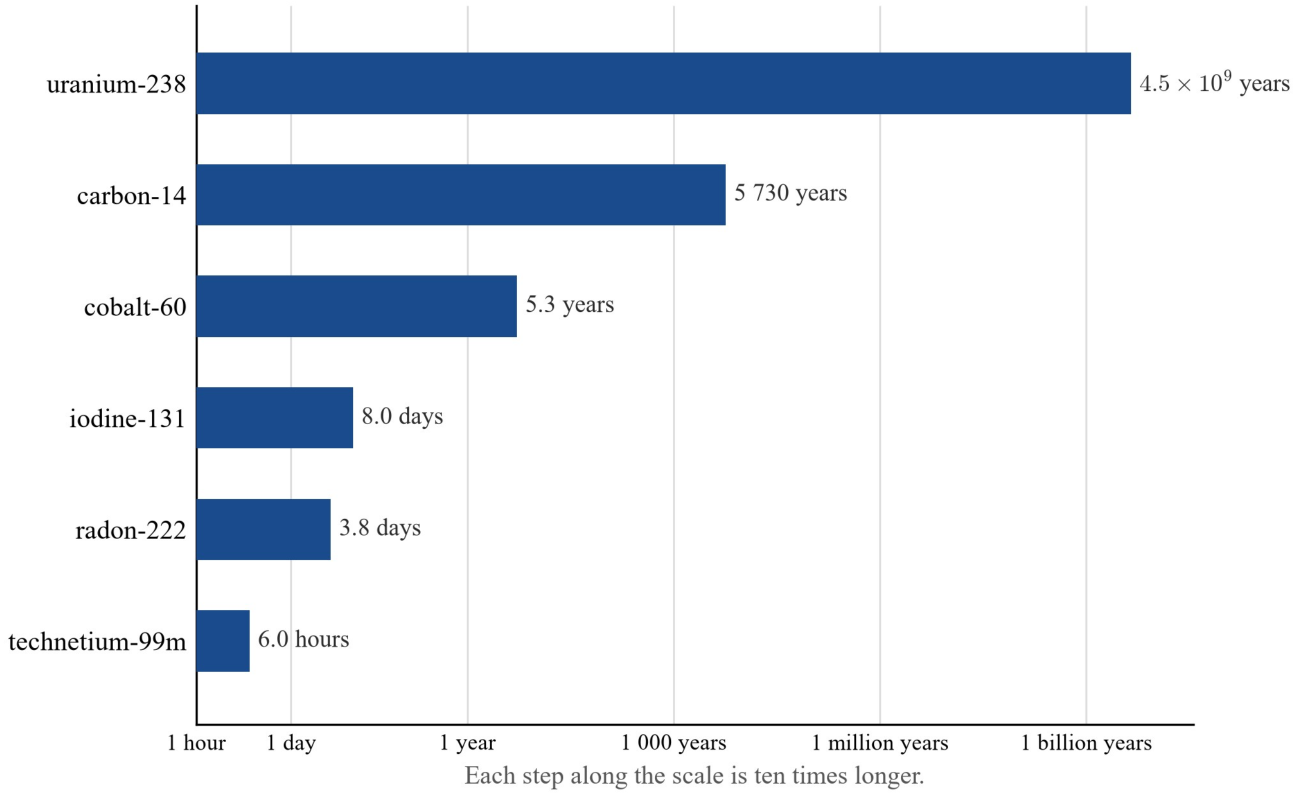
Half-lives range enormously (elaboration `VC2S10U06.E04`). Different radioisotopes decay on wildly different timescales. Some are gone in hours; others outlast the age of Earth. Here are the isotopes this subtopic uses, with their half-lives:

Isotope	Half-life	Where it appears in this subtopic
technetium-99m	6.0 hours	medical imaging tracer
radon-222	3.8 days	natural gas from uranium-bearing rock
iodine-131	8.0 days	treatment of thyroid disease
cobalt-60	5.3 years	gamma source in medicine and

Isotope	Half-life	Where it appears in this subtopic
		industry
carbon-14	5 730 years	natural radioisotope in once-living material
uranium-238	4 500 000 000 years (4.5 × 10^9 years)	natural radioisotope in rocks

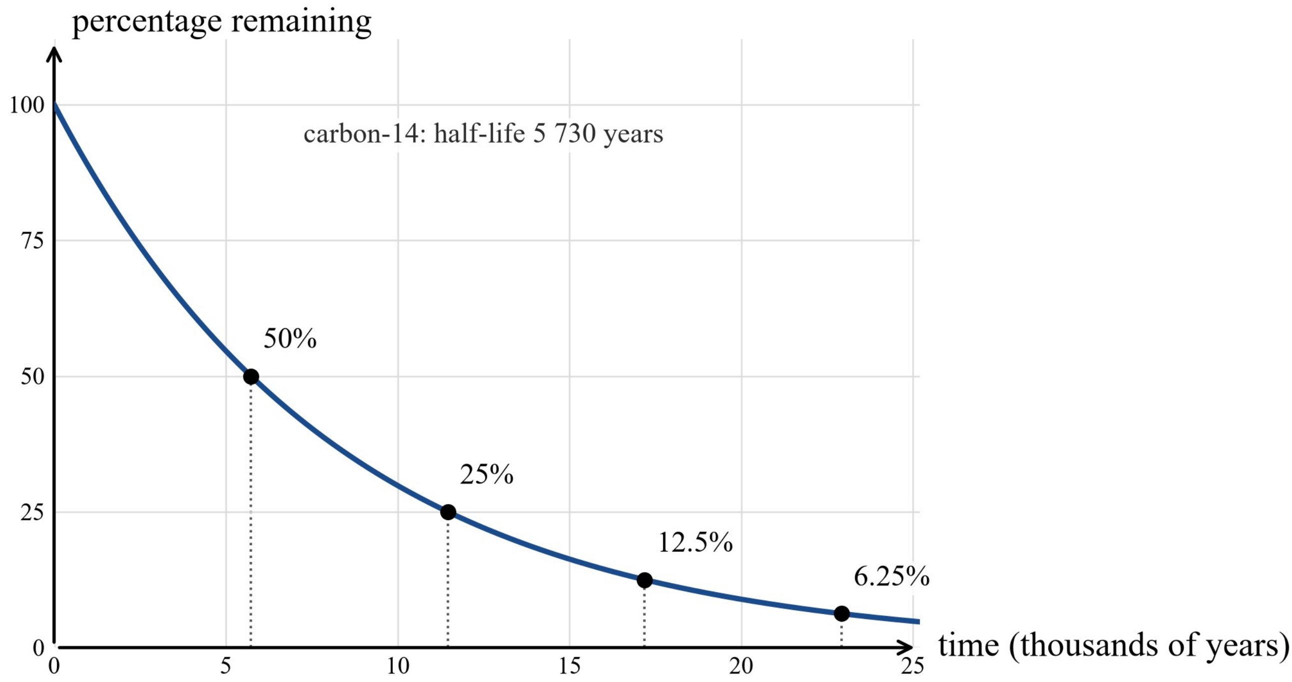
Source: IAEA, LiveChart of Nuclides, retrieved 2026-08-18 (carbon-14 given here as 5 730 years, the value used in radiocarbon work); ANSTO, Medical radioisotopes, ansto.gov.au, retrieved 2026-08-18.

The table reaches from hours to billions of years, which is exactly the kind of spread that scientific notation exists to describe (Maths interlock `VC2M9M02`). Uranium-238's half-life of 4 500 000 000 years is written 4.5 × 10^9 years — about a million times longer than the age of a human lifetime, and about the same as the age of Earth itself. That is why uranium-238 is still here, decaying slowly in rocks all over Australia, four and a half billion years after it was formed.



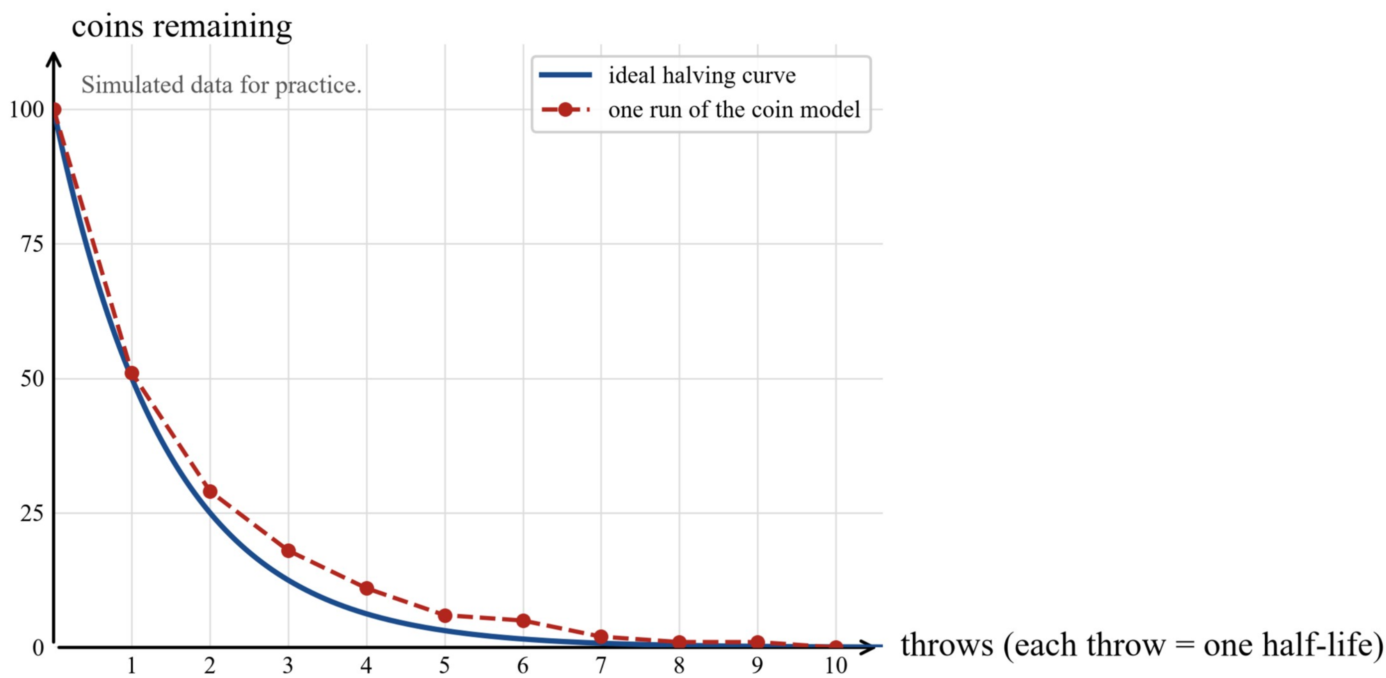
Half-lives of six isotopes compared on a scale where each step is ten times longer, from technetium-99m at 6.0 hours to uranium-238 at 4.5 billion years.

Carbon-14 sits in the middle of the range, and its half-life makes it a natural clock for once-living material. While a plant or animal is alive, it keeps taking in carbon, including a tiny trace of carbon-14, so the carbon-14 it contains is topped up. Once it dies, no new carbon enters, and the carbon-14 already there decays with its 5 730-year half-life, forming stable nitrogen-14 by beta decay. Measuring how much carbon-14 remains in a sample of once-living material — old wood, for example — tells you how long ago the organism died. After about ten half-lives (around 57 000 years for carbon-14) so little remains that there is not enough left to measure, which sets a limit on how old a sample carbon-14 can date. For far older material, such as rocks formed millions or billions of years ago, scientists use radioisotopes with much longer half-lives, such as uranium-238, which decays through a long chain of unstable nuclei and ends as stable lead.



Decay curve for carbon-14: the percentage of carbon-14 remaining falls from 100% to 50% at 5 730 years, 25% at 11 460 years, 12.5% at 17 190 years and 6.25% at 22 920 years.

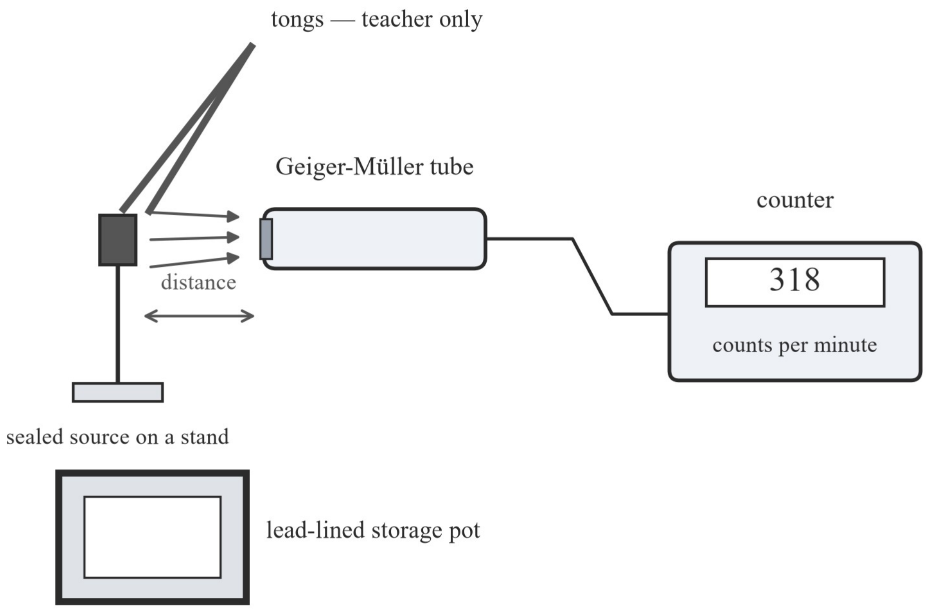
Simulating decay (elaboration `VC2S10U06.E04`). Because real decays are random, the halving pattern shows up clearly only when huge numbers of atoms are involved. A classroom simulation reproduces the same mathematics with coins or dice: each coin stands for one undecayed nucleus, each shake or throw stands for one equal interval of time, and every coin that lands a certain way is "decayed" and removed. With coins, each coin has a 1-in-2 chance of landing heads, so one throw plays the role of one half-life — half the coins, on average, survive each throw.



Simulated coin data for practice: one run starting from 100 coins roughly halves each throw, following the smooth halving curve more closely as the run is averaged with more runs.

One run will not halve exactly — randomness shows — but the average of many runs, or a digital simulation with thousands of "atoms", follows the smooth halving curve closely. Activity 1 lets you collect this data yourself, and the same pattern can be explored with a digital simulation of decaying atoms, in which the number of undecayed atoms and the count rate can be watched fall together.

Measuring decay. Radiation cannot be seen, heard or felt, so instruments are used to detect it. The familiar instrument is the **Geiger-Müller counter** (GM counter), a tube that produces a click — and adds one to a counting display — each time ionising radiation enters it. The number of decays detected per minute is the sample's **count rate**, measured in counts per minute (counts/min). Count rate is proportional to how many nuclei are still decaying, so it halves over each half-life just as the amount of the isotope does. That is why the definition of half-life can be given in terms of count rate.



Labelled sketch of a Geiger-Müller counter measuring the count rate from a sealed radioactive source held at a distance, with tongs and a lead-lined storage pot nearby.

There is one catch: a GM counter never reads zero, even with no sample nearby. Radiation is always present in the environment — from rocks and soil (including radon gas), from space, and from the small amounts of radioisotopes in food, buildings and our own bodies. This ever-present radiation is called **background radiation**, and its count rate is the **background count**. In Australia the average dose a person receives from natural background radiation is about 1.5 millisieverts per year (a millisievert is a unit used to measure the effect of a radiation dose on the body) — low by world standards, and far below levels known to cause harm. Source: ARPANSA material on natural background radiation, retrieved August 2026 (as at August 2026).

To find the count rate due to a sample alone, measure the background count first (with the sample removed), then subtract it from the reading taken with the sample present:

corrected count rate = measured count rate − background count rate

The worked examples and questions in this subtopic treat background correction as part of good measurement, exactly as it is in a real laboratory.

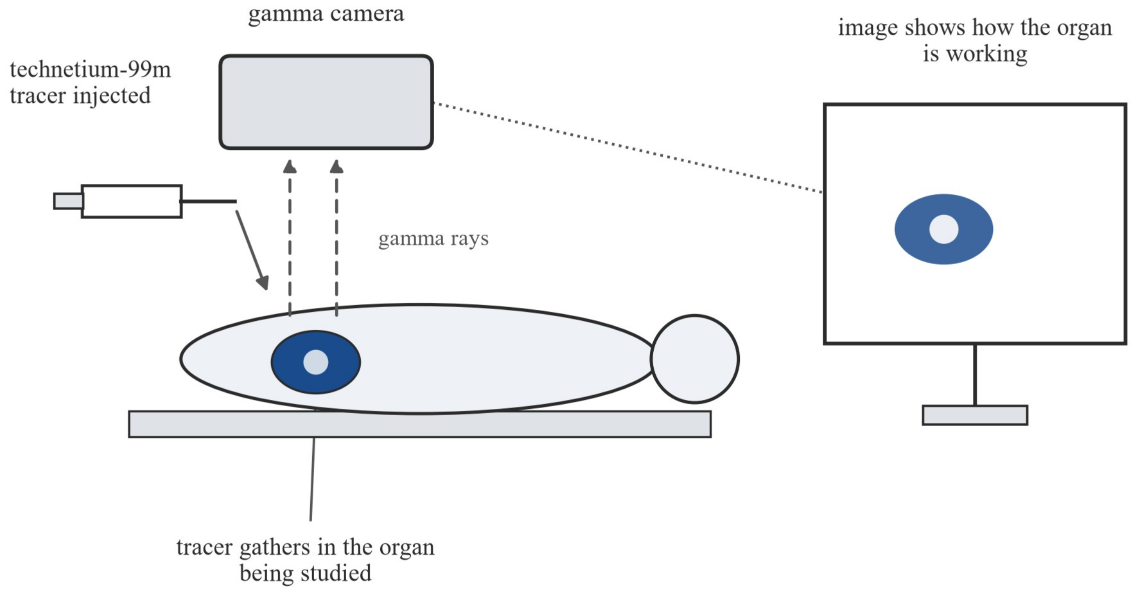
Radiation safety. Radioisotopes in school laboratories are handled by teachers only, as sealed sources, following the risk-assessment guidance of Science ASSIST (ASTA). The three protections used whenever radiation is handled are:

- **Time** — spend as little time near a source as possible;
- **Distance** — keep the source well away from the body; intensity falls away quickly with distance, and tongs or a source holder keep it at arm's length;
- **Shielding** — store sources in a lead-lined container, and place shielding between the source and anyone nearby when it is in use.

Students never handle radioactive sources in this course; investigations of count rate are teacher demonstrations, and the background count — which is perfectly safe to measure — is the students' own data.

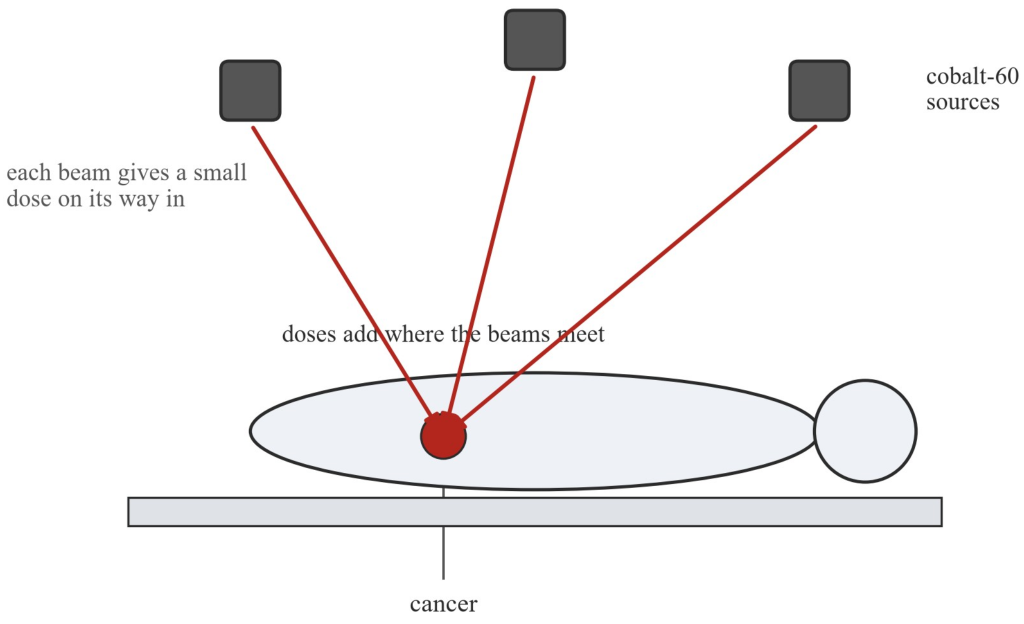
Uses of radioisotopes (elaboration `VC2S10U06.E06`). The properties you have just met — penetrating power, ionising power, and the built-in clock of the half-life — make radioisotopes valuable tools. Applications of radioactivity are found throughout medicine and industry.

In medicine — diagnosis. A **tracer** is a radioisotope attached to a substance the body uses, so that its path through the body can be followed from outside with a detector. The most widely used medical tracer is technetium-99m, made from molybdenum-99 produced in reactors including ANSTO's OPAL reactor at Lucas Heights and supplied to hospitals across Australia. Attached to different carrier substances, technetium-99m travels to particular organs — bones, heart, kidneys — where a gamma camera detects the radiation it gives out and builds an image of how the organ is working. Technetium-99m suits this job because it emits gamma rays that escape the body to the camera, and its 6.0-hour half-life is long enough to prepare and inject it and take the image, yet short enough that the patient's exposure is mostly over within a day. Source: ANSTO, Medical radioisotopes, ansto.gov.au, retrieved 2026-08-18.



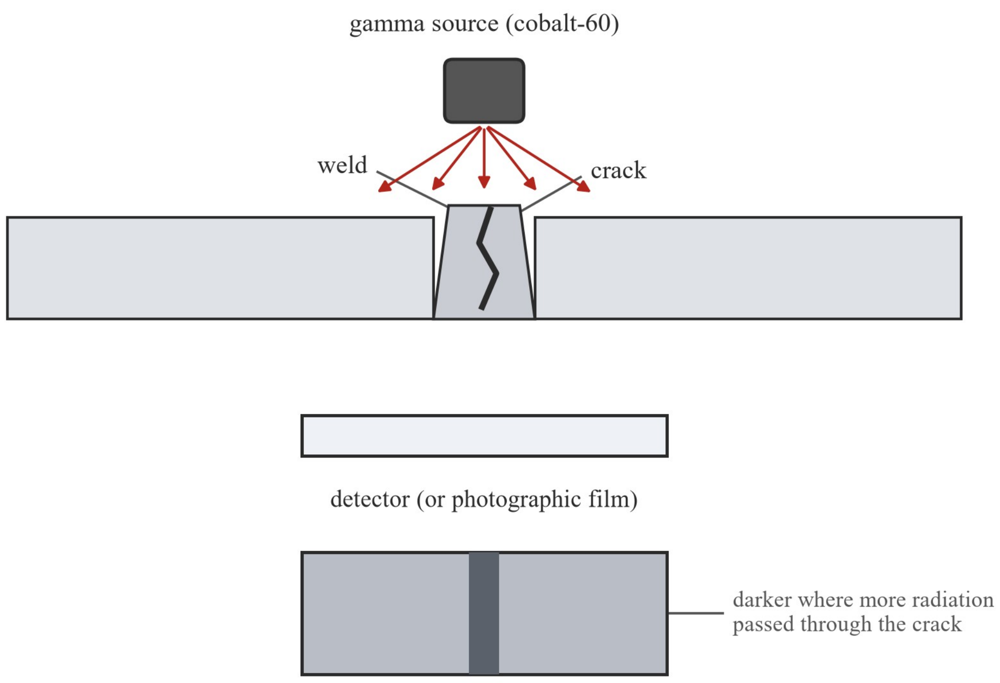
Labelled sketch of a medical tracer scan: technetium-99m is injected into a patient, gathers in the organ being studied, and a gamma camera detects the radiation to form an image on a screen.

In medicine — treatment. Radiation that damages cells can be aimed at diseased cells. In radiotherapy, gamma rays from a cobalt-60 source are directed at a cancer from several angles at once. Each beam on its own gives a small dose to the healthy tissue it passes through, but where all the beams meet at the cancer, the doses add to a large one — enough to kill the cancer cells while the surrounding tissue recovers. Iodine-131 is used the same idea-driven way against cancer of the thyroid gland: the thyroid naturally takes up iodine, so swallowed iodine-131 collects there and its beta radiation destroys the diseased tissue from inside, with an 8.0-day half-life that limits how long the exposure lasts. Both are examples of the same principle: choose the radiation type and the half-life to suit the job.



Labelled sketch of radiotherapy: gamma beams from three cobalt-60 sources aimed at a cancer from different angles, each beam giving a small dose along its path and a large combined dose where the beams meet.

In industry — checking for faults. Gamma rays pass through metal, and how much gets through depends on the thickness of metal in the way. To check a weld — in a pipeline, an aircraft part or a spacecraft component — a gamma source is placed on one side of the weld and a detector or photographic film on the other. A crack or air bubble inside the weld lets more radiation through, leaving a darker line on the image, so faults hidden inside solid metal are found without cutting anything open. Cobalt-60 is a common source for this work.



Labelled sketch of industrial checking: a gamma source above a welded pipe joint and a detector plate below, with a crack in the weld letting more radiation through and showing as a darker line on the image.

Other uses. Gamma irradiation kills bacteria and other micro-organisms, so it is used to sterilise sealed medical equipment such as syringes and bandages, and to treat some foods so they keep longer. Some smoke detectors contain a tiny amount of americium-241, an alpha emitter; the alpha particles ionise the air inside the detector, and smoke interrupts that ionisation and sets off the alarm. In every case the choice of isotope follows from the properties in this subtopic: the type of radiation, its penetrating power, and a half-life matched to the job.

The journey ends at stability. Every decay in this subtopic is one step on a journey from an unstable nucleus to a stable one. Iodine-131 reaches stable xenon-131 in a single beta decay. Cobalt-60 reaches stable nickel-60 by beta decay followed by gamma emission. Carbon-14 reaches stable nitrogen-14 in one beta decay, over thousands of years. Uranium-238 takes the long road: a chain of many decays, over billions of years, ending at stable lead. Slowly, and without any help from us, the unstable atoms formed before Earth was born are still becoming stable — and while they do, they give out the radiation we have learned to measure, to model and to use.

Activities

Activity 1 — A coin model of half-life (elaboration `VC2S10U06.E04`). You will need 100 identical coins, a cup for shaking, and a results table. The coins stand for the nuclei in a sample of a radioisotope; each throw stands for one half-life; every coin landing heads has "decayed" and is removed.

1. Count out 100 coins. Record 100 undecayed at throw 0.
2. Shake the coins in the cup and spread them out. Remove every head. Count and record the number of tails (the undecayed nuclei).
3. Throw only the surviving coins again. Repeat until fewer than 5 coins remain.
4. Draw a graph of undecayed nuclei against throw number.
5. Combine your results with other groups' by averaging the number remaining at each throw, and add the averaged data to your graph.

Questions to answer from your data: How well did each throw halve the number, and why was the halving never exact? How does the averaged curve compare with the smooth curve in the decay-curve figure, and what does that say about the difference between one small sample and a large one? Predict from your graph how many throws it would take for 100 coins to fall below 1, and check your prediction. (No safety precautions are needed — no radioactive material is used in this activity.)

Activity 2 — Modelling decays with bead nuclei. You will need two colours of small beads or modelling-clay balls (one colour for protons, one for neutrons) and a small tray. This activity models the nucleus itself, the way the achievement standard for this subtopic asks: model natural radioactive decay to show how stable atoms are formed.

1. Build the nucleus of carbon-14: 6 proton beads and 8 neutron beads.
2. Model its beta decay: swap one neutron bead for a proton bead, and move an "electron" bead out of the nucleus to show the emitted beta particle. Count the protons and neutrons in the nucleus now, and identify the element formed (7 protons).
3. Build a nucleus with 86 proton beads and 136 neutron beads — radon-222 (you may group beads in clusters to keep the model manageable). Model its alpha decay by removing a cluster of 2 protons and 2 neutrons. Count what remains and identify the new element (84 protons).
4. For each model, write a word description of the decay in the style used in the theory: starting isotope → product + emitted particle, with proton and neutron counts before and after.
5. Explain, using your models, why alpha and beta decay produce a different element while gamma emission does not.

Record your models with labelled sketches showing the counts before and after each change.

Activity 3 — Measuring the background count rate (teacher demonstration). If your school has a Geiger-Müller counter, your teacher will use it to measure the radiation already present in the room — no radioactive source is needed.

1. Set the counter to count for 1 minute and record the count. Repeat at least five times at the same bench position.
2. Tabulate the five readings and find the mean count per minute.
3. Take one further set of readings at a different position in the school (for example, a ground-floor room and an upper-floor room, or indoors and outdoors) and compare the means.

Questions to answer: Why do the repeated readings differ from one another even though nothing was changed? (Think about what the theory says regarding randomness.) Why is the mean a better estimate of the background count than any single reading? Suggest one reason the count rate might differ between the two positions. The teacher should follow Science ASSIST (ASTA) guidance for any use of radiation equipment, and students must not handle any radioactive source.

Worked examples

Example 1 — scaffolded

Chlorine has two common isotopes, chlorine-35 and chlorine-37. The atomic number of chlorine is 17. (a) State the number of protons in each isotope. (b) Find the number of neutrons in each isotope. (c) State the number of electrons in a neutral atom of each isotope. (d) Explain why the two isotopes are the same element, and why they behave alike in chemical reactions.

Working	Comment
Atomic number = number of protons = 17 for both	The proton number defines the element, so both isotopes have 17 protons.
Neutrons = mass number − protons	Mass number = protons + neutrons, rearranged.
chlorine-35: 35 − 17 = 18 neutrons	Subtract the proton number from the mass number.
chlorine-37: 37 − 17 = 20 neutrons	Same method for the second isotope.
Electrons = 17 in each	A neutral atom has the same number of electrons as protons.
Same proton number → same element; same electron arrangement → same chemistry	Chemical behaviour depends on the electrons, which are identical in the two isotopes.

(a) Both have **17 protons**. (b) chlorine-35 has **18 neutrons**; chlorine-37 has **20 neutrons**. (c) Each has **17 electrons**. (d) They are the same element because they have the same number of protons; they behave alike chemically because neutral atoms of both have the same number and arrangement of electrons.

Example 2 — scaffolded

Iodine-131 has a half-life of 8.0 days. A sample contains 16 g of iodine-131. (a) Find how many half-lives pass in 24 days. (b) Find the mass of iodine-131 remaining after 24 days. (c) State the fraction of the original iodine-131 that remains.

Working	Comment
Number of half-lives = elapsed time ÷ half-life	The definition, rearranged.
24 ÷ 8.0 = 3 half-lives	Three equal half-life intervals fit into 24 days.
Halve the mass three times: 16 → 8 → 4 → 2	Each half-life halves the amount remaining.
Mass remaining = **2 g**	After three halvings.
Fraction remaining = 1/2 × 1/2 × 1/2 = 1/8	Halve the fraction once per half-life.

(a) 3 half-lives. (b) **2 g**. (c) **1/8** of the original sample. (Check: 1/8 of 16 g is 2 g, which agrees.)

Example 3 — unscaffolded

A teacher measures the count rate from a sample of an unknown radioisotope. The readings below are taken at 6-hour intervals. The background count rate in the room is 20 counts/min.

Time (h)	0	6	12	18
Measured count rate (counts/min)	820	420	220	120

Determine the half-life of the isotope, and predict the measured count rate at 24 h.

First correct each reading for the background count: subtract 20 counts/min from every measured value.

Time (h)	0	6	12	18
Corrected count rate (counts/min)	800	400	200	100

The corrected count rate halves every 6 hours: 800 → 400 → 200 → 100. The half-life is therefore **6.0 h**. After one more half-life (at 24 h) the corrected count rate halves again, from 100 to 50 counts/min. The measured rate includes the background, so the predicted measured count rate is 50 + 20 = **70 counts/min**.

Note the reason for correcting: the counter always records the background radiation as well as the sample, and only the corrected rate is due to the sample alone. Halving the measured rate directly (820 → 410 → 205 …) would not give a clean pattern, because the background part never decays.

Example 4 — unscaffolded

Living wood contains carbon-14 at a level we can call 100%. A piece of ancient wood found preserved in a peat bog gives a carbon-14 level of 25% of the living value. The half-life of carbon-14 is 5 730 years. Estimate the age of the wood, and then: (a) explain why carbon-14 could not be used to date a rock formed millions of years ago; (b) state one assumption your estimate depends on.

25% is 1/4 of the original level, which is two halvings: 100% → 50% → 25%. So two half-lives have passed, and the age is 2 × 5 730 = **11 460 years**.

(a) Carbon-14 dating works only for material that was once alive, because only living organisms take in carbon-14 from the environment; most rocks were never living material. There is also a timescale problem: after about ten half-lives (around 57 000 years for carbon-14) less than one-thousandth of the original carbon-14 remains, which is too little to measure. A rock millions of years old is far beyond that limit, so a radioisotope with a much longer half-life, such as uranium-238, is used for rocks instead.

(b) Any one of: the level of carbon-14 in the environment when the tree was alive was the same as today's living level; no carbon-14 has been added to or removed from the sample by contamination since it died; the half-life has remained constant.

Practice questions

Scaffolded questions

Question 1 Uranium has atomic number 92. Two of its isotopes are uranium-235 and uranium-238. (a) State the number of protons in each isotope. (b) Calculate the number of neutrons in each isotope. (c) State what is the same, and what is different, about the nuclei of the two isotopes. (d) Explain why both isotopes are atoms of the element uranium.

Question 2 The three types of radiation from radioactive decay. (a) Copy and complete the table below.

Type	What it is	Charge
alpha	…	…
beta	…	…
gamma	…	…

(b) State which type is stopped by a sheet of paper.
(c) State which type is reduced by thick lead but not completely stopped.
(d) State which type is the most ionising.

Question 3 Iodine-131 has a half-life of 8.0 days. (a) Define the half-life of a radioisotope. (b) State the fraction of a sample of iodine-131 remaining after 8.0 days, 16 days and 32 days. (c) A freshly prepared sample has a corrected count rate of 400 counts/min. Calculate the corrected count rate after 16 days.

Question 4 Technetium-99m has a half-life of 6.0 hours. (a) State the fraction of a sample remaining after one half-life and after two half-lives. (b) Calculate the time taken for a sample to fall to one quarter of its starting amount. (c) Use the decay-curve figure to find the approximate percentage of a sample remaining after four half-lives. (d) Explain why a decaying sample never quite reaches zero, but eventually becomes too small to detect.

Question 5 Matching isotopes to uses. (a) Match each isotope to its use: technetium-99m, cobalt-60, iodine-131, americium-241 — (i) checking welds for faults, (ii) imaging organs with a tracer, (iii) the source inside some smoke detectors, (iv) treating thyroid disease. (b) State the property of gamma radiation that makes it suitable for checking faults inside metal. (c) State one reason a medical tracer should have a half-life of hours, not years.

Question 6 Safe practice with radiation. (a) Name the three protections used when working with radioactive sources. (b) State why sources are stored in lead-lined containers. (c) Explain why an alpha-emitting source is more dangerous inside the body than outside it. (d) State why students in this course measure only the background count rate, never a source.

Unscaffolded questions

Question 7 Carbon-12 and carbon-14 are both forms of carbon, yet one is stable and one decays by beta emission. (a) State the numbers of protons and neutrons in each isotope. (b) Explain why the two isotopes behave alike in chemical reactions. (c) State which part of the atom controls chemical behaviour and which part is involved in radioactive decay. (d) Name the element formed when carbon-14 decays, given that beta decay turns one neutron into a proton.

Question 8 Radon-222 (atomic number 86) decays by emitting an alpha particle to form polonium-218. (a) State the number of protons and neutrons in a radon-222 nucleus. (b) State the numbers of protons and neutrons carried away by the alpha particle. (c) Deduce the numbers of protons and neutrons in the polonium-218 nucleus. (d) Explain how these numbers show that the atom has become a different element.

Question 9 Iodine-131 (53 protons) decays by beta emission to xenon-131. (a) Describe what happens to one neutron in the nucleus during beta decay. (b) Explain why the mass number stays at 131 even though the element changes. (c) State the number of protons in the xenon-131 nucleus.

Question 10 A sample of radon-222 gives a corrected count rate of 600 counts/min. The half-life of radon-222 is 3.8 days. (a) State the corrected count rate after 3.8 days. (b) Calculate the corrected count rate after 11.4 days. (c) Find the time taken for the corrected count rate to fall to 75 counts/min.

Question 11 The corrected count rate from a sample of an unknown isotope falls from 480 counts/min to 60 counts/min in 30 hours. Determine the half-life of the isotope, showing how many half-lives have passed.

Question 12 A piece of ancient wood has a carbon-14 level equal to 12.5% of the level in living wood. The half-life of carbon-14 is 5 730 years. (a) Find how many half-lives have passed since the wood was living. (b) Calculate the age of the wood. (c) State one assumption this calculation makes about the carbon-14 in the sample.

Question 13 A student says: "If I watch one particular atom of iodine-131, I can work out exactly when it will decay, because I know the half-life." Explain what is wrong with this statement, and explain what the half-life does and does not let you predict. Use the coin model from Activity 1 in your explanation.

Question 14 Technetium-99m is the most widely used medical imaging tracer. Its half-life is 6.0 hours. (a) Give one reason the half-life must be long enough to prepare the tracer, inject it and take the image. (b) Give one reason a much longer half-life — say 5.3 years, like cobalt-60 — would make it unsuitable. (c) Give one reason a much shorter half-life — say 10 minutes — would also make it unsuitable.

Question 15 A student measures the background count rate for 5 minutes and obtains 120 counts. (a) Calculate the background count rate in counts/min. (b) A source is then placed near the counter and the reading is 324 counts/min. Calculate the corrected count rate due to the source. (c) Explain why the background count must be subtracted. (d) The student repeats the measurement with the source several times and gets slightly different readings each time. Explain why.

Question 16 A sample of isotope X is measured every 5 minutes. The background count rate is 20 counts/min.

Time (min)	0	5	10	15	20
Measured count rate (counts/min)	500	260	140	80	50

(a) Copy the table and add a row of corrected count rates.
(b) Determine the half-life of isotope X.
(c) Predict the measured count rate at 25 minutes.
(d) Explain why readings taken after about 30 minutes become hard to interpret.
(e) State one way the student could improve the reliability of each reading.

Answers

Question 1 (a) 92; (b) 143 and 146; (c) same protons, different neutrons; (d) same proton number. **Question 2** (a) alpha: 2 protons + 2 neutrons, positive; beta: fast electron, negative; gamma: high-energy electromagnetic wave, none; (b) alpha; (c) gamma; (d) alpha. **Question 3** (a) see solution; (b) 1/2, 1/4, 1/16; (c) 100 counts/min. **Question 4** (a) 1/2, 1/4; (b) 12 hours; (c) about 6%; (d) see solution. **Question 5** (a) (i) cobalt-60, (ii) technetium-99m, (iii) americium-241, (iv) iodine-131; (b) it penetrates metal; (c) see solution. **Question 6** (a) time, distance, shielding; (b) see solution; (c) see solution; (d) see solution. **Question 7** (a) carbon-12: 6 p, 6 n; carbon-14: 6 p, 8 n; (b) same electrons; (c) electrons for chemistry, nucleus for decay; (d) nitrogen. **Question 8** (a) 86 p, 136 n; (b) 2 p, 2 n; (c) 84 p, 134 n; (d) see solution. **Question 9** (a) it changes into a proton and an electron is emitted; (b) see solution; (c) 54. **Question 10** (a) 300 counts/min; (b) 75 counts/min; (c) 11.4 days. **Question 11** 10 hours. **Question 12** (a) 3; (b) 17 190 years; (c) see solution. **Question 13** see solution (decay of a single atom is random; half-life predicts large samples only). **Question 14** (a)–(c) see solution. **Question 15** (a) 24 counts/min; (b) 300 counts/min; (c) see solution; (d) decay is random. **Question 16** (a) 480, 240, 120, 60, 30; (b) 5.0 minutes; (c) 35 counts/min; (d) see solution; (e) see solution.

Fully-worked solutions

Question 1 (a) The atomic number is the proton number, so **both isotopes have 92 protons**. (b) Neutrons = mass number − protons. Uranium-235: 235 − 92 = **143 neutrons**. Uranium-238: 238 − 92 = **146 neutrons**. (c) The two nuclei have the **same number of protons** (92) but **different numbers of neutrons** (143 and 146), so they have different mass numbers. (d) An element is defined by its proton number. Both nuclei have 92 protons, so both are atoms of uranium.

Question 2 (a)

Type	What it is	Charge
alpha	a cluster of 2 protons and 2 neutrons	positive
beta	a fast-moving electron	negative
gamma	a high-energy electromagnetic wave	none (no charge)

(b) **Alpha** radiation is stopped by a sheet of paper.
(c) **Gamma** radiation is reduced by thick lead but is never completely stopped.
(d) **Alpha** radiation is the most ionising.

Question 3 (a) The **half-life** of a radioisotope is the time taken for half of the nuclei in a sample to decay — equivalently, the time for the count rate to fall to half its value. (b) After 8.0 days (one half-life): **1/2**. After 16 days (two half-lives): **1/4**. After 32 days (four half-lives): 1/2 × 1/2 × 1/2 × 1/2 = **1/16**. (c) 16 days is two half-lives, so the corrected count rate halves twice: 400 → 200 → **100 counts/min**.

Question 4 (a) After one half-life: **1/2**. After two half-lives: **1/4**. (b) One quarter = 1/2 × 1/2, which is two half-lives: 2 × 6.0 h = **12 hours**. (c) Reading the decay-curve figure at four half-lives gives about **6%** (6.25%). (d) Each half-life halves what remains; halving never produces zero, so the amount keeps getting smaller without ever quite disappearing. In practice the sample eventually contains so few undecayed nuclei (and such a low count rate) that it cannot be told apart from the background radiation.

Question 5 (a) (i) checking welds — **cobalt-60**; (ii) imaging organs with a tracer — **technetium-99m**; (iii) smoke-detector source — **americium-241**; (iv) treating thyroid disease — **iodine-131**. (b) Gamma radiation **penetrates metal**, so it can pass through a weld to a detector on the other side, and a fault inside the weld changes how much gets through. (c) Any one of: the patient's exposure to radiation would continue for years, giving a far larger total dose; the tracer would still be highly radioactive long after the scan was finished, creating a disposal and safety problem. A half-life of hours means most of the activity is gone within a day.

Question 6 (a) **Time, distance and shielding.** (b) Lead is dense and absorbs radiation strongly, so a lead-lined container keeps the radiation from the source away from anyone nearby while it is stored. (c) Alpha radiation is the most ionising but the least penetrating. Outside the body it is stopped by the outer layer of dead skin, so it does little harm. Inside the body there is no dead skin to stop it: the alpha source sits directly against living tissue and ionises it, doing much more damage. (d) Sources are handled only by teachers, as sealed sources, under a risk assessment; students' own investigation data come from the safe, ever-present background radiation.

Question 7 (a) Carbon-12: **6 protons and 6 neutrons**. Carbon-14: **6 protons and 8 neutrons**. (b) Both have 6 protons, so neutral atoms of both have 6 electrons in the same arrangement. Chemical behaviour depends on the electrons, so the two isotopes react alike. (c) The **electrons** control chemical behaviour; the **nucleus** is the part involved in radioactive decay. The nucleus of carbon-14 is unstable; its electrons are no different from carbon-12's. (d) One neutron becomes a proton, so the nucleus gains one proton: 6 + 1 = 7 protons. The element with 7 protons is **nitrogen** (nitrogen-14, which is stable).

Question 8 (a) Radon-222 has 86 protons; neutrons = 222 − 86 = **136 neutrons**. (b) An alpha particle is 2 protons and 2 neutrons, so it carries away **2 protons and 2 neutrons**. (c) Protons: 86 − 2 = **84**. Neutrons: 136 − 2 = **134**. (Check: 84 + 134 = 218, the mass number of polonium-218.) (d) The identity of an element is fixed by its proton number. The nucleus lost 2 protons, so its proton number fell from 86 (radon) to 84 (polonium): the atom is a different element.

Question 9 (a) One **neutron changes into a proton**, and an electron (the beta particle) is created and thrown out of the nucleus. (b) The total number of protons and neutrons is unchanged: one neutron was lost but one proton was gained, so the mass number stays at **131**. The proton number, however, rose by one, which is why the element changes. (c) The nucleus gained one proton: 53 + 1 = **54 protons**.

Question 10 (a) After one half-life the corrected count rate halves: **300 counts/min**. (b) 11.4 days ÷ 3.8 days = 3 half-lives. Halve three times: 600 → 300 → 150 → **75 counts/min**. (c) From 600 to 75 counts/min is 600 → 300 → 150 → 75, three halvings, so the time is 3 × 3.8 days = **11.4 days**.

Question 11 Count the halvings from 480 to 60 counts/min: 480 → 240 → 120 → 60. That is **3 half-lives**, and they took 30 hours in total. One half-life is 30 ÷ 3 = **10 hours**.

Question 12 (a) 12.5% = 1/8 = 1/2 × 1/2 × 1/2, so **3 half-lives** have passed. (b) Age = 3 × 5 730 years = **17 190 years**. (c) Any one of: the carbon-14 level in living material when the tree died was the same as today's level; the sample has gained no carbon-14 and lost none except by decay (no contamination); the half-life is constant.

Question 13 The statement is wrong because radioactive decay is **random for a single atom**: no measurement, including knowing the half-life, can say when one particular nucleus will decay. The half-life is a statement about a **large sample**: in any one half-life, half of the very many nuclei will decay on average. It lets you predict the fraction of a sample that remains after a given time, or how the count rate falls — never the fate of one atom. In the coin model, knowing that about half the coins land heads on each throw tells you roughly how many coins will remain, but it does not tell you which coin comes up heads next, or when a particular coin will be removed.

Question 14 (a) The tracer must still be radioactive when the scan is taken. If the half-life were too short, the isotope would decay away before it reached the organ and the camera could not collect enough radiation to form an image. (b) With a half-life of years, the patient would remain significantly radioactive for years, receiving a far larger total radiation dose than necessary — the dose should end soon after the scan is done. (c) With a half-life of 10 minutes, most of the tracer would decay during preparation and injection, before any image could be taken; too little would reach the organ to be useful.

Question 15 (a) 120 counts ÷ 5 minutes = **24 counts/min**. (b) Corrected rate = 324 − 24 = **300 counts/min**. (c) The counter always detects the background radiation as well as the source. Only the difference between the two readings is due to the source itself, so the background must be subtracted to find the source's true count rate. (d) Radioactive decay is random, so the number of decays detected in any one minute varies a little from minute to minute, even when nothing about the source or the setup changes. The background radiation varies randomly for the same reason.

Question 16 (a) Subtract the background of 20 counts/min from each reading:

Time (min)	0	5	10	15	20
Measured count rate (counts/min	500	260	140	80	50

Time (min)	0	5	10	15	20
Corrected count rate (counts/min)	480	240	120	60	30

(b) The corrected rate halves every 5 minutes: 480 → 240 → 120 → 60 → 30. The half-life is **5.0 minutes**.

(c) After one more half-life the corrected rate halves from 30 to 15 counts/min. Adding the background gives a measured rate of 15 + 20 = **35 counts/min**.

(d) After about 30 minutes the corrected count rate is near the size of the background count rate itself. The measured reading is then almost all background, and random fluctuations in the background become as large as the signal from the sample, so the sample's own count rate can no longer be read reliably.

(e) Any one of: repeat each reading several times and take the mean; count for longer than 1 minute each time (a longer counting time smooths out the random variation); measure the background several times and use its mean.

Where this leads: Subtopic 10B is the qualitative version of the nuclear content of VCE Physics Unit 1, Area of Study 2 ("How is energy from the nucleus utilised?"), reference-only for this book. VCE Physics adds nuclear equations and binding energy, which are not taught here (TOC D9); a student who can describe alpha, beta and gamma decay in words and particle counts, and can move from a half-life and an elapsed time to a remaining fraction by repeated halving, arrives with exactly the base that work assumes. The repeated-halving skill also underpins any later radiometric-dating question, and the scientific-notation practice with half-life timescales (Maths interlock `VC2M9M02`) is the same deep-time numeracy that Subtopic 9B draws on for the fossil record and Subtopic 13A for the scales of the universe. Within this chapter, Subtopic 10A delivers the other limb of `VC2S10U06` (the changing model of the atom and its particles), and Subtopic 10C uses the electron-shell model that isotope chemistry relies on.

The periodic table: groups, periods, electron shells, and trends in metallic character, atomic size and reactivity

Chapter 10 — Chemical sciences A: atoms, isotopes and the periodic table (Science, Levels 9 and 10)

Subtopic 10C · VC2 Science Understanding — Chemical sciences

CD code: `VC2S10U07` (delivered whole by this subtopic) **Content description (verbatim):** "the organisation of the elements in the periodic table is related to the structure and properties of atoms; patterns and trends include the significance of rows and periods, metallic and non-metallic properties, atomic size and reactivity" **Elaboration ids drawn on:** `VC2S10U07.E01` · `VC2S10U07.E02` · `VC2S10U07.E03` · `VC2S10U07.E04` · `VC2S10U07.E05` · `VC2S10U07.E06` (all six elaborations of this CD; none is withheld under the TOC's D10 ICIP decision) **Achievement standard (extract served):** "They describe patterns and trends in the periodic table." Subtopics 10A and 10B in this chapter deliver the split CD `VC2S10U06`: the changing model of the atom and its particles (10A), and isotopes, natural radioactive decay and half-life (10B).

Theory

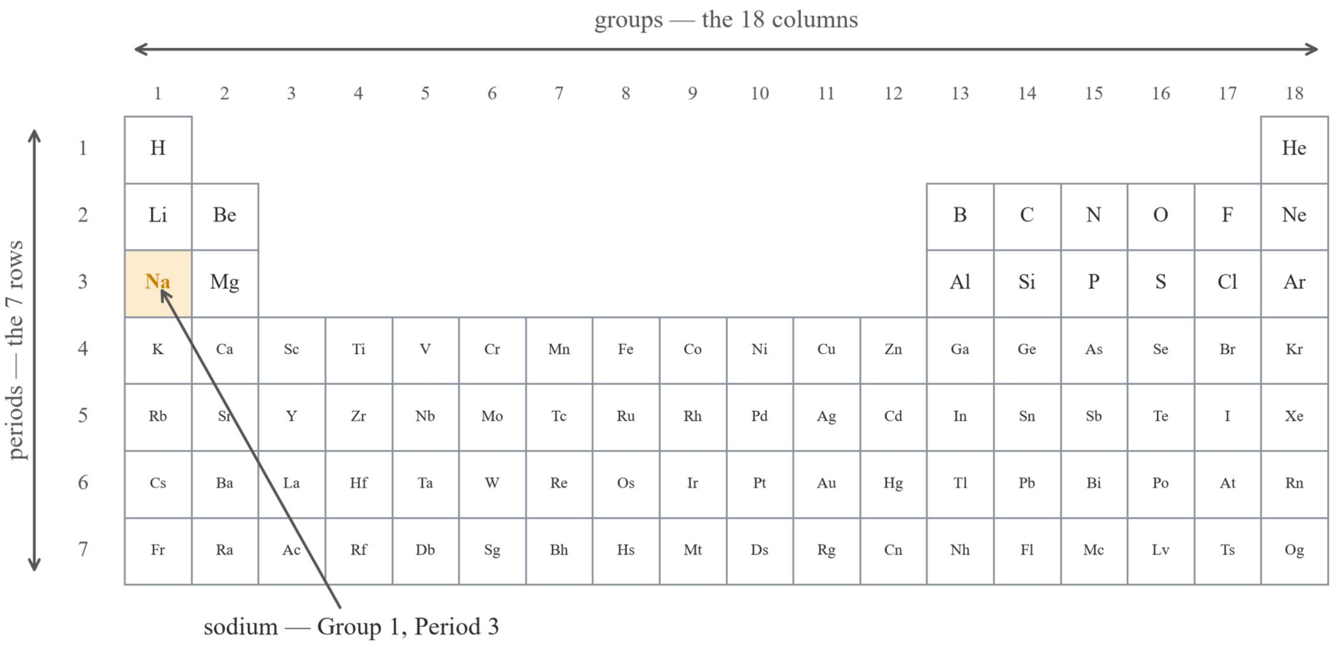
What the table is made of. In Subtopic 10A you met the modern picture of the atom: a tiny, dense nucleus of protons and neutrons, with electrons moving around it. Every atom of a given element has the same number of protons, and that number is the element's **atomic number**. An **element** is a substance made of only one kind of atom. More than a hundred elements are now known, and every one of them has a square in the **periodic table**.

The periodic table is not just a list. It is an organised table in which the position of an element tells you about the structure of its atoms — and the structure of its atoms tells you how the element behaves. That is the big idea of this subtopic.

How the table is organised (elaboration `VC2S10U07.E01`). The elements are arranged in order of increasing atomic number, from hydrogen (atomic number 1) at the top-left corner onward. The table has two directions, and you need to read both:

- The **periods** are the rows. The table has seven periods. Period 1 contains only hydrogen and helium; Periods 2 and 3 each contain eight elements; the later periods are longer.
- The **groups** are the columns. The table has eighteen groups, numbered 1 to 18. Elements in the same group have very similar chemical properties — you will see below why.

Reading the table is a two-direction skill. To describe any element completely you give **both** its group (column) and its period (row), just as you need both coordinates to locate a point on a grid. Sodium sits in Group 1 and Period 3; that pair of numbers, as you will see, encodes the arrangement of sodium's electrons.

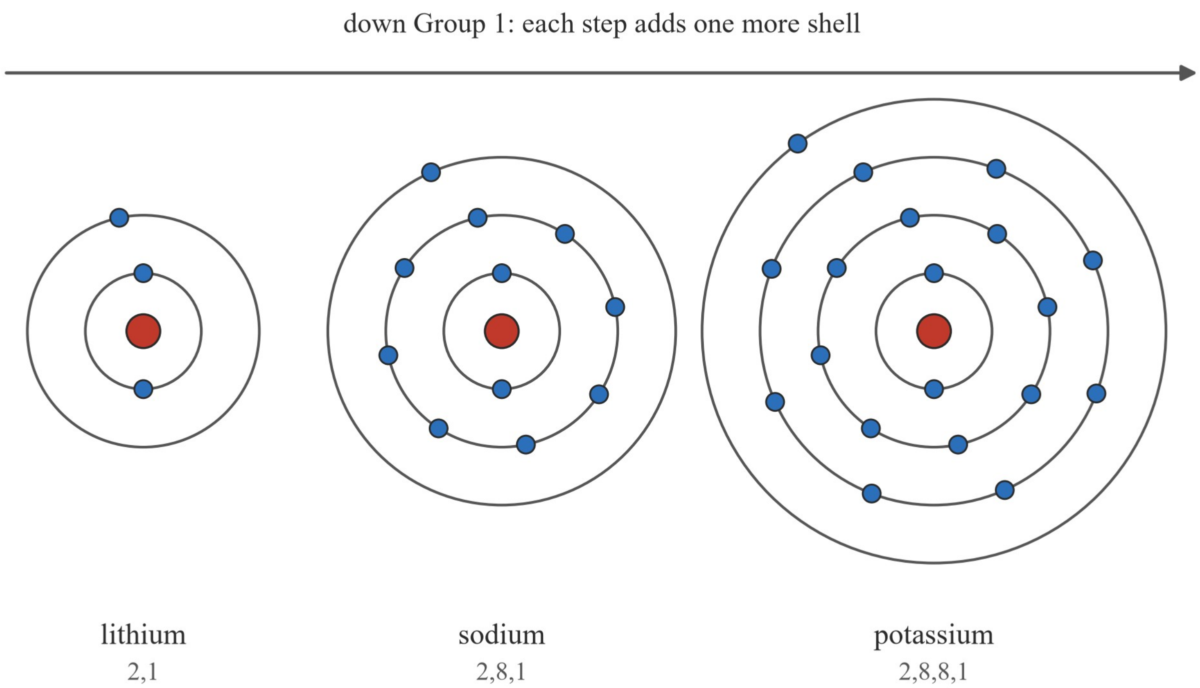


Outline of the periodic table drawn as a grid, with the eighteen group columns numbered across the top and the seven period rows numbered down the side, and sodium highlighted in Group 1, Period 3.

Electron shells — the Bohr model (elaboration `VC2S10U07.E04`). In this subtopic we describe atoms using the **Bohr model**, in which electrons occupy **shells** around the nucleus. A shell is a region at a certain distance from the nucleus that can hold up to a fixed number of electrons. The shells fill from the inside out:

- the first shell (closest to the nucleus) holds up to **2** electrons;
- the second shell holds up to **8** electrons;
- the third shell also holds up to **8** electrons for the first twenty elements.

An electron arrangement is written as a list of the numbers of electrons in each occupied shell, starting from the nucleus. For example, an atom with arrangement **2,8,1** has two electrons in the first shell, eight in the second and one in the third.



Bohr models of three Group 1 atoms side by side: lithium with two shells holding 2,1 electrons, sodium with three shells holding 2,8,1, and potassium with four shells holding 2,8,8,1, each step down adding one shell.

Here are the first twenty elements with their electron arrangements:

Element	Symbol	Atomic number	Electron arrangement	Group	Period
Hydrogen	H	1	1	1	1
Helium	He	2	2	18	1
Lithium	Li	3	2,1	1	2
Beryllium	Be	4	2,2	2	2
Boron	B	5	2,3	13	2
Carbon	C	6	2,4	14	2
Nitrogen	N	7	2,5	15	2
Oxygen	O	8	2,6	16	2
Fluorine	F	9	2,7	17	2
Neon	Ne	10	2,8	18	2
Sodium	Na	11	2,8,1	1	3
Magnesium	Mg	12	2,8,2	2	3
Aluminium	Al	13	2,8,3	13	3
Silicon	Si	14	2,8,4	14	3
Phosphorus	P	15	2,8,5	15	3
Sulfur	S	16	2,8,6	16	3
Chlorine	Cl	17	2,8,7	17	3
Argon	Ar	18	2,8,8	18	3
Potassium	K	19	2,8,8,1	1	4
Calcium	Ca	20	2,8,8,2	2	4

(For helium the single, full first shell of 2 electrons counts as a full outer shell, even though 8 electrons fill the outer shells of the larger noble gases.)

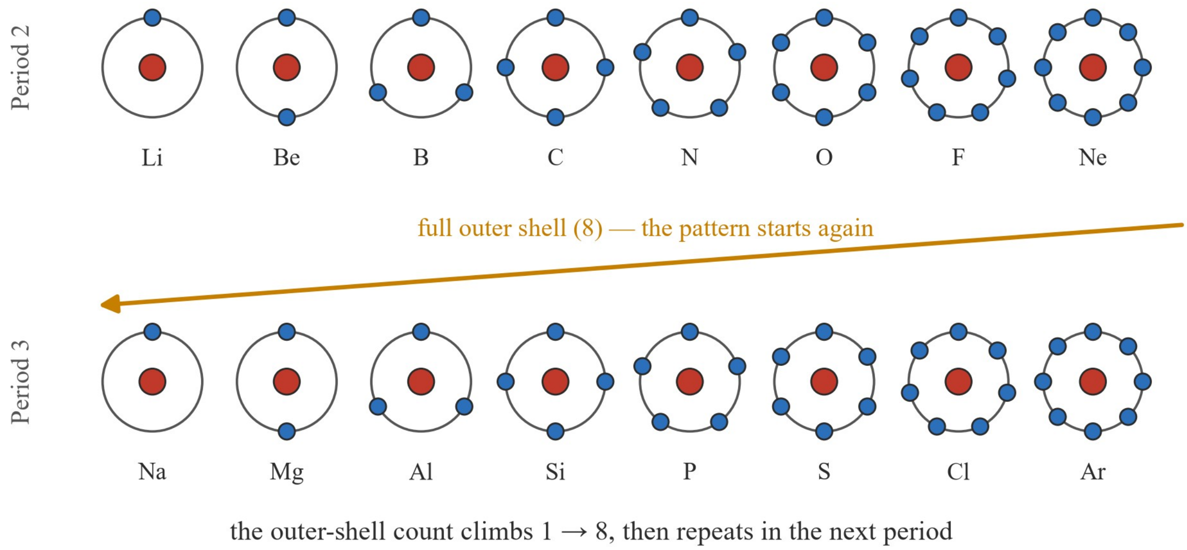
Position tells you structure. Look carefully at the table above and two rules emerge:

- **The group number tells you the number of electrons in the outer shell** (this rule holds for Groups 1, 2 and 13 to 18). Every Group 1 element — lithium, sodium, potassium — has exactly one outer electron. Every Group 17 element has seven. The Group 18 elements have full outer shells: 2 for helium and 8 for neon and argon.
- **The period number tells you the number of occupied shells.** Every Period 2 element has two shells; every Period 3 element has three shells.

So the pair "Group 1, Period 3" fixes sodium's electron arrangement completely: one outer electron (Group 1) on three shells (Period 3) gives 2,8,1 — eleven electrons, and therefore eleven protons, atomic number 11. The table has stored the atom's structure for you.

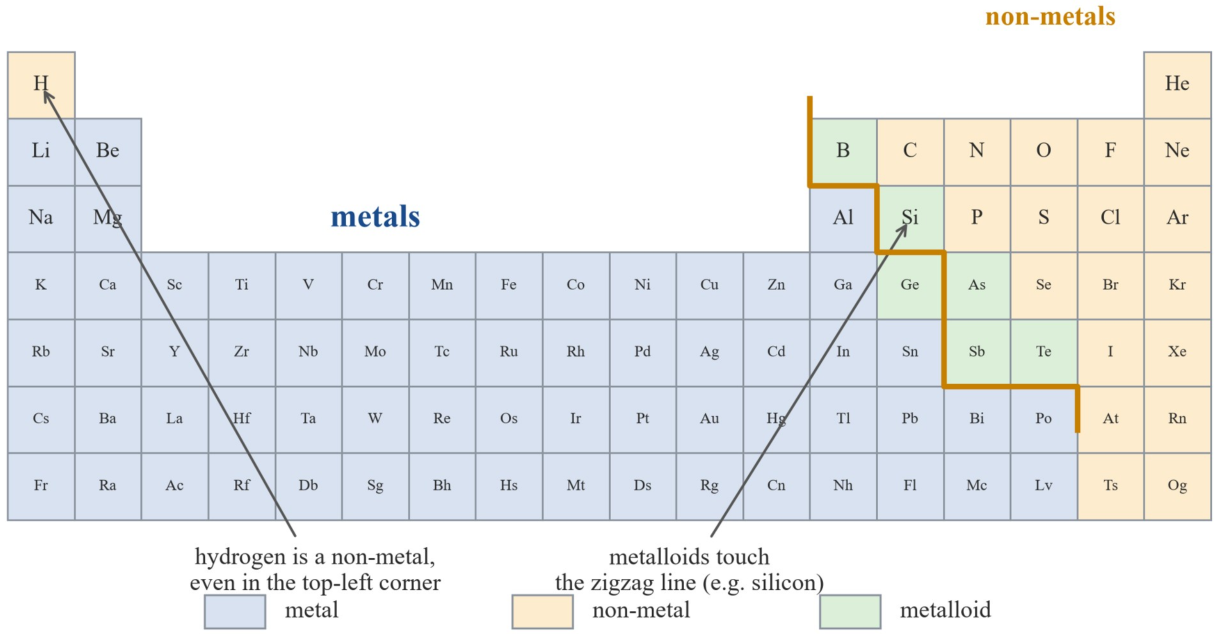
The electrons in the outer shell are the ones that take part in chemical reactions, so they matter most for how an element behaves.

Why whole groups behave alike (elaboration `VC2S10U07.E05`). Here is the deduction that ties the table together. Moving across a period, each element adds one electron to the same outer shell, so the outer-shell count rises 1, 2, 3, … until the shell is full. At the next period, the pattern starts again with one electron in a new outer shell. That means the outer-shell electron arrangement **repeats periodically** — and the chemical behaviour of the elements repeats with it. Elements in the same group have the same number of outer electrons, so they react in similar ways. The repeating pattern of properties in the table reflects the repeating pattern of electrons in outer shells.



Two rows of small atoms showing outer-shell electrons: Period 2 climbs from one outer electron to eight, then Period 3 starts again at one and climbs to eight, so the pattern repeats.

Metals and non-metals (elaboration `VC2S10U07.E03`). Most elements are metals. The **metals** fill the left side and centre of the table. The **non-metals** sit on the right, with hydrogen as an exception in the top-left corner. A zigzag line runs between the two families, from boron down toward the bottom-right. The elements that touch this line, such as silicon, have a mix of metal-like and non-metal-like properties; they are called **metalloids** (defined here as elements whose properties sit between those of metals and non-metals).



Periodic table shaded to show metals on the left and in the middle, non-metals on the right, and the zigzag line of metalloids between them, with hydrogen marked as a non-metal exception at the top left.

You can sort samples in the laboratory using physical properties:

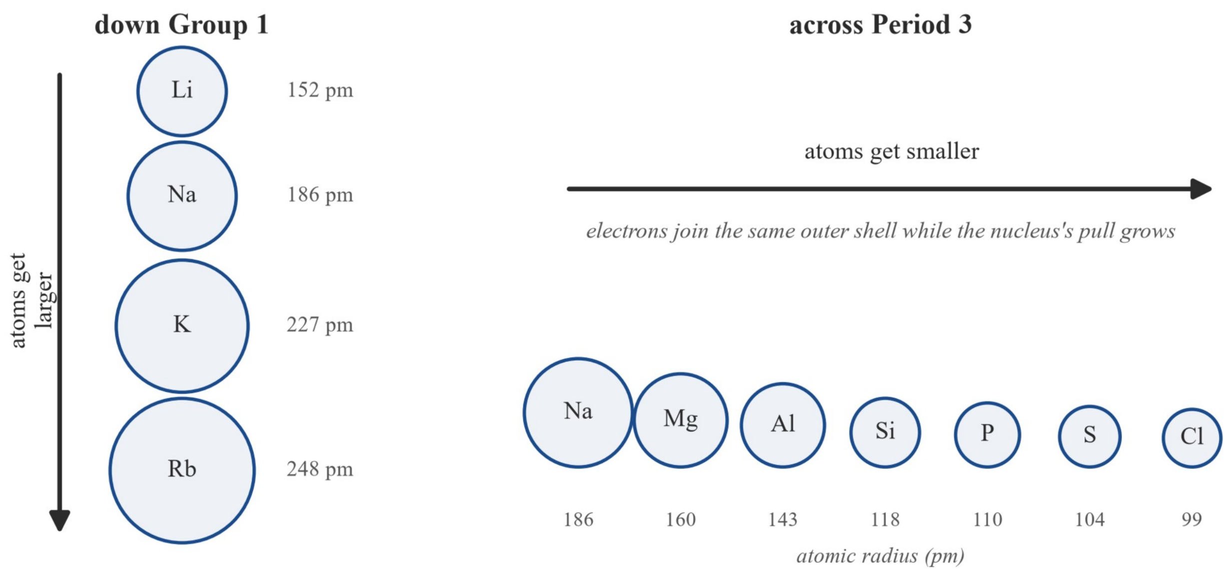
Property	Typical metals	Typical non-metals
Appearance (fresh surface)	shiny (lustrous)	dull, if solid
State at room temperature	solid (except mercury, a liquid)	several are gases; bromine is a liquid
Conduction of heat and electricity	good conductors	poor conductors (insulators); graphite is an exception — it conducts
When hammered or bent	malleable — can be shaped without breaking	brittle — a solid non-metal snaps or shatters
Density	usually high	usually low

These properties follow from the atoms, but at this level the practical test is the point: appearance, conduction and behaviour when hit are quick ways to classify an unknown sample.

Chemically, the two families behave in opposite ways. **Metals tend to lose their outer electrons when they react**; **non-metals tend to gain or share electrons**. That is why Group 1 metals are so eager to react (one outer electron is easy to lose) and why Group 17 non-metals are so eager to react too (one more electron fills their outer shell).

Trend 1 — atomic size. The size of an atom follows a pattern in both directions of the table:

- **Down a group, atoms get larger.** Each step down adds a whole new shell. Potassium (2,8,8,1) has four shells and is larger than sodium (2,8,1), which has three, which is larger than lithium (2,1), which has two.
- **Across a period, atoms get smaller.** From sodium to chlorine in Period 3, electrons are added to the **same** outer shell while protons are added to the nucleus. The growing positive charge of the nucleus pulls the shells in more strongly, so the atom shrinks as you move left to right. (Noble gases are usually left out of this comparison, because their size is measured in a different way.)

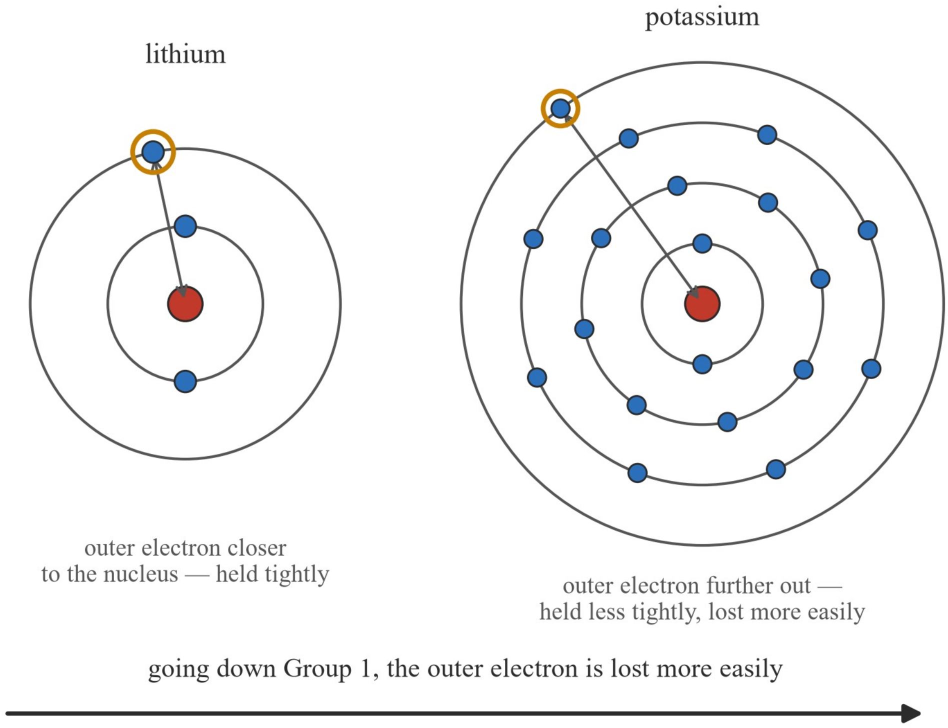


Atomic size trend: down Group 1 the atoms lithium, sodium, potassium and rubidium grow larger, while across Period 3 from sodium to chlorine the atoms grow smaller.

Trend 2 — metallic character. Metallic character means how strongly an element shows the properties of metals. It too follows both directions:

- **Down a group, metallic character increases.** In Group 14, carbon at the top is a non-metal, silicon in the middle is a metalloid, and tin and lead at the bottom are true metals.
- **Across a period, metallic character decreases.** Period 3 shows the whole journey: sodium, magnesium and aluminium are metals; silicon is a metalloid; phosphorus, sulfur and chlorine are non-metals; argon is a noble gas.

Both trends have the same root cause: how strongly the nucleus holds the outer electrons. Down a group the outer electrons sit in higher shells, further from the nucleus, and are held less tightly — which is what makes an element behave more like a metal.



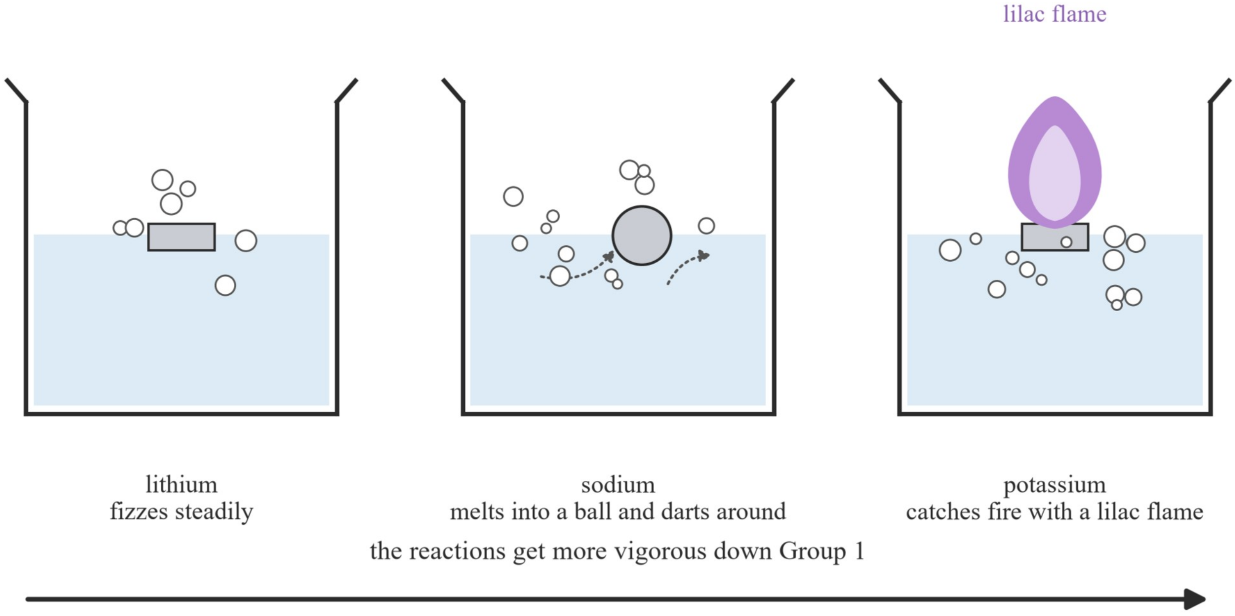
Two Bohr models comparing lithium and potassium: potassium's outer electron sits in a higher shell further from the nucleus, so it is held less tightly and lost more easily.

Trend 3 — reactivity (elaboration `VC2S10U07.E02`). Reactivity means how easily an element reacts. The clearest patterns are in Groups 1 and 17.

Group 1 — the alkali metals. Lithium, sodium and potassium are soft metals that can be cut with a knife. They react with water to form the metal hydroxide and hydrogen gas:

sodium + water → sodium hydroxide + hydrogen

The reactions get more vigorous going down the group. Lithium fizzes steadily on the water's surface. Sodium reacts faster, melts into a ball and darts around. Potassium reacts faster still and catches fire with a lilac flame. The reason comes from the shells: going down the group, the single outer electron sits in a higher shell, further from the nucleus, so it is held less tightly and lost more easily — and losing that electron is what the reaction is about. This is the same shell argument as the atomic-size trend, applied to how fast a reaction goes.



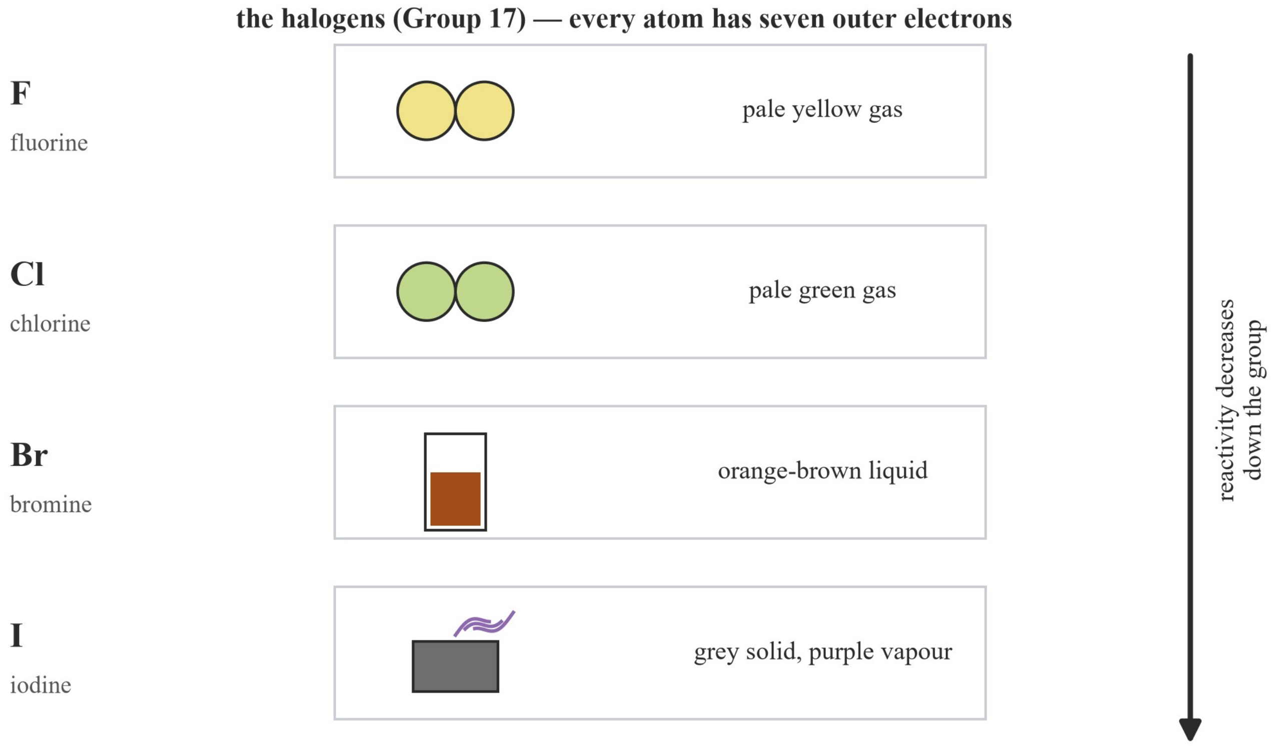
Three beakers of water: lithium fizzes steadily on the surface, sodium melts into a ball and darts around, and potassium catches fire with a lilac flame, with a label showing the reactions get more vigorous down Group 1.

Because they react with air and water, lithium, sodium and potassium are stored under oil. With oxygen they form oxides, so a freshly cut surface tarnishes within seconds. With dilute acids they react violently, so in the school laboratory alkali metals are handled only by a teacher, in tiny pieces, with eye protection.

Group 17 — the halogens. Fluorine, chlorine, bromine and iodine are non-metals with seven outer electrons. They react easily with metals; for example,

sodium + chlorine → sodium chloride

The halogens get **less** reactive going down the group — the opposite of Group 1. Fluorine is the most reactive, then chlorine (a pale green gas), bromine (an orange-brown liquid) and iodine (a grey solid that gives a purple vapour when heated). A halogen reacts by drawing an electron into its outer shell; going down the group the outer shell is further from the nucleus, so an incoming electron is attracted less strongly and the reaction is harder.



The halogens down Group 17: fluorine a pale yellow gas, chlorine a pale green gas, bromine an orange-brown liquid and iodine a grey solid giving a purple vapour, with an arrow showing reactivity decreases down the group.

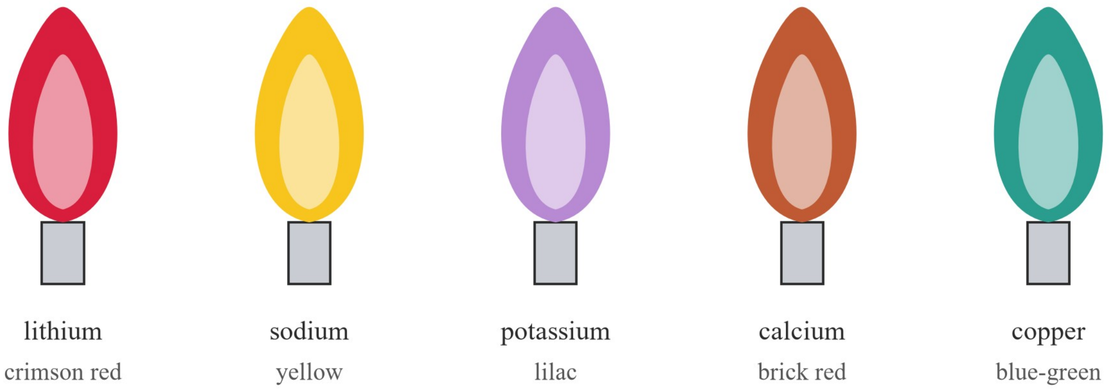
Group 18 — the noble gases. Helium, neon and argon have full outer shells. A full outer shell is a very stable arrangement, so the noble gases are almost completely unreactive. That unreactiveness is exactly what makes them useful: helium lifts balloons without any risk of burning, argon fills light bulbs to protect the hot wire from reacting, and neon gives a red-orange glow in display tubes when electricity passes through it.

Reactions with oxygen and with acids show the same idea of comparing reactivities. Magnesium burns in oxygen with a dazzling white flame to form magnesium oxide, while copper reacts with oxygen only slowly. Magnesium fizzes rapidly in dilute hydrochloric acid, zinc fizzes steadily, iron reacts slowly, and copper shows no reaction at all. Each comparison sorts the elements by how easily they give up electrons.

Flame tests and emission spectra (elaboration `VC2S10U07.E06`). When a sample containing a metal is heated strongly in a flame, the flame takes on a colour that depends on the metal:

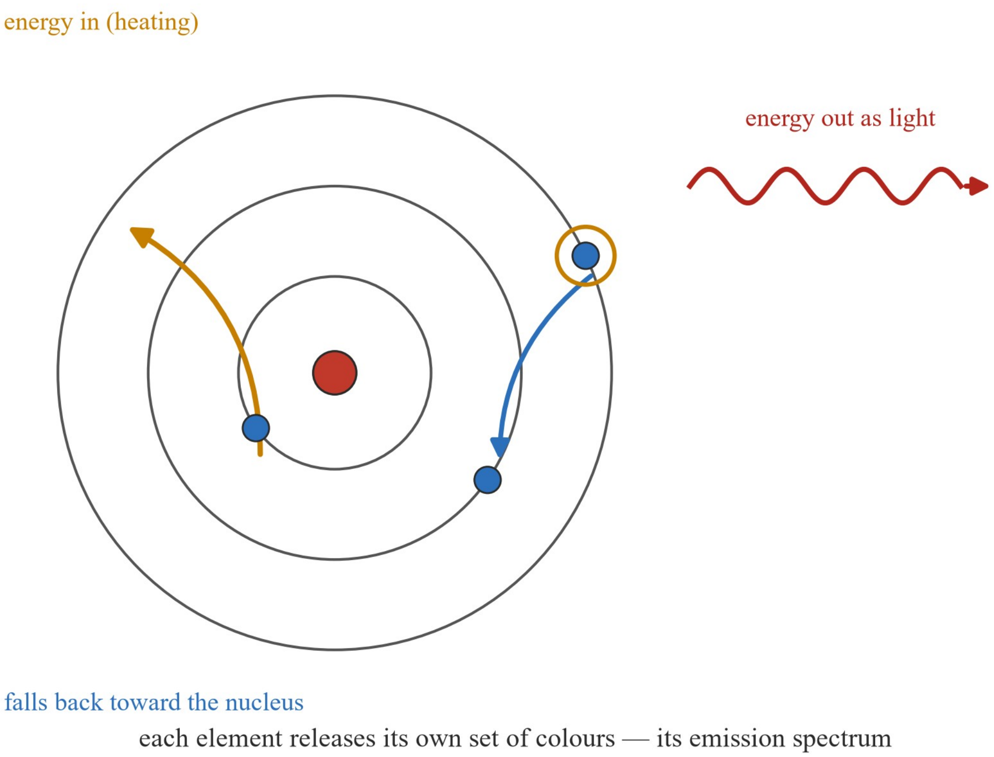
Element	Flame colour
Lithium	crimson red
Sodium	yellow
Potassium	lilac
Calcium	brick red
Copper	blue-green

Each metal gives the flame its own colour



Five flame test colours: lithium crimson red, sodium yellow, potassium lilac, calcium brick red and copper blue-green.

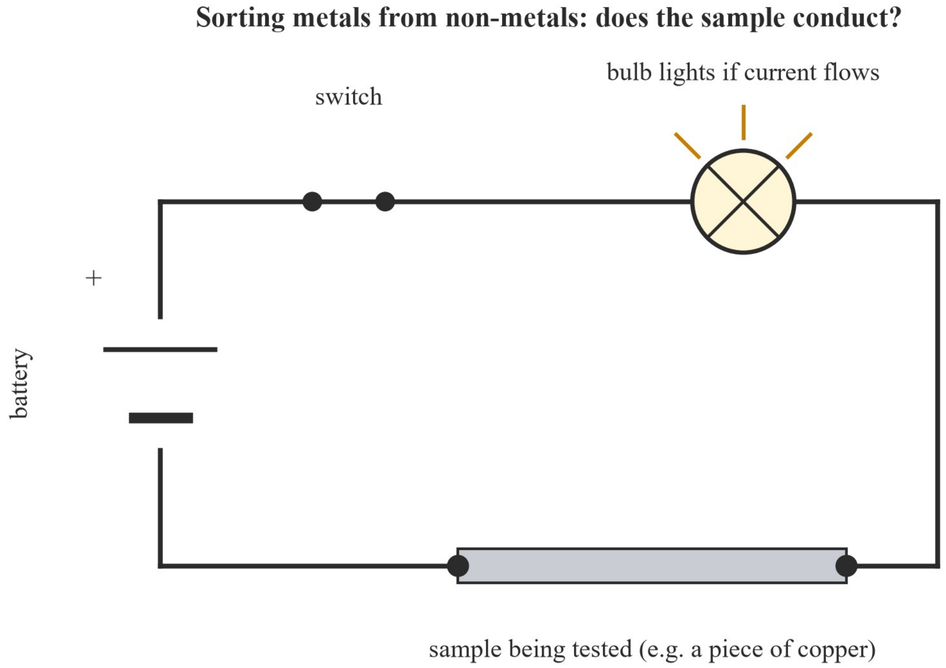
The Bohr model explains the colours. Heating gives energy to the electrons, and an electron moves outward, for a short time, to a higher shell. It does not stay there: it falls back toward the nucleus and releases the energy it gained as light. Each element releases its own set of colours, because each element has its own shell arrangement. The pattern of colours is the element's **emission spectrum**, and it acts like a fingerprint — no two elements share the same one. In the 1860s the chemists Robert Bunsen and Gustav Kirchhoff used flame colours and spectra to identify new elements, including caesium and rubidium. The same idea is used on a much larger scale in Subtopic 13A: astronomers read the spectra of starlight to work out which elements stars are made of.



Bohr model of an atom with an electron moving up to a higher shell when heated, then falling back toward the nucleus and releasing the gained energy as light.

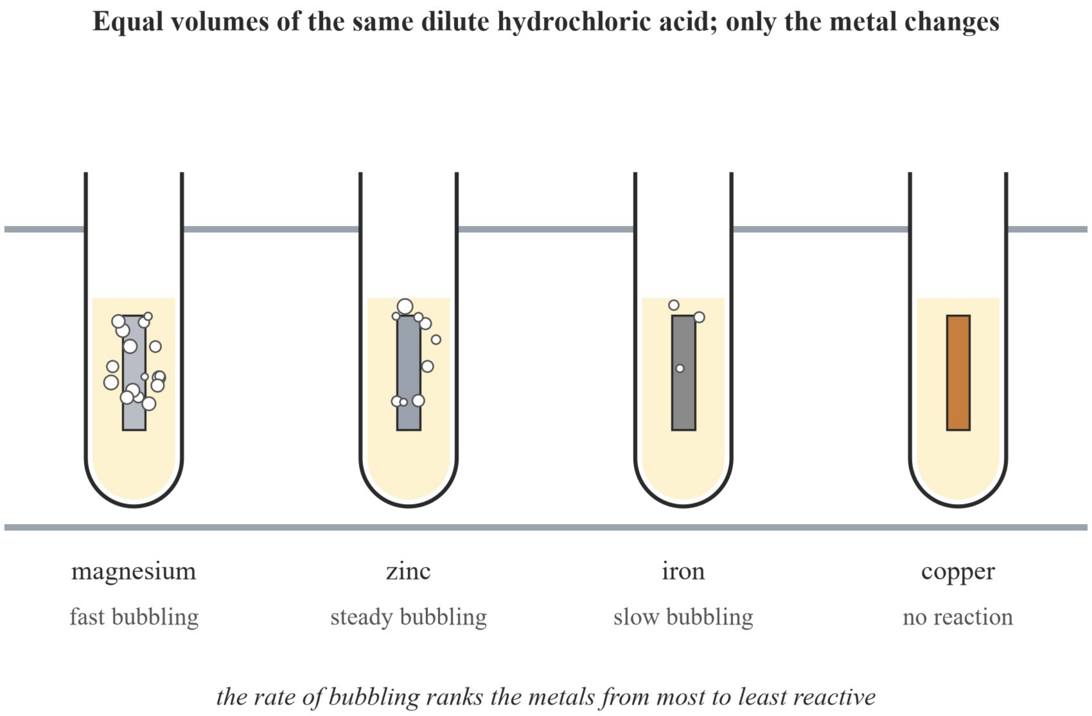
Activities

Activity 1 — Metals or non-metals? (elaboration `VC2S10U07.E03`). Set out samples: a piece of copper, aluminium foil, an iron nail, a lump of sulfur, and a piece of charcoal or graphite. For each sample, record (i) whether a freshly cleaned surface is shiny or dull, (ii) whether it conducts electricity, using a simple circuit of a battery, wires, a switch and a bulb, and (iii) what happens when it is gently tapped with a hammer — does it flatten, bend, snap or crumble? Sort the samples into metals and non-metals from your results, and say which sample did not fit its family's pattern and how. (Graphite is the classic trap: a non-metal that conducts.) Wear eye protection when tapping samples, and do not taste anything in the laboratory.



Labelled sketch of a simple circuit with a battery, switch, bulb and a gap holding the sample being tested, the bulb lighting when the sample conducts electricity.

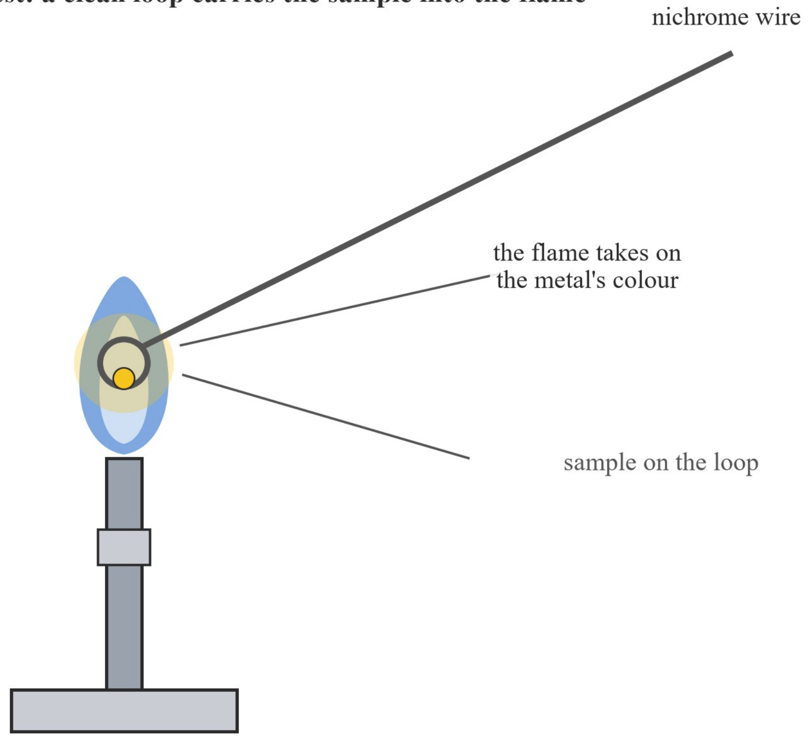
Activity 2 — Comparing how easily metals react (elaboration `VC2S10U07.E02`). Place equal volumes of the same dilute hydrochloric acid into four test tubes in a rack. Add a strip of magnesium to one, a strip of zinc to one, a cleaned iron nail to one and a piece of copper wire to one. Observe the rate of bubbling in each tube and rank the four metals from most to least reactive. Collect any gas given off and test it with a lighted splint — a pop identifies hydrogen. To make the comparison a fair one, keep every variable the same except the metal: same acid, same volume and concentration, same temperature, and strips of about the same size and surface. Wear eye protection; dilute acid is an irritant, and the teacher should prepare it following Science ASSIST (ASTA) safety guidance. The alkali metals react far too violently with water and dilute acids for student handling; reactions of lithium, sodium and potassium are teacher demonstrations only.



Four test tubes of dilute hydrochloric acid with metals added: magnesium bubbling fast, zinc bubbling steadily, iron bubbling slowly and copper showing no reaction.

Activity 3 — Flame tests (elaboration `VC2S10U07.E06`). Teacher-led. A nichrome wire loop is dipped in concentrated hydrochloric acid, heated in a blue Bunsen flame until it gives no colour, then dipped into a sample and returned to the flame. Test solutions containing lithium, sodium, potassium, calcium and copper in turn and record the colour each one gives. Note how briefly the colour appears and why the loop must be cleaned between samples — a trace of sodium, with its strong yellow flame, can hide another element's colour. State which colour would let you identify an unknown sample, and why each element gives its own colour, in terms of electrons and shells.

Flame test: a clean loop carries the sample into the flame



Labelled sketch of a flame test: a nichrome wire loop holding a sample is placed in the blue flame of a Bunsen burner, which colours the flame.

Worked examples

Example 1 — scaffolded

An atom has atomic number 11. (a) Write its electron arrangement. (b) State its group and period in the periodic table. (c) State whether it is a metal or a non-metal, and give one property you would expect the element to show.

Working	Comment
Atomic number 11 → 11 electrons	A neutral atom has the same number of electrons as protons.
Fill shells from the inside: 2, then 8, then the rest	Shell capacities are 2, 8, 8 for the first twenty elements.
Arrangement: **2,8,1**	2 + 8 + 1 = 11 electrons.
1 outer electron → Group 1	The group number gives the outer-shell electron count.
3 shells → Period 3	The period number gives the number of occupied shells.

The element is sodium, a metal. Expected properties (any one): shiny when freshly cut, a good conductor of heat and electricity, soft enough to cut, reacts easily with water.

Example 2 — scaffolded

Element X is in Group 2 and Period 3. (a) Deduce its electron arrangement and its atomic number. (b) Name the element. (c) Predict what you would observe when it reacts with dilute hydrochloric acid, and write a word equation for the reaction.

Working	Comment
Group 2 → 2 outer electrons	Group number = outer-shell electrons.
Period 3 → 3 occupied shells	Period number = number of shells.
Arrangement: **2,8,2**	Fill 2, then 8, then the 2 outer electrons.

Working	Comment
Atomic number = 2 + 8 + 2 = 12	Electrons = protons in a neutral atom.

(a) 2,8,2; atomic number 12. (b) Magnesium. (c) It fizzes as bubbles of hydrogen form; magnesium + hydrochloric acid → magnesium chloride + hydrogen.

Example 3 — unscaffolded

Three Group 1 metals are added to separate beakers of water. Lithium fizzes steadily on the surface. Sodium reacts faster, melts into a ball and darts around. Potassium reacts faster still and catches fire with a lilac flame. (a) State the trend in reactivity shown by these observations. (b) Explain the trend in terms of electron shells. (c) Rubidium sits below potassium in Group 1. Predict how its reaction with water would compare with potassium's. (d) Name the gas produced in all three reactions and describe the test for it.

(a) Reactivity **increases** going down Group 1: lithium is the least reactive of the three and potassium the most.
(b) Each Group 1 atom reacts by losing its single outer electron. Going down the group, that electron occupies a shell further from the nucleus, so the nucleus holds it less tightly and it is lost more easily. The easier the electron is lost, the more vigorous the reaction.
(c) Rubidium should react more vigorously than potassium, because its outer electron is in a higher shell again, even further from the nucleus and held even less tightly.
(d) Hydrogen. Collect the gas and hold a lighted splint to it: hydrogen burns with a pop.

Example 4 — unscaffolded

A technician flame-tests three known solutions and one unknown. Lithium solution gives crimson red, sodium solution gives yellow, potassium solution gives lilac. The unknown solution gives a brick-red flame. (a) Identify the metal in the unknown solution. (b) Explain, using the Bohr model, why heating an atom makes it give out light. (c) Explain why a flame colour can identify an element, while the colour of a solid sample often cannot.

(a) Calcium — brick red is calcium's flame colour.
(b) Heating gives energy to the electrons, moving one outward, for a short time, to a higher shell. When the electron falls back toward the nucleus it releases that energy as light.
(c) Each element has its own shell arrangement, so each releases its own set of colours — its emission spectrum, which is unique like a fingerprint. The colour of a solid sample depends on many other things as well (what the element is combined with, the size and surface of the grains), so it is not a reliable guide to which element is present.

Practice questions

Scaffolded questions

Question 1 The periodic table is a two-direction map. (a) State what property of the atoms the elements are arranged by, in order of increasing value. (b) Give the names of the rows and of the columns of the table. (c) State how many periods and how many groups the table has. (d) State what the period number of an element tells you about its atoms.

Question 2 Write the electron arrangement of each atom, then state its group and period. (a) Nitrogen, atomic number 7. (b) Aluminium, atomic number 13. (c) Chlorine, atomic number 17.

Question 3 A potassium atom has the electron arrangement 2,8,8,1. (a) State the group and period of potassium. (b) State whether potassium is a metal or a non-metal. (c) Predict whether potassium reacts with water more or less vigorously than sodium, and explain your prediction in terms of shells.

Question 4 Physical properties separate metals from non-metals. (a) List three physical properties typical of metals. (b) Explain why copper is used for electrical wiring. (c) Graphite is a form of the non-metal carbon, yet it is used inside electrodes. State the property that allows this. (d) Describe where the metals and the non-metals sit in the periodic table.

Question 5 Atomic size follows a pattern. (a) State the trend in atomic size going down Group 1, and explain it. (b) State the trend in atomic size going across Period 3 from sodium to chlorine, and explain it. (c) Arrange lithium, sodium and potassium in order of increasing atomic size.

Question 6 Flame tests identify metals. (a) Match each element to its flame colour: lithium, sodium, potassium — yellow, lilac, crimson red. (b) Explain, in terms of electrons and shells, why a heated atom gives out light. (c) Explain why the full emission spectrum of an element identifies it more reliably than a single flame colour.

Unscaffolded questions

Question 7 An element has the electron arrangement 2,8,6. State its group and period, name the element, say whether it is a metal or a non-metal, and predict one chemical behaviour you would expect from its position in the table.

Question 8 Element X is in Group 17 and Period 3. Deduce its electron arrangement and atomic number, name it, and predict how its reactivity compares with that of the element directly above it in the group. Explain your answer.

Question 9 Four mystery elements have these electron arrangements: A 2,8,1 · B 2,8,7 · C 2,8,8 · D 2,8,8,1. (a) State which two elements are in the same group, and give the group number. (b) Identify the most reactive metal of the four and explain your choice. (c) Explain why element C is almost completely unreactive. (d) Arrange A, B and D in order of decreasing atomic size, explaining the order.

Question 10 Group 1 metals react violently with water, but noble gases almost never react. Explain the difference, referring to outer electron shells.

Question 11 Metallic character trends. (a) State what "metallic character" means. (b) State the trend in metallic character going down a group and going across a period. (c) In Group 14, carbon is a non-metal while tin and lead are metals. Explain how this fits the trend you stated. (d) Silicon and phosphorus are next to each other in Period 3. State which has the greater metallic character and why.

Question 12 The halogens. (a) State how many outer-shell electrons a halogen atom has. (b) State the trend in reactivity going down Group 17 and explain it in terms of shells. (c) Chlorine, bromine and iodine are each brought near iron wool. Predict which reacts most easily and explain your prediction.

Question 13 Comparing sizes. (a) Which atom is larger, sodium or potassium? Explain. (b) Which atom is larger, sodium or chlorine? Both are in Period 3. Explain.

Question 14 A fireworks maker wants a bright red display and chooses a lithium compound for the red colour. (a) Explain why lithium gives a red flame, in terms of electrons and shells. (b) If the sample were contaminated with sodium, the display would look wrong. State what colour would appear and why flame colour makes the contamination easy to spot.

Question 15 You are asked to find out whether magnesium or zinc reacts more easily with dilute hydrochloric acid. (a) Write an investigable question for this task. (b) Identify the independent variable, the dependent variable, and two variables that must be kept the same. (c) Describe what you would measure or observe to decide which metal is more reactive. (d) State one safety precaution for this investigation and why it is needed.

Question 16 Three metals, P, Q and R, are tested. P gives slow bubbles in dilute hydrochloric acid and no reaction with cold water. Q gives fast bubbles in the acid and reacts slowly with cold water. R reacts vigorously with cold water and catches fire. (a) Rank P, Q and R from most to least reactive. (b) State which of the three could be a Group 1 metal and why. (c) Suggest a possible identity for Q, giving your reasoning. (d) Predict what would happen when P is heated in oxygen.

Answers

Question 1 (a) atomic number; (b) rows = periods, columns = groups; (c) 7 periods, 18 groups; (d) the number of occupied electron shells. **Question 2** (a) 2,5 — Group 15, Period 2; (b) 2,8,3 — Group 13, Period 3; (c) 2,8,7 — Group 17, Period 3. **Question 3** (a) Group 1, Period 4; (b) metal; (c) more vigorous — see solution. **Question 4** (a) any three from shiny, conducting, malleable, high density, solid at room temperature; (b) see solution; (c) it conducts electricity; (d) metals on the left and in the centre, non-metals on the right. **Question 5** (a) increases down the group — see solution; (b) decreases across the period — see solution; (c) lithium, sodium, potassium. **Question 6** (a) lithium — crimson red, sodium — yellow, potassium — lilac; (b) see solution; (c) see solution. **Question 7** Group 16, Period 3; sulfur; non-metal; prediction — see solution. **Question 8** 2,8,7; atomic number 17; chlorine; less reactive than fluorine — see solution. **Question 9** (a) A and D, Group 1; (b) D; (c) full outer shell; (d) D, A, B — see solution. **Question 10** see solution (one outer electron, easy to lose, against a full outer shell). **Question 11** (a) how strongly an element shows the properties of metals; (b) increases down a group, decreases across a period; (c) see solution; (d) silicon. **Question 12** (a) 7; (b) decreases down the group — see solution; (c) chlorine. **Question 13** (a) potassium; (b) sodium — see solution. **Question 14** (a) see solution; (b) yellow; sodium's strong yellow would stand out against the red. **Question 15** (a)–(d) see solution. **Question 16** (a) R, Q, P; (b) R; (c) see solution; (d) see solution.

Fully-worked solutions

Question 1 (a) The elements are arranged in order of increasing **atomic number** (the number of protons in the atom). (b) The rows are **periods**; the columns are **groups**. (c) The table has **7 periods** and **18 groups**. (d) The period number tells you the **number of occupied electron shells** in the atom.

Question 2 Fill shells in the order 2, 8, 8. (a) Nitrogen, 7 electrons: **2,5**. Five outer electrons → **Group 15**; two shells → **Period 2**. (b) Aluminium, 13 electrons: **2,8,3**. Three outer electrons → **Group 13**; three shells → **Period 3**. (c) Chlorine, 17 electrons: **2,8,7**. Seven outer electrons → **Group 17**; three shells → **Period 3**.

Question 3 (a) Arrangement 2,8,8,1: one outer electron → **Group 1**; four shells → **Period 4**. (b) Group 1 elements are the alkali metals, so potassium is a **metal**. (c) Potassium reacts **more vigorously** than sodium. Its outer electron sits in a higher shell, further from the nucleus, so it is held less tightly and lost more easily — and losing that electron is what the reaction with water depends on.

Question 4 (a) Any three of: shiny (lustrous) fresh surface; good conductor of heat and electricity; malleable; usually high density; solid at room temperature (mercury is the exception). (b) Copper is a **good conductor of electricity** and is malleable, so it can be drawn into wires that carry current with little resistance. (c) Graphite **conducts electricity**, which is unusual for a non-metal. (d) Metals fill the **left side and centre** of the table; non-metals sit on the **right-hand side**, with hydrogen as an exception at the top-left. The two families are separated by a zigzag line.

Question 5 (a) Atomic size **increases down Group 1**. Each element adds a new shell: lithium has two shells, sodium three, potassium four, so the outer electrons sit further from the nucleus. (b) Atomic size **decreases across Period 3** from sodium to chlorine. Electrons are added to the same outer shell while protons are added to the nucleus, so the growing positive charge of the nucleus pulls the shells in more strongly. (c) **Lithium, sodium, potassium** — size increases down the group.

Question 6 (a) Lithium — crimson red; sodium — yellow; potassium — lilac. (b) Heating gives energy to the electrons, moving one outward, for a short time, to a higher shell. When it falls back toward the nucleus it releases the energy it gained as light. (c) The spectrum is the element's **complete** set of colours, produced by its particular shell arrangement. Two elements could share one flame colour, but no two elements share the same full pattern, so the spectrum acts like a fingerprint.

Question 7 Arrangement 2,8,6: six outer electrons → **Group 16**; three shells → **Period 3**. With 2 + 8 + 6 = 16 electrons (atomic number 16) the element is **sulfur**, a **non-metal**. As a Group 16 non-metal it tends to gain or share electrons when it reacts; for example, it reacts with oxygen when burned to form sulfur dioxide.

Question 8 Group 17 → 7 outer electrons; Period 3 → 3 shells. Arrangement **2,8,7**; atomic number 2 + 8 + 7 = **17**; the element is **chlorine**. The element directly above it is fluorine. Chlorine is **less reactive** than fluorine: a halogen reacts by drawing an electron into its outer shell, and chlorine's outer shell is further from the nucleus than fluorine's, so an incoming electron is attracted less strongly.

Question 9 (a) A (2,8,1) and D (2,8,8,1) both have one outer electron, so both are in **Group 1**. (b) **D** is the most reactive metal. A and D are the metals (Group 1 atoms lose their single outer electron easily), and D's outer electron is in a higher shell than A's, further from the nucleus and held less tightly, so it is lost more easily. (c) C has the arrangement 2,8,8 — a **full outer shell**. A full outer shell is stable, so the atom has no tendency to lose, gain or share electrons, which is what makes element C (argon) almost completely unreactive. (d) **D, A, B**. D has four shells, so it is largest. A and B both have three shells, but B has more protons pulling on the same shells, so B is smaller than A.

Question 10 A Group 1 metal has **one electron in its outer shell**, and that electron is lost easily in reactions — the easier it is to lose, the more violent the reaction, as the electron moves further from the nucleus down the group. A noble gas has a **full outer shell** (2 for helium, 8 for the others), which is a stable arrangement. With nothing to lose and no need to gain, noble gas atoms have almost no tendency to react at all.

Question 11 (a) Metallic character is how strongly an element shows the properties of metals — shiny appearance, conduction of heat and electricity, and a tendency to lose electrons in reactions. (b) Metallic character **increases down a group** and **decreases across a period** from left to right. (c) Going down Group 14, the outer electrons sit in higher shells, further from the nucleus, and are held less tightly, so they are lost more easily — the elements behave more like metals. Carbon, at the top, holds its outer electrons tightly and is a non-metal; tin and lead, at the bottom, give up electrons easily and are metals. (d) **Silicon.** Both are in Period 3, and metallic character decreases across a period; silicon comes before phosphorus, so it is the more metallic of the two.

Question 12 (a) A halogen atom has **7** outer-shell electrons. (b) Reactivity **decreases down Group 17**. A halogen reacts by drawing an electron into its outer shell. Going down the group, the outer shell is further from the nucleus, so an incoming electron is attracted less strongly and the reaction becomes harder. (c) **Chlorine** reacts most easily, because it is highest of the three in the group: its outer shell is closest to the nucleus, so it attracts an incoming electron most strongly.

Question 13 (a) **Potassium** is larger. Both are in Group 1, but potassium has four occupied shells while sodium has three; going down a group adds a shell, so the atom is larger. (b) **Sodium** is larger. Both are in Period 3, so their outer electrons are in the same shell, but sodium has fewer protons than chlorine. Chlorine's nucleus pulls the shells in more strongly, making it smaller.

Question 14 (a) Heating gives energy to lithium's electrons, moving one outward, for a short time, to a higher shell. When the electron falls back, the energy is released as light — for lithium, red light. The colour is fixed by lithium's own shell arrangement. (b) A **yellow** colour would appear, because sodium gives a strong yellow flame. It would stand out against the red at once, since each element's flame colour is unique — that uniqueness is what lets a flame colour reveal even a small contamination.

Question 15 (a) For example: *Which reacts more easily with dilute hydrochloric acid, magnesium or zinc?* The question names both the variable being changed and the response being measured. (b) Independent variable: the metal (magnesium or zinc). Dependent variable: the rate of reaction, judged from the bubbling. Variables kept the same (any two): volume and concentration of the acid, temperature of the acid, size and surface condition of the metal strips. (c) Observe and compare the **rate of bubbling** in the two tubes under the same conditions: the metal that produces bubbles faster is reacting more easily. Timing how long each strip takes to stop reacting, or collecting the gas and comparing volumes after a set time, would strengthen the comparison. (d) Wear **eye protection**, because dilute hydrochloric acid is an irritant and the reaction can spit. Keep flames away, because the gas produced is hydrogen, which is flammable.

Question 16 (a) **R, Q, P** — R reacts most easily (vigorously with cold water), then Q (fast with acid, slow with water), then P (slow with acid, none with water). (b) **R** could be a Group 1 metal: reacting vigorously with cold water and catching fire matches the behaviour of the alkali metals such as potassium. (c) Q is a metal that reacts steadily with acid and slowly with water — behaviour like **magnesium**, which fizzes easily with dilute acid but reacts with water only slowly. (d) When heated in oxygen, P would be expected to react and form a metal oxide, though more slowly than Q or R, since it is the least reactive of the three — a slow reaction with oxygen matches its low reactivity with acid and water.

Where this leads: the shells-and-trends model taught here is the direct precursor of VCE Chemistry Unit 1, Area of Study 1 ("How do the chemical structures of materials explain their properties and reactions?"), reference-only for this book. VCE extends the shell model by adding extra structure within the shells themselves, and uses the trends to explain how atoms bond; those extensions, including the energy ideas VCE uses to explain bonding, are VCE-only and are not taught here (TOC D9). This subtopic also builds the habit of reading the periodic table as a data table with two independent axes — group and period at once — which VCE Chemistry assumes. Subtopics 10A and 10B deliver the chapter's split CD `VC2S10U06`; balancing symbol equations for the reactions met here is developed in Subtopic 11B.