

Radioactivity

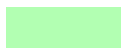
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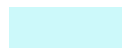
Revision notes for one topic, free to download.

These are the summary notes only. The full edition of this booklet also carries the worked examples, the required practicals and the formula sheets, with every topic in one place.

Colour Codes



Definitions



Diagrams



Notes and warnings



Sub-topic headings

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Define Mass (nucleon) number, A

- the total number of protons and neutrons in a nucleus.

Define Ion

- a charged atom, formed when an atom loses (or gains) electrons.

Define Beta-minus particle (β^-)

- β^- — a fast electron emitted from the nucleus when a neutron changes into a proton.

Define Gamma ray (γ)

- high-frequency electromagnetic radiation from the nucleus.

Define Ionising radiation

- radiation with enough energy to knock electrons off atoms, forming ions.

Define Activity

- the number of nuclear decays per second, measured in becquerel (Bq); 1 Bq = 1 decay per second.

Define Irradiation

- exposing an object or person to radiation from an outside source, without it becoming radioactive.

Define Dose

- a measure of the amount of radiation a person receives; kept as low as is useful.

Define Atomic (proton) number, Z

- the number of protons in a nucleus; it identifies the element.

Define Isotope

- atoms of the same element with the same number of protons but different numbers of neutrons.

Define Alpha particle (α)

- two protons and two neutrons, equivalent to a helium nucleus.

Define Positron (β^+)

- the antiparticle of the electron, emitted when a proton changes into a neutron.

Define Neutron radiation

- neutrons emitted from an unstable nucleus; they carry no charge.

Define Background radiation

- the low-level ionising radiation that is around us all the time, from natural and artificial sources.

Define Half-life

- the time taken for half the undecayed nuclei in a sample to decay, or for the activity of a source to fall by half.

Define Contamination

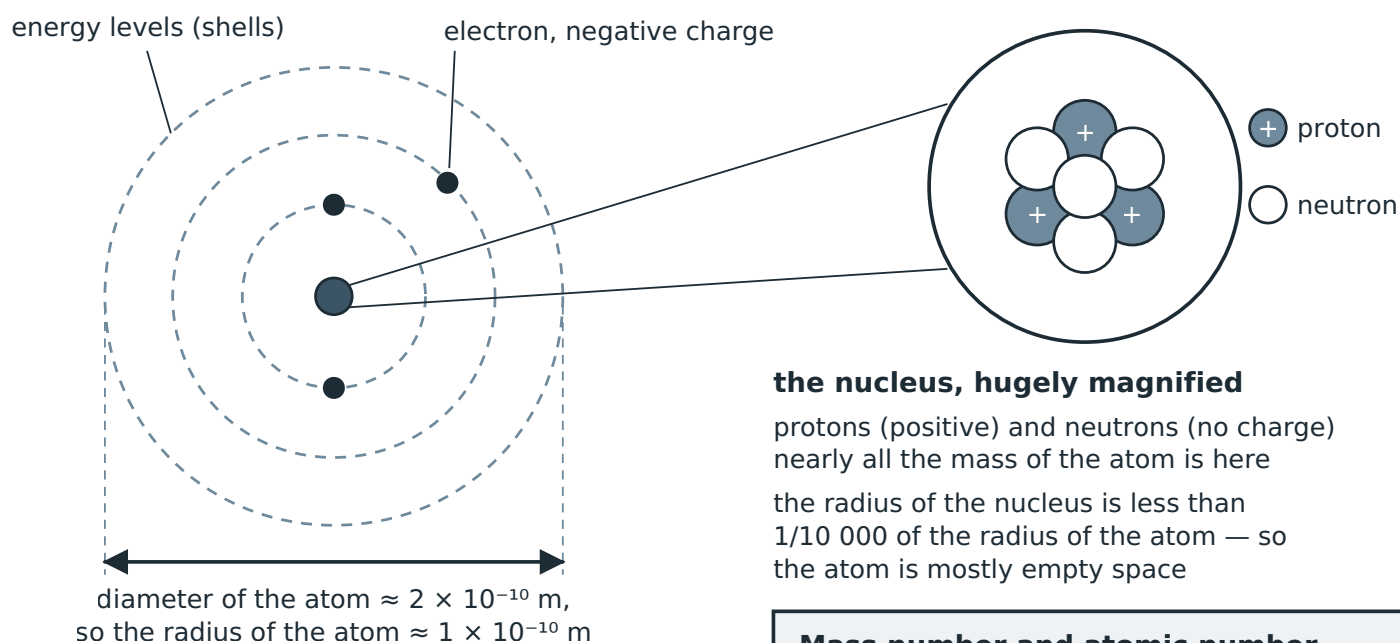
- getting radioactive material onto or inside an object or person, so that it keeps irradiating them.

The nuclear atom (6.1, 6.2)

An atom is a **positively charged nucleus**, made of **protons and neutrons**, surrounded by **negatively charged electrons**. The **nuclear radius is much smaller** than the radius of the atom, and **almost all of the mass** of the atom is in the nucleus.

- Typical **atom or small molecule**: about 1×10^{-10} m across — this order of magnitude must be recalled (6.2).
- The nucleus is about 1×10^{-14} m across, roughly **10 000 times smaller**, so the atom is mostly empty space.

The scale of the atom and its nucleus



the nucleus, hugely magnified

protons (positive) and neutrons (no charge)
nearly all the mass of the atom is here
the radius of the nucleus is less than
 $1/10\,000$ of the radius of the atom — so
the atom is mostly empty space

Electrons and energy levels

Electrons sit at different distances from the nucleus — different energy levels.

Absorbing electromagnetic radiation moves an electron to a higher level, further out; emitting it moves the electron closer in.

Mass number and atomic number

${}^7_3\text{Li}$ mass number = 7
(protons + neutrons)
atomic number = 3 (protons)

neutrons = $7 - 3 = 4$; electrons = 3
so the atom has no overall charge.

Isotopes: same atomic number but a different mass number, eg lithium-6.

Atomic number, mass number and isotopes (6.3–6.6)

Nuclei are written with the **mass (nucleon) number above the atomic (proton) number, before the symbol** — carbon-13 is ${}^{13}_6\text{C}$, so it has 6 protons and $13 - 6 = 7$ neutrons.

Particle	Relative mass	Relative charge
Proton	1	+1
Neutron	1	0
Electron	very small (about 1/1836)	-1
Positron	very small (same as electron)	+1

- The nucleus of each element has a **characteristic positive charge**, set by its number of protons. Change that number and you change the element.
- **Isotopes** of an element have the same number of protons but **different numbers of neutrons**, so they differ in mass. Chemically they behave identically.
- In an atom the **number of protons equals the number of electrons**, so the atom is **neutral** overall.

Electron orbits and the formation of ions (6.7, 6.8, 6.9)

- In each atom the electrons **orbit the nucleus at different set distances** (6.7).
- An electron **changes orbit when electromagnetic radiation is absorbed or emitted** (6.8): absorbing radiation moves it **further from** the nucleus; falling back to an orbit **closer in** **emits** electromagnetic radiation.
- If an atom absorbs enough energy an outer electron leaves altogether, so the atom becomes a **positive ion** (6.9) — exactly what ionising radiation does as it passes through matter.

Radiation from unstable nuclei (6.10, 6.11, 6.15, 6.16)

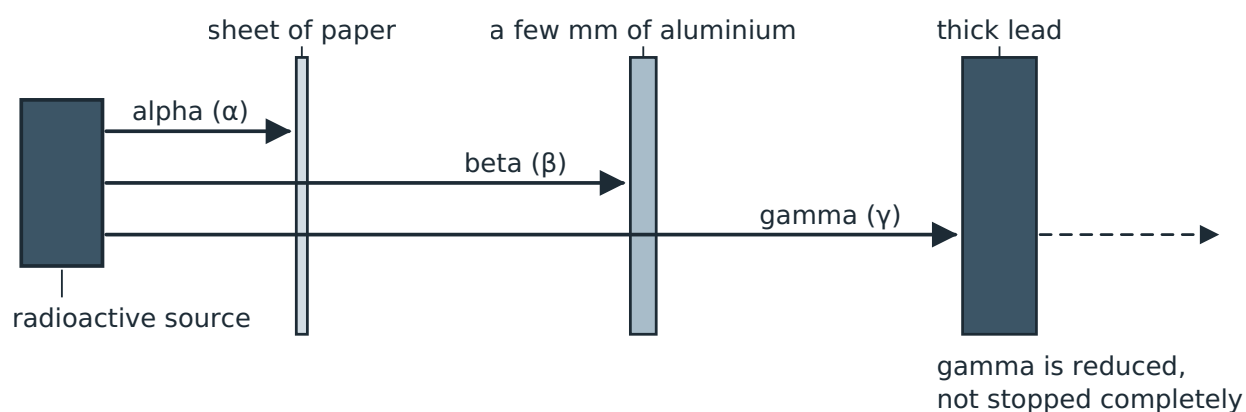
Unstable nuclei emit **alpha**, β^- (**beta minus**), β^+ (**positron**), **gamma rays** and **neutron radiation** in a **random** process — you cannot predict which nucleus will decay, or when (6.10).

Alpha, β^- , β^+ and **gamma** are **ionising radiations** (6.11). And (6.15) an **alpha particle** is equivalent to a **helium nucleus**, a **beta particle** is an **electron emitted from the nucleus**, and a **gamma ray** is **electromagnetic radiation**.

	Alpha (α)	Beta-minus (β^-)	Gamma (γ)
What it is	Helium nucleus: 2 protons + 2 neutrons	Fast electron from the nucleus	High-frequency electromagnetic wave
Symbol	${}^4_2\text{He}$ or ${}^4_2\alpha$	${}^0_{-1}\text{e}$ or ${}^0_{-1}\beta$	${}^0_0\gamma$
Relative charge / mass	+2 / 4	-1 / very small	0 / no mass
Ionising power	Strongest	Moderate	Weakest
Penetration	Least — stopped by paper, skin or a few cm of air	Stopped by a few mm of aluminium	Most — reduced by thick lead or metres of concrete, never fully stopped
Range in air	A few centimetres	About a metre	Effectively unlimited
Deflection by fields	Deflected (positive)	Deflected the other way, and more	Not deflected

The pattern: the **more strongly ionising** a radiation is, the **faster it gives up its energy**, so the **less far it penetrates**.

Alpha, beta and gamma radiation: ionising power and penetration



Radiation	What it is	Charge	Relative mass	Ionising power	Range in air	Stopped by
alpha (α)	a helium nucleus: 2 protons and 2 neutrons	+2	4	very high	about 5 cm	a sheet of paper
beta (β)	a high-speed electron from the nucleus	-1	$\approx 1/1800$ (tiny)	medium	about 1 m	a few mm of aluminium
gamma (γ)	electromagnetic radiation from the nucleus	0	0	low	over 1 km and spreads	thick lead or concrete

Background radiation (6.12, 6.13)

Background radiation is the low-level ionising radiation present around us all the time, whether or not a source is in the room. Most of it is **natural**, and its origins are both the **Earth** and **space**.

Source	Origin	Notes
Radon gas	Earth	Radioactive gas from rocks and soil; the largest single contributor, worse in granite areas
Rocks, soil and buildings	Earth	Granite, brick and concrete contain uranium, thorium and potassium isotopes
Food and drink	Earth	All living material contains carbon-14 and potassium-40
Cosmic rays	Space	High-energy particles from the Sun and beyond; the dose rises with altitude
Medical sources	Artificial	X-rays, CT scans, tracers and radiotherapy — the largest artificial contribution
Nuclear industry and weapons fallout	Artificial	A very small percentage of the total

Detecting and measuring radioactivity (6.14)

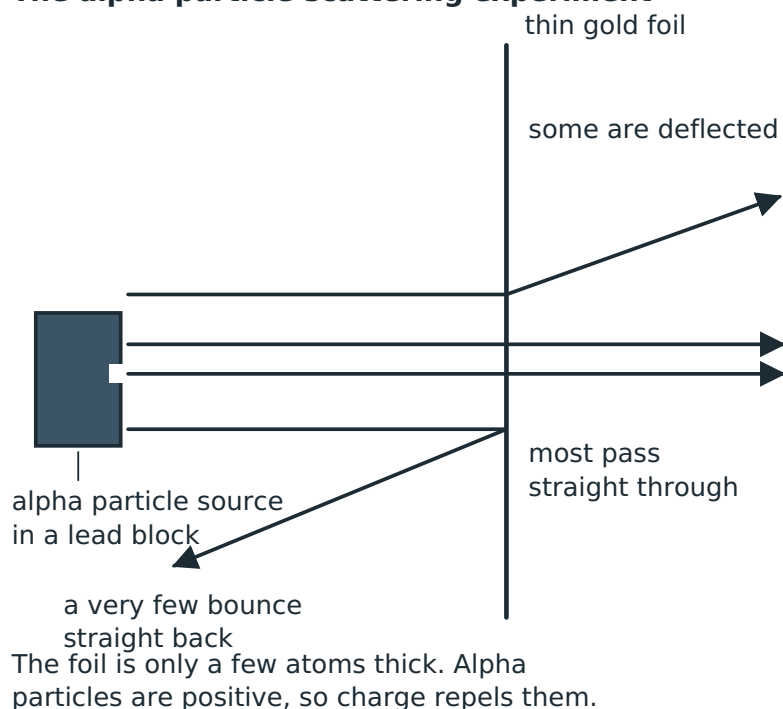
- **Photographic film** — radiation darkens the film. Workers wear a film badge with different windows (plastic, aluminium, lead), so it shows how much and what type of radiation they have received.
- **Geiger-Müller tube** — with a counter, it clicks and counts each ionising particle or ray entering it, giving a **count rate** in counts per second.
- Always **measure the background count first** and subtract it from your readings.

How the atomic model changed (6.17)

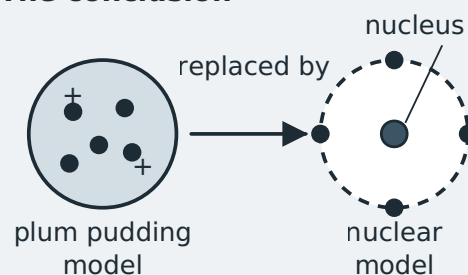
1. **Plum pudding model** (early 1900s) — the atom was pictured as a ball of positive charge with negative electrons scattered through it, like plums in a pudding. There was no nucleus.
2. **Rutherford's alpha particle scattering experiment** — a thin gold foil was fired at with alpha particles in an evacuated tube, and a detector recorded where they went. - **Most passed straight through**, undeflected → the atom is **mostly empty space**. - **Some were deflected** through small angles → the centre carries a **positive charge**, repelling the positive alphas. - **A very few (about 1 in 8000) bounced almost straight back** → the centre is **very small**, very **dense** and holds **almost all of the mass** and all of the positive charge. - The plum pudding model could not explain the large deflections, so it was replaced by the **nuclear model**.
3. **Bohr model** — Bohr refined the nuclear model by proposing that electrons orbit **at set distances** in fixed energy levels, rather than anywhere. This matched observations of the light emitted by atoms.

Rutherford's alpha-particle scattering experiment

The alpha particle scattering experiment



The conclusion



Most passed straight through, so the atom is mostly empty space.

A few were deflected, so there is a concentrated positive charge.

A very few bounced back, so that charge and nearly all the mass sit in a tiny, dense nucleus.

So the plum pudding model (a ball of positive charge with electrons stuck in it) was replaced by the nuclear model.

Decay processes and nuclear equations (6.18–6.22)

- **β^- decay (6.18):** inside the nucleus a **neutron becomes a proton plus an electron**. The proton stays; the electron is emitted at high speed as the beta particle.
- **β^+ decay (6.19):** a **proton becomes a neutron plus a positron**, and the positron is emitted.
- After a decay, a nucleus is often left with excess energy. It **rearranges** and loses that energy as **gamma radiation (6.21)** — gamma emission alone changes neither the mass number nor the atomic number.

Effects of each decay on the numbers (6.20):

Emission	Mass (nucleon) number A	Atomic (proton) number Z
Alpha (α)	decreases by 4	decreases by 2
Beta-minus (β^-)	unchanged	increases by 1
Beta-plus / positron (β^+)	unchanged	decreases by 1
Gamma (γ)	unchanged	unchanged
Neutron emission	decreases by 1	unchanged

WATCH OUT

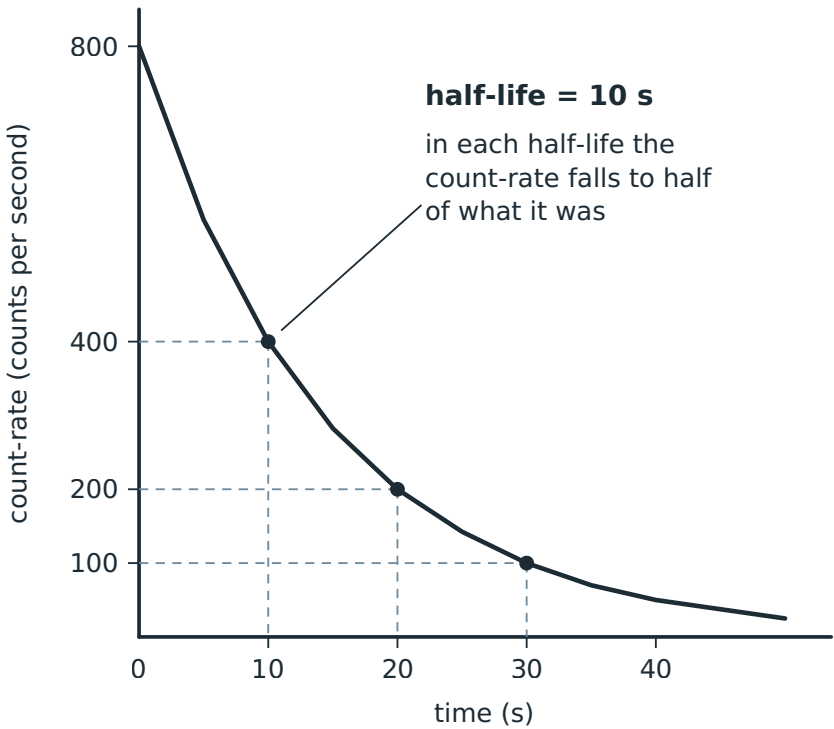
The beta particle is **not** one of the atom's orbiting electrons. It is created **in the nucleus** at the moment a neutron turns into a proton, and it is that new electron that shoots out.

Positron emission works the same way: fluorine-18 decays as $^{18}_9\text{F} \rightarrow ^{18}_8\text{O} + ^0_{+1}\text{e}$. **Neutron emission** removes one nucleon and no charge: $^{13}_4\text{Be} \rightarrow ^{12}_4\text{Be} + ^1_0\text{n}$.

Activity and half-life (6.23–6.27)

- As the undecayed nuclei are used up, fewer are left to decay each second, so the **activity decreases over time (6.23)**. The decay curve falls steeply at first, then flattens, never quite reaching zero.
- The **unit of activity is the becquerel, Bq (6.24)** — one decay per second.
- **Half-life (6.25)** is the time taken for **half the undecayed nuclei to decay**, or for the **activity of a source to fall by half**. Both definitions are accepted.
- Radioactive decay is **random**: it is impossible to predict when a particular nucleus will decay. But because a sample contains an enormous number of nuclei, the **half-life lets us predict the activity of that large number** reliably (6.26) — this is why radioactivity is described statistically.

Activity, decay curves and half-life



half-lives passed	fraction left	count-rate (per s)
0	1 (all)	800
1	$\frac{1}{2}$	400
2	$\frac{1}{4}$	200
3	$\frac{1}{8}$	100

Net decline after 3 half-lives:
the count-rate falls from 800 to 100, that is to $\frac{1}{8}$ of the start.

As a ratio, the net decline is 1 : 8 (final : initial).

After 4 half-lives it is 1 : 16.

Radioactive decay is random — you cannot predict which nucleus will decay next, or when.
With a large number of nuclei the average behaviour is the smooth curve above.

ANALOGY

HALF-LIFE

Think of a tray of popcorn in a hot pan. You cannot say which kernel pops next — that is random. But you can say that after each 30 seconds about half the still-unpopped kernels will have popped. A fixed *fraction* per unit time, not a fixed *number*, is what a half-life is. Where it breaks down: kernels stop popping as the pan cools, whereas an isotope's half-life never changes — heat, pressure and bonding make no difference.

Time (hours)	0	1	2	3	4
Count rate (counts/s) Determine the half-life.	480	340	240	170	120

Dangers of ionising radiation and precautions (6.29, 6.31)

- Ionising radiation damages living cells: it can kill them outright (**tissue damage**, radiation burns, radiation sickness) or damage the DNA of a surviving cell, causing **mutations** that may lead to **cancer** (6.29).
- Precautions follow directly: keep exposure **time** short and your **distance** large, use **shielding** (lead, concrete, lead-lined aprons), handle sources with **long tongs**, never point a source at anyone, and store sources in a **lead-lined box**.
- **Precautions for people exposed to radiation** (6.31): the **dose to a patient is limited** — the smallest useful dose, the beam aimed only at the target tissue, other parts shielded, and the benefit must outweigh the risk. **Medical personnel** are exposed repeatedly, so they stand behind lead screens or leave the room, wear **film badges**, and have limited working hours with sources.

Contamination and irradiation (6.32)

- **Irradiation** is being **exposed to radiation from a source outside** you. The object or person does **not** become radioactive, and the exposure stops once the source is removed or shielded.
- **Contamination** is getting **radioactive atoms onto or inside** an object or person — on skin or clothing, or breathed in, swallowed or injected. The source is now with you and keeps irradiating you until removed or decayed.

Comparing the hazards: external **gamma** irradiation is dangerous because gamma penetrates the body, but it stops when you move away. Contamination by an **alpha** emitter is far worse than external alpha: alpha cannot get through skin from outside, but once inside it is intensely ionising in a very small volume of tissue. Contamination is the harder hazard because it cannot be walked away from — the danger continues, and depends on the half-life of the isotope.

ANALOGY

CONTAMINATION VS IRRADIATION

Irradiation is standing near a bonfire: you feel the heat while you are there, it stops when you walk away, and you are not on fire yourself. Contamination is a hot ember stuck in your jumper: it goes wherever you go and keeps burning you until you get it out.

HIGHER TIER

NOTE

What Combined Science does not need in Topic 6. Statements 6.28, 6.30 and 6.33–6.46 are in the GCSE in Physics only: the **uses of radioactivity** (smoke alarms, food irradiation, sterilising equipment, tracers and thickness gauges), the effect of **half-life on danger, radiation in medicine** (radiotherapy, tracers, PET scanning), **evaluating nuclear power, nuclear fission** and the chain reaction, and **nuclear fusion**. None of it can be examined in Combined Science.

There are **no core practicals** in Topic 6. The suggested practical is to investigate models that simulate radioactive decay — for example throwing 100 dice, removing every six, and plotting the number left against the number of throws to get a decay curve.

Use of mathematics for Topic 6 — use **ratios and proportional reasoning** to convert units and compute rates; **balance equations** representing alpha, beta or gamma radiation in terms of masses and charges; **HT ONLY** calculate the **net decline, expressed as a ratio**, after a given number of half-lives.