

Atomic structure

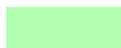
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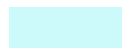
Revision notes for one topic, free to download.

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 Nucleus

- the tiny, positively charged centre of an atom, holding the protons and neutrons and almost all of its mass.

Define Isotopes

- atoms of the same element with different numbers of neutrons.

Define Plum pudding model

- the atom as a ball of positive charge with negative electrons embedded in it.

Define Radioactive decay

- the random process in which an unstable nucleus gives out radiation to become more stable.

Define Count-rate

- the number of decays recorded each second by a detector, e.g. a Geiger-Müller tube.

Define Beta particle (β)

- a high speed electron ejected from the nucleus as a neutron turns into a proton.

Define Half-life

- the time for the number of nuclei of an isotope in a sample to halve, or for the count- rate (or activity) to fall to half its initial level.

Define Irradiation

- exposing an object to nuclear radiation; the irradiated object does not become radioactive.

Define Atomic number

- the number of protons in an atom of an element.

Define Mass number

- the total number of protons and neutrons in an atom.

Define Ion

- a charged particle formed when an atom loses (positive ion) or gains electrons.

Define Nuclear model

- the mass of the atom concentrated in a small, charged nucleus at the centre.

Define Activity

- the rate at which a source of unstable nuclei decays, measured in becquerel (Bq).

Define Alpha particle (α)

- two neutrons and two protons; the same as a helium nucleus.

Define Gamma ray (γ)

- electromagnetic radiation from the nucleus.

Define Radioactive contamination

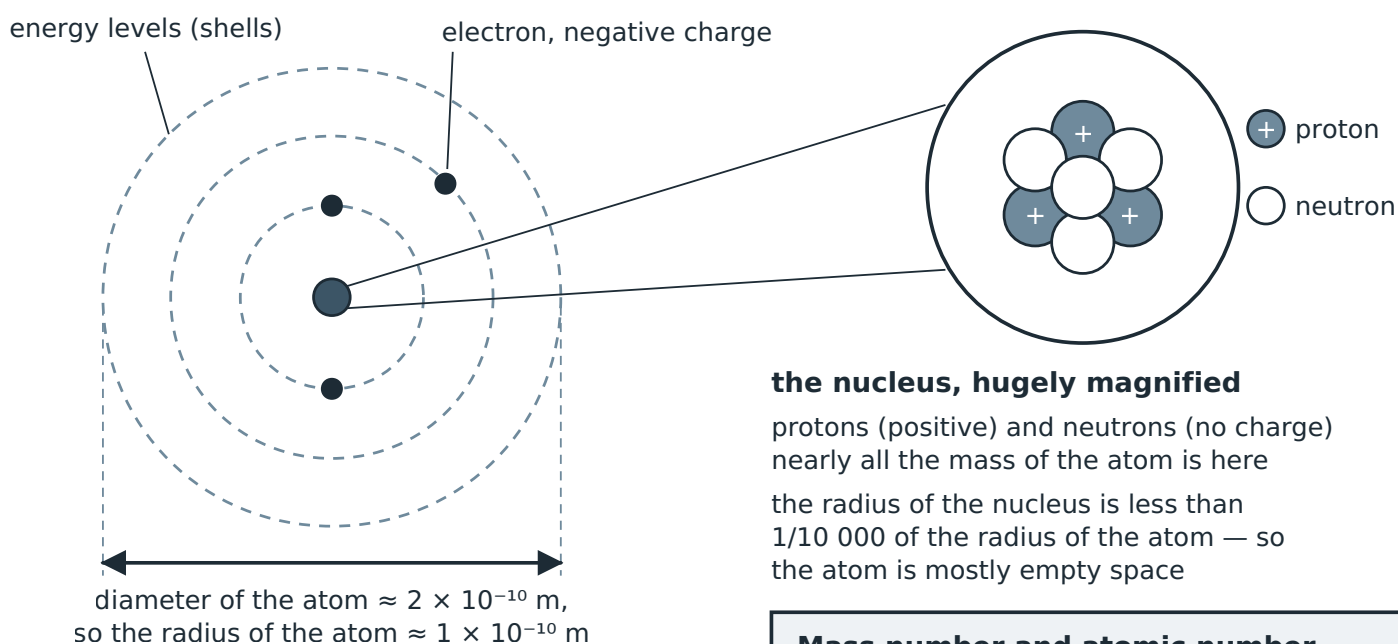
- the unwanted presence of materials containing radioactive atoms on other materials.

21.1 Atoms and isotopes

21.1.1 The structure of an atom

- Atoms are very small, with a radius of about 1×10^{-10} m.
- The basic structure is a positively charged nucleus composed of both protons and neutrons, surrounded by negatively charged electrons.
- The radius of a nucleus is less than 1/10 000 of the radius of an atom, yet most of the mass of an atom is concentrated in the nucleus — an atom is mostly empty space.
- The electrons are arranged at different distances from the nucleus (different energy levels). Electron arrangements may change:
- **absorption of electromagnetic radiation** → the electron moves **further from the nucleus**, to a **higher energy level**;
- **emission of electromagnetic radiation** → the electron moves **closer to the nucleus**, to a **lower energy level**.
- You should be able to **recognise expressions given in standard form**, e.g. 1×10^{-10} m is 0.000 000 000 1 m.

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.

ANALOGY

Scale of the atom. If the nucleus were a pea on the centre spot of a football stadium, the electrons would be in the back row of the stands, and everything between empty space.

21.1.2 Mass number, atomic number and isotopes

Particle	Relative charge	Relative mass	Where it is
Proton	+1	1	In the nucleus
Neutron	0	1	In the nucleus
Electron	-1	very small ($\approx 1/1800$)	Orbiting at different energy levels

- In an atom the number of electrons is equal to the number of protons in the nucleus, so **atoms have no overall electrical charge**.
- All atoms of a particular element have the same number of protons. The number of protons in an atom of an element is its **atomic number**.
- The **total number of protons and neutrons** in an atom is its **mass number**.
- Atoms are written with the **mass number above the atomic number** before the symbol, e.g. $^{238}_{92}\text{U}$ has 92 protons, 92 electrons and $238 - 92 = 146$ neutrons.
- **Isotopes** are atoms of the same element with **different numbers of neutrons** — the **same atomic number, different mass numbers**. Only the nuclear mass and stability differ.
- Atoms turn into positive ions if they lose one or more outer electron(s). An ion is written with its charge, e.g. Na^+ has one fewer electron than protons.

WATCH OUT

Changing the number of **neutrons** gives a different **isotope** of the same element. Changing the number of **protons** gives a **different element**. Changing the number of **electrons** gives an **ion**.

21.1.3 The development of the model of the atom

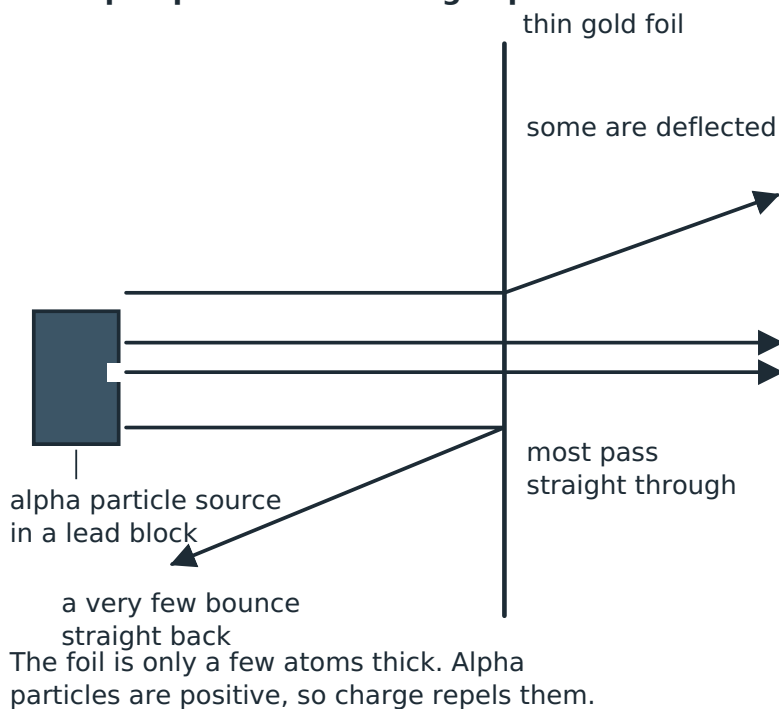
- New experimental evidence may lead to a scientific model being changed or replaced. The atom is the classic example.

In order	The idea	Prompted by
Indivisible spheres	Atoms are tiny spheres that cannot be divided	—
Plum pudding	The atom is a ball of positive charge with negative electrons embedded in it	Discovery of the electron
Nuclear model	Mass concentrated at the centre (nucleus) , and the nucleus is charged	Alpha particle scattering
Bohr model	Electrons orbit the nucleus at specific distances	Bohr's calculations agreeing with observations
Protons	Nuclear charge divides into whole numbers of identical particles — protons	Later experiments
Neutrons	Neutrons exist within the nucleus , about 20 years after the nucleus was accepted	The experimental work of James Chadwick

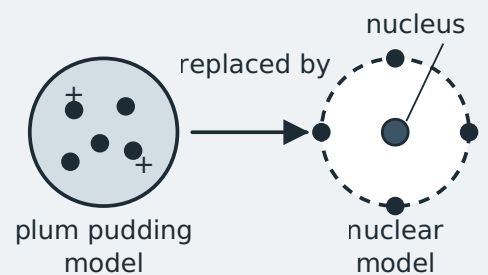
- **Alpha particle scattering:** alpha particles were fired at very thin gold foil. **Most passed straight through**, some were **deflected**, and a very small number **bounced almost straight back**.
- Why the new evidence changed the model: plum pudding predicted that all alpha particles would pass through with at most tiny deflections, because the positive charge was spread thinly. Instead the results led to the conclusion that the mass of an atom was concentrated at the centre (nucleus) and that the nucleus was charged, so the nuclear model replaced the plum pudding model.
- **Plum pudding vs nuclear model:** in plum pudding, charge and mass are **spread throughout** the atom; in the nuclear model they sit in a **tiny central nucleus**, with electrons orbiting and most of the atom **empty space**.
- **Details of the experimental work supporting the Bohr model, and of Chadwick's work, are not required.**

The 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.

21.2 Atoms and nuclear radiation

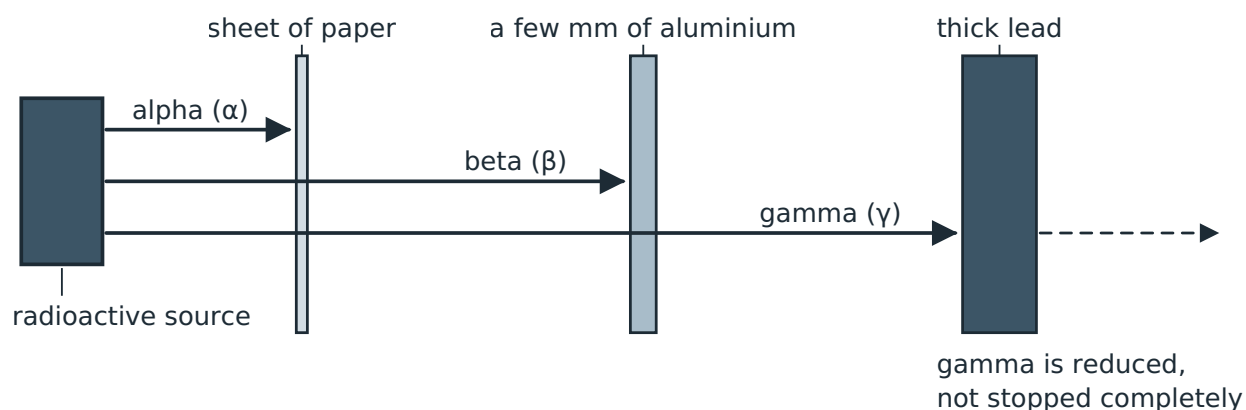
21.2.1 Radioactive decay and nuclear radiation

- Some atomic nuclei are unstable. The nucleus gives out radiation as it changes to become more stable — a random process called radioactive decay.
- Decay is **random**: you cannot predict which nucleus will decay next, or when, and it is unaffected by temperature, pressure or chemical state.
- Activity is the rate at which a source of unstable nuclei decays, measured in **becquerel (Bq)**. 1 Bq = 1 decay per second.
- Count-rate is the number of decays recorded each second by a detector (e.g. a **Geiger-Müller tube**); it is smaller than the activity because a detector catches only some of the radiation.

The nuclear radiation emitted may be an **alpha particle (α)**, a **beta particle (β)**, a **gamma ray (γ)** or a **neutron (n)**.

	Alpha (α)	Beta (β)	Gamma (γ)
Nature	2 neutrons + 2 protons — a helium nucleus	High speed electron ejected from the nucleus as a neutron turns into a proton	Electromagnetic radiation from the nucleus
Relative charge	+2	-1	0
Relative mass	4	very small ($\approx 1/1800$)	0
Penetration	Least penetrating	Moderate	Most penetrating
Range in air	About 5 cm	About 1 m	Very large (many metres)
Ionising power	Strongly ionising	Moderately ionising	Weakly ionising
Stopped by	A sheet of paper (or skin)	A few mm of aluminium	Many cm of lead or several m of concrete
Deflection in a field	Deflected (opposite way to beta), small deflection	Deflected, larger deflection (much lighter)	Not deflected

Alpha, beta and gamma radiation compared



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

- Neutron (n) radiation is also emitted by some nuclei; it is uncharged, so it is not deflected by fields, and it is very penetrating.
- Required knowledge of the properties of alpha, beta and gamma is limited to their penetration through materials, their range in air and their ionising power.**
- Choosing a source** — the trade-off is always penetration versus ionisation: **alpha** for a smoke alarm (strongly ionises the air but cannot escape the casing); **beta** for monitoring the thickness of paper or foil (some gets through, and the amount changes with thickness); **gamma** for a medical tracer or for sterilising equipment (penetrating enough to escape the body or packaging, and weakly ionising).

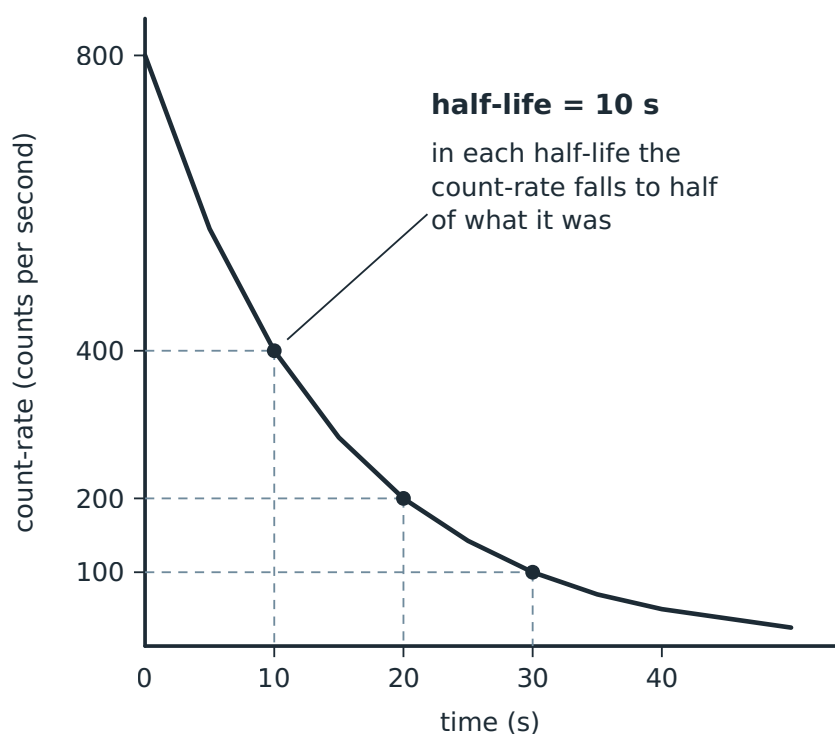
21.2.2 Nuclear equations

- Nuclear equations are used to represent radioactive decay. An **alpha particle** is written ${}^4_2\text{He}$ and a **beta particle** ${}^0_{-1}\text{e}$.
- The emission of nuclear radiation may cause a change in the mass and/or the charge of the nucleus:
- Alpha decay causes both the mass and the charge of the nucleus to decrease — mass number falls by **4**, atomic number falls by **2**.
- Beta decay does not cause the mass of the nucleus to change, but does cause the charge of the nucleus to increase — mass number is **unchanged**, atomic number rises by **1**.
- Emission of a gamma ray does not cause the mass or the charge of the nucleus to change.**
- Balancing is limited to the mass numbers and the atomic numbers. You are not required to identify the daughter element, nor to recall specific decay examples.

21.2.3 Half-lives and the random nature of radioactive decay

- Radioactive decay is random.
- The half-life of a radioactive isotope is the time it takes for the number of nuclei of the isotope in a sample to halve, or the time it takes for the count-rate (or activity) from a sample containing the isotope to fall to half its initial level.
- Half-life works **despite** the randomness because a sample holds an enormous number of nuclei: each has a fixed chance of decaying in a given time, so averaging over billions gives a reliable pattern — yet you still cannot say which nucleus will go next.
- You should be able to **determine the half-life from given information** — a table, a graph or a description. On an **activity–time graph**, read the initial activity, halve it, read across to the curve and down to the time axis; repeating this from several starting points and taking a mean is more reliable.

Half-life on an activity–time graph



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

Higher tier only

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 is popcorn in a pan. Every unpopped kernel has the same chance of popping in the next second and you cannot say which will go next — that is the randomness. Yet the time for half the remaining kernels to pop is reliably the same, because there are so many. Rolling a huge pile of dice and removing every six behaves the same way.

ANALOGY

Irradiation is standing in the sun; contamination is getting glittery sun cream all over you. Step into the shade and the sunlight stops instantly — you are not carrying it. The glitter, though, sits on your skin doing its thing until you scrub it off.

21.2.4 Radioactive contamination

- Radioactive contamination is the unwanted presence of materials containing radioactive atoms on other materials. The hazard from contamination is due to **the decay of the contaminating atoms**, and the type of radiation emitted affects the level of hazard.
- **Irradiation is the process of exposing an object to nuclear radiation. The irradiated object does not become radioactive.**
- **Comparing the hazards:** contamination keeps emitting for as long as the contaminating atoms remain and is hard to remove — inside the body, alpha is the most dangerous, being strongly ionising and depositing all its energy in nearby tissue. Irradiation stops the instant the source is removed or shielded and leaves the object safe to handle — outside the body, gamma and beta are the greater hazard, since alpha cannot penetrate the skin. Precautions: gloves, tongs and sealed sources against contamination; shielding, distance and short exposure times against irradiation.
- **Suitable precautions must be taken to protect against any hazard that the radioactive source used in the process of irradiation may present.**
- It is important that the findings of studies into the effects of radiation on humans are published and shared with other scientists so that they can be checked by peer review — other qualified scientists check the method, data and conclusions, which catches mistakes and bias and makes the findings more trustworthy.