Nuclear Physics

IGCSE Physics ▪ Topic 5

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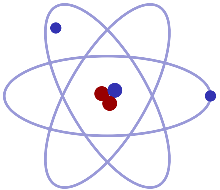


What we will cover

1 The atom

The nuclear atom

A tiny positive **nucleus** 原子核 (protons and neutrons) holds nearly all the mass. Electrons orbit in shells.

- proton number Z – the element
- nucleon number A – protons $+$ neutrons

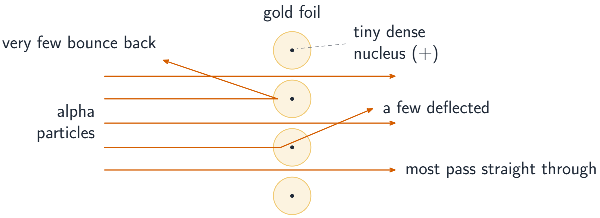
> **Isotopes** 同位素 have the same Z, different A – same chemistry, different nuclear behaviour.

Ions

An atom is neutral, but it can gain or lose electrons to become an **ion 离子**.

- Lose one or more electrons $\rightarrow$ a positive ion (now there are more protons than electrons).
- Gain one or more electrons $\rightarrow$ a negative ion.

Alpha-scattering evidence



Alpha particles α 粒子 on gold foil:

- most pass straight $\rightarrow$ mostly empty
- a few deflect $\rightarrow$ positive nucleus
- a very few bounce back $\rightarrow$ tiny, heavy nucleus

What alpha scattering showed, and what a nucleus contains

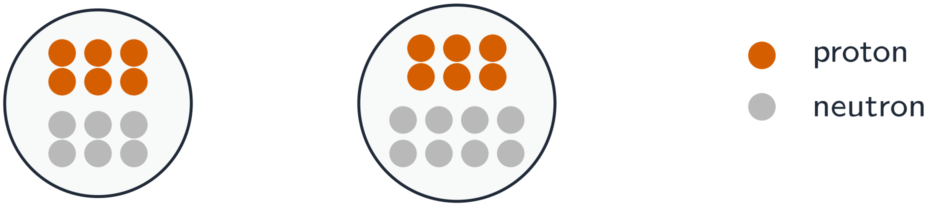
the experiment	**alpha particles** α 粒子 – small, fast, positive – fired at a very thin gold foil
most passed straight through	so the atom is mostly empty space
a few deflected	so there is a concentrated positive charge
a very few bounced back	so that charge is in a tiny, massive nucleus
nucleons 核子	the nucleus holds protons (positive) and neutrons (neutral); their total is the nucleon number A
isotopes 同位素	same proton number, different neutron number – so the same chemistry and different mass

> Each observation supports one conclusion. State the pair together – that is how the mark scheme is written.

Inside the nucleus

Nucleons 核子: **protons** 质子 $(+1)$ and **neutrons** 中子 (0). Notation ${}^{A}_{Z}\mathrm{X}$.

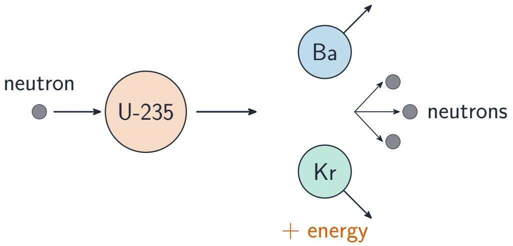
- Z = proton number; A = nucleon number; neutrons $= A - Z$
- **isotopes** 同位素: same Z, different A

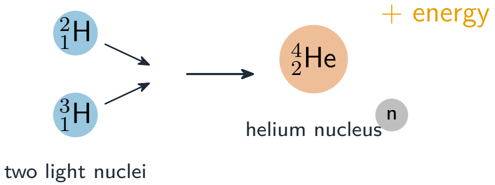


carbon-12
6 protons, 6 neutrons

carbon-14
6 protons, 8 neutrons

Fission and fusion





fission *核裂变: a heavy nucleus splits*

fusion *核聚变: light nuclei join (the Sun)*

Both lose a little mass, turned into energy; the A and Z numbers balance on each side.

Fission and fusion, in detail

nuclear fission 核裂变	a large nucleus splits when it absorbs a neutron, giving out energy
the equation	${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$
the chain reaction	those three neutrons can split three more nuclei – controlled in a reactor by absorbing some of them
nuclear fusion 核聚变	two light nuclei join to make a heavier one, also giving out energy
where it happens	in the Sun, joining hydrogen nuclei into helium
why it is hard here	the nuclei repel, so fusion needs enormous temperature and pressure

Both release energy because the products are more stable than the reactants – fission for heavy nuclei, fusion for light ones.

2 Radioactivity

Radioactivity

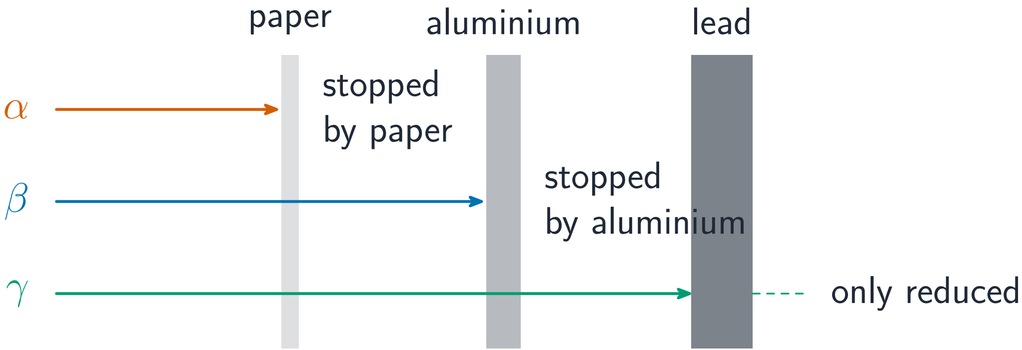
An **unstable** 不稳定 nucleus **decays** 衰变, giving out radiation. Decay is spontaneous and random. **Background radiation** 背景辐射 (radon, rocks, cosmic rays) is always present – subtract it:

250 next to source, 30 background

corrected $= 220$ counts/min

Three types of radiation

- α – He nucleus $(+2)$: most **ionising** 电离, stopped by paper
- β – fast electron (-1): aluminium
- γ – EM wave (0): least ionising, only reduced by lead



Why alpha ionises most and penetrates least

alpha	charge $+2$, and slow and heavy – so it interacts strongly and often
the consequence	most ionising, and least penetrating: stopped by paper or a few cm of air
beta	charge -1, fast and light – moderate on both counts; stopped by a few mm of aluminium
gamma	no charge, an electromagnetic wave – least ionising, most penetrating; reduced by thick lead or concrete
the explanation	ionising power comes from charge and from how long the particle spends near each atom
deflection	in a field alpha and beta bend in opposite directions, and gamma not at all

> Ionising power and penetration are inversely related, and both follow from the same cause. Explain from charge and speed, never by listing.

Why the three radiations differ

Alpha	Charge $+2$, slow and heavy: it pulls hard on the electrons it passes, so it is the most **ionising** 电离的 and the least penetrating – easily **absorbed** 吸收 by paper or skin.
Beta	Charge -1, fast and light: it ionises less and travels further, stopped by a few millimetres of aluminium.
Gamma	No charge, no mass – a wave. Least ionising, most penetrating; only thick lead or concrete reduces it much.
The reasoning	Explain from charge and **kinetic energy** 动能, not from a memorised list: it is the charge that does the ionising and the mass that stops the particle.

Ionising power and penetration run in opposite directions – an ionising particle loses its energy quickly, which is exactly why it stops.

Deflection in fields

Charged α and β bend opposite ways; the lighter β bends more. Uncharged γ is not deflected.

> α is ${}^{4}_{2}\mathrm{He}^{2+}$; β is an electron (or positron); γ is a photon. Charge and mass decide the bend.

Deflection, detection and safe use

In fields	Because alpha and beta particles are charged, they are deflected by an **electric field** 电场 and by a **magnetic field** 磁场 – in *opposite* directions, since the charges are opposite. Gamma is undeflected.
Detecting it	Radiation is measured with a **detector** 探测器 joined to a counter – a Geiger–Müller tube – and the background count is subtracted first.
Reducing the dose	Less **exposure** 照射 time, more distance, and shielding. All three, wherever a source is handled.
Nuclide notation	A **nuclide** 核素 is written ${}^{A}_{Z}X$: nucleon number above, proton number below.

> Gamma is used to **sterilise** 灭菌 sealed equipment and food precisely *because* it penetrates – the property that makes it dangerous makes it useful.

3 Decay and half-life

Decay equations

$$\alpha : {}^{A}_{Z}\mathsf{X} \to {}^{A-4}_{Z-2}\mathsf{Y} + {}^{4}_{2}\alpha$$

$$\beta : {}^{A}_{Z}\mathsf{X} \to {}^{A}_{Z+1}\mathsf{Y} + {}^{0}_{-1}\beta$$

γ emission: only energy leaves, A and Z unchanged.

${}^{226}_{88}$Ra emits α

$${}^{226}_{88}\mathsf{Ra} \to {}^{222}_{86}\mathsf{Rn} + {}^{4}_{2}\alpha$$

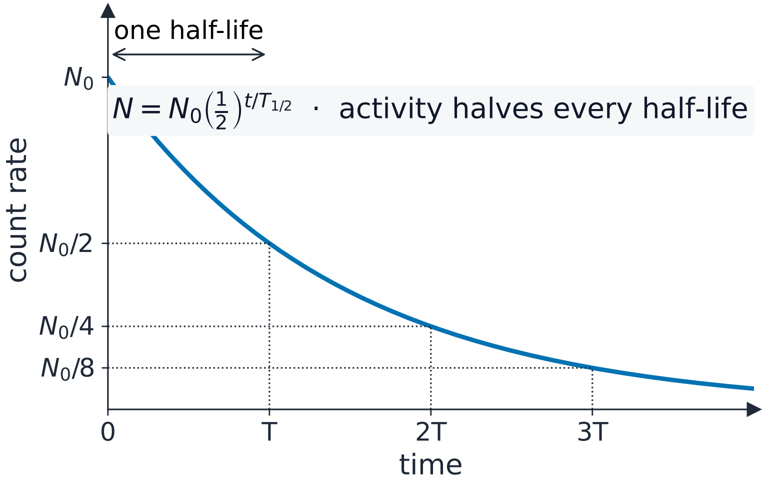
Half-life

Half-life 半衰期: the time for half the unstable nuclei (or the count rate) to halve.

$800 \to 100$ counts/min, $T = 5$ days

three halvings $\Rightarrow$ 15 days

Half-life, in detail



$800 \to 100$ counts/min, $T = 5$ days three halvings $\Rightarrow 15$ days

Half-life, and why it needs a large sample

the definition	the time for half the undecayed nuclei in a sample to decay
decay is random	we cannot say when one nucleus will decay, or follow it
so we use a sample 样品	a large number of nuclei behaves predictably even though each one does not
the pattern	after one half-life $\frac{1}{2}$ remains, after two $\frac{1}{4}$, after three $\frac{1}{8}$
reading a graph	find the time for the count rate to halve – and it is the same wherever you start
background radiation	subtract it from every reading before working out the half-life

> "The same wherever you start" is what makes half-life meaningful, and forgetting to subtract background is what makes an answer wrong.

Uses and safety

Match the source to the job:

- smoke alarms – α
- **sterilising** 消毒 – penetrating γ
- thickness gauge – β

> Lower the **dose** 剂量: less time, more distance, **shielding** 屏蔽 (lead).

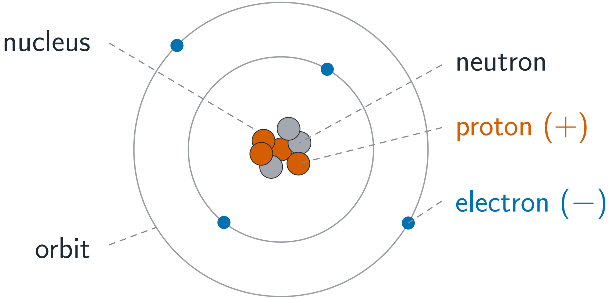
Handle with tongs; store in a lead box.

Keeping the dose low

the hazard	ionising radiation harms **living cells** 细胞 – it can cause cell death, **mutations** 突变 and cancer
dose 剂量	the amount of radiation received; the aim is always to keep it as low as reasonably achievable
time	spend as little time near the source as possible
distance	use tongs or a long handle – intensity falls with the square of distance
shielding	lead or concrete between you and the source
storage	keep sources in a lead-lined container, labelled, and locked away when not in use

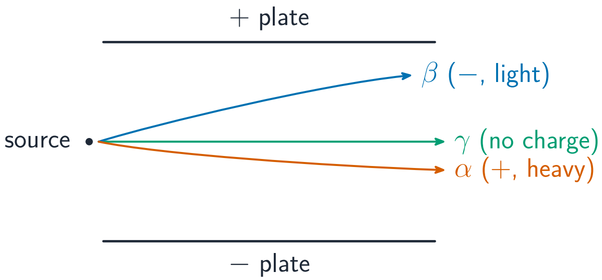
> Time, distance, shielding is the whole answer to any handling question. Naming all three earns the marks; describing one at length does not.

The atom



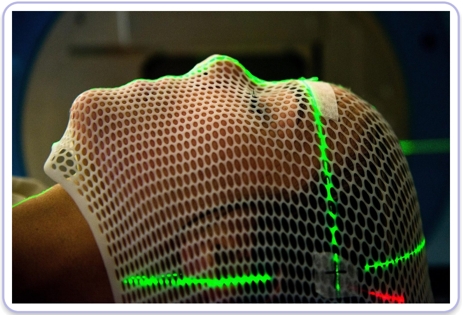
> The nuclear atom: a tiny dense nucleus of protons and neutrons, with electrons in orbits around it

Deflection in fields, continued



Alpha and beta bend in opposite directions; the lighter beta bends more, and uncharged gamma is not deflected

Uses of radioactivity



Radiotherapy: a mesh mask holds the patient still while alignment lasers aim gamma rays precisely at a tumour to treat cancer

Matching the source to the job

the rule	choose by the type of radiation and by the half-life
smoke alarms 烟雾报警器	an alpha source – easily blocked, so it is safe outside the alarm, and a long half-life means it lasts for years
thickness control	a beta source – the amount passing through a sheet of paper or metal changes with its thickness
sterilising 消毒	gamma rays, which penetrate the sealed packaging to kill **bacteria** 细菌 inside
medical tracers	a short half-life, so the patient's dose falls quickly once the scan is done
radiocarbon dating	carbon-14's half-life of 5730 years matches the age range being measured

Every choice pairs penetration with the barrier it must cross, and half-life with how long the source must last.

Tracers, gauges, and half-life from a graph

Choosing the isotope

- a **medical tracer** 医用示踪剂: a **radioactive** 放射性 gamma emitter with a short half-life, injected into the body; gamma escapes to a detector outside, and the activity soon falls to a safe level
- thickness gauge: a beta source; what passes through changes with thickness
- smoke alarm: an alpha source with a long half-life

Half-life with background

1. measure the background count rate with the source removed
2. subtract it from every reading
3. plot the corrected count rate; read the time for it to halve from any value

> **Relative** 相对 charges: proton $+1$, neutron 0, electron -1; relative masses 1, 1, negligible.

Exam tips

- The **nucleon number** (top) is protons + neutrons; the **proton number** (bottom) is protons only. Number of neutrons = nucleon number − proton number.
- **Isotopes** have the same proton number but different nucleon numbers – the same element with a different number of neutrons.
- Rank the radiations two ways: **alpha** is the most ionising but least penetrating (stopped by paper); **gamma** is the least ionising but most penetrating (needs thick lead). Beta is in between (stopped by a few mm of aluminium).
- In every **decay equation** the top numbers must balance and the bottom numbers must balance. Alpha decay: $A-4$, $Z-2$. Beta decay: A unchanged, $Z+1$.
- Always subtract the **background count rate** before using a source's readings. After n half-lives the count rate has halved n times – count the halvings rather than guessing from the total time.

4 Recap

Topic 5 – key takeaways

1 Nucleus

$^{A}_{Z}\mathrm{X}$; isotopes share Z

2 Radiation

α (paper), β (Al), γ (lead)

3 Decay

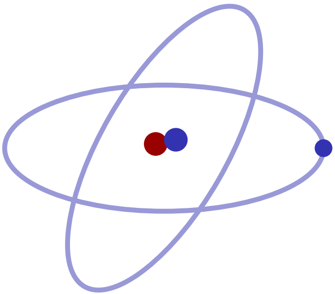
A & Z balance; α, β, γ

4 Half-life

count rate halves each half-life

Check yourself

1. How many neutrons in $^{197}_{79}$Au?
2. Which radiation is stopped by paper?
3. $^{24}_{11}$Na emits β – the new proton number?
4. After 2 half-lives, what fraction is left?



Answers **1.** $197 - 79 = 118$ **2.** alpha **3.** 12 **4.** one quarter