# Nuclear physics

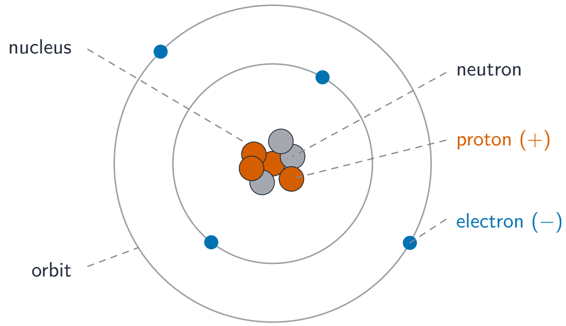
IGCSE Physics

## The atom

An **atom** 原子 is made of a tiny central **nucleus** 原子核 with **electrons** 电子 moving around it (in **orbit** 轨道, like planets around the Sun).

- The nucleus has a positive **charge** 电荷.
- The electrons have a negative charge.
- The atom as a whole is neutral, because the positive and negative charges are equal.

Almost all the **mass** 质量 is in the nucleus, but the nucleus is very small compared with the whole atom. So an atom is mostly empty space.




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

### Ions

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

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

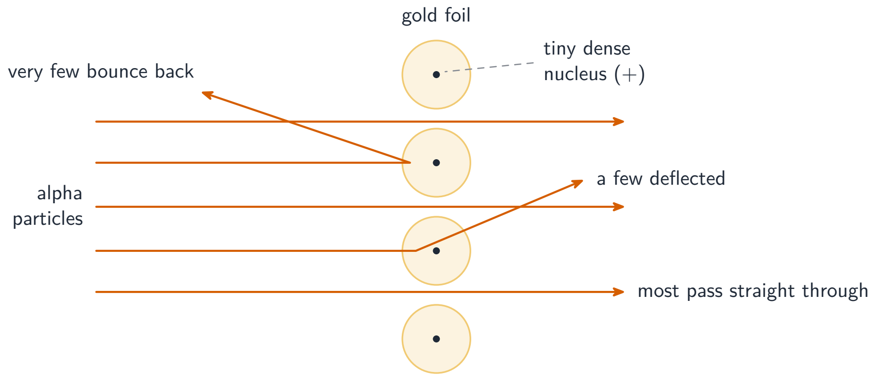


### The alpha-scattering experiment

This experiment gave the evidence for the nuclear model. **Alpha particles** $\alpha$ 粒子 (small, fast, positive) were fired at a very thin **gold foil** 金箔, and the **scattering** 散射 (the way they bounced off) was watched.

The results and what they tell us:

- Almost all the alpha particles went straight through. → The atom is mostly empty space.
- A few were **deflected** 偏转 (bent) through small angles. → The nucleus has a positive charge, which pushes the positive alpha particles away.
- A very few bounced almost straight back. → The nucleus is very small and very heavy, and holds most of the mass of the atom.




*Most alpha particles pass straight through; a few are deflected and a very few bounce back off the tiny dense nucleus*

## Inside the nucleus

The nucleus is made of two kinds of particle, together called **nucleons** 核子:

- **protons** 质子, which have a **relative** 相对 charge of +1;
- **neutrons** 中子, which have a relative charge of 0 (they are neutral).

An electron has a relative charge of −1. A proton and a neutron each have a **relative mass** of about 1; an electron is almost massless in comparison.

Two numbers describe a nucleus:

- the **proton number** 质子数 $Z$ (also called the atomic number) — the number of protons;
- the **nucleon number** 核子数 $A$ (also called the mass number) — the number of protons plus neutrons.

So the number of neutrons is $A - Z$.

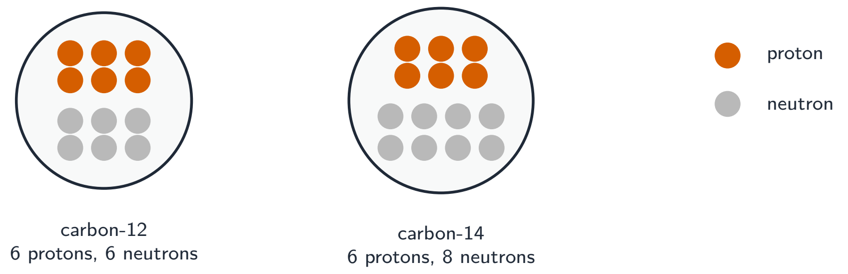
We write a nucleus in **nuclide** 核素 notation:

$$^{A}_{Z}\mathrm{X}$$

where X is the chemical symbol. For example, $^{197}_{79}\mathrm{Au}$ has 79 protons and $197-79 = 118$ neutrons. The relative charge of the whole nucleus is just $+Z$ (here $+79$), and its relative mass is about $A$.

## Isotopes

**Isotopes** 同位素 are atoms of the same element (the same $Z$) but with different numbers of neutrons (different $A$). They behave the same in chemistry but differently in the nucleus. For example, $^{12}_{6}\mathrm{C}$ and $^{14}_{6}\mathrm{C}$ are both carbon.



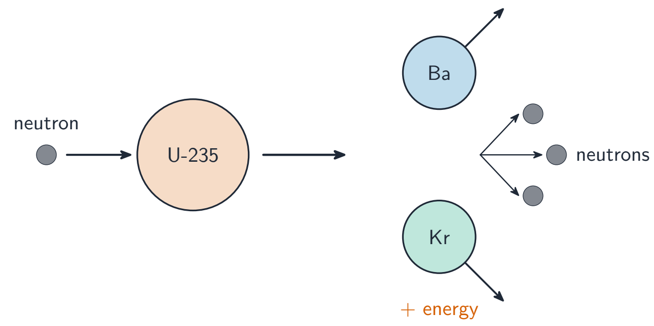

*Isotopes of carbon have the same six protons but different numbers of neutrons, so they are the same element with a different mass*

## Nuclear fission and fusion

In **nuclear fission** 核裂变, a heavy nucleus absorbs a neutron and then splits into two smaller nuclei, giving out two or three neutrons and a lot of **energy** 能量:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}\mathrm{n} \rightarrow \ ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3\,^{1}_{0}\mathrm{n}$$



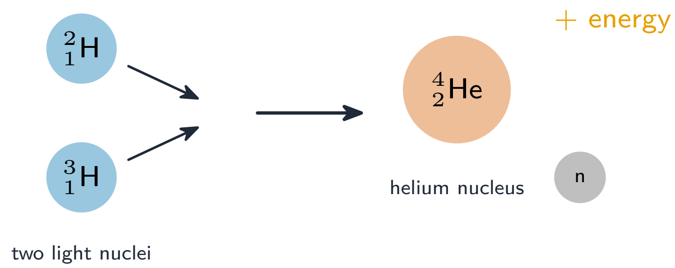



*A neutron splits a U-235 nucleus into two smaller nuclei, releasing more neutrons and energy*

The top numbers (nucleon numbers) balance on both sides, and so do the bottom numbers (proton numbers). You can use this to find a missing number — for example, how many neutrons are released.

In **nuclear fusion** 核聚变, two light nuclei join to make a heavier one, also giving out energy. This is how the Sun makes its energy, joining **hydrogen** 氢 nuclei to make **helium** 氦. The reaction below — two heavy forms of hydrogen (deuterium and tritium) joining into helium — is the one used in fusion reactors on Earth:

$$^{2}_{1}\mathrm{H} + ^{3}_{1}\mathrm{H} \rightarrow \ ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}$$




*In fusion two light nuclei join into a heavier one, releasing a neutron and energy — the deuterium–tritium reaction used in fusion reactors*

In both fission and fusion, a small amount of mass is lost and turned into energy.

*A nuclear power station uses the energy from fission to make electricity; the towers release waste heat as steam*

## Radioactivity

A nucleus that is **unstable** 不稳定 will sooner or later break down and give out **radiation** 辐射. This is **radioactive** 放射性 **decay** 衰变. A nucleus may be unstable because it has too many neutrons, or because it is too heavy.

Decay is **spontaneous** 自发 (it happens on its own, and you cannot speed it up or slow it down) and **random** 随机 (you cannot say which nucleus will decay next, or exactly when).

### Background radiation

Some radiation is around us all the time. This is **background radiation** 背景辐射. Its main sources are:

- **radon** 氡 gas in the air (usually the biggest source);
- rocks and buildings;
- food and drink;
- **cosmic rays** 宇宙射线 from space.



### Measuring radiation

Radiation can be measured with a **detector** 探测器 joined to a **counter** 计数器. The **count rate** 计数率 is the number of counts each second (or each minute).

To find the true count rate from a source, first measure the background count rate on its own, then subtract it. The answer is the **corrected** 修正 count rate:

$$\text{corrected count rate} = \text{measured count rate} - \text{background count rate}$$

**Worked example.** A detector placed next to a source reads 250 counts/min. With the source taken away, the background count rate is 30 counts/min. Find the corrected count rate.

$$250 - 30 = 220 \text{ counts/min}$$

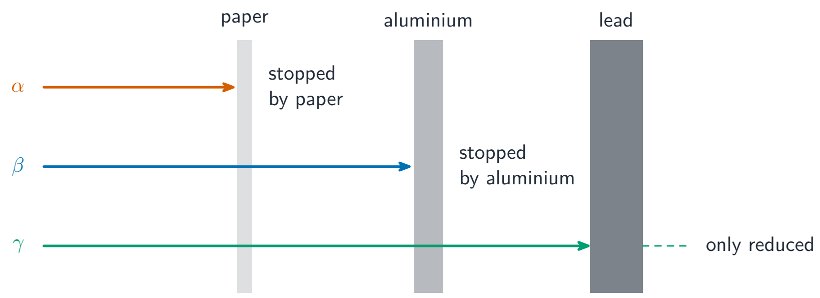

*A portable Geiger counter detects ionising radiation and shows the count rate on its screen*

## The three types of radiation

The radiation can be one of three types. Each type is **ionising** 电离, which means it can knock electrons off atoms in its path.

| Type | What it is | Ionising effect | Stopped by |
|---|---|---|---|
| alpha ($\alpha$) | a helium nucleus: 2 protons + 2 neutrons, charge +2 | strongest | a sheet of paper, or a few cm of air |
| beta ($\beta$) | a fast-moving electron, charge −1 | medium | a few mm of **aluminium** 铝 |
| gamma ($\gamma$) | a high-energy **electromagnetic wave** 电磁波, no charge | weakest | thick **lead** 铅 or concrete (only reduced, never fully stopped) |

So an **alpha particle** is the most **ionising** but the least **penetrating** 穿透 (it is easily **absorbed** 吸收). A **beta particle** $\beta$ 粒子 is in the middle. **Gamma radiation** $\gamma$ 射线 is the least ionising but the most penetrating.



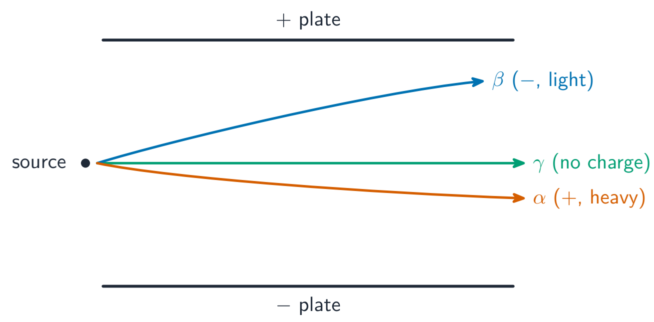

*Paper stops alpha, a few millimetres of aluminium stops beta, and thick lead only reduces gamma*

We can explain the ionising effects from charge and **kinetic energy** 动能: an alpha particle has a large charge (+2) and is slow and heavy, so it pulls strongly on the electrons it passes and ionises a lot. A beta particle has a smaller charge and moves faster, so it ionises less.



### Deflection 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. They bend in *opposite* directions, because their charges have opposite signs, and the lighter beta particle bends more. Gamma rays have no charge, so they are not deflected at all.




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

## Decay equations

When a nucleus decays, the nucleon and proton numbers must balance on both sides.

**Alpha decay** — the nucleus loses 2 protons and 2 neutrons, so $A$ falls by 4 and $Z$ falls by 2. It becomes a *different element*:

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

**Worked example.** A radium nucleus $^{226}_{88}\mathrm{Ra}$ emits an alpha particle. Find the nucleon number and proton number of the new nucleus.

Alpha decay lowers $A$ by 4 and $Z$ by 2:

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

So the new nucleus (radon) has nucleon number 222 and proton number 86.

**Beta decay** — inside the nucleus a neutron changes into a proton plus an electron:

$$\text{neutron} \to \text{proton} + \text{electron}$$

The fast electron leaves as the beta particle. So $A$ stays the same but $Z$ rises by 1, giving a different element:

$$^{24}_{11}\mathrm{Na} \rightarrow\ ^{24}_{12}\mathrm{Mg} +^{\ 0}_{-1}\beta$$

**Gamma emission** — the nucleus loses only energy, so $A$ and $Z$ do not change. Alpha and beta decay leave the nucleus more **stable** 稳定; gamma is often given out at the same time to carry away spare energy.

## Half-life

Because decay is random, we cannot follow one nucleus. Instead we describe a large **sample** 样品 using its half-life.

The **half-life** 半衰期 of an isotope is the time taken for half the unstable nuclei in a sample to decay. After each half-life, the count rate (or the number of unstable nuclei left) falls to half.

For example, if a source has a count rate of 800 counts/min and a half-life of 3 hours:

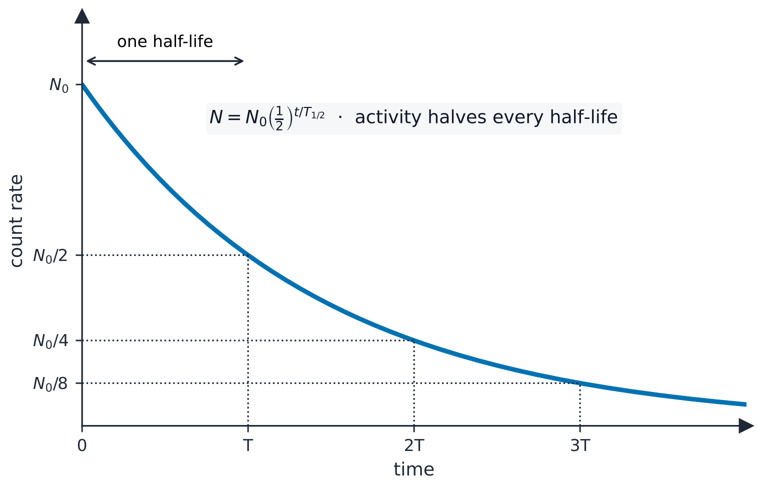
| **Time / hours** | **0** | **3** | **6** | **9** |
|---|---|---|---|---|
| Count rate / (counts/min) | 800 | 400 | 200 | 100 |

After 6 hours (two half-lives) the count rate has halved twice: $800 \rightarrow 400 \rightarrow 200$. You can read a half-life off a decay graph by finding the time for the count rate to drop from any value to half of it. If the readings include background radiation, subtract the background count rate from every reading first, then find the half-life from the corrected values.

**Worked example.** The activity of a source falls from 800 counts/min to 100 counts/min. Its half-life is 5 days. How long did this take?

Count the halvings: $800 \rightarrow 400 \rightarrow 200 \rightarrow 100$ is three half-lives, so the time is $3 \times 5 = 15$ days.



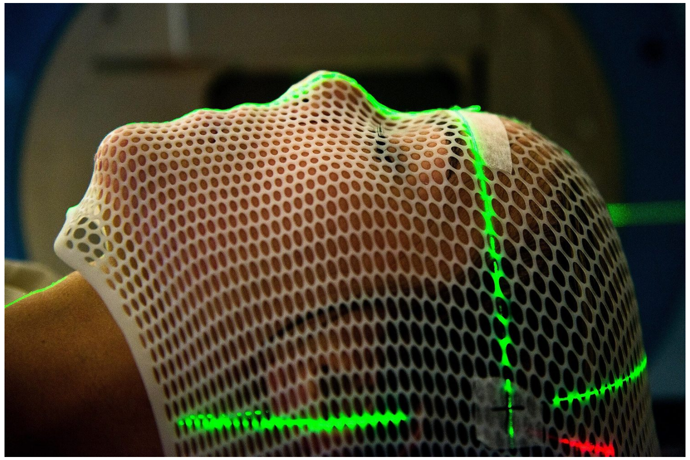



*Each half-life $T$ the count rate halves: $N_0 \rightarrow N_0/2 \rightarrow N_0/4 \rightarrow N_0/8$*

## Uses of radioactivity

The isotope chosen for a job depends on its type of radiation and its half-life:

- **smoke alarms** 烟雾报警器 use an alpha source (alpha is easily blocked, so it is safe outside the alarm, and a long half-life means it lasts for years);
- using radiation on food, or on equipment, kills **bacteria** 细菌 and germs — this needs penetrating gamma rays to **sterilise** 消毒 the sealed item;
- measuring and controlling the thickness of paper or metal sheets uses a beta source (the amount that passes through changes with the thickness);
- a **medical tracer** 医用示踪剂 is a small amount of a gamma-emitting isotope with a short half-life, injected into the body: a detector outside the body follows where it goes, gamma rays escape from the body easily, and the activity soon falls to a safe level;
- gamma rays are used to find and to treat **cancer** 癌症 inside the body, because they can pass out of (or into) the body.



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

## Safety

Ionising radiation harms **living cells** 细胞. It can cause cell death, **mutations** 突变 (changes to the genes) and cancer.

When working with radioactive sources, keep the **dose** 剂量 (the amount of radiation received) low by:



- reducing the **exposure** 照射 time — spend as little time near the source as possible;
- increasing the distance between you and the source;
- using **shielding** 屏蔽, such as lead, between the source and your body.

Radioactive sources should be handled with tongs (not bare hands), kept pointing away from people, and stored in a lead-lined box.

## 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.