

# Nuclear physics

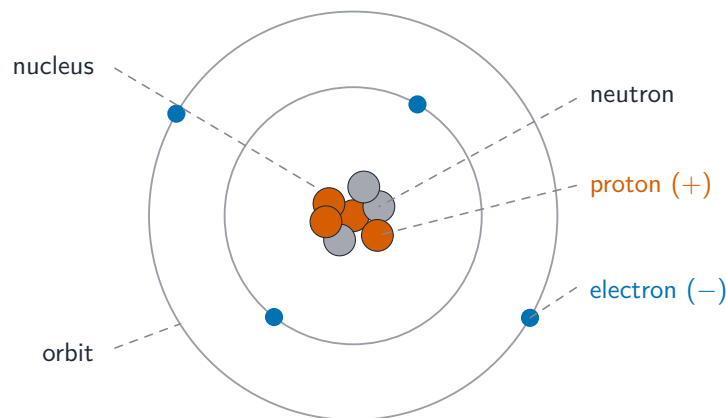
## IGCSE Physics

### 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.

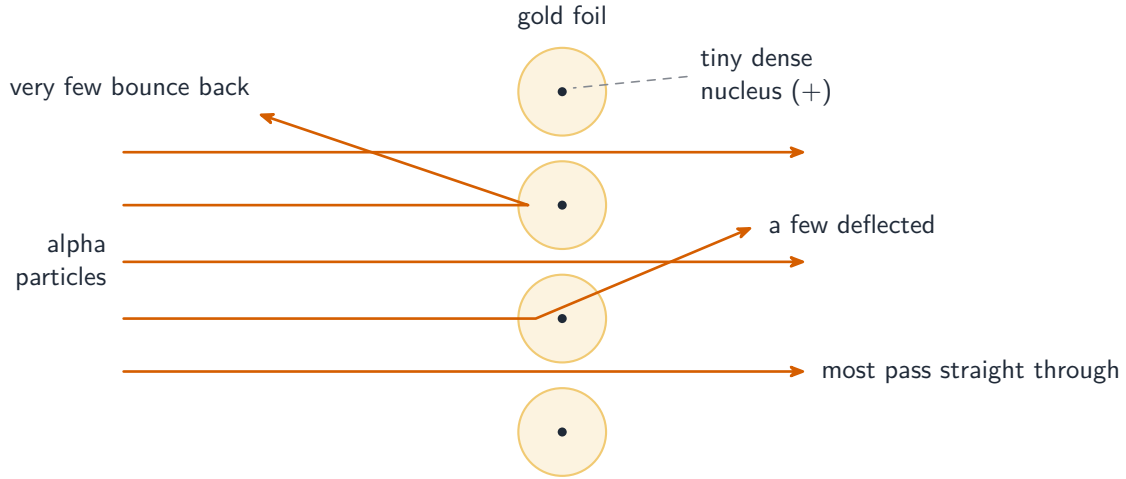
### The alpha-scattering experiment

This experiment gave the evidence for the nuclear model. **Alpha particles** 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:



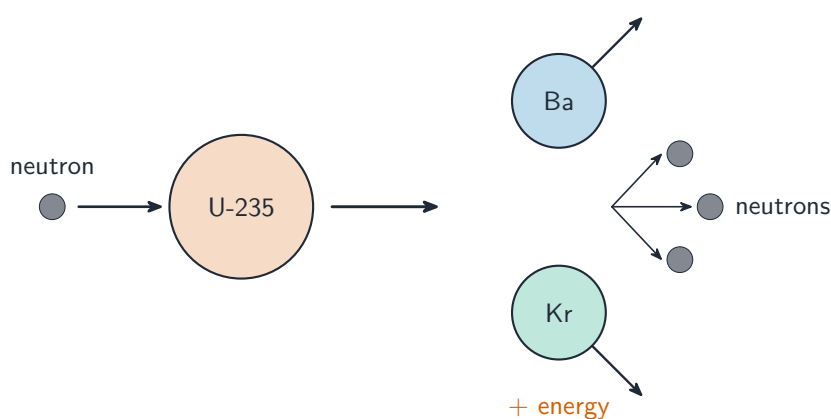
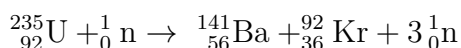
where X is the chemical symbol. For example,  ${}^{197}_{79}\text{Au}$  has 79 protons and  $197 - 79 = 118$  neutrons. The relative charge of the whole nucleus is just  $+Z$  (here  $+79$ ), and its relative mass is about  $A$ .

## 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,  $^{12}_6\text{C}$  and  $^{14}_6\text{C}$  are both carbon.

## Nuclear fission and fusion

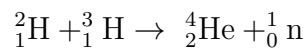
In **nuclear fission** 核裂变, a heavy nucleus absorbs a neutron and then splits into two smaller nuclei, giving out two or three neutrons and a lot of **energy** 能量:



*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:



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*

Image: Ad Meskens, CC BY-SA 3.0 (commons.wikimedia.org)

## 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:

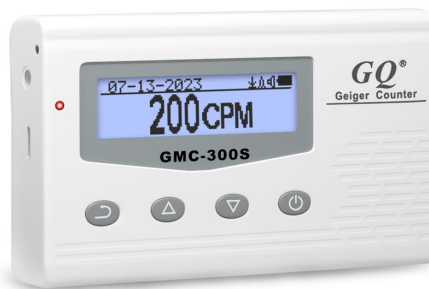
- **radon** 氡 gas in the air (usually the biggest source);
- rocks and buildings;
- food and drink;
- **cosmic rays** 宇宙射线 from space.

## 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:

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



*A Geiger counter detects radiation and shows the count rate, here in counts per minute (CPM)*

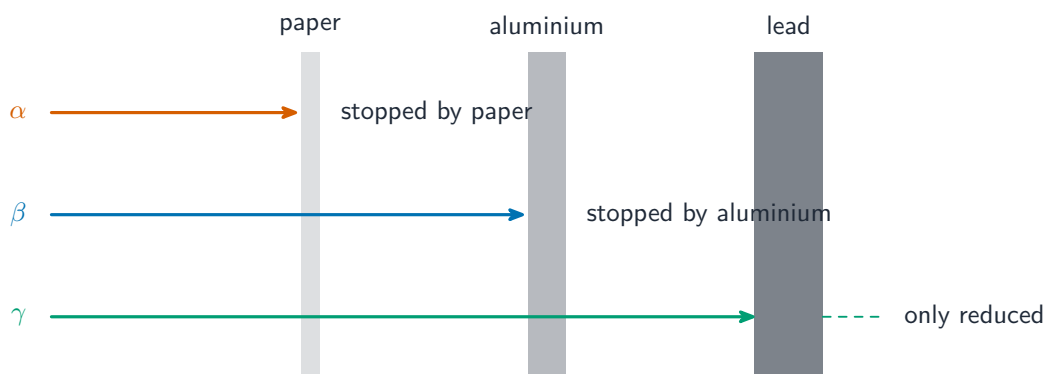
Image: GQ Electronics, Product image (gq-llc.myshopify.com)

## 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 <b>aluminium</b> 铝
gamma ( $\gamma$ )	a high-energy <b>electromagnetic wave</b> 电磁波, no charge	weakest	thick <b>lead</b> 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** 粒子 is in the middle. **Gamma radiation** 射线 is the least ionising but the most penetrating.

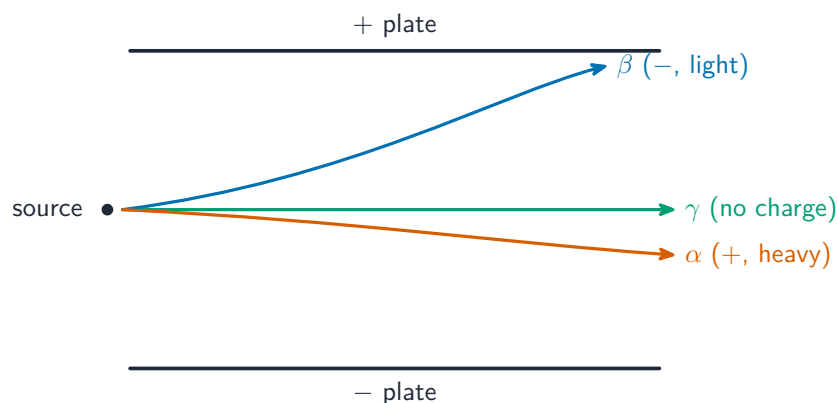


*Paper stops alpha, a few millimetres of aluminium stops beta, and thick lead only reduces gamma*

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.

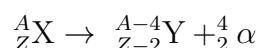


*Alpha and beta bend in opposite directions; the lighter beta bends more, and uncharged gamma is not deflected*

## Decay equations

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

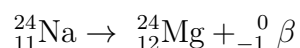
**Alpha decay** —the nucleus loses 2 protons and 2 neutrons, so  $A$  falls by 4 and  $Z$  falls by 2. It becomes a *different element*:



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



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



**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

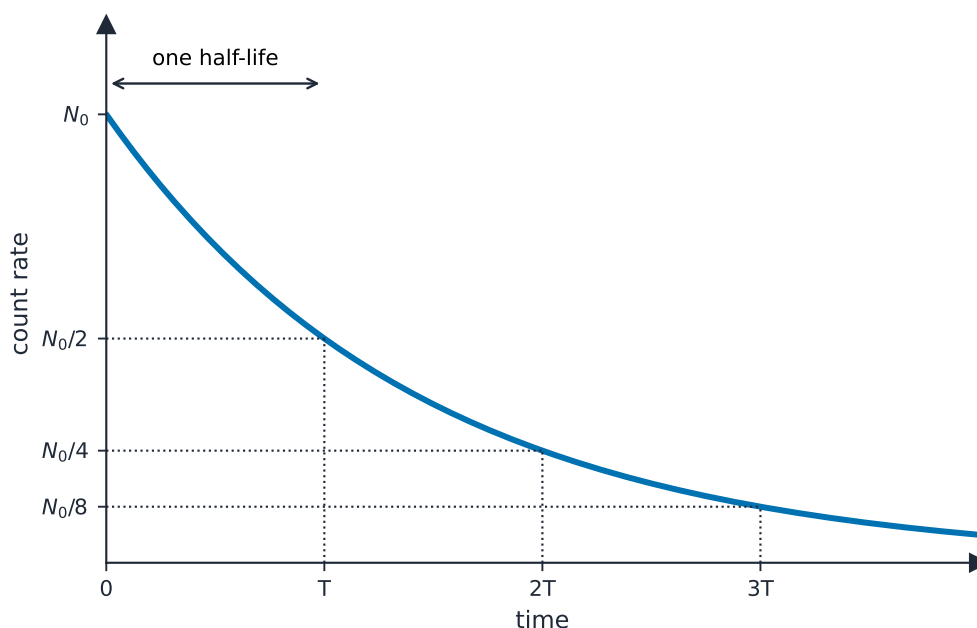
Because decay is random, we cannot follow one nucleus. Instead we describe a large **sample** 样品 using its half-life.

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.



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);
- 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.

## 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.