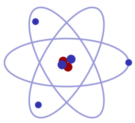
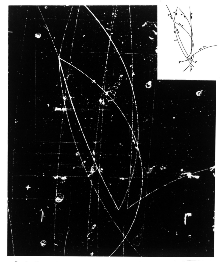
Particle Physics

AS Physics ▪ Topic 11

A-Level Physics



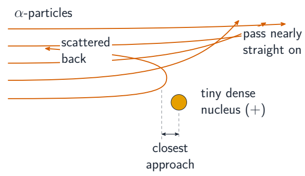
What we will cover



Production and decay of neutral lambda and anti-lambda hyperons

1 The nuclear atom

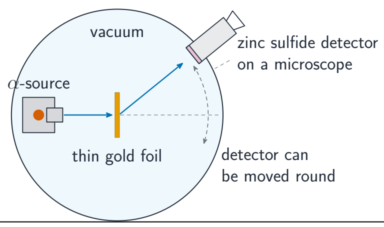
α-particle scattering



- mostly pass straight through, with very little **deflection** 偏转,
- sometimes deflect through small angles,
- rarely (about 1 in 8000) deflect through angles greater than $90°$.
- so: a tiny, dense, positively charged **nucleus** 原子核 at the centre
- the atom is **mostly empty space** (most α-particles pass straight through),

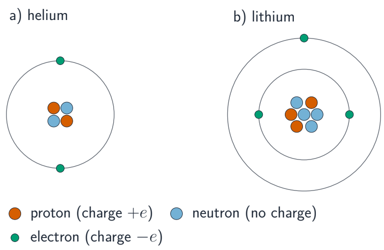
The experiment itself

> Almost every α went straight through; a very few came straight back. That is only possible if the positive charge sits in a tiny, massive core.



The nuclear model

The rare large deflections need a **tiny, dense, positively charged nucleus** at the centre to push the α away.



- **protons** 质子 ($+e$) and **neutrons** 中子 (0) in the nucleus, $\approx 1\,\mathrm{u}$ each
- **electrons** 电子 ($-e$) around it, $\frac{1}{1836}$ of the mass

Unified atomic mass unit

The **unified atomic mass unit** 统一原子质量单位, symbol u, is set so that one atom of ${}^{12}_{6}\mathrm{C}$ has a mass of exactly $12\,\mathrm{u}$.

$$\boxed{1\,\mathrm{u} = 1.661\times10^{-27}\,\mathrm{kg}}$$

proton	neutron	electron
$\approx 1.007\,\mathrm{u}$	$\approx 1.009\,\mathrm{u}$	$\approx 5.5\times10^{-4}\,\mathrm{u}$

A **nucleon** 核子 is about $1\,\mathrm{u}$, so the nucleon number A is very nearly the mass in u.

Nuclide notation and isotopes

A nucleon number

Z X proton number

- neutrons $N = A - Z$
- **isotopes** 同位素: same Z, different numbers of **neutrons** 中子 and so different A (e.g. ${}^{12}_{6}\mathrm{C}$, ${}^{14}_{6}\mathrm{C}$) – chemically alike, nuclearly different

In every nuclear process the **nucleon** 核子 number A and the charge are conserved. Balance both to write any decay equation.

Reading the notation

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

A = nucleon number (protons + neutrons)

Z = proton number

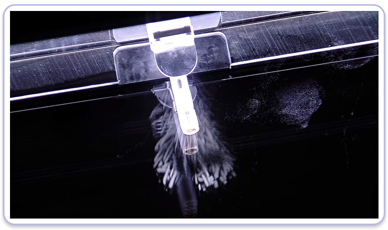
Top is the **nucleon number** 核子数 A, bottom the **proton number** 质子数 Z. **Isotopes** 同位素 share Z and differ in A.

2 Radioactive emissions

Three kinds of radiation

α	β	γ
He nucleus $+2e$, $\approx 4\,\mathrm{u}$ stopped by paper discrete energy	fast electron/positron $\pm e$, tiny mass stopped by Al continuous energy	**photon** 光子 0 charge, 0 mass attenuated by lead discrete energy

Tracks in a cloud chamber

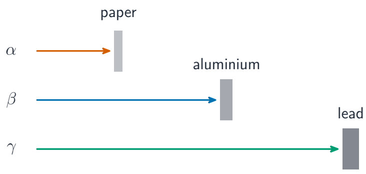


α tracks are short, straight and thick – heavily ionising, quickly stopped.

Penetrating power

- α – paper
- β – a few mm of aluminium
- γ – only attenuated by lead

Ionising power is the reverse order: α strongest.



A γ-ray is a photon, not a particle

- made of a high-energy **photon** 光子 – part of the **electromagnetic spectrum** 电磁波谱
- zero rest mass, zero charge
- long range in air; **attenuated** 衰减 rather than stopped – several cm of lead, or a metre of concrete
- weakest **ionising** 电离 power of the three
- a discrete energy spectrum: the nucleus drops between two nuclear energy levels

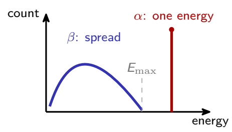
> It is usually a tidy-up step: an α or β decay leaves the **daughter nucleus** 子核 in an **excited state** 激发态, and the γ carries off the surplus.

> That is why γ alone never changes A or Z.

Antiparticles and the neutrino

Every particle has an **antiparticle** 反粒子: same mass, opposite charge (positron = anti-electron). β-decay always emits a third particle:

- β^-: an **antineutrino** 反中微子 $\bar{\nu}_e$
- β^+: a **neutrino** 中微子 ν_e



> α: energy shared by 2 bodies → discrete. β: shared by 3 → continuous – the neutrino takes a varying share.

Why the neutrino had to exist

The problem	In β-decay the emitted electron comes out with a *range* of energies, not the single value a two-body decay demands.
The fix	A third particle carries off the rest. Neutrinos and antineutrinos have zero charge, very small mass, and barely interact.
What it saves	They are hard to detect, but they must be there to balance energy, **momentum** 动量 and the other conserved quantities.
Counting nucleons	The **nucleon number** 核子数 A is the total number of **nucleons** 核子 – protons plus neutrons – and it balances on both sides of every decay equation.

> A conservation law that appears to fail is a prediction: something unseen is carrying the difference.

Writing decay equations

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

$$ {}^{A}_{Z}\mathrm{X} \to {}^{A}_{Z+1}\mathrm{Y} + {}^{0}_{-1}\beta + \bar{\nu}_e $$

Balance A (top) and Z (bottom) on both sides: **nucleon** 核子 number is conserved, and so is charge – **conservation of charge** 电荷守恒.

U-238 (α) and C-14 (β^-)

$$ {}^{238}_{92}\mathrm{U} \to {}^{234}_{90}\mathrm{Th} + {}^{4}_{2}\alpha $$

$$ {}^{14}_{6}\mathrm{C} \to {}^{14}_{7}\mathrm{N} + {}^{0}_{-1}\beta + \bar{\nu}_e $$

check: A $238 = 234 + 4$ ✓ Z $92 = 90 + 2$ ✓

3 Fundamental particles

Quarks

Six **quark** 夸克 flavours:

- u, c, t carry $+\frac{2}{3}e$
- d, s, b carry $-\frac{1}{3}e$

Each **antiquark** 反夸克 has the opposite charge.

Particle Physics
└Fundamental particles

Quarks, in detail

charge $+\frac{2}{3}e$	up u	charm c	top t
charge $-\frac{1}{3}e$	down d	strange s	bottom b

each antiquark has the opposite charge

> Only u and d build ordinary matter – a proton is uud, a neutron udd. The other four appear only at high energy.

Particle Physics
└Fundamental particles

Hadrons: baryons and mesons

Particles built from quarks are **hadrons** 强子:

baryons 重子
three quarks
proton (u u d), neutron (u d d)

mesons 介子
one quark + one antiquark
e.g. $\pi^+ = u\bar{d}$

Protons and neutrons are not fundamental – they are baryons.

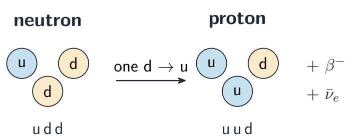
Particle Physics
└Fundamental particles

β-decay at the quark level

A neutron → proton: one down quark becomes an up quark.

$$d \to u + \beta^- + \bar{\nu}_e$$

$$(\beta^+ \colon u \to d + \beta^+ + \nu_e.)$$



Beta-minus decay: one down quark becomes an up quark, turning a neutron into a proton

> Some particles are **fundamental** 基本粒子 (point-like, with no smaller parts as far as we know); others are built from fundamental ones.

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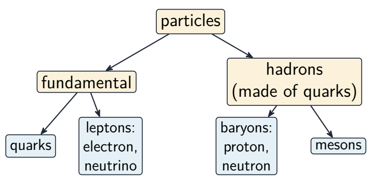
Classifying particles



> Fundamental: **quarks** 夸克 and **leptons** 轻子 (electron, neutrino).

> Built from quarks: protons, neutrons, baryons, mesons.

Particle Physics
└Fundamental particles

Exam tips

- Describe the **nuclear atom** (a small, dense, positive nucleus) using the alpha-scattering evidence.
- Compare α, β and γ by **charge, mass, ionising power and penetration**.
- Use quark composition (proton *uud*, neutron *udd*) and check that **charge and nucleon number balance** in an equation.
- In β^- decay a neutron becomes a proton, an electron and an antineutrino.

4 Recap

Topic 11 – key takeaways

1 Nuclear atom

tiny dense $+$ nucleus; $^{A}_{Z}$X, A & charge conserved

2 Radiation

α (paper), β (Al), γ (lead)

3 β & neutrinos

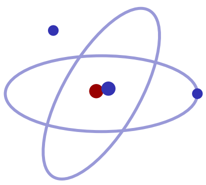
3 bodies $\rightarrow$ continuous spectrum

4 Quarks

hadrons from quarks; quarks & leptons fundamental

Check yourself

1. What did the rare large α deflections show?
2. $^{226}_{88}$Ra decays by α – the daughter's A and Z?
3. Which radiation is a photon?
4. Quark content of a neutron?



Answers **1.** a tiny dense nucleus **2.** $A = 222$, $Z = 86$ **3.** γ **4.** u d d