Particle physics

A-Level Physics

The nuclear atom

Geiger–Marsden -particle scattering

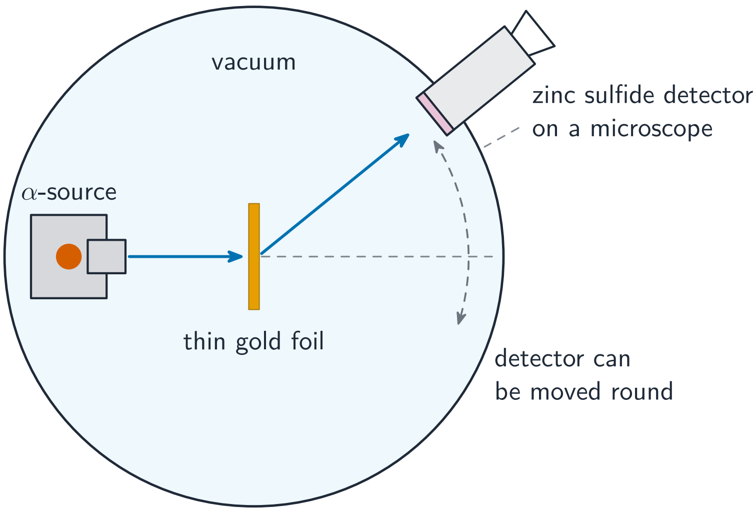
Alpha particles 粒子 fired at a thin gold foil were seen to:

- 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°.

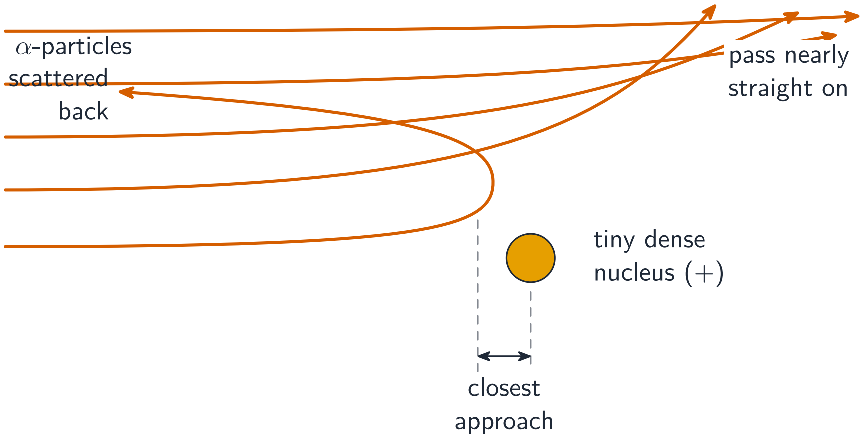
From this Rutherford worked out:

- the atom is **mostly empty space** (most -particles pass straight through),
- there is a **tiny, dense, positively charged nucleus** 原子核 at the centre (the rare large deflections need a concentrated charge to push the away),
- almost all of the atom's mass is in this nucleus.

Order of magnitude: atom diameter $\sim 10^{-10}$ m, nucleus diameter $\sim 10^{-15}$ m —the nucleus is about 10^5 times smaller than the atom.



The α-scattering experiment —α-particles strike a thin gold foil in a vacuum



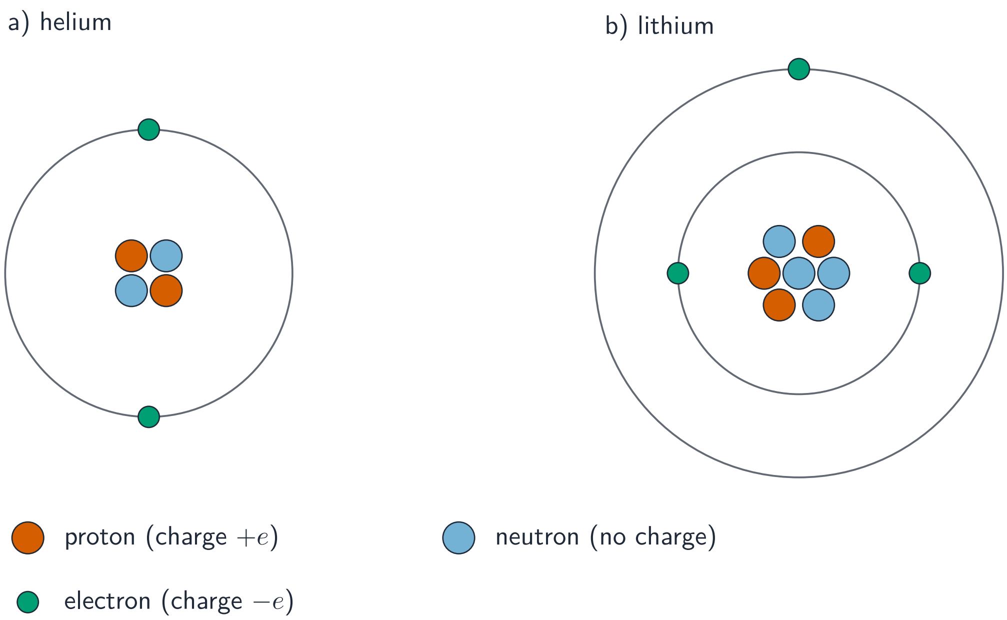
Most α-particles pass nearly straight through; a few are deflected sharply by the tiny nucleus

Simple nuclear model

An atom has:

- a central nucleus of **protons** 质子 (positive, charge $+e$) and **neutrons** 中子 (no charge),
- **electrons** 电子 (charge $-e$) around the nucleus.

The proton and neutron have almost the same mass (≈ 1 u); the electron is about $\frac{1}{1836}$ of the proton's mass.



Simple models of a helium atom and a lithium atom (not to scale)

Notation and key numbers

For a **nuclide** 核素 written ${}^{A}_{Z}\mathrm{X}$:

- **proton number** 质子数 Z (also the atomic number): the number of protons. It fixes the element.
- **nucleon number** 核子数 A (also the mass number): the total number of **nucleons** 核子 (protons + neutrons).
- number of neutrons $N = A - Z$.

A neutral atom has the same number of electrons as protons.

Isotopes

Isotopes 同位素 are atoms of the same element (same Z) with different numbers of neutrons (different A). They behave the same chemically but differently in the nucleus. Example: ${}^{12}_{6}\mathrm{C}$ and ${}^{14}_{6}\mathrm{C}$ are isotopes of carbon.

Conservation laws in nuclear processes

In any nuclear process:

- nucleon number A is conserved (total A before = total A after),
- **charge** is conserved (this is **conservation of charge** 电荷守恒).

These two rules let you balance decay and reaction equations.

Unified atomic mass unit

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

$$1\ \mathrm{u} = 1.661 \times 10^{-27}\ \mathrm{kg}.$$

A proton has mass ≈ 1.007 u; a neutron ≈ 1.009 u; an electron $\approx 5.5 \times 10^{-4}$ u.

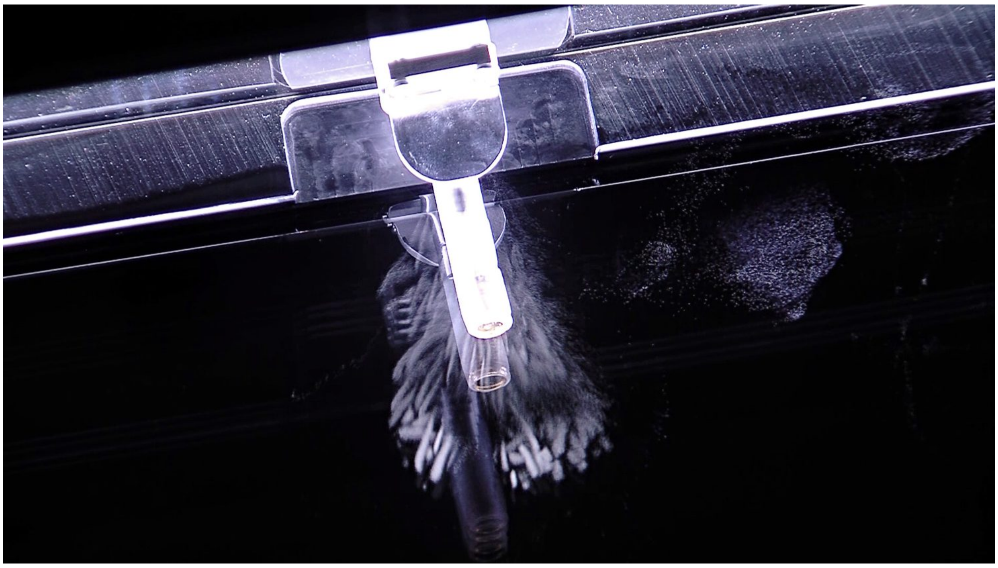
Radioactive emissions

An unstable nucleus rearranges itself and gives out one of three kinds of **radiation** 辐射. This is **radioactive** 放射性 decay. Each kind has its own properties.

-radiation

- **Made of**: a helium-4 nucleus, ${}^{4}_{2}\alpha$ (two protons + two neutrons).
- **Mass**: ≈ 4 u.
- **Charge**: $+2e$.
- **Range in air**: a few cm. Stopped by a sheet of paper.
- **Ionising power**: strong —it is good at **ionising** 电离.
- **Energy spectrum**: **discrete** 分立 (one decay gives -particles at one or a few sharp energies).

A **cloud chamber** 云室 makes the tracks visible: each -particle leaves a short, straight, thick trail of tiny droplets as it ionises the air. The short equal lengths show the -particles all carry about the same energy.



Alpha-particle tracks in a cloud chamber, fanning out from an americium-241 source

Image: Nuledo, CC BY-SA 4.0 (commons.wikimedia.org)

-radiation

Two types of **beta particle** 粒子:

- β^-: a fast electron, given out when a neutron turns into a proton.
- β^+: a **positron** 正电子 (the electron's antiparticle), given out when a proton in a proton-rich nucleus turns into a neutron.

Properties (both types):

- **Mass**: $\approx 1/1836$ u (much less than).
- **Charge**: $-e$ for β^-, $+e$ for β^+.
- **Range in air**: about 1 m. Stopped by a few mm of aluminium.
- **Energy spectrum**: **continuous** 连续 up to a maximum (see below).

-radiation

- **Made of**: a high-energy **photon** 光子—part of the **electromagnetic spectrum** 电磁波谱.
- **Mass**: zero (rest mass).
- **Charge**: zero.
- **Range in air**: large (follows the inverse-square law). Strongly **attenuated** 衰减 by several cm of lead or about a metre of concrete.
- **Ionising power**: weakest.
- **Energy spectrum**: discrete (a **gamma ray** 射线 is given out as the nucleus drops between two nuclear energy levels).

A nucleus often gives out a -photon as a ”tidy-up” step after an or decay leaves the **daughter nucleus** 子核 in an **excited state** 激发态.

Antiparticles, neutrinos and antineutrinos

Every particle has an **antiparticle** 反粒子 with the **same mass** but **opposite charge**. The positron is the antiparticle of the electron.

In -decay, a third particle is always given out as well:

- β^- decay: an **antineutrino** 反中微子 $\bar{\nu}_\mathrm{e}$.
- β^+ decay: a **neutrino** 中微子 ν_e.

Neutrinos and antineutrinos have zero charge, very small mass, and barely interact — they are very hard to detect, but they must be there to balance energy, **momentum** 动量 and other conserved quantities in -decay.

Why has a continuous spectrum (and does not)

In -decay the **energy** 能量 released is shared between just two particles (the daughter nucleus and the). Conservation of momentum and energy then fixes the ’s energy to one value (discrete).

In -decay the energy is shared between **three** particles (the daughter nucleus, the , and the (anti)neutrino). The can take any share from zero up to a maximum, so its energy spectrum is continuous.

Writing decay equations

A general -decay:

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

(check: $A = (A-4) + 4$, $Z = (Z-2) + 2$.)

A general β^- decay:

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + {}^{0}_{-1}\beta + \bar{\nu}_\mathrm{e}. $$

A general β^+ decay:

$$ {}^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z-1}\mathrm{Y} + {}^{0}_{+1}\beta + \nu_\mathrm{e}. $$

Fundamental particles

A bubble chamber reveals the curved tracks of charged particles.

Image: CERN, CC BY-SA 4.0 (commons.wikimedia.org)

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.

Quarks

A **quark** 夸克 is a fundamental particle. There are six **flavours** 味:

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

Each quark has an **antiquark** 反夸克 with the same size of charge but the opposite sign: $\bar{u}$ (charge $-\frac{2}{3}e$), $\bar{d}$ (charge $+\frac{1}{3}e$). No other quark property is tested.

Hadrons: baryons and mesons

Particles built from quarks are **hadrons** 强子. Two types:

- **baryons** 重子—three quarks. Examples: proton (u u d), neutron (u d d). Charge check: $\frac{2}{3}+\frac{2}{3}-\frac{1}{3}=+1$ for the proton; $\frac{2}{3}-\frac{1}{3}-\frac{1}{3}=0$ for the neutron.
- **mesons** 介子—one quark and one antiquark (for example π^+ is $\mathrm{u\bar{d}}$).

Protons and neutrons are **not** fundamental —they are baryons made of quarks.

Quark changes in -decay

In β^- decay a neutron turns into a proton; in quark terms, **one down quark turns into an up quark**:

$$\mathrm{d} \to \mathrm{u} + \beta^- + \bar{\nu}_\mathrm{e}.$$

In β^+ decay a proton turns into a neutron; **one up quark turns into a down quark**:

$$\mathrm{u} \to \mathrm{d} + \beta^+ + \nu_\mathrm{e}.$$

Leptons

Leptons 轻子 are fundamental particles that are not made of quarks. Electrons and neutrinos are leptons. (Heavier leptons —the muon and tau —are not needed for this syllabus.)

Quick particle sorter

When asked ”which list has only fundamental particles?”: **quarks, electrons, positrons, neutrinos, antineutrinos** are fundamental; protons, neutrons, baryons, mesons and hadrons are not.