

The nuclear atom

International Baccalaureate · IB Diploma · Chemistry · HL

Scope and prerequisites

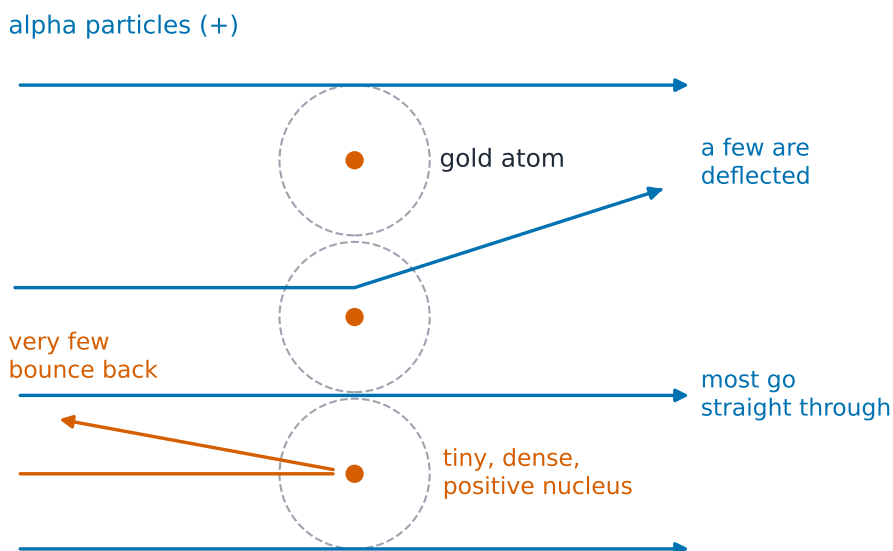
This handout teaches Structure 1.2, The nuclear atom, for the course first assessed in 2025. Sections marked **AHL** are for Higher Level only.

Prerequisites: the particle model of matter from Structure 1.1, and positive and negative charge. Use the data booklet for relative atomic masses.

Inside the atom

■ What did Rutherford see?

In 1909 Geiger and Marsden fired alpha particles, which are small and positive, at a sheet of gold foil only a few hundred atoms thick. Almost all of them went straight through. But about 1 in 8000 bounced back towards the source. Rutherford said it was “as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you”.

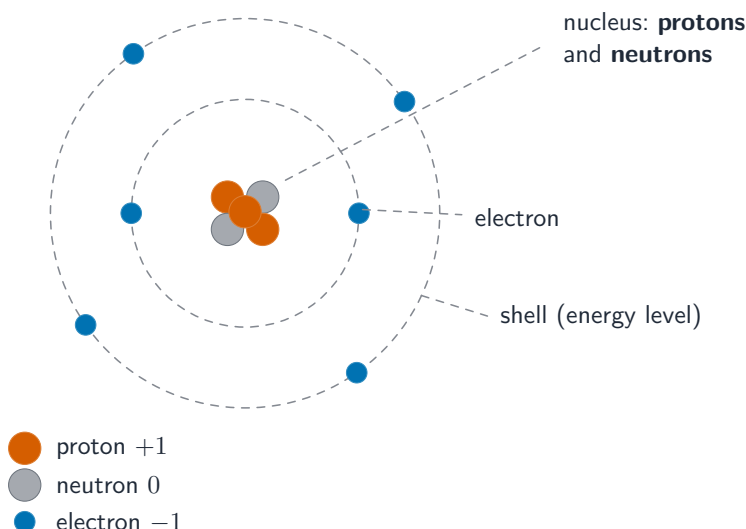


Most of an atom is empty space; its mass and positive charge sit in a tiny nucleus

- Most alpha particles pass straight through, so an atom is mostly empty space.
- A few are deflected, so there is a region of concentrated positive charge that repels them.
- Very few bounce back, so that region, the **nucleus**, is tiny and holds almost all the mass.

The nucleus is about 10^{-15} m across, and the atom about 10^{-10} m: the atom is about 100 000 times wider than its nucleus.

■ Protons, neutrons and electrons



Protons and neutrons are in the nucleus; electrons occupy the space around it

Particle	Relative mass	Relative charge	Where
proton	1	+1	nucleus
neutron	1	0	nucleus
electron	1/1836 (about 0.0005)	-1	outside the nucleus

Protons and neutrons together are called **nucleons**. An atom has equal numbers of protons and electrons, so it has no overall charge.

Atomic number and mass number

■ Nuclear symbols

- The **atomic number** Z is the number of protons. It decides which element the atom is.
- The **mass number** A is the number of protons plus neutrons.
- Number of neutrons = $A - Z$.

The **nuclear symbol** writes A at the top left and Z at the bottom left: ${}^{23}_{11}\text{Na}$ has 11 protons, $23 - 11 = 12$ neutrons and 11 electrons.

■ Ions

An **ion** has gained or lost electrons. The number of protons does not change.

Species	Protons	Neutrons	Electrons
$^{23}_{11}\text{Na}$	11	12	11
$^{23}_{11}\text{Na}^+$	11	12	10
$^{32}_{16}\text{S}^{2-}$	16	16	18
$^{27}_{13}\text{Al}^{3+}$	13	14	10

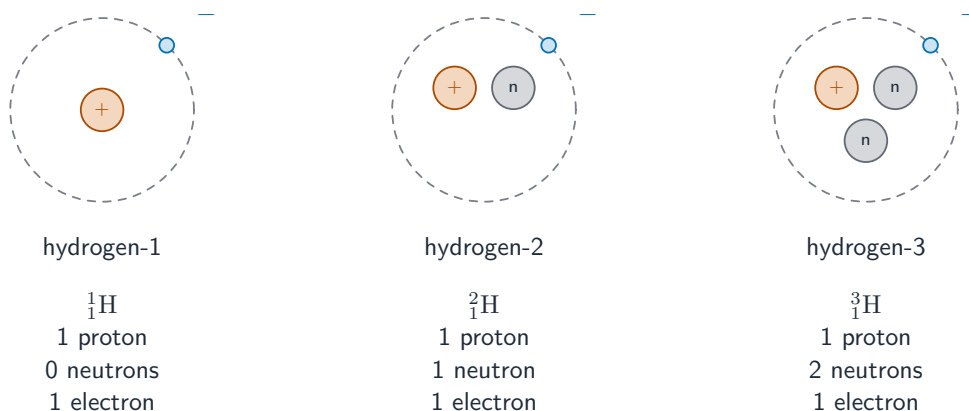
A positive ion has fewer electrons than protons; a negative ion has more.

Isotopes

■ Same element, different mass

Isotopes are atoms of the same element with different numbers of neutrons: the same Z , a different A .

Hydrogen isotopes (not to scale)



Isotopes differ only in the number of neutrons

- Isotopes have the same number of electrons, so they have the **same chemical properties**.
- They have different masses, so their **physical properties** differ slightly: density, rate of diffusion, and melting and boiling points. Heavy water, D_2O , boils at 101.4°C .
- Some isotopes are radioactive. Carbon-14 is used to date old wood and bone; cobalt-60 is used in radiotherapy; iodine-131 is used to treat thyroid disease.

■ Relative atomic mass from abundances

The relative atomic mass A_r of an element is the weighted mean of the masses of its isotopes, using their **abundances** (percentages in a natural sample).

$$A_r = \frac{\sum(\text{isotope mass} \times \text{abundance})}{100}$$

■ Worked example: chlorine

Chlorine is 75.8% ^{35}Cl and 24.2% ^{37}Cl .

$$A_r = \frac{35 \times 75.8 + 37 \times 24.2}{100} = \frac{2653 + 895.4}{100} = 35.5$$

The answer lies nearer 35 because ^{35}Cl is the more abundant isotope.

■ Worked example: finding an abundance

Copper has two isotopes, ^{63}Cu and ^{65}Cu , and $A_r = 63.55$. Let the abundance of ^{63}Cu be $x\%$.

$$63x + 65(100 - x) = 63.55 \times 100$$

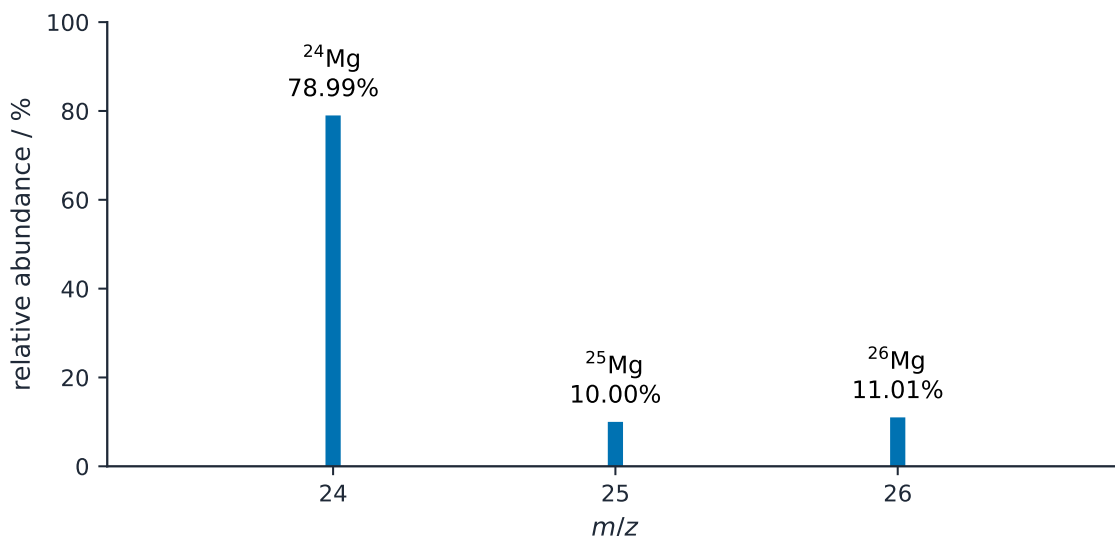
$$6500 - 2x = 6355 \quad \Rightarrow \quad x = 72.5$$

So ^{63}Cu is 72.5% and ^{65}Cu is 27.5%. (Using the exact isotope masses, 62.93 and 64.93, gives the measured 69%; with whole-number masses the answer is approximate.)

AHL: Mass spectra of elements

■ How a mass spectrum is read

A **mass spectrometer** turns atoms into positive ions and separates them by their mass-to-charge ratio, m/z . For ions with a 1+ charge, m/z equals the mass of the isotope.



Each line is one isotope; its height is the isotope's relative abundance

- The number of lines is the number of isotopes.
- The position of each line gives the isotope's mass.
- The height gives its relative abundance.

■ Worked example: magnesium

$$A_r = \frac{24 \times 78.99 + 25 \times 10.00 + 26 \times 11.01}{100} = \frac{1895.8 + 250.0 + 286.3}{100} = 24.32$$

The data booklet value is 24.31.

■ When heights are not percentages

Sometimes the heights are given as relative intensities that do not add up to 100. Then divide by their total instead of by 100. For a spectrum with lines at m/z 10 (height 23) and 11 (height 100):

$$A_r = \frac{10 \times 23 + 11 \times 100}{23 + 100} = \frac{1330}{123} = 10.8$$

This is boron.

Practice

1. State the relative mass, relative charge and position of a proton, a neutron and an electron.
2. Explain what the gold-foil experiment showed about the structure of the atom.
3. Give the numbers of protons, neutrons and electrons in $^{40}_{20}\text{Ca}^{2+}$ and in $^{19}_9\text{F}^-$.

- A species has 26 protons, 30 neutrons and 23 electrons. Write its nuclear symbol with its charge.
- Explain why ^{35}Cl and ^{37}Cl have the same chemical properties.
- State one physical property that differs between isotopes, and explain why.
- Neon is 90.5% ^{20}Ne , 0.3% ^{21}Ne and 9.2% ^{22}Ne . Calculate its A_r to 2 decimal places.
- Gallium has isotopes ^{69}Ga and ^{71}Ga , and $A_r = 69.8$. Calculate the abundance of each.
- AHL.** A spectrum of an element has lines at m/z 79 (50.7%) and 81 (49.3%). Calculate A_r and identify the element.
- AHL.** Lines at m/z 28, 29 and 30 have heights 92.2, 4.7 and 3.1. Calculate A_r and identify the element.
- AHL.** Explain why the mass spectrum of chlorine gas, Cl_2 , has lines at m/z 70, 72 and 74.

Answers.

- Proton: 1, +1, nucleus. Neutron: 1, 0, nucleus. Electron: 1/1836, -1, outside the nucleus.
- Most alpha particles passed straight through, so the atom is mostly empty space. A few were deflected or bounced back, so the positive charge and most of the mass are in a tiny, dense nucleus.
- Ca^{2+} : 20 protons, 20 neutrons, 18 electrons. F^- : 9 protons, 10 neutrons, 10 electrons.
- $^{56}_{26}\text{Fe}^{3+}$.
- They have the same number of electrons (and the same electron configuration), and chemical reactions involve electrons.
- Density, rate of diffusion, melting or boiling point: the isotopes have different masses.
- $(20 \times 90.5 + 21 \times 0.3 + 22 \times 9.2)/100 = (1810 + 6.3 + 202.4)/100 = 20.19$.
- $69x + 71(100 - x) = 6980$, so $7100 - 2x = 6980$ and $x = 60$: ^{69}Ga 60%, ^{71}Ga 40%.
- AHL.** $(79 \times 50.7 + 81 \times 49.3)/100 = 79.99$, about 80: bromine (data booklet 79.90).
- AHL.** $(28 \times 92.2 + 29 \times 4.7 + 30 \times 3.1)/(92.2 + 4.7 + 3.1) = 2810.9/100 = 28.11$: silicon.
- AHL.** Each Cl_2 molecule holds two atoms, each ^{35}Cl or ^{37}Cl : $^{35}\text{Cl}-^{35}\text{Cl}$ is 70, $^{35}\text{Cl}-^{37}\text{Cl}$ is 72 and $^{37}\text{Cl}-^{37}\text{Cl}$ is 74.

Exam tips

- The atomic number is the number of protons; never say “the number of electrons”, which changes in an ion.

- In an ion, change only the electrons: add for a negative charge, subtract for a positive one.
- Isotopes: “same number of protons, different number of neutrons”. Say “same chemical properties because the same electron configuration”.
- Give A_r to the precision the data allows, and check that it lies between the lightest and heaviest isotope, nearer the more abundant one.
- **AHL.** If the line heights do not add up to 100, divide by their sum.