The nuclear atom

International Baccalaureate · IB Diploma · Chemistry · HL

Scope and prerequisites

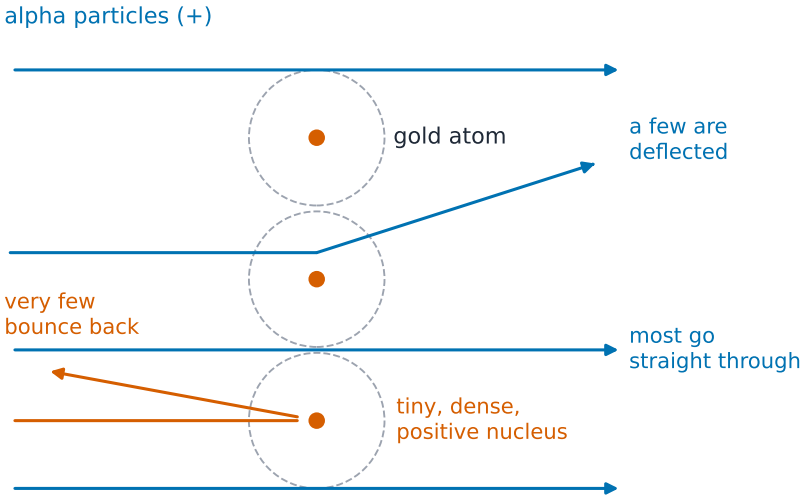
This handout teaches Structure 1.2, The nuclear atom, for the course first assessed in 2025. Sections marked **AHL** are for Higher Level only.

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".

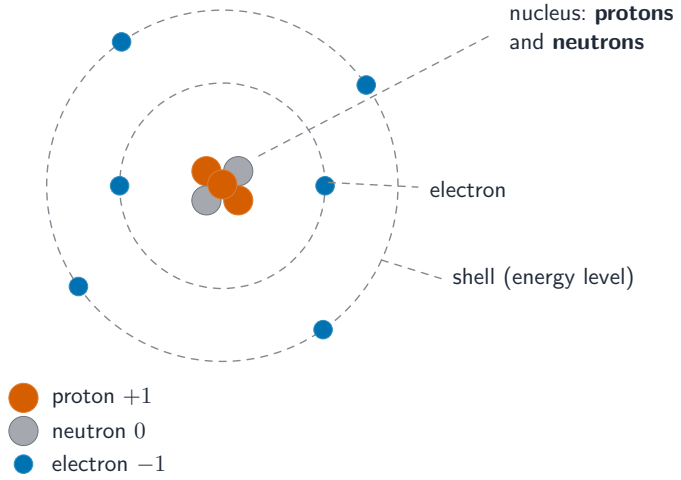


Most of an atom is empty space; its mass and positive charge sit in a tiny nucleus

- 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: ${}^{23}_{11}\mathrm{Na}$ 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.

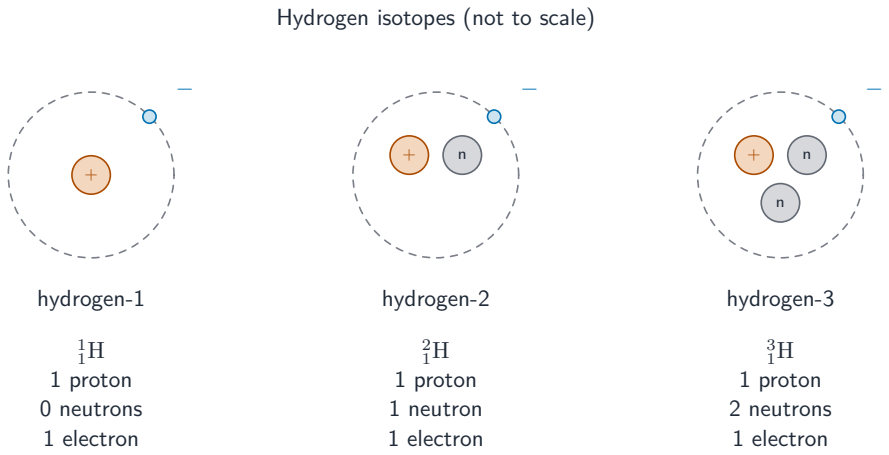
Species	Protons	Neutrons	Electrons
$^{23}_{11}\mathrm{Na}$	11	12	11
$^{23}_{11}\mathrm{Na}^{+}$	11	12	10
$^{32}_{16}\mathrm{S}^{2-}$	16	16	18
$^{27}_{13}\mathrm{Al}^{3+}$	13	14	10

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-1	hydrogen-2	hydrogen-3
$^{1}_{1}\mathrm{H}$	$^{2}_{1}\mathrm{H}$	$^{3}_{1}\mathrm{H}$
1 proton	1 proton	1 proton
0 neutrons	1 neutron	2 neutrons
1 electron	1 electron	1 electron

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, $\mathrm{D_2O}$, 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% $^{35}\mathrm{Cl}$ and 24.2% $^{37}\mathrm{Cl}$.

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

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

Worked example: finding an abundance

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

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

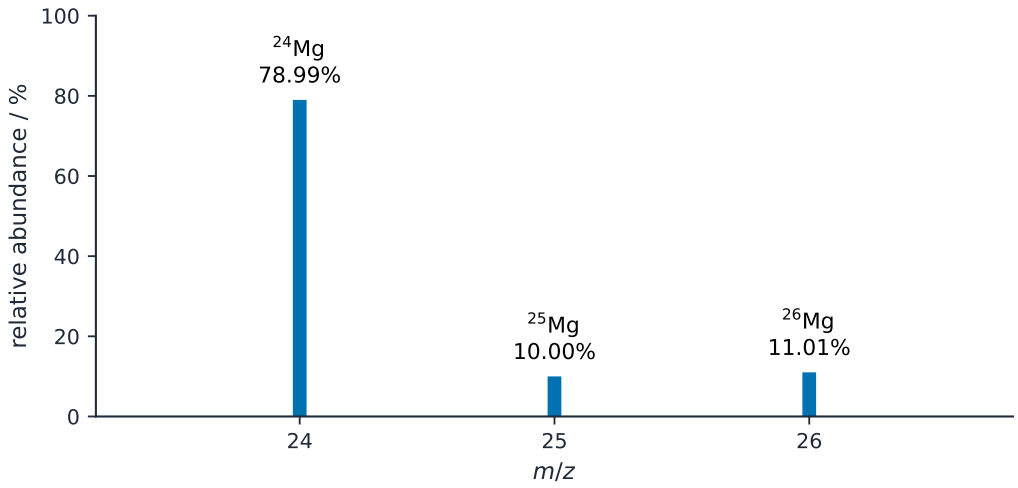
$$6500 - 2x = 6355 \quad \Rightarrow \quad x = 72.5$$

So $^{63}\mathrm{Cu}$ is 72.5% and $^{65}\mathrm{Cu}$ 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 $^{40}_{20}Ca^{2+}$ and in $^{19}_{9}F^{-}$.
4. A species has 26 protons, 30 neutrons and 23 electrons. Write its nuclear symbol with its charge.
5. Explain why ^{35}Cl and ^{37}Cl have the same chemical properties.
6. State one physical property that differs between isotopes, and explain why.
7. Neon is 90.5% ^{20}Ne, 0.3% ^{21}Ne and 9.2% ^{22}Ne. Calculate its A_r to 2 decimal places.
8. Gallium has isotopes ^{69}Ga and ^{71}Ga, and $A_r = 69.8$. Calculate the abundance of each.
9. **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.
10. **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.
11. **AHL.** Explain why the mass spectrum of chlorine gas, Cl_2, has lines at m/z 70, 72 and 74.

Answers.

1. Proton: 1, +1, nucleus. Neutron: 1, 0, nucleus. Electron: 1/1836, −1, outside the nucleus.
2. 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.
3. Ca^{2+}: 20 protons, 20 neutrons, 18 electrons. F^-: 9 protons, 10 neutrons, 10 electrons.
4. $^{56}_{26}Fe^{3+}$.
5. They have the same number of electrons (and the same electron configuration), and chemical reactions involve electrons.
6. Density, rate of diffusion, melting or boiling point: the isotopes have different masses.
7. $(20 \times 90.5 + 21 \times 0.3 + 22 \times 9.2)/100 = (1810 + 6.3 + 202.4)/100 = 20.19$.
8. $69x + 71(100 - x) = 6980$, so $7100 - 2x = 6980$ and $x = 60$: ^{69}Ga 60%, ^{71}Ga 40%.
9. **AHL.** $(79 \times 50.7 + 81 \times 49.3)/100 = 79.99$, about 80: bromine (data booklet 79.90).
10. **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.
11. **AHL.** Each Cl_2 molecule holds two atoms, each ^{35}Cl or ^{37}Cl: ^{35}Cl–^{35}Cl is 70, ^{35}Cl–^{37}Cl is 72 and ^{37}Cl–^{37}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.