9701 CHEMISTRY · TOPIC 2 · AS LEVEL

Atoms, Molecules and Stoichiometry

01 · RELATIVE MASSES

A_r — weighted mean mass of an atom relative to ^{12}C taken as exactly 12. **M_r** — the same for a molecule or formula unit. Both are ratios, so no units.

A_r = Σ(isotopic mass × %abundance) ÷ 100. Read abundances off a mass spectrum (x-axis m/z, y-axis relative abundance).

02 · THE MOLE

n = m ÷ M
N = n × L (L = 6.02 × 10^{23} mol^{-1})

One mole is the amount containing as many particles as there are atoms in 12 g of ^{12}C. Always state *what* the particles are — atoms, molecules or ions.

03 · SOLUTIONS AND GASES

n = c × V(dm^3) · c = n ÷ V
pV = nRT · V_m = 24.0 dm^3 at r.t.p.

Ideal-gas units: p in Pa, V in m^3 (1 dm^3 = 1 × 10^{-3} m^3), T in K, R = 8.31 J K^{-1} mol^{-1}. cm^3 ÷ 1000 = dm^3.

04 · EMPIRICAL AND MOLECULAR FORMULAE

Empirical — simplest whole-number ratio of atoms. **Molecular** — the actual number in one molecule; it is a whole-number multiple of the empirical formula.

Method. % or mass → ÷ A_r → divide by the smallest → ×2 or ×3 to clear halves and thirds.

C 40.0 %, H 6.7 %, O 53.3 %:
3.33 : 6.7 : 3.33 → 1 : 2 : 1 → **CH_2O**
If M_r = 180, 180 ÷ 30 = 6 → **$C_6H_{12}O_6$**

05 · BALANCING AND STATE SYMBOLS

Balance atoms first, then charge. Every equation needs **(s) (l) (g) (aq)**. Ionic equations show only the species that change — cancel the spectator ions.

Half-equations: balance atoms, then O with H_2O, then H with H^+, then charge with e^-.

06 · REACTING-MASS CALCULATIONS

The route every time:
mass or volume → **moles** → mole ratio from the equation → moles of the wanted species → mass or volume.

Never compare masses directly across an equation — only moles carry the ratio.

07 · WORKED EXAMPLE — LIMITING REACTANT

4.00 g Mg reacts with 100 cm^3 of 2.00 mol dm^{-3} HCl.
$Mg + 2HCl \rightarrow MgCl_2 + H_2$

n(Mg) = 4.00 ÷ 24.3 = 0.165 mol
n(HCl) = 2.00 × 0.100 = 0.200 mol
HCl needed for all the Mg = 2 × 0.165 = 0.329 mol > 0.200
→ **HCl is limiting**

$n(H_2)$ = 0.200 ÷ 2 = 0.100 mol
$V(H_2)$ = 0.100 × 24.0 = **2.40 dm^3 at r.t.p.**

08 · WORKED EXAMPLE — REACTING MASSES

What mass of CaO forms from 25.0 g of $CaCO_3$?
$CaCO_3 \rightarrow CaO + CO_2$

$n(CaCO_3)$ = 25.0 ÷ 100.1 = 0.250 mol
ratio 1 : 1 → n(CaO) = 0.250 mol
m(CaO) = 0.250 × 56.1 = **14.0 g**

Check by difference: the 11.0 g lost is the CO_2.

09 · TYPES OF FORMULA

Type	Ethanoic acid
empirical	CH_2O
molecular	$C_2H_4O_2$
structural	CH_3COOH
displayed	every bond drawn

An ionic compound has only an empirical formula — the lattice has no molecules.

10 · WORKED EXAMPLE — COMBUSTION DATA

0.150 g of a hydrocarbon burns to give 0.440 g CO_2 and 0.270 g H_2O.

n(C) = 0.440 ÷ 44.0 = 0.0100 mol
n(H) = 2 × (0.270 ÷ 18.0) = 0.0300 mol
ratio C : H = 1 : 3 → **CH_3**
If M_r = 30, molecular formula = **C_2H_6**

11 · AVOGADRO'S LAW

Equal volumes of gases at the same temperature and pressure contain equal numbers of molecules. So for gases the **volume ratio equals the mole ratio** — no need to convert.

$N_2 + 3H_2 \rightarrow 2NH_3$: 10 cm^3 of N_2 needs 30 cm^3 of H_2 and gives 20 cm^3 of NH_3, all measured under the same conditions.

12 · PERCENTAGE COMPOSITION

% by mass = (n × A_r) ÷ M_r × 100

% N in NH_4NO_3 (M_r = 80.0):
(2 × 14.0) ÷ 80.0 × 100 = **35.0 %**

Compare fertilisers this way — urea $CO(NH_2)_2$ is 46.7 % N.

13 · THE FOUR ROUTES TO MOLES

From mass — n = m ÷ M
From solution — n = c × V(dm^3)
From gas volume — n = V ÷ 24.0 dm^3 at r.t.p., or n = pV ÷ RT
From particles — n = N ÷ 6.02 × 10^{23}

14 · WORKED EXAMPLE — GAS VOLUMES

50 cm^3 of C_3H_8 burns in 300 cm^3 of O_2, all volumes at the same conditions.
$C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O(l)$

O_2 needed = 5 × 50 = 250 cm^3 → 50 cm^3 O_2 left over
CO_2 formed = 3 × 50 = 150 cm^3
Water is a liquid at r.t.p., so it adds no volume.

Final gas volume = 150 + 50 = **200 cm^3**

15 · YIELD AND ATOM ECONOMY

% yield = actual ÷ theoretical × 100
atom economy = M_r(desired) ÷ ΣM_r(products) × 100

Theoretical yield comes from the limiting reactant. Losses come from side reactions, reversible reactions and transfer losses. An addition reaction has 100 % atom economy.

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Titrations and Gas Calculations

16 · STANDARD SOLUTIONS

Dissolve a weighed mass, transfer with washings to a volumetric flask, make up to the mark, invert to mix. Concentration in mol dm^{-3} or g dm^{-3}; **g dm^{-3} = mol dm^{-3} × M**.

Dilution: $c_1V_1 = c_2V_2$. Moles are unchanged by dilution.

17 · TITRATION TECHNIQUE

Pipette the aliquot, rinse the burette with the titrant, record initial and final readings to **0.05 cm^3**, discard the rough titre and average only **concordant** titres (within 0.10 cm^3).

Rinse the conical flask with distilled water only. Adding more water does not change the moles present, so it does not affect the titre.

18 · WORKED EXAMPLE — TITRATION

25.0 cm^3 of NaOH needs 22.40 cm^3 of 0.100 mol dm^{-3} H_2SO_4.
$2NaOH + H_2SO_4 \rightarrow Na_2SO_4 + 2H_2O$

$n(H_2SO_4) = 0.100 \times 0.02240 = 2.24 \times 10^{-3}$ mol
$n(NaOH) = 2 \times 2.24 \times 10^{-3} = 4.48 \times 10^{-3}$ mol
$c(NaOH) = 4.48 \times 10^{-3} \div 0.0250 =$ **0.179 mol dm^{-3}**

Give 3 s.f. — the data limits it.

19 · BACK TITRATION

Used when the sample is insoluble or reacts slowly (an impure carbonate, an antacid). React with a **known excess** of acid, then titrate the leftover acid with standard alkali.

n reacted with sample = n added – n left over

20 · WORKED EXAMPLE — GAS LAW

0.240 g of a gas occupies 240 cm^3 at 100 kPa and 300 K. Find M_r.

$V = 240 \times 10^{-6}$ m^3, $p = 1.00 \times 10^5$ Pa
$n = pV \div RT = (1.00 \times 10^5 \times 2.40 \times 10^{-4}) \div (8.31 \times 300)$
$n = 24.0 \div 2493 = 9.63 \times 10^{-3}$ mol
$M = 0.240 \div 9.63 \times 10^{-3} =$ **24.9 g mol^{-1}**

21 · IDEAL GASES

Assumptions: negligible molecular volume, no intermolecular forces, elastic collisions, random rapid motion.

Real gases deviate most at **high pressure and low temperature**, where molecules are close together and attractions matter. Behaviour is most ideal at high T and low p.

22 · WATER OF CRYSTALLISATION

For $MX \cdot xH_2O$, find moles of the anhydrous salt and moles of water lost on heating, then take the ratio.

2.50 g $CuSO_4 \cdot xH_2O \rightarrow$ 1.60 g $CuSO_4$
$n(CuSO_4) = 1.60 \div 159.6 = 0.01003$ mol
$n(H_2O) = 0.90 \div 18.0 = 0.0500$ mol
ratio 1 : 4.99 → **x = 5**

23 · APPARATUS AND UNCERTAINTY

Apparatus	Uncertainty
burette (per reading)	± 0.05 cm^3
pipette 25.0 cm^3	± 0.06 cm^3
balance (per reading)	± 0.001 g

A titre needs **two** burette readings, so the total uncertainty is ± 0.10 cm^3. % uncertainty = uncertainty ÷ measurement × 100; reduce it by using a larger titre or a bigger sample mass.

24 · WORKED EXAMPLE — BACK TITRATION

1.00 g of impure $CaCO_3$ is added to 30.0 cm^3 of 1.00 mol dm^{-3} HCl. The excess needs 22.0 cm^3 of 0.500 mol dm^{-3} NaOH.

n(HCl) added = 0.0300 mol
n(HCl) left = 0.0220 × 0.500 = 0.0110 mol
n(HCl) reacted = 0.0190 mol

$CaCO_3 + 2HCl \rightarrow CaCl_2 + H_2O + CO_2$
$n(CaCO_3) = 0.00950$ mol
$m = 0.00950 \times 100.1 = 0.951$ g → **purity 95.1 %**

25 · IONIC EQUATIONS TO KNOW

Neutralisation
$H^+ + OH^- \rightarrow H_2O$

Carbonate + acid
$CO_3^{2-} + 2H^+ \rightarrow H_2O + CO_2$

Precipitation
$Ag^+ + Cl^- \rightarrow AgCl(s)$
$Ba^{2+} + SO_4^{2-} \rightarrow BaSO_4(s)$

Metal + acid
$Mg + 2H^+ \rightarrow Mg^{2+} + H_2$

26 · WORKED EXAMPLE — DILUTION

What volume of 2.00 mol dm^{-3} HCl is needed to make 250 cm^3 of 0.150 mol dm^{-3} acid?

$c_1V_1 = c_2V_2$
$V_1 = (0.150 \times 250) \div 2.00$
$V_1 =$ **18.8 cm^3**

Pipette this into a 250 cm^3 volumetric flask and make up to the mark.

27 · SOURCES OF ERROR IN A TITRATION

Rinsing the burette with water rather than the titrant dilutes it and the titre reads high. An air bubble in the jet leaves the same false high reading when it clears.

Overshooting the end point, misreading the meniscus, and swirling too little all shift the titre. Read the bottom of the meniscus at eye level against a white tile.

Repeat until two titres agree within 0.10 cm^3, and average only those.

28 · WORKED EXAMPLE — PURITY

2.50 g of impure Na_2CO_3 is dissolved and made up to 250 cm^3. A 25.0 cm^3 portion needs 20.0 cm^3 of 0.100 mol dm^{-3} HCl.

$Na_2CO_3 + 2HCl \rightarrow 2NaCl + H_2O + CO_2$
$n(HCl) = 2.00 \times 10^{-3}$ mol
$n(Na_2CO_3)$ in 25 $cm^3 = 1.00 \times 10^{-3}$ mol
in 250 $cm^3 = 0.0100$ mol
$m = 0.0100 \times 106.0 = 1.06$ g
purity = 1.06 ÷ 2.50 × 100 = **42.4 %**

MARKS LOST HERE

— Leaving volumes in cm^3 inside n = cV, or in dm^3 inside sc-camel-p-v = nRT.

— Ignoring the mole ratio and assuming 1 : 1.

— Forgetting to test which reactant is limiting.

— Rounding mid-calculation, or quoting more significant figures than the data allows.

— Omitting state symbols, or leaving spectator ions in an ionic equation.