

1.21. Formulae, equations and amounts of substance

The mole is the key concept for chemical calculations

DEFINITION: The mole is the amount of substance in grams that has the same number of particles as there are atoms in 12 grams of carbon-12.

DEFINITION: Relative atomic mass is the **average mass** of one atom compared to one twelfth of the mass of one atom of carbon-12

DEFINITION: Molar Mass is the mass in grams of 1 mole of a substance and is given the unit of g mol^{-1}

Molar Mass for a compound can be calculated by adding up the mass numbers (from the periodic table) of each element in the compound

eg $\text{CaCO}_3 = 40.1 + 12.0 + 16.0 \times 3 = 100.1$

Calculating amount in moles

$$\text{amount} = \frac{\text{mass}}{\text{MolarMass}}$$

Unit of mass: grams
Unit of amount: mol

Example 1: Calculate the number of moles of CuSO_4 in 35.0g of CuSO_4

$$\begin{aligned} \text{moles} &= \frac{\text{mass}}{Mr} \\ &= 35.0 / (63.5 + 32.0 + 16.0 \\ &\quad \times 4) \\ &= 0.219 \text{ mol} \end{aligned}$$

Many questions will involve changes of units

1000 mg = 1 g

1000 g = 1 kg

1000 kg = 1 tonne

- 1.1) Calculate the amount in mol in 25.0 g of ZnCO_3
- 1.2) Calculate the amount in mol in 30.0 g of O_2
- 1.3) Calculate the amount in mol in 40.0 g of H_2SO_4
- 1.4) Calculate the mass of 0.500 mol of CaF_2
- 1.5) Calculate the mass of 0.250 mol of Li_2CO_3
- 1.6) Calculate the mass of 3.00 mol of KHSO_4
- 1.7) 0.500 mol of an element weigh 12.15 g. What is the relative atomic mass of the element and what is the element?

Example 2: Calculate the number of moles in 75.0 mg of $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

$$\begin{aligned} \text{moles} &= \frac{\text{mass}}{Mr} \\ &= 0.075 / (40 + 32.0 + 16.0 \times 4 + 18.0 \times 2) \\ &= 4.36 \times 10^{-4} \text{ mol} \end{aligned}$$

Avogadro's constant

The mole is the amount of substance in grams that has the same number of particles as there are atoms in 12 grams of carbon-12.

Avogadro's constant

There are 6.02×10^{23} atoms in 12 grams of carbon-12. Therefore explained in simpler terms 'One mole of any specified entity contains 6.02×10^{23} of that entity':

Avogadro's constant can be used for atoms, molecules and ions

1 mole of copper atoms will contain 6.02×10^{23} atoms

1 mole of carbon dioxide molecules will contain 6.02×10^{23} molecules

1 mole of sodium ions will contain 6.02×10^{23} ions

$$\text{No of particles} = \text{amount of substance (in mol)} \times \text{Avogadro's constant}$$

Example 3 : Calculate the number of atoms of tin in a 6.00 g sample of tin metal.

$$\text{moles} = \text{mass}/A_r$$

$$= 6.00/ 118.7$$

$$= 0.05055 \text{ mol}$$

$$\text{number atoms} = \text{moles} \times 6.022 \times 10^{23}$$

$$= 0.05055 \times 6.022 \times 10^{23}$$

$$= 3.04 \times 10^{22}$$

Example 4 : Calculate the number of chloride ions in a 25.0 cm³ of a solution of magnesium chloride of concentration 0.400 mol dm⁻³

$$\text{moles} = \text{concentration} \times \text{volume}$$

$$\text{MgCl}_2 = 0.400 \times \mathbf{0.0250}$$

$$= 0.0100 \text{ mol}$$

$$\text{moles of chloride ions} = 0.0100 \times 2$$

$$= 0.0200$$

There are two moles of chloride ions for every one mole of MgCl₂

$$\text{number ions of Cl}^- = \text{moles} \times 6.022 \times 10^{23}$$

$$= 0.0200 \times 6.022 \times 10^{23}$$

$$= 1.20 \times 10^{22} \text{ (to 3 sig fig)}$$

Calculations using the Avogadro constant

In the following questions use this value of the Avogadro constant = 6.0225×10^{23}

- 2.1) How many grams are there in 8.20×10^{24} molecules of H₂SO₄?
- 2.2) How many moles are present in 2.45×10^{23} molecules of C₂H₄?
- 2.3) How many calcium ions are there in 261 grams of Ca(NO₃)₂?
- 2.4) How many grams are there in 2.40×10^{24} molecules of NH₃?
- 2.5) How many grams are there in 6.90×10^{25} molecules of H₂?
- 2.6) How many molecules are there in 0.180 kg of CO₂?
- 2.7) The mass of one proton is 1.6725×10^{-24} g. Calculate the mass of one mole of ¹H⁺ ions using the Avogadro constant
- 2.8) The mass of one atom of ¹²C is 1.99×10^{-23} g. Use this information to calculate a value for the Avogadro constant.
- 2.9) The mass of one mole of ¹H atoms is 1.0078g and that of one ¹H atom is 1.6734×10^{-24} g. Use these data to calculate a value for the Avogadro constant accurate to five significant figures.
- 2.10) How does the number of atoms in one mole of helium compare with the number of molecules in one mole of ammonia?
- 2.11) Calculate the number of moles, and hence the number of molecules, of NH₃ in 0.654 g of ammonia gas.
- 2.12) Calculate the mass, in grams, of a single atom of sodium (23.0).
- 2.13) Calculate the number of **atoms** in 1 mol of carbon dioxide.
- 2.14) How many sulfur atoms are there in 0.0350 mol of sulfur S₈ molecules?
- 2.15) Calculate the number of oxygen **molecules** that react with 2.61 g of sodium.
- 2.16) 26.2 g of aluminium sulfate, Al₂(SO₄)₃, was dissolved in water. Calculate the number of sulfate ions, SO₄²⁻, present in the solution formed.

Empirical Formula

Definition: An empirical formula is the **simplest** ratio of atoms of each **element** in the compound.

General method

Step 1 : Divide each mass (or % mass) by the atomic mass of the element

Step 2 : For each of the answers from step 1 divide by the smallest one of those numbers.

Step 3: sometimes the numbers calculated in step 2 will need to be multiplied up to give whole numbers.

These whole numbers will be the empirical formula.

The same method can be used for the following types of data:

1. masses of each element in the compound
2. percentage mass of each element in the compound

Example 4 : Calculate the empirical formula for a compound that contains 1.82 g of K, 5.93 g of I and 2.24 g of O

Step1: Divide each mass by the atomic mass of the element

$$K = 1.82 / 39.1 \quad I = 5.93 / 126.9 \quad O = 2.24 / 16$$

$$= 0.0465 \text{ mol} \quad = 0.0467 \text{ mol} \quad = 0.14 \text{ mol}$$

Step 2 For each of the answers from step 1 divide by the smallest one of those numbers.

$$K = 0.0465 / 0.0465 \quad I = 0.0467 / 0.0465 \quad O = 0.14 / 0.0465$$

$$= 1 \quad = 1 \quad = 3$$

Empirical formula = KIO_3

Molecular formula from empirical formula

Definition: A molecular formula is the **actual** number of atoms of each element in the compound.

From the relative molecular mass (M_r) work out how many times the mass of the empirical formula fits into the M_r .

Example 5: work out the molecular formula for the compound with an empirical formula of $\text{C}_3\text{H}_6\text{O}$ and a M_r of 116

$\text{C}_3\text{H}_6\text{O}$ has a mass of 58

The empirical formula fits twice into M_r of 116

So molecular formula is $\text{C}_6\text{H}_{12}\text{O}_2$

The M_r does not need to be exact to turn an empirical formula into the molecular formula because the molecular formula will be a whole number multiple of the empirical formula

Empirical and Molecular formulae questions

- 3.1) A compound of calcium contains by mass 23.29% of calcium, 18.64% of sulfur and 2.32% of hydrogen, the remainder being oxygen. Determine the empirical formula of this compound.
- 3.2) Compound **A**, which contains carbon, hydrogen and oxygen only, has 38.7% carbon and 9.68% hydrogen by mass, the remainder being oxygen. Calculate the empirical formula of **A**.
- 3.3) A chromium compound contains 28.4% of sodium and 32.1% of chromium by mass, the remainder being oxygen. Calculate the empirical formula of this compound.
- 3.4) A compound **B** contains 36.5% of sodium and 25.5% of sulfur by mass, the rest being oxygen. Calculate the empirical formula of this compound **B**
- 3.5) A salt, **C**, contains 16.2% by mass of magnesium, 18.9% by mass of nitrogen and 64.9% by mass of oxygen. Calculate the empirical formula of this compound **C**
- 3.6) Compound **D** contains 45.9 % of potassium and 16.5 % of nitrogen by mass, the remainder being oxygen. Calculate the empirical formula of this compound **D**
- 3.7) Compound **E** contains 21.6 % by mass of sodium, 33.3 % by mass of chlorine and 45.1 % by mass of oxygen. Calculate the empirical formula of this compound **E**
- 3.8) Analysis of a compound **F** showed that it contained 49.31% of carbon, 6.85% of hydrogen and 43.84% of oxygen by mass. The *Mr* of **F** is 146.0. Calculate the empirical formula of **F** and hence deduce its molecular formula.
- 3.9) Compound **G** contains 15.38% of carbon, 7.69% of hydrogen, 35.90% of nitrogen and 41.03% of oxygen by mass. Calculate the empirical formula of this compound **G**
- 3.10) Ethyne can be used to make compound **H** (*Mr* = 215.8) which contains 22.24% carbon, 3.71% hydrogen and 74.05% bromine, by mass. Calculate the empirical formula of **H** and hence deduce its molecular formula.
- 3.11) Concentrated nitric acid reacts with magnesium to form an oxide of nitrogen which contains 30.4% by mass of nitrogen. Calculate the empirical formula of this oxide of nitrogen.
- 3.12) An oxide of nitrogen contains 25.9% by mass of nitrogen. Determine the empirical formula of this oxide.
- 3.13) Sulfamic acid contains 14.42% by mass of nitrogen, 3.09% hydrogen and 33.06% sulfur. The remainder is oxygen. Calculate the empirical formula of this sulfamic acid

Hydrated salt

A hydrated salt contains water of crystallisation

$\text{Cu}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$
hydrated copper (II) nitrate(V).

$\text{Cu}(\text{NO}_3)_2$
Anhydrous copper (II) nitrate(V).

Example 6

$\text{Na}_2\text{SO}_4 \cdot x\text{H}_2\text{O}$ has a molar mass of 322.1, Calculate the value of x

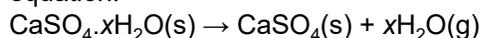
$$\text{Molar mass } x\text{H}_2\text{O} = 322.1 - (23 \times 2 + 32.1 + 16 \times 4) = 180$$

$$X = 180/18 = 10$$

Heating in a crucible

This method could be used for measuring mass loss in various thermal decomposition reactions and also for mass gain when reacting magnesium in oxygen.

The water of crystallisation in calcium sulfate crystals can be removed as water vapour by heating as shown in the following equation.



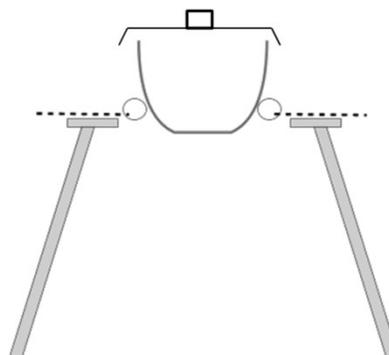
Method.

- Weigh an empty clean dry crucible and lid.
- Add 2g of hydrated calcium sulfate to the crucible and weigh again.
- Heat strongly with a Bunsen for a couple of minutes.
- Allow to cool.
- Weigh the crucible and contents again.
- Heat crucible again and reweigh until you reach a constant mass (do this to ensure reaction is complete).

Large amounts of hydrated calcium sulfate, such as 50g, should not be used in this experiment as the decomposition is likely to be incomplete.

The crucible needs to be dry otherwise a wet crucible would give an inaccurate result. It would cause mass loss to be too large as water would be lost when heating.

The lid improves the accuracy of the experiment as it prevents loss of solid from the crucible but should be loose fitting to allow gas to escape.



Small amounts of the solid, such as 0.100 g, should **not** be used in this experiment as errors in weighing are too high.

Example 7 3.51 g of hydrated zinc sulfate were heated and 1.97 g of anhydrous zinc sulphate were obtained.

Calculate the value of the integer x in $\text{ZnSO}_4 \cdot x\text{H}_2\text{O}$

Calculate the mass of $\text{H}_2\text{O} = 3.51 - 1.97 = 1.54\text{g}$

$$\begin{aligned} \text{Calculate moles of ZnSO}_4 &= \frac{1.97}{161.5} \\ &= 0.0122 \end{aligned}$$

$$\begin{aligned} \text{Calculate moles of H}_2\text{O} &= \frac{1.54}{18} \\ &= 0.085 \end{aligned}$$

$$\begin{aligned} \text{Calculate ratio of mole of ZnSO}_4 \text{ to H}_2\text{O} &= \frac{0.0122}{0.0122} \\ &= 1 \end{aligned}$$

$$\begin{aligned} &= \frac{0.085}{0.0122} \\ &= 7 \end{aligned}$$

$$X = 7$$

Questions on hydrated salts

- 5.1) In an experiment, the M_r of a different hydrated sodium carbonate was found to be 250. Use this value to calculate the number of molecules of water of crystallisation, x , in this hydrated sodium carbonate, $\text{Na}_2\text{CO}_3 \cdot x\text{H}_2\text{O}$
- 5.2) Hydrated sodium carbonate has the formula $\text{Na}_2\text{CO}_3 \cdot 10\text{H}_2\text{O}$. Calculate the percentage, by mass, of Na_2CO_3 in hydrated sodium carbonate.
- 5.3) A hydrated sodium sulfate contains 44.1% by mass of sodium sulfate. Hydrated sodium sulfate can be represented by the formula $\text{Na}_2\text{SO}_4 \cdot x\text{H}_2\text{O}$ where x is an integer. Calculate the value of x .
- 5.4) Hydrated calcium nitrate can be represented by the formula $\text{Ca}(\text{NO}_3)_2 \cdot x\text{H}_2\text{O}$ where x is an integer. A 9.06 g sample of $\text{Ca}(\text{NO}_3)_2 \cdot x\text{H}_2\text{O}$ contains 2.76 g of water of crystallisation. Calculate the value of x .
- 5.5) 6.57 g of hydrated zinc sulfate ($\text{ZnSO}_4 \cdot x\text{H}_2\text{O}$) was heated and 3.69 g of anhydrous zinc sulfate was obtained. Calculate the value of the integer x in $\text{ZnSO}_4 \cdot x\text{H}_2\text{O}$
- 5.6) 15.82g of hydrated sodium thiosulfate $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ are heated to remove the water of crystallisation. Calculate the maximum mass of anhydrous sodium thiosulfate that will form.

Answers

- 1.1) 0.199mol
1.2) 0.9375mol
1.3) 0.408mol
1.4) 39.1g
1.5) 18.5g
1.6) 408.6g
1.7) 24.3 Mg
- 2.1) 1336g
2.2) 0.407mol
2.3) 9.58×10^{23}
2.4) 67.7g
2.5) 229g
2.6) 2.46×10^{24}
2.7) 1.0073g
2.8) 6.03×10^{23}
2.9) 6.0225×10^{23}
2.10) the same
2.11) 2.32×10^{22}
2.12) 3.82×10^{-23}
2.13) 1.81×10^{24}
2.14) 1.69×10^{23}
2.15) 1.71×10^{22}
2.16) 1.38×10^{23}
- 3.1) CaSH_4O_6
3.2) CH_3O
3.3) Na_2CrO_4
3.4) Na_2SO_3
3.5) MgN_2O_6
3.6) KNO_2
3.7) NaClO_3
3.8) $\text{C}_3\text{H}_5\text{O}_2$ and $\text{C}_6\text{H}_{10}\text{O}_4$
3.9) $\text{CH}_6\text{N}_2\text{O}_2$
3.10) $\text{C}_2\text{H}_4\text{Br}$ and $\text{C}_4\text{H}_8\text{Br}_2$
3.11) NO_2
3.12) N_2O_5
3.13) H_3NSO_3
- 4.1) $\text{C}_5\text{H}_{12}\text{O}$
4.2) $\text{C}_3\text{H}_8\text{O}_2$
4.3) $\text{C}_4\text{H}_8\text{O}_2$
- 5.1) 8
5.2) 37%
5.3) 10
5.4) 4
5.5) 7
5.6) 10.08 g