IB DP CHEMISTRY

Structure 1 · Models of the Particulate Nature of Matter

MARK SCHEME

S1.1 The Particulate Nature of Matter · S1.2 The Nuclear Atom · S1.3 Electron Configurations
S1.4 Counting Particles: The Mole · S1.5 Ideal Gases

Standard and Higher Level · Syllabus 2025

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Original exam-style questions written for the IB Diploma Programme Chemistry course (first assessment 2025)

Section A — Multiple Choice: Answer Key (15 marks)

1. Answer: **C** — Kinetic theory models an ideal gas as particles in continuous, random motion, with negligible volume and negligible forces between them except during (elastic) collisions.

2. Answer: **C** — During a phase change, all the energy supplied goes into overcoming attractive forces between particles (increasing potential energy); average kinetic energy, and hence temperature, stays constant until the change of state is complete.

3. Answer: **C** — Combustion of magnesium produces a new substance (magnesium oxide) via a chemical reaction; the other options are all physical changes with no new substance formed.

4. Answer: **B** — Neutrons = mass number − atomic number = 39 − 19 = 20.

5. Answer: **A** — Isotopes are atoms of the same element (same number of protons / atomic number) with different numbers of neutrons, and therefore different mass numbers.

6. Answer: **C** — $A_r = (10 \cdot 19.9 + 11 \cdot 80.1)/100 = 10.80$.

7. Answer: **A** — Filling subshells in order of increasing energy for 17 electrons gives $1s^2 2s^2 2p^6 3s^2 3p^5$ (2+2+6+2+5 = 17).

8. Answer: **C** — First ionization energy is the energy needed to remove one electron from each atom in one mole of gaseous atoms in their ground state, producing one mole of singly charged gaseous cations.

9. Answer: **A** — A large jump occurs when the next electron to be removed comes from a full inner shell (much closer to the nucleus and less shielded); this pattern is consistent with the atom having 2 electrons in its outermost shell, removed relatively easily before the jump.

10. Answer: **A** — $n = m/M = 25.0/40.00 = 0.625$ mol.

11. Answer: **C** — The Avogadro constant (6.02×10^{23} mol^{-1}) is the number of elementary entities contained in exactly one mole of a substance.

12. Answer: **B** — $V = nV_m = 0.100 \cdot 22.7 = 2.27$ dm^3.

13. Answer: **A** — $n = pV/(RT) = (1.00 \times 10^5 \cdot 1.00 \times 10^{-3})/(8.31 \cdot 300) = 0.0401$ mol.

14. Answer: **B** — Boyle's law: at constant temperature, pV = constant, so pressure is inversely proportional to volume.

15. Answer: **B** — The IB data booklet defines STP as 273 K (0°C) and 1.00×10^5 Pa, at which the molar volume of an ideal gas is 22.7 dm^3 mol^{-1}.

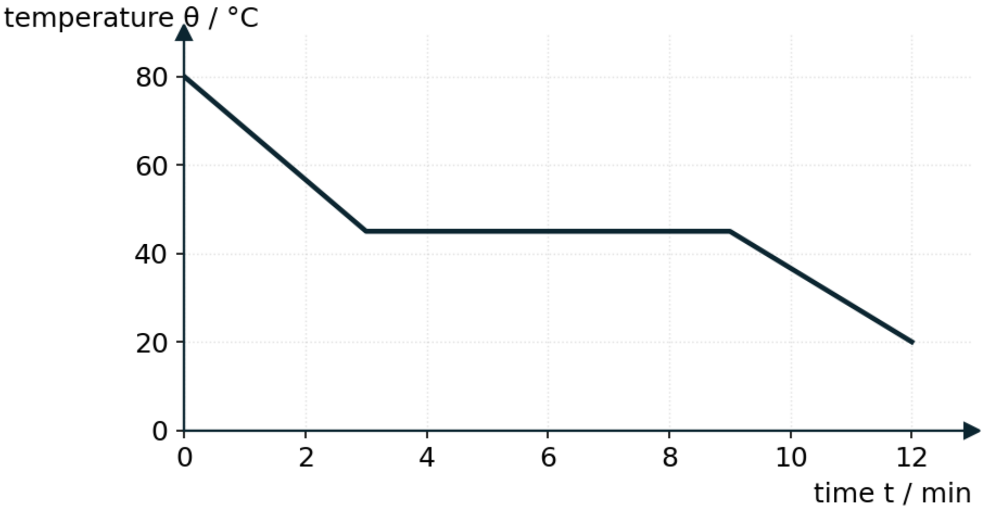
Section B — Structured Questions: Worked Solutions (65 marks)

Mark-scheme notation: M = method mark, A = accuracy mark (dependent on the preceding M mark), R = reasoning mark.

S1.1 Particulate Nature of Matter

Question 1 [7 marks]

A pure liquid substance is allowed to cool slowly. The graph shows how its temperature changes with time as it solidifies.



Cooling curve for the substance (temperatures and times are given data).

(a) Identify the freezing point of the substance and the time interval over which freezing occurs. **[2]**

Freezing point = 45°C, occurring between t = 3.0 min and t = 9.0 min (the plateau in the graph). **A1 A1**

(b) Explain, in terms of particle behaviour, why the temperature remains constant during this plateau even though the substance is continuously losing thermal energy. **[3]**

During freezing, particles are coming together and forming the ordered arrangement of the solid lattice, releasing energy as new intermolecular/interparticle attractive forces form (decreasing potential energy). This released energy compensates for the energy being lost to the surroundings, so the **average kinetic energy of the particles (and hence temperature) remains constant** until freezing is complete. **R1 R1 A1**

(c) State the physical state(s) of the substance present during the plateau, and describe how the arrangement of particles changes over this time interval. **[2]**

Both **solid and liquid** are present simultaneously during the plateau. As time progresses, an increasing proportion of particles adopt the fixed, ordered arrangement of the solid, while a decreasing proportion remain in the more disordered, mobile liquid arrangement. **A1 A1**

Question 2 [6 marks]

Classify each of the following changes as a physical change or a chemical change, giving a brief reason in each case.

(a) Ice melting to form liquid water. **[2]**

Physical change. No new substance is formed; only intermolecular forces are overcome as H_2O changes state from solid to liquid, and the change is easily reversed by cooling. **A1 R1**

(b) Iron rusting in damp air. **[2]**

Chemical change. Iron reacts with oxygen and water to form a new substance, hydrated iron(III) oxide (rust), with different chemical properties from the original iron; the change is not easily reversed. **A1 R1**

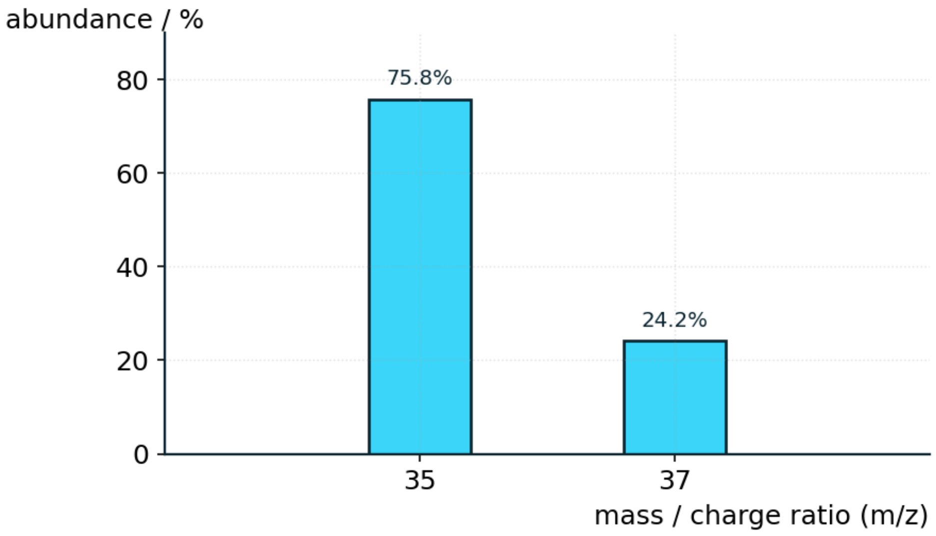
(c) Sugar dissolving in water. **[2]**

Physical change. The sugar molecules become dispersed among the water molecules, but no new chemical substance is formed; the sugar can be recovered unchanged by evaporating the water. **A1 R1**

S1.2 The Nuclear Atom

Question 3 [7 marks]

A sample of chlorine gas is analysed using a mass spectrometer. The graph shows the relative abundance of each isotope present.



Mass spectrum of chlorine (isotopic masses and abundances are given data).

(a) State the mass number and percentage abundance of each isotope of chlorine shown in the spectrum. **[2]**

Chlorine-35: 75.8%; Chlorine-37: 24.2%. **A1 A1**

(b) Calculate the relative atomic mass of chlorine, to 2 decimal places, using this data. **[3]**

$A_r = \Sigma(\text{mass}\times\text{abundance})/100 = (35\cdot75.8 + 37\cdot24.2)/100 = \mathbf{35.48}$. **M1 M1 A1**

(c) State the number of protons, neutrons, and electrons in a neutral atom of chlorine-37. **[2]**

Protons = 17; neutrons = 37 − 17 = 20; electrons = 17 (equal to the number of protons in a neutral atom). **A1 A1**

Question 4 [6 marks]

An atom of a particular isotope has 26 protons and a mass number of 56.

(a) Identify the element, and write the full isotopic symbol for this atom (in the form mass-number-element or ${}^{A}_{Z}E$ notation). **[2]**

26 protons corresponds to atomic number 26, which is **iron, Fe**. The isotope is written as iron-56 (or ${}^{56}Fe$). **A1 A1**

(b) Calculate the number of neutrons in this atom. **[2]**

Neutrons = mass number − atomic number = 56 − 26 = **30**. **M1 A1**

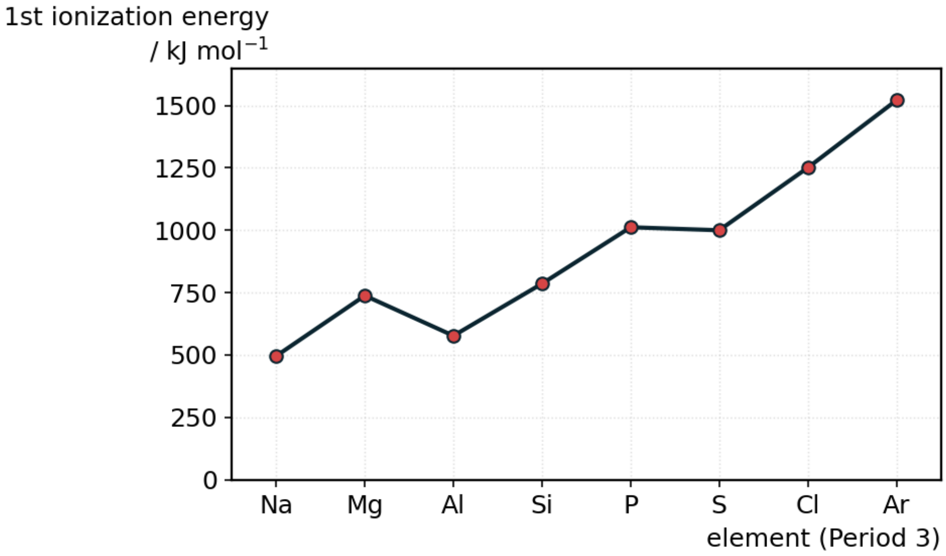
(c) This atom loses two electrons to form an Fe^{2+} ion. State the number of electrons in this ion. **[2]**

Electrons in Fe^{2+} = 26 − 2 = **24**. **M1 A1**

S1.3 Electron Configurations

Question 5 [7 marks]

The graph shows the first ionization energy of the elements across Period 3, from sodium to argon.



First ionization energy across Period 3 (given data).

(a) Describe and explain the general trend in first ionization energy from sodium to argon. **[2]**

First ionization energy generally **increases** across the period. Nuclear charge increases while electrons are added to the same outer shell (similar shielding), so the outer electrons are held more strongly and require more energy to remove. **A1 R1**

(b) Explain, in terms of electron configuration, why the first ionization energy of aluminium is lower than that of magnesium, despite aluminium having a greater nuclear charge. **[3]**

Magnesium's outer electron configuration is $3s^2$, a full and relatively stable/low-energy subshell. Aluminium's additional electron occupies the higher-energy 3p subshell ($3s^2 3p^1$), which is slightly shielded by the 3s electrons and further from the nucleus in energy terms, making it easier to remove despite the higher nuclear charge. **R1 R1 A1**

(c) Explain why the first ionization energy of sulfur is lower than that of phosphorus. **[2]**

Phosphorus ($3p^3$) has three unpaired electrons, one in each 3p orbital (extra stability from a half-filled subshell). Sulfur ($3p^4$) must place its fourth 3p electron into an already-occupied orbital, causing extra electron–electron repulsion that makes this paired electron easier to remove. **R1 R1**

Question 6 [6 marks]

Vanadium, V, has atomic number 23.

(a) Write the full ground-state electron configuration of a vanadium atom. **[2]**

$1s^2 2s^2 2p^6 3s^2 3p^6 3d^3 4s^2$ (total electrons = 2+2+6+2+6+3+2 = 23). **M1 A1**

(b) State the number of unpaired electrons in a ground-state vanadium atom. **[2]**

The $3d^3$ subshell has 3 electrons distributed one to each of 3 different d orbitals (Hund's rule), giving **3 unpaired electrons**. **A1 A1**

(c) Write the electron configuration of the V^{3+} ion. **[2]**

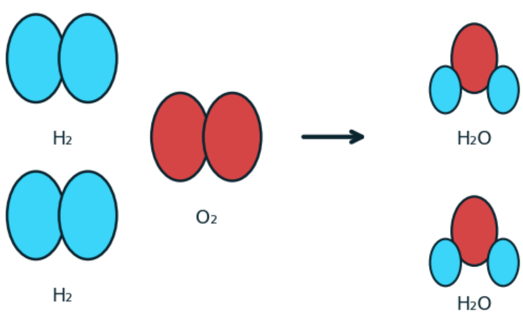
Electrons are removed first from 4s, then from 3d: V^{3+} has 20 electrons ⇒ $1s^2 2s^2 2p^6 3s^2 3p^6 3d^2$. **M1 A1**

S1.4 Counting Particles: The Mole

Question 7 [7 marks]

Hydrogen gas reacts with oxygen gas to form water vapour, as shown: $2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$. In an experiment, 10.0 g of hydrogen gas reacts completely. (M_r: H_2 = 2.02, O_2 = 32.00, H_2O = 18.02.)

$$2H_2(g) + O_2(g) \rightarrow 2H_2O(g)$$



Particle (mole-ratio) representation of the balanced equation.

(a) Calculate the amount, in moles, of H_2 reacted. **[2]**

$n(H_2) = m/M = 10.0/2.02 =$ **4.950 mol**. **M1 A1**

(b) Using the mole ratio in the equation, calculate the mass of O_2 required to react completely with this hydrogen. **[2]**

$n(O_2) = ½n(H_2) = 4.950/2 = 2.475$ mol.
$m(O_2) = n \times M = 2.475 \cdot 32.00 =$ **79.2 g**. **M1 A1**

(c) Calculate the mass of water produced in this reaction. **[3]**

$n(H_2O) = n(H_2) = 4.950$ mol (1:1 mole ratio from the equation). **M1 M1 A1**
$m(H_2O) = n \times M = 4.950 \cdot 18.02 =$ **89.2 g**.

Question 8 [6 marks]

A compound contains 40.0% carbon, 6.7% hydrogen, and 53.3% oxygen by mass. (A_r: C = 12.01, H = 1.01, O = 16.00.)

(a) Determine the empirical formula of the compound. **[3]**

Moles: C = 40.0/12.01 = 3.331; H = 6.7/1.01 = 6.634; O = 53.3/16.00 = 3.331. **M1 M1 A1**
Divide by the smallest value: C = 1.00, H = 1.99, O = 1.00 ≈ 1 : 2 : 1.
Empirical formula = $\mathbf{CH_2O}$.

(b) The molar mass of the compound is 180.16 g mol^{-1}. Determine its molecular formula. **[2]**

Empirical formula mass = 12.01 + 2(1.01) + 16.00 = 30.03 g mol^{-1}. **M1 A1**
Ratio = 180.16/30.03 ≈ 6.0 ⇒ molecular formula = $\mathbf{C_6H_{12}O_6}$.

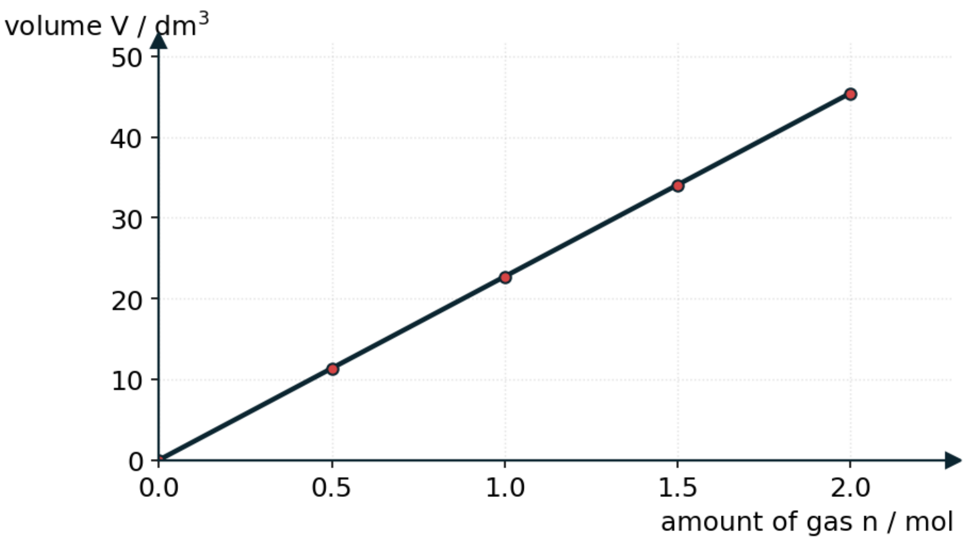
(c) Suggest an identity for this compound. **[1]**

$C_6H_{12}O_6$ is consistent with **glucose** (a simple sugar). **A1**

S1.5 Ideal Gases

Question 9 [7 marks]

The graph shows how the volume of a sample of ideal gas at STP (273 K, 1.00×10^5 Pa) varies with the amount of gas present, in moles.



Volume against amount of gas at STP (given data).

(a) Use the graph to determine the molar volume of an ideal gas at STP. **[2]**

Gradient of the graph = molar volume V_m = **22.7 dm^3 mol^{-1}** (e.g. from the point at n = 2.0 mol, V = 45.4 dm^3). **M1 A1**

(b) Calculate the volume occupied by 3.0 mol of an ideal gas at STP. **[2]**

$V = nV_m = 3.0 \cdot 22.7 =$ **$68.1\ dm^3$**. **M1 A1**

(c) A sample of carbon dioxide gas ($M = 44.01\ g\ mol^{-1}$) has a volume of $5.68\ dm^3$ at STP. Calculate the amount, in moles, and the mass of this gas. **[3]**

$n = V/V_m = 5.68/22.7 = 0.250$ mol. **M1 M1 A1**
$m = n \times M = 0.250 \cdot 44.01 =$ **11.0 g**.

Question 10 [6 marks]

A $2.00\ dm^3$ container holds a sample of nitrogen gas, N_2 ($M = 28.01\ g\ mol^{-1}$), at a pressure of 150 kPa and a temperature of 298 K. ($R = 8.31\ J\ mol^{-1}\ K^{-1}$.)

(a) Calculate the amount, in moles, of gas present. **[2]**

$n = pV/(RT) = (1.50\times10^5 \cdot 2.00\times10^{-3})/(8.31 \cdot 298) =$ **0.1211 mol**. **M1 A1**

(b) Calculate the mass of nitrogen gas present. **[2]**

$m = nM = 0.1211 \cdot 28.01 =$ **3.393 g**. **M1 A1**

(c) State and explain what would happen to the pressure of the gas if the temperature were increased, with the volume kept constant. **[2]**

The pressure would **increase**. At a higher temperature, gas particles have greater average kinetic energy and move faster, so they collide with the container walls more frequently and with greater force, increasing the pressure. **A1 R1**