Past-paper walk-through

Intramolecular Force and Potential Energy ▪ 2.2

eXercise

Questions in this set

- 2026 Q4
- 2025 Q1
- 2023 Q2
- 2023 Q6
- 2019 Q2
- 2018 Q3

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

Question 4

2026 ▪ Q4

White phosphorus, $P_4(g)$, can decompose into $P_2(g)$ at elevated temperatures. A balanced chemical equation, K_p expression, and Lewis diagrams for the chemical species involved in the reaction are given.

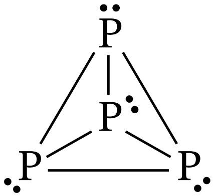
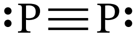
$$P_4(g) \rightleftharpoons 2\,P_2(g) \qquad K_p = \frac{(P_{P_2})^2}{P_{P_4}} = ?$$

| Compound | P_4 | P_2 | |—|—|—| | Lewis diagram | [Tetrahedral arrangement of 4 P atoms, each bonded to the other three by single bonds, each P atom bearing one lone pair] | [: P $\equiv$ P : — a P atom triple-bonded to another P atom, each bearing one lone pair] |

Question 4

(a) The average bond length in P_4 molecules is 221 pm, whereas the average bond length in P_2 molecules is 189 pm. **Explain** why the average bond length in P_4 is greater than the average bond length in P_2.

Question 4

Compound	P_4	P_2
Lewis diagram		

Question 4

2026 ▪ Q4

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| Compound | P_4 | P_2 | |—|—|—| | Lewis diagram | [Tetrahedral arrangement of 4 P atoms, each bonded to the other three by single bonds, each P atom bearing one lone pair] | [$: P \equiv P :$ — a P atom triple-bonded to another P atom, each bearing one lone pair] |

(b) A sample of $P_4(s)$ is placed in a sealed rigid container and heated to 1600. K, at which point the initial partial pressure of $P_4(g)$ is 0.470 atm. Some of the $P_4(g)$

Question 4

decomposes into $P_2(g)$ as the system reaches equilibrium. At equilibrium, the partial pressure of $P_2(g)$ is determined to be 0.630 atm.
Calculate the value of the equilibrium constant, K_p, for the reaction at 1600. K. Show the work that leads to your answer.

Question 4

2026 ▪ Q4

White phosphorus, $P_4(g)$, can decompose into $P_2(g)$ at elevated temperatures. A balanced chemical equation, K_p expression, and Lewis diagrams for the chemical species involved in the reaction are given.

$$P_4(g) \rightleftharpoons 2\,P_2(g) \qquad K_p = \frac{(P_{P_2})^2}{P_{P_4}} = ?$$

| Compound | P_4 | P_2 | |—|—|—| | Lewis diagram | [Tetrahedral arrangement of 4 P atoms, each bonded to the other three by single bonds, each P atom bearing one lone pair] | [$: P \equiv P :$ — a P atom triple-bonded to another P atom, each bearing one lone pair] |

(c) The reaction is thermodynamically favorable under standard conditions only at temperatures above 1500 K. A student claims that the reaction must be endothermic

Question 4

because it is favorable only at high temperatures. Do you agree or disagree? **Justify** your answer using $\Delta S^\circ{}_{rxn}$ and $\Delta G^\circ{}_{rxn}$.

Question 1

2025 ▪ Q1

Answer the following questions about magnesium.

(a) An incomplete mass spectrum for magnesium is shown in the diagram.

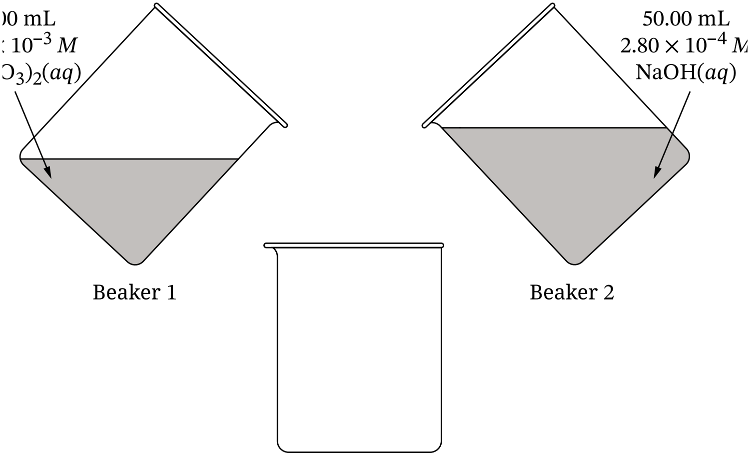
[Bar graph titled “Relative Abundance” vs. “Mass (amu)”; y-axis from 0 to 100 in increments of 20; x-axis shows tick marks at 24, 25, 26; a single thick vertical bar is drawn at mass 24 reaching a relative abundance of about 79.]

The percent abundance of magnesium-24 is 79%. The percent abundances of the other two natural isotopes of magnesium, magnesium-25 and magnesium-26, are approximately equal.

(a)(i) Complete the mass spectrum in part A by drawing thick lines in the appropriate locations to represent the percent abundance of magnesium-25 and magnesium-26.

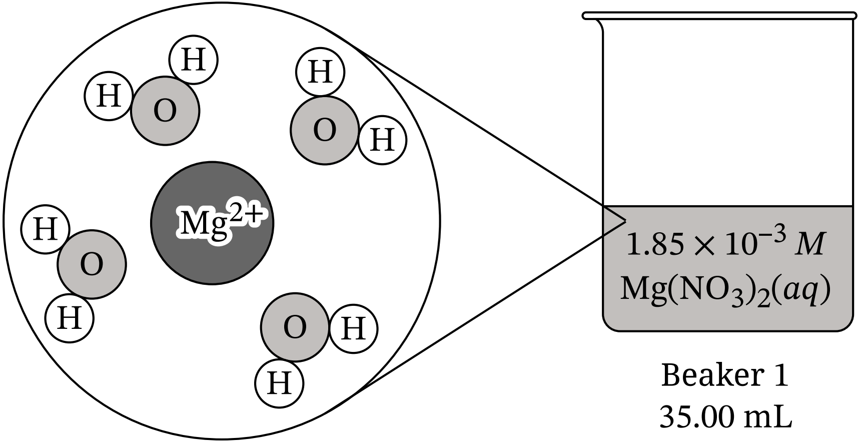
(a)(ii) Describe the difference in atomic structure that accounts for the difference in mass between magnesium-25 and magnesium-26.

Question 1



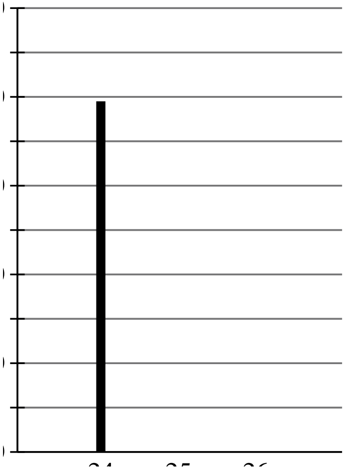
)0 mL
: 10^{-3} M
$O_3)_2(aq)$
Beaker 1
50.00 mL
2.80×10^{-4} M
$NaOH(aq)$
Beaker 2

Question 1



Beaker 1
35.00 mL

Question 1



Question 1

2025 ▪ Q1

Answer the following questions about magnesium.

(b) A student prepares a 1.85×10^{-3} *M* solution of $Mg(NO_3)_2(aq)$ in beaker 1 and a 2.80×10^{-4} *M* solution of $NaOH(aq)$ in beaker 2, as shown.

[Particle diagram: a magnesium ion, Mg^{2+}, at the center surrounded by six water molecules (H2O), each oriented with its oxygen atom pointing toward the central Mg^{2+} ion and its two hydrogen atoms pointing outward.]

[Beaker 1: labeled "1.85×10^{-3} *M* $Mg(NO_3)_2(aq)$", "Beaker 1", "35.00 mL".]

[Beaker 2: labeled "2.80×10^{-4} *M* $NaOH(aq)$", "Beaker 2", "50.00 mL".]

The particle diagram shown represents a magnesium ion, Mg^{2+}, in beaker 1. A sodium ion, Na^{+}, in beaker 2 has a weaker attraction to water than the Mg^{2+} does. Explain this phenomenon using Coulomb's law and each of the following.

(b)(i) The relative charge of the ions

Question 1

(b)(ii) The relative radii of the ions

Question 1

2025 ▪ Q1

Answer the following questions about magnesium.

(c) Calculate the pH of the solution in beaker 2.

Question 1

2025 ▪ Q1

Answer the following questions about magnesium.

(d) A student combines 35.00 mL of 1.85×10^{-3} M $Mg(NO_3)_2(aq)$ with 50.00 mL of 2.80×10^{-4} M $NaOH(aq)$, as shown in the diagram. Calculate $[Mg^{2+}]$ after the two solutions are combined but before any reaction takes place. (Assume that volumes are additive.)

[Diagram of two conical/Erlenmeyer flasks being poured into an empty Beaker 3. Left flask: "35.00 mL", "1.85×10^{-3} M", "$Mg(NO_3)_2(aq)$", labeled "Beaker 1". Right flask: "50.00 mL", "2.80×10^{-4} M", "$NaOH(aq)$", labeled "Beaker 2". Both flasks have an arrow pointing down into the empty "Beaker 3" between them.]

Question 1

2025 ▪ Q1

Answer the following questions about magnesium.

(e) The dissolution of magnesium hydroxide is represented by the following equation.

$$\mathrm{Mg(OH)_2}(s) \rightleftharpoons \mathrm{Mg^{2+}}(aq) + 2\,\mathrm{OH^-}(aq) \qquad K_{sp} = 5.61 \times 10^{-12}$$

(e)(i) Write the expression for the solubility product constant, K_{sp}.

(e)(ii) After the two solutions are combined in beaker 3 as described in part D, but before any reaction takes place, $\left[\mathrm{OH^-}\right] = 1.65 \times 10^{-4}\ M$. Using your answer to part D, calculate the value of the reaction quotient, Q.

(e)(iii) Using the reaction quotient, Q, predict whether a precipitate should form as the mixture in beaker 3 approaches equilibrium. Justify your answer.

Question 1

2025 ▪ Q1

Answer the following questions about magnesium.

(f) In a separate experiment, the student adds $HNO_3(aq)$ to decrease the pH of a saturated solution containing undissolved $Mg(OH)_2(s)$. Does the amount of undissolved $Mg(OH)_2(s)$ increase, decrease, or remain the same as the $HNO_3(aq)$ is added? Justify your answer.

Solution 1

(a)

Mark scheme

- No separate response required — this is the context/stem describing the incomplete mass spectrum (magnesium-24 at 79% abundance) that parts (i) and (ii) below refer to.

(a)(i)

Mark scheme

- Draw two vertical bars at masses 25 and 26, each reaching a relative abundance of approximately 10 to 11 (since Mg-25 and Mg-26 together make up the remaining ~21% and are approximately equal, so roughly 10–11% each).

Solution 1

(a)(ii)

Mark scheme

- Magnesium-26 has one more neutron than magnesium-25 does (Mg-25 has 13 neutrons, Mg-26 has 14 neutrons; both isotopes have 12 protons, since they are the same element).

Solution 1

(b)

Mark scheme

- No separate response required — this is the context/stem introducing the 1.85×10^{-3} M $Mg(NO_3)_2$(aq) and 2.80×10^{-4} M NaOH(aq) solutions (with a particle diagram of hydrated Mg^{2+}) that parts (i) and (ii) below refer to.

(b)(i)

Mark scheme

- The charge on the sodium ion (Na^+, $+1$) is less than the charge on the magnesium ion (Mg^{2+}, $+2$). A smaller charge results in a weaker Coulombic attraction between Na^+ and water.

Solution 1

(b)(ii)

Mark scheme

- The Na^+ ion is larger (has a greater ionic radius) than the Mg^{2+} ion, so the distance between Na^+ and the oxygen atom of the water molecule will be greater. As distance increases, Coulombic attraction decreases, so Na^+ is less strongly attracted to water than Mg^{2+}.

Solution 1

(c)

Mark scheme

- pOH $= -\log(2.80 \times 10^{-4}) = 3.553.$ pH $= 14 -$ pOH $= 14 - 3.553 = 10.447.$

Solution 1

(d)

Mark scheme

- Using $M_1V_1 = M_2V_2$: $M_2 = \dfrac{(1.85 \times 10^{-3}\ M)(0.03500\ \mathsf{L})}{0.03500\ \mathsf{L} + 0.05000\ \mathsf{L}} = 7.62 \times 10^{-4}\ M$. So $[\mathrm{Mg}^{2+}]$ after combining but before reaction is $7.62 \times 10^{-4}\ M$.

Solution 1

(e)

Mark scheme

- No separate response required — this is the context/stem giving the $Mg(OH)_2$ dissolution equilibrium and $K_{sp} = 5.61 \times 10^{-12}$ that parts (i)–(iii) below refer to.

(e)(i)

Mark scheme

- $K_{sp} = [Mg^{2+}][OH^-]^2$.

Solution 1

(e)(ii)

Mark scheme

- Using $[Mg^{2+}] = 7.62 \times 10^{-4}$ M (from part D) and $[OH^-] = 1.65 \times 10^{-4}$ M (given): $Q = [Mg^{2+}][OH^-]^2 = (7.62 \times 10^{-4})(1.65 \times 10^{-4})^2 = 2.07 \times 10^{-11}$.

(e)(iii)

Mark scheme

- Q $(2.07 \times 10^{-11}) > K_{sp}$ (5.61×10^{-12}), so a precipitate should form. Equivalently: the concentration of ions in solution (represented by Q) is greater than that of a saturated solution, so a precipitate will form.

Solution 1

(f)

Mark scheme

- The amount of undissolved $Mg(OH)_2(s)$ will decrease. The H^+ from $HNO_3(aq)$ reacts with OH^-, decreasing $[OH^-]$ and causing $Q < K_{sp}$. As a result, more $Mg(OH)_2(s)$ will dissolve until equilibrium is reestablished, resulting in less undissolved $Mg(OH)_2(s)$.

Question 2

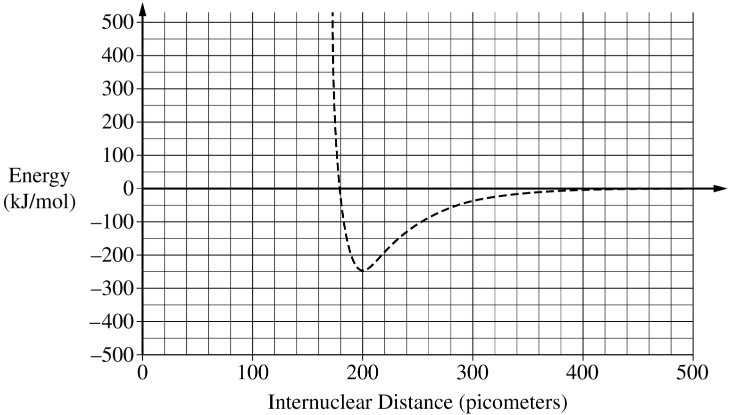
2023 ▪ Q2

In the gas phase, $AlCl_3$ is a molecular substance. A reaction of gaseous $AlCl_3$ at high temperature is represented by the following balanced equation.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

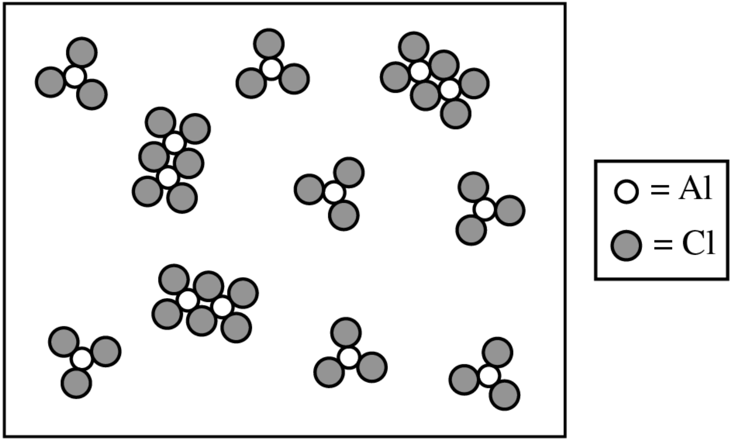
(a) How many grams of $Cl(g)$ can be formed from 1.25 mol of $AlCl_3(g)$?

Question 2



ɔn the graph, what is the bond length, in picometers, for Cl_2 ? __________

Question 2



Question 2

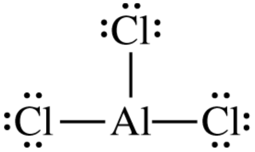


Diagram 1

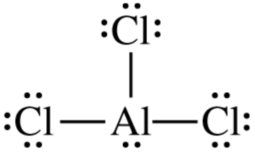


Diagram 2

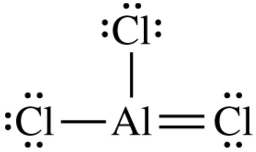


Diagram 3

Question 2

2023 ▪ Q2

In the gas phase, $AlCl_3$ is a molecular substance. A reaction of gaseous $AlCl_3$ at high temperature is represented by the following balanced equation.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(b) Additional reactions that involve Al or Cl are shown in the following table.

Reaction Number	Equation	ΔH°_{rxn} (kJ/mol$_{rxn}$)
2	$Al(s) + \frac{3}{2}Cl_2(g) \rightarrow AlCl_3(g)$	-583
3	$Al(s) \rightarrow Al(g)$	$+326$
4	$Cl_2(g) \rightarrow 2\,Cl(g)$	$+243$

Calculate the value of ΔH_1°, in kJ/mol$_{rxn}$, for reaction 1 above using reactions 2, 3, and 4.

Question 2

2023 ▪ Q2

In the gas phase, $AlCl_3$ is a molecular substance. A reaction of gaseous $AlCl_3$ at high temperature is represented by the following balanced equation.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(c)(i) A potential energy diagram for Cl_2 is shown in the following graph.
[Graph: potential energy (kJ/mol) vs. internuclear distance (picometers) for Cl_2; y-axis from -500 to 500 kJ/mol in steps of 100; x-axis from 0 to 500 picometers in steps of 100; dashed curve starts high near $x = 0$, plunges to a minimum of about -250 kJ/mol near $x \approx 200$ pm, then rises and levels off near 0 kJ/mol as x increases toward 500 pm.]
Based on the graph, what is the bond length, in picometers, for Cl_2?

Question 2

(c)(ii) A student finds that the average Al – Cl bond length is 220 picometers and the average bond energy is 425 kJ/mol. Draw the potential energy curve for the average Al – Cl bond on the preceding graph.

Question 2

2023 ▪ Q2

In the gas phase, $AlCl_3$ is a molecular substance. A reaction of gaseous $AlCl_3$ at high temperature is represented by the following balanced equation.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(d)(i) Three proposed Lewis diagrams for the $AlCl_3(g)$ molecule are shown. [Diagram 1: Cl bonded to Al with a single bond above (Cl with 3 lone pairs) and two Cl atoms bonded to Al with single bonds on either side (each Cl with 3 lone pairs) — trigonal arrangement, all single Al–Cl bonds, Al with no lone pair shown.] [Diagram 2: same trigonal arrangement of three Cl atoms singly bonded to Al, each Cl shown with 3 lone pairs — visually similar layout to Diagram 1.] [Diagram 3: two Cl atoms singly bonded to Al (each with 3 lone pairs) and one Cl atom double-bonded to Al (shown with 2 lone pairs) — Cl=Al on the right side.]

Diagram 1, Diagram 2, Diagram 3 (labeled beneath each structure).

Question 2

The $AlCl_3(g)$ molecule has a trigonal planar geometry. Which diagram (1, 2, or 3) can be eliminated based on geometry? Justify your choice based on VSEPR theory.
(d)(ii) Which of the three diagrams is the best representation for the bonding in $AlCl_3$? Justify your choice based on formal charges.

Question 2

2023 ▪ Q2

In the gas phase, $AlCl_3$ is a molecular substance. A reaction of gaseous $AlCl_3$ at high temperature is represented by the following balanced equation.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(e) $AlCl_3$ is known to dimerize reversibly in the gas phase. The dimerization equilibrium is represented by the following equation.

$$2\,AlCl_3(g) \rightleftharpoons Al_2Cl_6(g)$$

Write the expression for the equilibrium constant, K_p, for this reaction.

Question 2

2023 ▪ Q2

In the gas phase, $AlCl_3$ is a molecular substance. A reaction of gaseous $AlCl_3$ at high temperature is represented by the following balanced equation.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(f) A particle-level diagram of an equilibrium mixture of $AlCl_3(g)$ and $Al_2Cl_6(g)$ at $400°$C in a 25 L closed container is shown.

[Particle diagram inside a rectangular box: several clusters of gray/white circles representing $AlCl_3$ monomers (isolated groupings of 1 white Al + 3 gray Cl) and Al_2Cl_6 dimers (larger fused clusters of 2 white Al + 6 gray Cl), scattered throughout the container. Legend: white circle = Al, gray circle = Cl.]

Using the particle-level diagram, calculate the value of K_p for the reaction if the total pressure in the container is 22.1 atm.

Solution 2

(a)

Mark scheme

- $1.25 \text{ mol AlCl}_3 \times \frac{3 \text{ mol Cl}}{1 \text{ mol AlCl}_3} \times \frac{35.45 \text{ g Cl}}{1 \text{ mol Cl}} = 133 \text{ g Cl}$ (3 sig figs).

Solution 2

(b) Mark scheme

- Apply Hess's law using reactions 2, 3, and 4: reverse reaction 2 ($AlCl_3(g) \rightarrow Al(s) + \frac{3}{2}Cl_2(g)$, $\Delta H = -(-583) = +583$ kJ/mol$_{rxn}$) and multiply reaction 4 by $\frac{3}{2}$ ($\frac{3}{2}Cl_2(g) \rightarrow 3\,Cl(g)$, $\Delta H = 1.5(+243) = +365$ kJ/mol$_{rxn}$), then add reaction 3 unchanged: $\Delta H_1^\circ = -\Delta H_2^\circ + \Delta H_3^\circ + 1.5(\Delta H_4^\circ) = -(-583) + 326 + 1.5(243) = 1274$ kJ/mol$_{rxn}$.

Solution 2

(c)(i)

Mark scheme

- Bond length $\approx$ 200 picometers ($\pm$10 pm), read from the internuclear distance at the minimum (lowest potential energy point) of the Cl_2 curve shown.

Solution 2

(c)(ii)

Mark scheme

- Draw a new potential-energy curve for the Al–Cl bond with its minimum at an internuclear distance of 220 $\pm$ 10 pm — longer than Cl_2's 200 pm bond length (1 point) — and a minimum energy value of -425 ± 20 kJ/mol that approaches zero as the internuclear distance approaches 500 pm — a shallower well than Cl_2's since the Al–Cl bond energy (425 kJ/mol) is less than the Cl–Cl bond energy shown on the original curve (1 point).

Solution 2

(d)(i)

Mark scheme

- Diagram 2 is not a valid representation. In Diagram 2, Al has four electron domains (three single Al–Cl bonds plus one lone pair on Al), which would give a trigonal pyramidal (not trigonal planar) molecular geometry — inconsistent with the known trigonal planar geometry of $AlCl_3(g)$.

Solution 2

(d)(ii)

Mark scheme

- Diagram 1 is the best representation. All atoms in Diagram 1 have a formal charge of zero, whereas atoms in Diagrams 2 and 3 have nonzero formal charges — the Lewis structure that minimizes (here, eliminates) formal charges is preferred.

Solution 2

(e)

Mark scheme

- $K_p = \dfrac{P_{\mathrm{Al_2Cl_6}}}{\left(P_{\mathrm{AlCl_3}}\right)^2}$.

Solution 2

(f) Mark scheme

- Using mole fractions read from the particle diagram ($\chi_{AlCl_3} = \frac{7}{10}$, $\chi_{Al_2Cl_6} = \frac{3}{10}$) and total pressure 22.1 atm: $K_p = \dfrac{\chi_{Al_2Cl_6}(P_{total})}{(\chi_{AlCl_3}(P_{total}))^2} = \dfrac{\frac{3}{10}(22.1)}{\left(\frac{7}{10}(22.1)\right)^2} = 0.0277.$

Question 6

2023 ▪ Q6

Answer the following questions related to HBr(l) and HF(l).

(a) In the following table, list all of the types of intermolecular forces present in pure samples of HBr(l) and HF(l).

Liquid	HBr(l)	HF(l)
Intermolecular forces present		

(b)(i) The enthalpy of vaporization, ΔH°_{vap}, for each liquid is provided in the following table.

Liquid	HBr(l)	HF(l)
ΔH°_{vap}	17.3 kJ/mol	25.2 kJ/mol

Based on the types and relative strengths of intermolecular forces, explain why ΔH°_{vap} of HF(l) is greater than that of HBr(l).

(b)(ii) Calculate the amount of thermal energy, in kJ, required to vaporize 6.85 g of HF(l).

Question 6

(c) Based on the arrangement of electrons in the Br and F atoms, explain why the bond length in an HBr molecule is greater than that in an HF molecule.

Solution 6

(a)

Mark scheme

- HBr(l): London dispersion forces and dipole-dipole attractions. HF(l): London dispersion forces, dipole-dipole attractions, and hydrogen bonding.

Solution 6

(b)(i)

Mark scheme

- ΔH°_{vap} is greater for HF(l) than HBr(l) because the overall intermolecular forces in HF(l) are stronger than those in HBr(l), due to the hydrogen bonding present in HF(l) (in addition to dispersion and dipole-dipole forces), so more energy is required to separate the HF(l) molecules.

Solution 6

(b)(ii)

Mark scheme

- $6.85\ \text{g HF} \times \dfrac{1\ \text{mol}}{20.01\ \text{g}} \times \dfrac{25.2\ \text{kJ}}{1\ \text{mol}} = 8.63\ \text{kJ}.$

Solution 6

(c)

Mark scheme

- Br has two additional occupied electron shells ($n = 3$ and $n = 4$) compared to F ($n = 2$). These extra electron shells increase the distance between the H and Br nuclei (larger atomic/covalent radius for Br), giving the H–Br bond a greater bond length than the H–F bond.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.
(a) The molecular formulas of diatomic bromine, chlorine, fluorine, and iodine are written below. Circle the formula of the molecule that has the longest bond length. Justify your choice in terms of atomic structure.

Br_2 Cl_2 F_2 I_2

A chemistry teacher wants to prepare Br_2. The teacher has access to the following three reagents: $NaBr(aq)$, $Cl_2(g)$, and $I_2(s)$.
| Half-Reaction | E° at 25°C (V) | |—|—| | $Br_2 + 2\,e^- \rightarrow 2\,Br^-$ | 1.07 | |
$Cl_2 + 2\,e^- \rightarrow 2\,Cl^-$ | 1.36 | | $I_2 + 2\,e^- \rightarrow 2\,I^-$ | 0.53 |

Question 2

Half-Reaction	$E°$ at 25°C (V)
$Br_2 + 2\,e^- \rightarrow 2\,Br^-$	1.07
$Cl_2 + 2\,e^- \rightarrow 2\,Cl^-$	1.36
$I_2 + 2\,e^- \rightarrow 2\,I^-$	0.53

Question 2

Bond	Bond Energy (kJ/mol)
Br – Br	193
Cl – Cl	243
Br – Cl	?

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(b) Using the data in the table above, write the balanced equation for the thermodynamically favorable reaction that will produce Br_2 when the teacher combines two of the reagents. Justify that the reaction is thermodynamically favorable by calculating the value of E° for the reaction.

Br_2 and Cl_2 can react to form the compound BrCl.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(c) The boiling point of Br_2 is 332 K, whereas the boiling point of BrCl is 278 K. Explain this difference in boiling point in terms of all the intermolecular forces present between molecules of each substance.

The compound BrCl can decompose into Br_2 and Cl_2, as represented by the balanced chemical equation below.

$$2\,\mathrm{BrCl}(g) \rightleftharpoons \mathrm{Br}_2(g) + \mathrm{Cl}_2(g) \qquad \Delta H^\circ = 1.6\ \mathrm{kJ/mol}_{rxn}$$

A 0.100 mole sample of pure BrCl(g) is placed in a previously evacuated, rigid 2.00 L container at 298 K. Eventually the system reaches equilibrium according to the equation above.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(d) Calculate the pressure in the container before equilibrium is established.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(e) Write the expression for the equilibrium constant, K_{eq}, for the decomposition of BrCl.

After the system has reached equilibrium, 42 percent of the original BrCl sample has decomposed.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(f) Determine the value of K_{eq} for the decomposition reaction of BrCl at 298 K.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(g) Calculate the bond energy of the Br-Cl bond, in kJ/mol, using ΔH° for the reaction (1.6 kJ/mol$_{rxn}$) and the information in the following table.

Bond	Bond Energy (kJ/mol)
$Br-Br$	193
$Cl-Cl$	243
$Br-Cl$	?

Solution 2

(a)

Mark scheme

- I2 (circled). I2 has the longest bond length because the atomic radius of I is greater than the radii of the other halogen atoms (Br, Cl, F), so the internuclear distance between the two bonded I atoms is greater than in the other diatomic halogens. 1 point for circling I2 with a valid atomic-structure justification.

Solution 2

(b)

Mark scheme

- Balanced equation ($Cl2$ is a strong enough oxidizer to oxidize Br since $E°(Cl2/Cl\ )$=1.36 V > $E°(Br2/Br\ )$=1.07 V, whereas I2 cannot): 2 Br (aq) + Cl2(g) $\rightarrow$ Br2 + 2 Cl (aq). 1 point for the correct balanced equation. $E° = E°(\text{reduced species}) - E°(\text{oxidized species}) = 1.36\ V - 1.07\ V = +0.29\ V$; a positive E° confirms the reaction is thermodynamically favorable. 1 point for the correct E° calculation.

Solution 2

(c)

Mark scheme

- $Br_2(l)$ has only London dispersion forces between its nonpolar molecules. $BrCl(l)$ is polar, so it has both London forces and dipole-dipole forces. 1 point for correctly identifying the IMFs present in each substance. However, Br_2 has a larger, more polarizable electron cloud than BrCl, so the London forces in $Br_2(l)$ are stronger than the combined (London + dipole-dipole) forces in $BrCl(l)$; this is why Br_2's boiling point (332 K) is higher than BrCl's (278 K) despite BrCl being polar. 1 point for this valid explanation invoking polarizability.

Solution 2

(d)

Mark scheme

- P = nRT/V = (0.100 mol)(0.08206 L · atm · mol ^{1} · K ^{1})(298 K) / (2.00 L) = 1.22 atm. 1 point for the correct pressure with consistent units.

Solution 2

(e)

Mark scheme

- Keq = [Br2][Cl2] / $[BrCl]^2$ (equivalently, in terms of partial pressures: Keq = P(Br2) · P(Cl2) / $P(BrCl)^2$). 1 point for a correct equilibrium expression.

Solution 2

(f)

Mark scheme

- ICE table (partial pressures, atm) for 2 BrCl(g) Br2(g) + Cl2(g): Initial 1.22, 0, 0; Change −2x, +x, +x; Equilibrium 0.71, 0.26, 0.26. Since 42% of BrCl decomposed, P(BrCl decomposed) = (0.42)(1.22 atm) = 0.51 atm = 2x, so x = 0.26 atm. 1 point for the correct stoichiometric (ICE) values at equilibrium. Keq = $(0.26)(0.26)/(0.71)^2$ = 0.13. 1 point for a Keq value consistent with the student's ICE table (a molar-concentration-based solution also earns full credit).

Solution 2

(g)

Mark scheme

- $\Delta H^\circ = \Sigma$(bond energies)broken $-$ Σ(bond energies)formed. 1.6 kJ/mol $=$ 2(Br—Cl bond energy) $-$ (193 kJ/mol $+$ 243 kJ/mol); (436 $+$ 1.6) kJ/mol $=$ 2(Br—Cl bond energy); Br—Cl bond energy $=$ 219 kJ/mol. 1 point for the correct calculation.

Question 3

2018 ▪ Q3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(a) Write the ground-state electron configuration of the Fe^{2+} ion.

Ion	Ionic Radius (pm)
Fe^{2+}	92
Fe^{3+}	79

Question 3

Mass of $Fe(s)$ with inert impurity	6.724 g
Mass of $Fe_2O_3(s)$ produced	7.531 g

Question 3

Ion	Ionic Radius (pm)
Fe^{2+}	92
Fe^{3+}	79

Question 3

2018 ▪ Q3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(b) The radii of the ions are given in the table above. Using principles of atomic structure, explain why the radius of the Fe^{2+} ion is larger than the radius of the Fe^{3+} ion.

Question 3

2018 ▪ Q3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(c) Fe^{3+} ions interact more strongly with water molecules in aqueous solution than Fe^{2+} ions do. Give one reason for this stronger interaction, and justify your answer using Coulomb's law.

A student obtains a solution that contains an unknown concentration of $Fe^{2+}(aq)$. To determine the concentration of $Fe^{2+}(aq)$ in the solution, the student titrates a sample of the solution with $MnO_4^-(aq)$, which converts $Fe^{2+}(aq)$ to $Fe^{3+}(aq)$, as represented by the following equation.

$$5\,Fe^{2+}(aq) + MnO_4^-(aq) + 8\,H^+(aq) \rightarrow 5\,Fe^{3+}(aq) + Mn^{2+}(aq) + 4\,H_2O(l)$$

Question 3

2018 ▪ Q3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(d) Write the balanced equation for the half-reaction for the oxidation of $Fe^{2+}(aq)$ to $Fe^{3+}(aq)$.

Question 3

2018 ▪ Q3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(e) The student titrates a 10.0 mL sample of the $Fe^{2+}(aq)$ solution. Calculate the value of $[Fe^{2+}]$ in the solution if it takes 17.48 mL of added 0.0350 *M* $KMnO_4(aq)$ to reach the equivalence point of the titration.

To deliver the 10.0 mL sample of the $Fe^{2+}(aq)$ solution in part (e), the student has the choice of using one of the pieces of glassware listed below.

- 25 mL buret - 25 mL graduated cylinder - 25 mL beaker - 25 mL volumetric flask

Question 3

2018 ▪ Q3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(f) Explain why the 25 mL volumetric flask would be a poor choice to use for delivering the required volume of the $Fe^{2+}(aq)$ solution.

In a separate experiment, the student is given a sample of powdered Fe(s) that contains an inert impurity. The student uses a procedure to oxidize the Fe(s) in the sample to $Fe_2O_3(s)$. The student collects the following data during the experiment.

Mass of Fe(s) with inert impurity	6.724 g
Mass of $Fe_2O_3(s)$ produced	7.531 g

Question 3

2018 ▪ Q3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(g) Calculate the number of moles of Fe in the $Fe_2O_3(s)$ produced.

Question 3

2018 ▪ Q3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(h) Calculate the percent by mass of Fe in the original sample of powdered Fe(s) with the inert impurity.

Question 3

2018 ▪ Q3

Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+}.

(i) If the oxidation of the Fe(s) in the original sample was incomplete so that some of the 7.531 g of product was FeO(s) instead of Fe_2O_3(s), would the calculated mass percent of Fe(s) in the original sample be higher, lower, or the same as the actual mass percent of Fe(s)? Justify your answer.

Solution 3

(a)

Mark scheme

- Ground-state electron configuration of $Fe2+$: 1s2 2s2 2p6 3s2 3p6 3d6, i.e., [Ar]3d6 (the two 4s electrons are removed first when Fe forms $Fe2+$). 1 point is earned for the correct electron configuration.

Solution 3

(b)

Mark scheme

- Both ions have the same nuclear charge (26 protons), but Fe2+ has one more electron in its outermost (3d) shell than Fe3+. The greater number of electrons in that shell for Fe2+ results in greater electron-electron repulsion, which leads to a larger radius. 1 point is earned for a valid explanation.

Solution 3

(c)

Mark scheme

- By Coulomb's law, F is proportional to q1*q2/r^2 (need not be explicitly stated). $Fe3+$ has a higher charge than $Fe2+$, so it attracts the partially negative O of water molecules more strongly. OR: the smaller ionic radius of $Fe3+$ allows it to get closer to a water molecule, increasing the force of attraction (smaller r increases F). 1 point is earned for a valid explanation using Coulomb's law.

Solution 3

(d)

Mark scheme

- Half-reaction: $Fe^{2+}(aq) \rightarrow Fe^{3+}(aq) + e^-$. 1 point is earned for the correct half-reaction.

Solution 3

(e)

Mark scheme

- 17.48 mL x 0.0350 mol $KMnO_4$/1000 mL = 0.000612 mol $KMnO_4$. Using the stoichiometry 5 Fe^{2+} : 1 MnO_4^-: 0.000612 mol $KMnO_4$ x (5 mol Fe^{2+}/1 mol $KMnO_4$) = 0.003059 mol Fe^{2+}. [Fe^{2+}] = 0.003059 mol / 0.0100 L = 0.306 M. 1 point is earned for calculating the number of moles of $KMnO_4$ (may be implicit); 1 point is earned for the correct concentration of Fe^{2+}.

Solution 3

(f)

Mark scheme

- A 25 mL volumetric flask is designed to contain (measure) only 25.00 mL precisely, it has a single calibration mark and cannot accurately deliver a smaller, arbitrary volume like 10.0 mL. 1 point is earned for a valid explanation.

Solution 3

(g)

Mark scheme

- 7.531 g Fe2O3 x (1 mol Fe2O3/159.70 g Fe2O3) = 0.04716 mol Fe2O3. 0.04716 mol Fe2O3 x (2 mol Fe/1 mol Fe2O3) = 0.09431 mol Fe. 1 point is earned for the correct calculation.

Solution 3

(h)

Mark scheme

- 0.09431 mol Fe x 55.85 g Fe/mol = 5.267 g Fe. Percent by mass = (5.267 g Fe / 6.724 g sample) x 100 = 78.33%. 1 point is earned for the correct calculation of mass percent, based on the answer to part (g).

Solution 3

(i)

Mark scheme

- The calculated mass percent of Fe would be LOWER than the actual mass percent. A sample containing any FeO (rather than only Fe2O3) has a higher actual mass percent of Fe than a completely oxidized (Fe2O3-only) sample would, because FeO has a higher Fe:O mass ratio. So when the moles of Fe are calculated assuming all 7.531 g of product is Fe2O3, the calculated number of moles of Fe (and hence the calculated mass percent of Fe) will be lower than the true value. 1 point is earned for the correct answer (lower) and a valid explanation.