

Past-paper walk-through

Reaction Quotient and Equilibrium Constant ■ 7.3

eXercise

Questions in this set

- 2025 Q1
- 2025 Q3
- 2024 Q5
- 2023 Q2
- 2022 Q2
- 2021 Q1
- 2019 Q2
- 2017 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 1

2025 ■ Q1

Answer the following questions about magnesium.

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

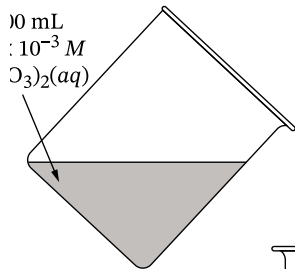
[Bar graph titled “Relative Abundance” vs. “Mass (amu)”]; y-axis from 0 to 100 in increments of 20; x-axis shows tick marks at 24, 25, 26; a single thick vertical bar is drawn at mass 24 reaching a relative abundance of about 79.]

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.

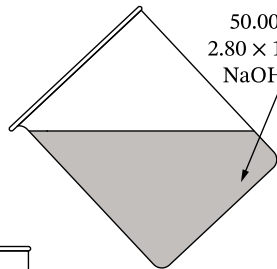
(a)(ii) Describe the difference in atomic structure that accounts for the difference in mass between magnesium-25 and magnesium-26.

Question 1



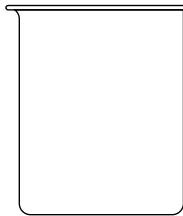
10.0 mL
 $1.0 \times 10^{-3} M$
 $\text{Ca}_3(\text{PO}_4)_2(aq)$

Beaker 1

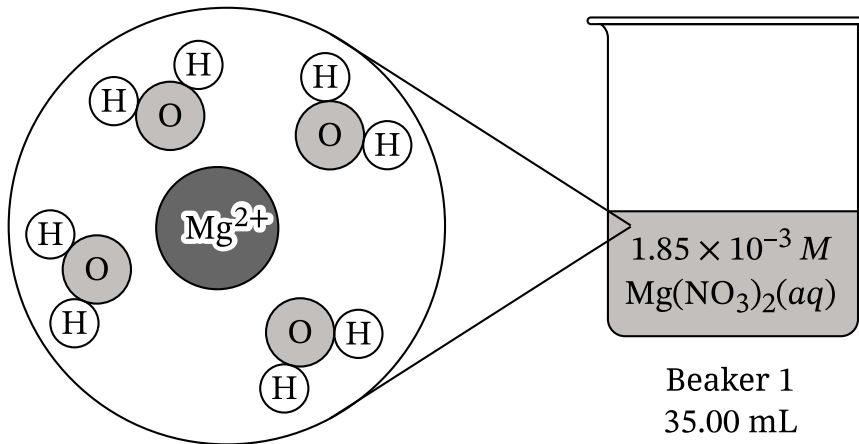


50.00 mL
 $2.80 \times 10^{-4} M$
 $\text{NaOH}(aq)$

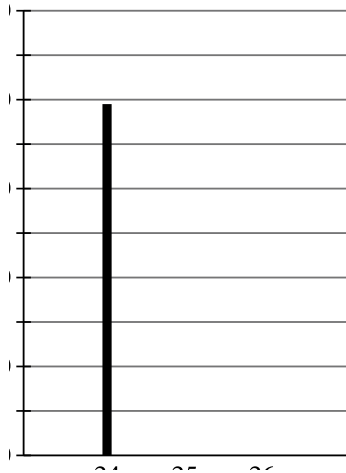
Beaker 2



Question 1



Question 1



Question 1

2025 ■ Q1

Answer the following questions about magnesium.

(b) A student prepares a $1.85 \times 10^{-3} \text{ M}$ solution of $\text{Mg}(\text{NO}_3)_2(\text{aq})$ in beaker 1 and a $2.80 \times 10^{-4} \text{ M}$ solution of $\text{NaOH}(\text{aq})$ in beaker 2, as shown.

[Particle diagram: a magnesium ion, Mg^{2+} , at the center surrounded by six water molecules (H_2O), each oriented with its oxygen atom pointing toward the central Mg^{2+} ion and its two hydrogen atoms pointing outward.]

[Beaker 1: labeled " $1.85 \times 10^{-3} \text{ M Mg}(\text{NO}_3)_2(\text{aq})$ ", "Beaker 1", "35.00 mL".]

[Beaker 2: labeled " $2.80 \times 10^{-4} \text{ M NaOH}(\text{aq})$ ", "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 $1.85 \times 10^{-3} \text{ M}$ $\text{Mg}(\text{NO}_3)_2(\text{aq})$ with 50.00 mL of $2.80 \times 10^{-4} \text{ M}$ $\text{NaOH}(\text{aq})$, as shown in the diagram. Calculate $[\text{Mg}^{2+}]$ after the two solutions are combined but before any reaction takes place. (Assume that volumes are additive.)

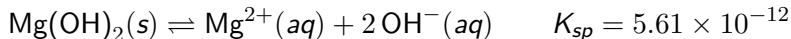
[Diagram of two conical/Erlenmeyer flasks being poured into an empty Beaker 3. Left flask: "35.00 mL", " $1.85 \times 10^{-3} \text{ M}$ ", " $\text{Mg}(\text{NO}_3)_2(\text{aq})$ ", labeled "Beaker 1". Right flask: "50.00 mL", " $2.80 \times 10^{-4} \text{ M}$ ", " $\text{NaOH}(\text{aq})$ ", labeled "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.



(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, $[\text{OH}^{-}] = 1.65 \times 10^{-4} \text{ M}$. 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 $\text{HNO}_3(aq)$ to decrease the pH of a saturated solution containing undissolved $\text{Mg}(\text{OH})_2(s)$. Does the amount of undissolved $\text{Mg}(\text{OH})_2(s)$ increase, decrease, or remain the same as the $\text{HNO}_3(aq)$ 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 $1.85 \times 10^{-3} \text{ M Mg(NO}_3)_2(\text{aq})$ and $2.80 \times 10^{-4} \text{ M NaOH(aq)}$ 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

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

Solution 1

(d)

Mark scheme

- Using $M_1 V_1 = M_2 V_2$: $M_2 = \frac{(1.85 \times 10^{-3} \text{ M})(0.03500 \text{ L})}{0.03500 \text{ L} + 0.05000 \text{ L}} = 7.62 \times 10^{-4} \text{ M}$.
So $[\text{Mg}^{2+}]$ after combining but before reaction is $7.62 \times 10^{-4} \text{ M}$.

Solution 1

(e)

Mark scheme

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

(e)(i)

Mark scheme

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

Solution 1

(e)(ii)

Mark scheme

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

(e)(iii)

Mark scheme

- $Q (2.07 \times 10^{-11}) > K_{sp} (5.61 \times 10^{-12})$, 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 $\text{Mg}(\text{OH})_2(\text{s})$ will decrease. The H^+ from $\text{HNO}_3(\text{aq})$ reacts with OH^- , decreasing $[\text{OH}^-]$ and causing $Q < K_{\text{sp}}$. As a result, more $\text{Mg}(\text{OH})_2(\text{s})$ will dissolve until equilibrium is reestablished, resulting in less undissolved $\text{Mg}(\text{OH})_2(\text{s})$.

Question 3

2025 ■ Q3

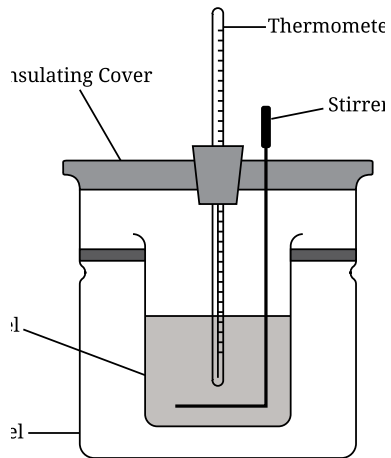
White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(a) In the box in part A, complete the Lewis diagram for P_4 by drawing the nonbonding electrons.

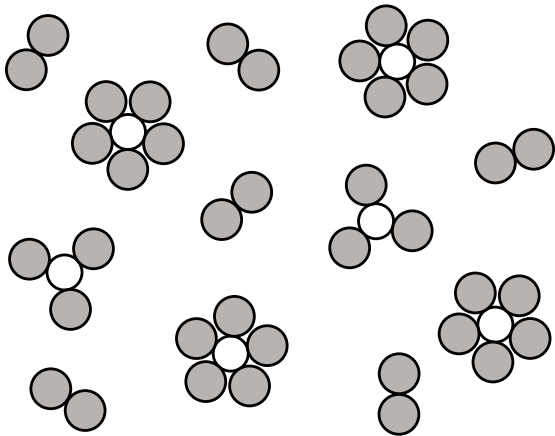
Question 3



Question 3

Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	22.00° C
Final temperature	22.38° C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g·°C)

Question 3



Question 3

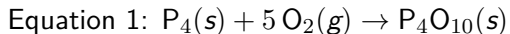
2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(b) The reaction of white phosphorus with oxygen to form $P_4O_{10}(s)$ is thermodynamically favorable at 298 K. The reaction is represented by equation 1.



Question 3

(b)(i) The entropy change of the reaction, ΔS° , is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.

(b)(ii) The enthalpy change of the reaction, ΔH° , is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** by entropy. Is the student's claim correct? Justify your answer by using the relationship between ΔG° , ΔH° , and ΔS° .

Question 3

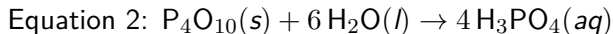
2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(c) $P_4O_{10}(s)$ reacts exothermically with water to form phosphoric acid, as represented by equation 2.



Question 3

A chemist uses a calorimetry experiment to determine the enthalpy change for the reaction, as represented by the following diagram.

[Calorimeter diagram: a coffee-cup-style calorimeter labeled "Thermometer" (inserted through the insulating cover), "Stirrer" (inserted alongside the thermometer), "Insulating Cover" (the lid), "Inner Vessel" (the cup holding the solution, shaded), and "Outer Vessel" (the outer supporting cup).]

The chemist carries out the calorimetry experiment and records the following information.

Quantity	Value	—	—	Mass of P_4O_{10}	0.100 g	Mass of H_2O	100.0 g
Initial temperature	22.00°C	Final temperature	22.38°C	Molar mass of P_4O_{10}	283.9 g/mol	Specific heat of H_2O	4.18 J/(g · °C)

(c)(i) Calculate the amount of heat, q , released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.

Question 3

(c)(ii) Calculate the value of ΔH_{rxn}° for equation 2 in kJ/mol_{rxn} . Include the sign in your answer.

Question 3

2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(d) The chemist weighed out 0.100 g P_4O_{10} of and 100.0 g of H_2O to perform a second trial. In the second trial, some of the solid P_4O_{10} stuck to the weighing paper and was not transferred to the calorimeter. Given that P_4O_{10} is the limiting reactant,

Question 3

would ΔT for the second trial be greater than, less than, or equal to the value in the first trial? Justify your answer.

$\text{P}_4(\text{s})$ also reacts readily with $\text{Cl}_2(\text{g})$ to produce phosphorus trichloride, $\text{PCl}_3(\text{g})$, which in turn reacts with $\text{Cl}_2(\text{g})$ in an equilibrium process to produce $\text{PCl}_5(\text{g})$. The reactions are represented by equations 3 and 4.



Question 3

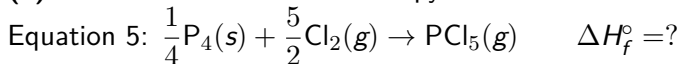
2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(e) Calculate the standard enthalpy of formation of $PCl_5(g)$ represented by equation 5.



The following particle-level diagram represents the contents of the vessel in an equilibrium mixture at 546 K involving equation 4.

Question 3

[Particle diagram: a box containing multiple particles at random positions representing an equilibrium mixture; a key indicates two-atom particles (grey-grey) = Cl_2 , four-atom tetrahedral-looking particles (grey with three white) = PCl_3 , and six-atom particles (grey with five white) = PCl_5 . The box shows several Cl_2 particles (pairs of grey circles), several PCl_3 particles (grey center with three white circles), and several PCl_5 particles (grey center with five white circles) scattered throughout.]

Question 3

2025 ■ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4 , showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P_4 skeleton, with no lone pairs drawn yet.]

(f) Equation 4 for the reaction that occurs is shown.



(f)(i) If each particle in the diagram represents a partial pressure of 1.00 atm, what is the value of K_p for the equilibrium mixture at 546 K?

Question 3

(f)(ii) Does the value of K_p increase, decrease, or remain the same when the temperature is increased to 596 K? Justify your answer based on ΔH_2° .

Solution 3

(a)

Mark scheme

- Complete Lewis diagram for P_4 : the four P atoms form a tetrahedron, each bonded to the other three P atoms by single bonds, and each P atom bears one lone (nonbonding) pair of electrons — giving each P three bonding pairs plus one lone pair, satisfying the octet rule.

Solution 3

(b)

Mark scheme

- No separate response required — this is the context/stem presenting equation 1 ($\text{P}_4(\text{s}) + 5 \text{O}_2(\text{g}) \rightarrow \text{P}_4\text{O}_{10}(\text{s})$), thermodynamically favorable at 298 K, that parts (i) and (ii) below refer to.

(b)(i)

Mark scheme

- Because gas particles are more dispersed (have more accessible microstates) than solids, the entropy decreases as the reactants (which include a gas, O_2) convert into the solid product (P_4O_{10}).

Solution 3

(b)(ii)

Mark scheme

- Yes, the student's claim is correct. Given $\Delta G_{rxn}^{\circ} = \Delta H_{rxn}^{\circ} - T\Delta S_{rxn}^{\circ}$, the reaction must have $\Delta G_{rxn}^{\circ} < 0$ to be favorable. Because the reaction is exothermic, $\Delta H_{rxn}^{\circ} < 0$ and enthalpy contributes to favorability. $\Delta S_{rxn}^{\circ} < 0$, so entropy does NOT contribute to favorability — i.e., enthalpy alone drives it.

Solution 3

(c)

Mark scheme

- No separate response required — this is the context/stem describing the calorimetry experiment for the exothermic reaction of $\text{P}_4\text{O}_{10}(\text{s})$ with water (equation 2: $\text{P}_4\text{O}_{10}(\text{s}) + 6 \text{H}_2\text{O}(\text{l}) \rightarrow 4 \text{H}_3\text{PO}_4(\text{aq})$) that parts (i) and (ii) below use.

Solution 3

(c)(i)

Mark scheme

- $q = mc\Delta T = (100.1 \text{ g})(4.18 \text{ J/(g}\cdot^{\circ}\text{C)})(22.38^{\circ}\text{C} - 22.00^{\circ}\text{C}) = 160 \text{ J} = 0.16 \text{ kJ}$
(reported to the correct number of significant figures).

Solution 3

(c)(ii)

Mark scheme

■ $q_{rxn} = -q_{surr} = -0.16 \text{ kJ}.$

$$\Delta H_{rxn}^{\circ} = \frac{-0.16 \text{ kJ}}{0.100 \text{ g P}_4\text{O}_{10}} \times \frac{283.9 \text{ g P}_4\text{O}_{10}}{1 \text{ mol P}_4\text{O}_{10}} \times \frac{1 \text{ mol P}_4\text{O}_{10}}{1 \text{ mol}_{rxn}} = -450 \text{ kJ/mol}_{rxn}.$$

The correct (negative) sign must be included.

Solution 3

(d)

Mark scheme

- Less than. If less P_4O_{10} is present (some stuck to the weighing paper), less thermal energy will be transferred to the water during the reaction, causing the temperature increase (ΔT) to be less than it was with the full 0.100 g of P_4O_{10} .

Solution 3

(e)

Mark scheme

- Using Hess's law:

$$\Delta H_{f,\text{PCl}_5(g)}^\circ = \frac{1}{4}\Delta H_1^\circ + \Delta H_2^\circ = \frac{1}{4}(-1148) + (-88) = -375 \text{ kJ/mol.}$$

Solution 3

(f)

Mark scheme

- No separate response required — this is the context/stem presenting equation 4 ($\text{PCl}_3(g) + \text{Cl}_2(g) \rightleftharpoons \text{PCl}_5(g)$, $\Delta H_2^\circ = -88 \text{ kJ/mol}_{\text{rxn}}$) that parts (i) and (ii) below refer to.

Solution 3

(f)(i)

Mark scheme

- Reading partial pressures of 1.00 atm per particle from the diagram (4 PCl_5 , 2 PCl_3 , 6 Cl_2 particles): $K_p = \frac{P_{\text{PCl}_5}}{(P_{\text{PCl}_3})(P_{\text{Cl}_2})} = \frac{4.00}{(2.00)(6.00)} = \frac{1}{3} = 0.333$.

Solution 3

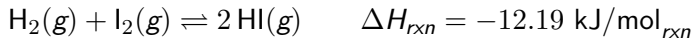
(f)(ii)

Mark scheme

- Decrease. The negative value of ΔH_2° indicates the reaction is exothermic. Because exothermic reactions favor reactant formation at higher temperature (the equilibrium shifts toward reactants as heat is added), the value of K_p decreases.

Question 5

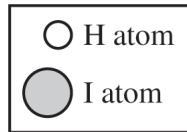
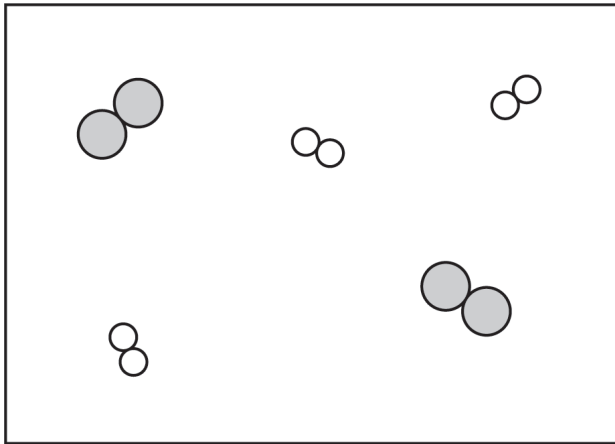
2024 ■ Q5



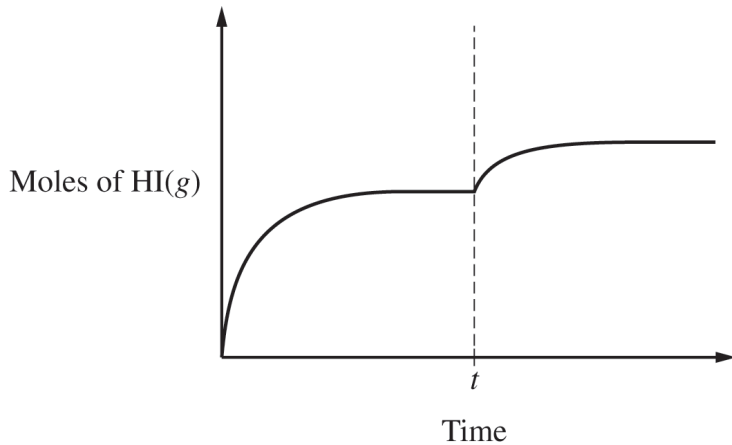
5. Hydrogen gas and iodine gas react to form hydrogen iodide at an elevated temperature, as represented by the following equation.

(a) Write the expression for the equilibrium constant, K_c , for this reaction.

Question 5



Question 5



Question 5

2024 ■ Q5



5. Hydrogen gas and iodine gas react to form hydrogen iodide at an elevated temperature, as represented by the following equation.

(b)(i) $\text{H}_2(g)$ and $\text{I}_2(g)$ are added to a previously evacuated container and allowed to react.

At a certain time, the value of the reaction quotient, Q , is 0.67. The following particle diagram is an incomplete representation of the system at this time. The diagram shows the relative number of $\text{H}_2(g)$ and $\text{I}_2(g)$ molecules, but the $\text{HI}(g)$ molecules are not included. Draw the number of $\text{HI}(g)$ molecules needed to complete the diagram so that it accurately represents the system.

Question 5

[Rectangular particle-diagram box containing: 2 pairs of bonded circles representing I_2 molecules — one pair (2 gray/shaded circles bonded together) upper-left, one pair (2 white/open circles bonded together) upper-right; 2 pairs of bonded circles representing H_2 molecules — one pair (2 small white circles bonded) center, one pair (2 gray circles bonded) lower-middle-right, one more pair (2 small white circles bonded) lower-left. A legend to the right of the box: open/white circle = H atom, gray/shaded circle = I atom. Molecule counts shown: 2 I_2 molecules (one gray-gray pair, one white-white pair — actually representing I_2 and possibly another diatomic), plus H_2 -type pairs — the diagram shows a total of 3 diatomic pairs that are H-containing and 2 that are I-containing among the 5 total pairs drawn, matching an $H_2 : I_2$ ratio consistent with $Q = 0.67$. Student must add the correct number of HI molecules (single white-gray bonded pairs) to complete the diagram.]

Question 5

(b)(ii) A student monitors the number of moles of $\text{HI}(g)$ over time. Hypothesize an experimental change that could have been applied to the system in the rigid container at time t to result in the change in the number of moles of $\text{HI}(g)$ shown in the graph. Assume that the student did not add more $\text{HI}(g)$ to the system.

[Graph: y-axis "Moles of $\text{HI}(g)$ " (unlabeled scale), x-axis "Time"; curve rises steeply from the origin, levels off into a plateau, then at a dashed vertical line marked t the curve jumps up abruptly to a new, higher level and levels off again into a second plateau.]

(b)(iii) After equilibrium is established, the mixture is transferred to a larger container at constant temperature. As a result, would the number of moles of $\text{HI}(g)$ increase, decrease, or remain the same? Justify your answer.

Solution 5

(a)

Mark scheme

$$\blacksquare K_c = \frac{[\text{HI}]^2}{[\text{H}_2][\text{I}_2]}.$$

Solution 5

(b)(i)

Mark scheme

- Complete the particle diagram (consistent with part (a)) by drawing enough HI molecules (one H atom + one I atom joined) so that the diagram is consistent with $Q = 0.67 = \frac{[\text{HI}]^2}{[\text{H}_2][\text{I}_2]}$, given the numbers of H_2 and I_2 molecules already shown in the box.

Solution 5

(b)(ii)

Mark scheme

- Accept either: decreased the temperature; OR added more $\text{H}_2(\text{g})$ and/or $\text{I}_2(\text{g})$ to the reaction vessel — either change would shift the equilibrium to produce more $\text{HI}(\text{g})$ over time, consistent with the graph's rise in moles of HI after time t .

Solution 5

(b)(iii)

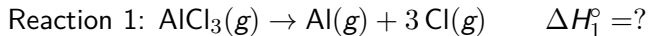
Mark scheme

- Remain unchanged. Accept either justification: (1) The moles of gaseous reactants and products in the balanced equation are equal, so transferring to a larger container does not shift the equilibrium (Q remains equal to K), so moles of HI stay the same. (2) Increasing the volume decreases the concentrations of reactants and products by an equal proportion; since there are equal moles of gaseous reactants and products, there is no shift in equilibrium position, so the moles of HI remain the same.

Question 2

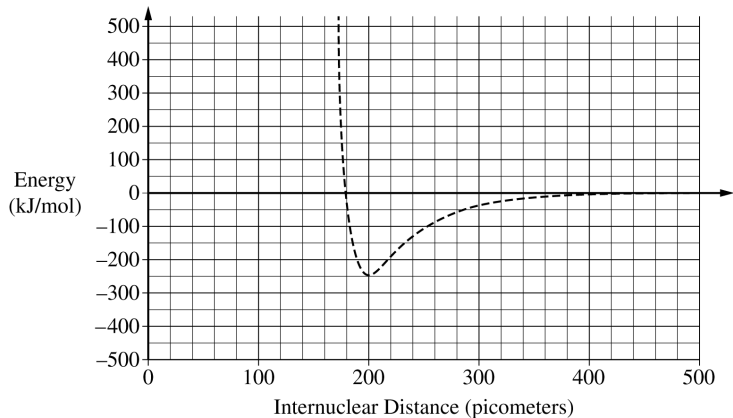
2023 ■ Q2

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.



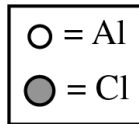
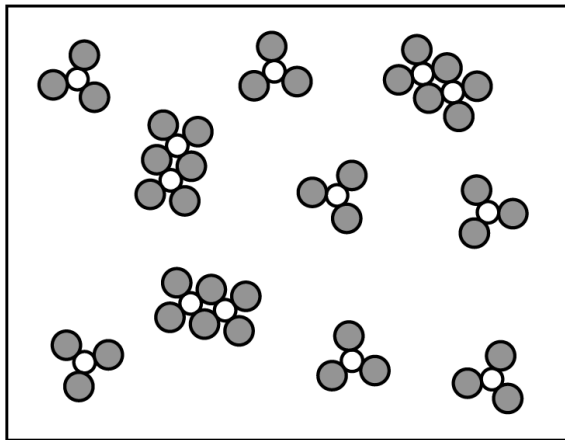
(a) How many grams of $\text{Cl}(g)$ can be formed from 1.25 mol of $\text{AlCl}_3(g)$?

Question 2



on the graph, what is the bond length, in picometers, for Cl_2 ? _____

Question 2



Question 2

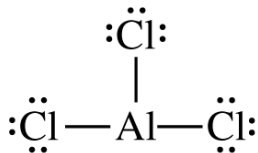


Diagram 1

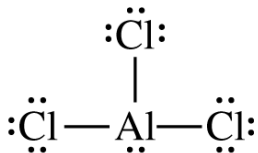


Diagram 2

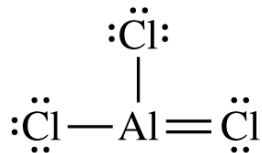


Diagram 3

Question 2

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.

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

Reaction Number	Equation	ΔH_{rxn}° (kJ/mol _{rxn})	2
	$\text{Al}(s) + \frac{3}{2}\text{Cl}_2(g) \rightarrow \text{AlCl}_3(g)$	-583	3
	$\text{Al}(s) \rightarrow \text{Al}(g)$	+326	4
	$\text{Cl}_2(g) \rightarrow 2\text{Cl}(g)$	+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.



(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.



(d)(i) Three proposed Lewis diagrams for the $\text{AlCl}_3(g)$ 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) — $\text{Cl}=\text{Al}$ on the right side.]

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

Question 2

The $\text{AlCl}_3(g)$ 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.

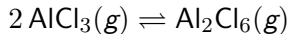
Question 2

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.



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



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.



(f) A particle-level diagram of an equilibrium mixture of $\text{AlCl}_3(g)$ and $\text{Al}_2\text{Cl}_6(g)$ 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

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

Solution 2

(b) Mark scheme

- Apply Hess's law using reactions 2, 3, and 4: reverse reaction 2 ($\text{AlCl}_3(g) \rightarrow \text{Al}(s) + \frac{3}{2}\text{Cl}_2(g)$, $\Delta H = -(-583) = +583 \text{ kJ/mol}_{\text{rxn}}$) and multiply reaction 4 by $\frac{3}{2}$ ($\frac{3}{2}\text{Cl}_2(g) \rightarrow 3 \text{ Cl}(g)$, $\Delta H = 1.5(+243) = +365 \text{ kJ/mol}_{\text{rxn}}$), then add reaction 3 unchanged:
$$\Delta H_1^\circ = -\Delta H_2^\circ + \Delta H_3^\circ + 1.5(\Delta H_4^\circ) = -(-583) + 326 + 1.5(243) = 1274 \text{ kJ/mol}_{\text{rxn}}.$$

Solution 2

(c)(i)

Mark scheme

- Bond length ≈ 200 picometers (± 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 ± 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 $\text{AlCl}_3(\text{g})$.

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

$$\blacksquare K_p = \frac{P_{\text{Al}_2\text{Cl}_6}}{(P_{\text{AlCl}_3})^2}.$$

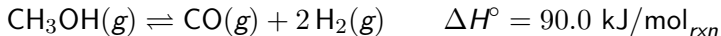
Solution 2

(f) Mark scheme

- Using mole fractions read from the particle diagram ($\chi_{\text{AlCl}_3} = \frac{7}{10}$, $\chi_{\text{Al}_2\text{Cl}_6} = \frac{3}{10}$)
and total pressure 22.1 atm: $K_p = \frac{\chi_{\text{Al}_2\text{Cl}_6}(P_{\text{total}})}{(\chi_{\text{AlCl}_3}(P_{\text{total}}))^2} = \frac{\frac{3}{10}(22.1)}{(\frac{7}{10}(22.1))^2} = 0.0277$.

Question 2

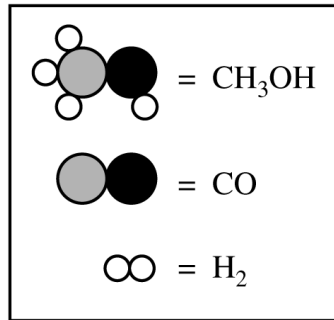
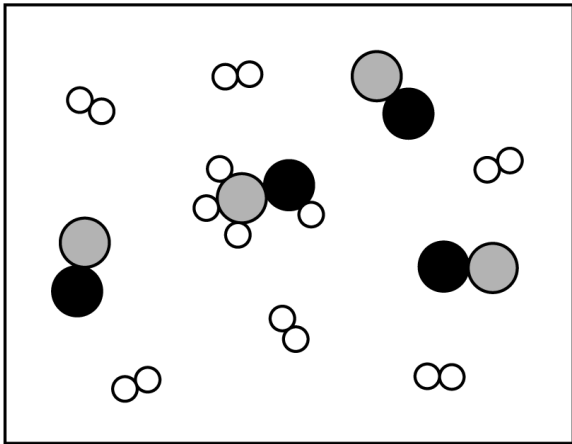
2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

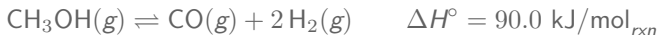
(a) Are the hydrogen atoms oxidized or are they reduced in the forward reaction? Justify your answer in terms of oxidation numbers.

Question 2



Question 2

2022 ■ Q2



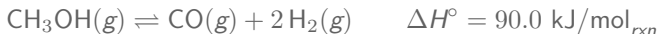
Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(b) In the following box, draw the complete Lewis electron-dot diagram for the carbon monoxide molecule in which every atom obeys the octet rule. Show all bonding and nonbonding valence electrons.

[A blank box is provided containing the unconnected atomic symbols “C” and “O”, for the student to complete into a full Lewis structure.]

Question 2

2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(c)(i) The values of the standard molar entropies of the compounds involved in the reaction are given in the following table.

Substance	S° (J/(K · mol))	CH ₃ OH(<i>g</i>)	240.	CO(<i>g</i>)	198	H ₂ (<i>g</i>)
			131			

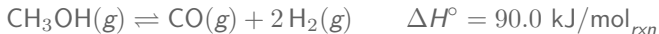
Use the data in the table to calculate the value of the standard entropy change, ΔS° , in J/(K · mol_{rxn}), for the reaction.

Question 2

(c)(ii) Calculate the value of ΔG° , in $\text{kJ/mol}_{\text{rxn}}$, for the reaction at 375 K. Assume that ΔH° and ΔS° are independent of temperature.

Question 2

2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(d) The following particle-level diagram shows a representative sample of the equilibrium mixture represented by the equation given.

[A rectangular box (the "container") contains a mixture of particles at equilibrium: several two-linked-open-circle pairs (H₂), and several three-part particles each made of one gray sphere + one black sphere + one small open circle (CO), plus one larger cluster shown as CH₃OH. A key box beside it identifies: a cluster of one gray sphere +

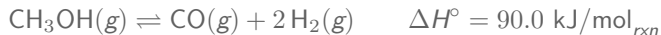
Question 2

one black sphere + three small open circles = CH_3OH ; one gray sphere + one black sphere = CO ; two small open circles joined = H_2 . Counting the container: there appear to be 1 CH_3OH particle, 4 CO particles, and 8 H_2 particles.]

Use information from the particle diagram to calculate the partial pressure of CO at equilibrium when the total pressure of the equilibrium mixture is 12.0 atm.

Question 2

2022 ■ Q2

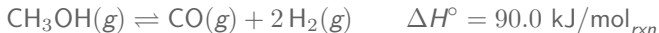


Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(e) Write the expression for the equilibrium constant, K_p , for the reaction.

Question 2

2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(f)



The reaction system represented by the equation is allowed to achieve equilibrium at a different temperature. The following table gives the partial pressure of each species in the equilibrium mixture.

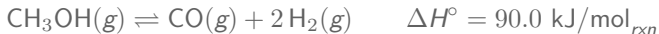
Question 2

Substance	Partial Pressure at Different Temperature		CH ₃ OH(<i>g</i>)	2.7 atm
CO(<i>g</i>)	4.2 atm	H ₂ (<i>g</i>)	8.4 atm	

Use the information in the table to calculate the value of the equilibrium constant, K_p , at the new temperature.

Question 2

2022 ■ Q2



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(g) The volume of the container is rapidly doubled with no change in temperature. As equilibrium is re-established, does the number of moles of $\text{CH}_3\text{OH}(g)$ increase, decrease, or remain the same? Justify your answer by comparing the value of the reaction quotient, Q , with the value of the equilibrium constant, K_p .

Solution 2

(a)

Mark scheme

- The H atoms are reduced because they change from an oxidation number of +1 (in CH_3OH) to 0 (in H_2) in the forward reaction.

Solution 2

(b)

Mark scheme

- Complete Lewis electron-dot diagram for CO obeying the octet rule: a carbon–oxygen triple bond ($\text{:C}\equiv\text{O:}$) with one lone pair on carbon and one lone pair on oxygen, giving each atom an octet (triple bond = 6 shared electrons + 1 lone pair = 8 electrons around each atom).

Solution 2

(c)(i)

Mark scheme

- $\Delta S^{\circ}_{\text{rxn}} = \Sigma \Delta S^{\circ}_{\text{products}} - \Sigma \Delta S^{\circ}_{\text{reactants}} = (\Delta S^{\circ}_{\text{CO(g)}} + 2\Delta S^{\circ}_{\text{H}_2\text{(g)}}) - \Delta S^{\circ}_{\text{CH}_3\text{OH(g)}}$ (1 point for correct stoichiometry, may be implicit). Using the table values (S° : $\text{CH}_3\text{OH(g)} = 240. \text{ J/(K} \cdot \text{mol)}$, $\text{CO(g)} = 198 \text{ J/(K} \cdot \text{mol)}$, $\text{H}_2\text{(g)} = 131 \text{ J/(K} \cdot \text{mol)}$): $\Delta S^{\circ}_{\text{rxn}} = 198 + 2(131) - 240. = 220. \text{ J/(K} \cdot \text{mol}_{\text{rxn}})$ (1 point for the correct calculated value).

Solution 2

(c)(ii)

Mark scheme

- $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ = 90.0 \text{ kJ/mol}_{\text{rxn}} - (375 \text{ K})(0.220 \text{ kJ/(K} \cdot \text{mol}_{\text{rxn}})) = +7.5 \text{ kJ/mol}_{\text{rxn}}$ (assuming ΔH° and ΔS° are independent of temperature).

Solution 2

(d)

Mark scheme

- From the particle-level diagram, CO particles make up 3 of the 10 total gas particles shown in the container. With a total pressure of 12.0 atm: $P_{\text{CO}} = (3/10)(12.0 \text{ atm}) = 3.6 \text{ atm}$.

Solution 2

(e)

Mark scheme

- $K_p = (P_{\text{CO}})(P_{\text{H}_2})^2 / (P_{\text{CH}_3\text{OH}})$.

Solution 2

(f)

Mark scheme

- Using the partial pressures at the new equilibrium temperature ($\text{CH}_3\text{OH} = 2.7$ atm, $\text{CO} = 4.2$ atm, $\text{H}_2 = 8.4$ atm): $K_p = (P_{\text{CO}})(P_{\text{H}_2})^2 / (P_{\text{CH}_3\text{OH}}) = (4.2)(8.4)^2 / (2.7) = 110$.

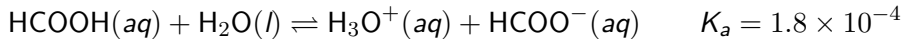
Solution 2

(g) Mark scheme

- Comparison of Q and K (1 point): doubling the container volume causes the partial pressure of each species to decrease by a factor of two; because there are more moles of gaseous products than reactants, the resulting decrease in the numerator of Q is larger (raised to a higher net power) than the decrease in the denominator, making $Q_p < K_p$ — explicitly $Q_p = [(P_{\text{CO}}/2)(P_{\text{H}_2}/2)^2] / (P_{\text{CH}_3\text{OH}}/2) = K_p/4 \approx 27 < K_p$. Answer and justification (1 point): the number of moles of $\text{CH}_3\text{OH}(\text{g})$ will decrease. Since $Q_p < K_p$, the reaction proceeds forward as equilibrium re-establishes, increasing the partial pressures (moles) of the products and decreasing the moles of CH_3OH .

Question 1

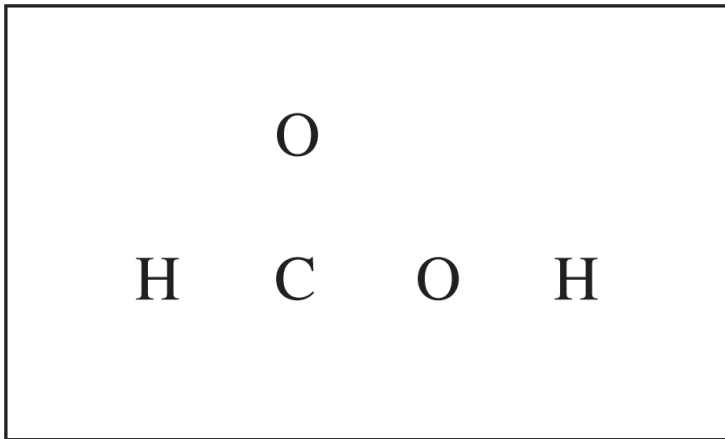
2021 ■ Q1



Methanoic acid, HCOOH , ionizes according to the equation above.

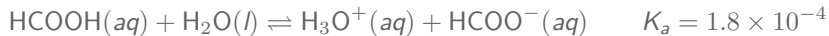
(a) Write the expression for the equilibrium constant, K_a , for the reaction.

Question 1



Question 1

2021 ■ Q1

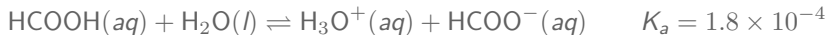


Methanoic acid, HCOOH , ionizes according to the equation above.

(b) Calculate the pH of a 0.25 M solution of HCOOH .

Question 1

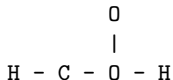
2021 ■ Q1



Methanoic acid, HCOOH , ionizes according to the equation above.

(c) In the box below, complete the Lewis electron-dot diagram for HCOOH . Show all bonding and nonbonding valence electrons.

[Box containing the skeletal atom arrangement of HCOOH (no bonds or lone pairs drawn), laid out as:

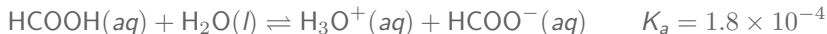


Question 1

i.e. a central C bonded to: an O atom above it (drawn separated, no bond line shown), an H atom to its left, and an O atom to its right which is in turn bonded to a further H atom on the far right. The student must add all bonding and nonbonding valence electrons to complete the Lewis structure.]

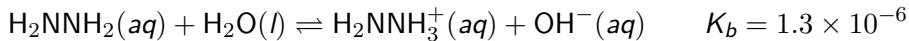
Question 1

2021 ■ Q1



Methanoic acid, HCOOH , ionizes according to the equation above.

(d)(i)



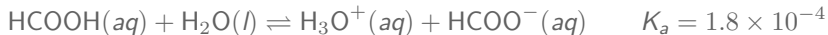
In aqueous solution, the compound H_2NNH_2 reacts according to the equation above. A 50.0 mL sample of 0.25 M $\text{H}_2\text{NNH}_2(aq)$ is combined with a 50.0 mL sample of 0.25 M $\text{HCOOH}(aq)$.

Write the balanced net ionic equation for the reaction that occurs when H_2NNH_2 is combined with HCOOH .

(d)(ii) Is the resulting solution acidic, basic, or neutral? Justify your answer.

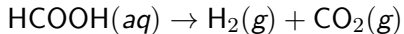
Question 1

2021 ■ Q1



Methanoic acid, HCOOH , ionizes according to the equation above.

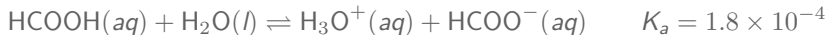
(e) When a catalyst is added to a solution of $\text{HCOOH}(aq)$, the reaction represented by the following equation occurs.



Is the reaction a redox reaction? Justify your answer.

Question 1

2021 ■ Q1



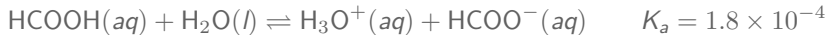
Methanoic acid, HCOOH , ionizes according to the equation above.

(f) [Graph: Total Pressure (atm) on the y-axis (from 0 to above 24, with a dashed horizontal line at 24) vs. Time (hours) on the x-axis. The curve rises steeply from the origin, curving and leveling off asymptotically to a plateau at a total pressure of 24 atm.]

The reaction occurs in a rigid 4.3 L vessel at 25°C , and the total pressure is monitored, as shown in the graph above. The vessel originally did not contain any gas. Calculate the number of moles of $\text{CO}_2(g)$ produced in the reaction. (Assume that the amount of $\text{CO}_2(g)$ dissolved in the solution is negligible.)

Question 1

2021 ■ Q1



Methanoic acid, HCOOH , ionizes according to the equation above.

(g) After the reaction has proceeded for several minutes, does the amount of catalyst increase, decrease, or remain the same? Justify your answer.

Solution 1

(a)

Mark scheme

- $K_a = \frac{[\text{H}_3\text{O}^+][\text{HCOO}^-]}{[\text{HCOOH}]}$ — the correct equilibrium-constant expression for the dissociation of HCOOH (products over reactant; water omitted as pure liquid).

Solution 1

(b)

Mark scheme

- ICE table for $\text{HCOOH} + \text{H}_2\text{O} \rightleftharpoons \text{H}_3\text{O}^+ + \text{HCOO}^-$, initial $[\text{HCOOH}] = 0.25 \text{ M}$:

$$K_a = 1.8 \times 10^{-4} = \frac{x^2}{0.25 - x}. \text{ Assuming } x \ll 0.25:$$

$x^2 = (1.8 \times 10^{-4})(0.25) \Rightarrow x = [\text{H}_3\text{O}^+] = 0.0067 \text{ M}$ (1 pt). Then
 $\text{pH} = -\log[\text{H}_3\text{O}^+] = -\log(0.0067) = 2.17$ (1 pt, consistent with the calculated concentration).

Solution 1

(c)

Mark scheme

- Correct complete Lewis structure of HCOOH (formic acid): $\text{H}-\text{C}(=\text{O})-\text{O}-\text{H}$. The central C is bonded to: an H atom (single bond), a terminal O by a double bond (that terminal O carries 2 lone pairs), and a second O by a single bond (that O carries 2 lone pairs and is also single-bonded to the second H). All bonding pairs and all nonbonding (lone) pairs of valence electrons must be shown explicitly.

Solution 1

(d)(i)

Mark scheme

- $\text{H}_2\text{NNH}_2(aq) + \text{HCOOH}(aq) \rightarrow \text{H}_2\text{NNH}_3^+(aq) + \text{HCOO}^-(aq)$ — the weak base H_2NNH_2 accepts a proton from the weak acid HCOOH ; already balanced as written (state symbols not required).

Solution 1

(d)(ii)

Mark scheme

- Acidic. The resulting solution is a mixture of the conjugate acid H_2NNH_3^+ and the conjugate base HCOO^- . Because the K_a of H_2NNH_3^+ is greater than the K_b of HCOO^- , production of $\text{H}_3\text{O}^+(\text{aq})$ occurs to a greater extent than production of $\text{OH}^-(\text{aq})$, so the solution is acidic.

Solution 1

(e)

Mark scheme

- Yes, it is a redox reaction. Accept either valid justification: the oxidation number of hydrogen changes from +1 in HCOOH to 0 in H_2 (reduction); or the oxidation number of carbon changes from +2 in HCOOH to +4 in CO_2 (oxidation).

Solution 1

(f) Mark scheme

- Reaction $\text{HCOOH}(\text{aq}) \rightarrow \text{H}_2(\text{g}) + \text{CO}_2(\text{g})$ produces H_2 and CO_2 in a 1:1 mole ratio, so each contributes half the total pressure:

$P_{\text{CO}_2} = 24 \text{ atm} \times \frac{1 \text{ atm CO}_2}{2 \text{ atm product}} = 12 \text{ atm}$ (1 pt, may be implicit). Then using the ideal gas law $PV = nRT$ with $V=4.3 \text{ L}$, $T=298 \text{ K}$:

$$n = \frac{PV}{RT} = \frac{(12 \text{ atm})(4.3 \text{ L})}{(0.08206 \text{ L} \cdot \text{atm} \cdot \text{mol}^{-1}\text{K}^{-1})(298 \text{ K})} = 2.1 \text{ mol CO}_2 \text{ (1 pt).}$$

Solution 1

(g)

Mark scheme

- It would remain the same. In a catalyzed reaction the catalyst is not consumed — it participates in the mechanism but is regenerated — so the net amount of catalyst present stays constant over time.

Question 2

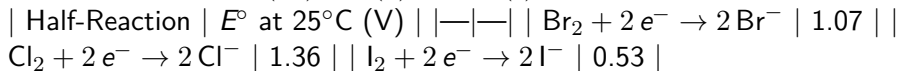
2019 ■ Q2

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.



A chemistry teacher wants to prepare Br_2 . The teacher has access to the following three reagents: NaBr(aq) , $\text{Cl}_2(\text{g})$, and $\text{I}_2(\text{s})$.



Question 2

Half-Reaction	E° at 25°C (V)
$\text{Br}_2 + 2 e^- \rightarrow 2 \text{Br}^-$	1.07
$\text{Cl}_2 + 2 e^- \rightarrow 2 \text{Cl}^-$	1.36
$\text{I}_2 + 2 e^- \rightarrow 2 \text{I}^-$	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 .

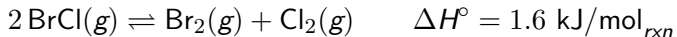
Question 2

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.



A 0.100 mole sample of pure $\text{BrCl}(g)$ 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 (Cl_2 is a strong enough oxidizer to oxidize Br since $E^\circ(\text{Cl}_2/\text{Cl}^-) = 1.36 \text{ V} > E^\circ(\text{Br}_2/\text{Br}^-) = 1.07 \text{ V}$, whereas I_2 cannot): $2 \text{Br}(\text{aq}) + \text{Cl}_2(\text{g}) \rightarrow \text{Br}_2 + 2 \text{Cl}^-(\text{aq})$. 1 point for the correct balanced equation. $E^\circ = E^\circ(\text{reduced species}) - E^\circ(\text{oxidized species}) = 1.36 \text{ V} - 1.07 \text{ V} = +0.29 \text{ V}$; a positive E° confirms the reaction is thermodynamically favorable. 1 point for the correct E° calculation.

Solution 2

(c)

Mark scheme

- Br₂(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, Br₂ has a larger, more polarizable electron cloud than BrCl, so the London forces in Br₂(l) are stronger than the combined (London + dipole-dipole) forces in BrCl(l); this is why Br₂'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

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

Solution 2

(e)

Mark scheme

- $K_{eq} = [\text{Br}_2][\text{Cl}_2] / [\text{BrCl}]^2$ (equivalently, in terms of partial pressures: $K_{eq} = P(\text{Br}_2) \cdot P(\text{Cl}_2) / P(\text{BrCl})^2$). 1 point for a correct equilibrium expression.

Solution 2

(f)

Mark scheme

- ICE table (partial pressures, atm) for $2 \text{ BrCl(g)} \rightleftharpoons \text{Br}_2\text{(g)} + \text{Cl}_2\text{(g)}$: Initial 1.22, 0, 0; Change $-2x$, $+x$, $+x$; Equilibrium 0.71, 0.26, 0.26. Since 42% of BrCl decomposed, $P(\text{BrCl decomposed}) = (0.42)(1.22 \text{ atm}) = 0.51 \text{ atm} = 2x$, so $x = 0.26 \text{ atm}$. 1 point for the correct stoichiometric (ICE) values at equilibrium. $K_{\text{eq}} = (0.26)(0.26)/(0.71)^2 = 0.13$. 1 point for a K_{eq} value consistent with the student's ICE table (a molar-concentration-based solution also earns full credit).

Solution 2

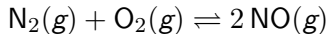
(g)

Mark scheme

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

Question 3

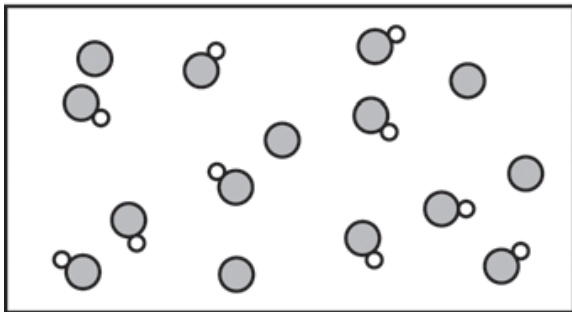
2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(a) Write the expression for the equilibrium constant, K_p , for the forward reaction.

Question 3



Question 3

2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(b) A student injects $\text{N}_2(g)$ and $\text{O}_2(g)$ into a previously evacuated, rigid vessel and raises the temperature of the vessel to 2000°C . At this temperature the initial partial pressures of $\text{N}_2(g)$ and $\text{O}_2(g)$ are 6.01 atm and 1.61 atm, respectively. The system is allowed to reach equilibrium. The partial pressure of $\text{NO}(g)$ at equilibrium is 0.122 atm. Calculate the value of K_p .

Question 3

2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(c)(i) Nitrogen monoxide, $\text{NO}(g)$, can undergo further reactions to produce acids such as HNO_2 , a weak acid with a K_a of 4.0×10^{-4} and a $\text{p}K_a$ of 3.40.

A student is asked to make a buffer solution with a pH of 3.40 by using 0.100 M $\text{HNO}_2(aq)$ and 0.100 M $\text{NaOH}(aq)$.

Explain why the addition of 0.100 M $\text{NaOH}(aq)$ to 0.100 M $\text{HNO}_2(aq)$ can result in the formation of a buffer solution. Include the net ionic equation for the reaction that occurs when the student adds the $\text{NaOH}(aq)$ to the $\text{HNO}_2(aq)$.

Question 3

(c)(ii) Determine the volume, in mL, of $0.100\text{ M NaOH}(aq)$ the student should add to $100.\text{ mL}$ of $0.100\text{ M HNO}_2(aq)$ to make a buffer solution with a pH of 3.40. Justify your answer.

Question 3

2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(d) A second student makes a buffer by dissolving 0.100 mol of $\text{NaNO}_2(s)$ in 100. mL of 1.00 M $\text{HNO}_2(aq)$. Which is more resistant to changes in pH when a strong acid or a strong base is added, the buffer made by the second student or the buffer made by the first student in part (c) ? Justify your answer.

Question 3

2017 ■ Q3



At high temperatures, $\text{N}_2(g)$ and $\text{O}_2(g)$ can react to produce nitrogen monoxide, $\text{NO}(g)$, as represented by the equation above.

(e) A new buffer is made using $\text{HNO}_2(aq)$ as one of the ingredients. A particulate representation of a small representative portion of the buffer solution is shown below. (Cations and water molecules are not shown.) Is the pH of the buffer represented in the diagram greater than, less than, or equal to 3.40 ? Justify your answer.

[Diagram: a rectangular box containing a scattered arrangement of small circles representing particles, with a legend above showing two symbol types: " HNO_2 molecule" (drawn as two overlapping circles) and " NO_2^- ion" (drawn as a single circle).]

Question 3

The box shows a mixture of both symbol types scattered throughout, with noticeably more HNO_2 -molecule symbols (two-circle pairs) than NO_2^- -ion symbols (single circles) — approximately 8 paired (HNO_2) symbols and 4 single (NO_2^-) symbols visible.]

Solution 3

(a)

Mark scheme

- $K_p = (P_{\text{NO}})^2 / [(P_{\text{N}_2})(P_{\text{O}_2})]$. 1 point earned for a correct K_p expression.

Solution 3

(b)

Mark scheme

- ICE table (atm): Initial $\text{N}_2 = 6.01$, $\text{O}_2 = 1.61$, $\text{NO} = 0$; Change $-x$, $-x$, $+2x$; Equilibrium $6.01-x$, $1.61-x$, 0.122 . Since $2x = 0.122$ atm, $x = 0.0610$ atm, so at equilibrium $P_{\text{N}_2} = 5.95$ atm and $P_{\text{O}_2} = 1.55$ atm. $K_p = (0.122)^2 / [(5.95)(1.55)] = 0.00161$. 1 point earned for the correct equilibrium partial pressures of reactants and products (may be implicit); 1 point earned for the correct calculation of K_p .

Solution 3

(c)(i)

Mark scheme

- NaOH will neutralize some of the HNO₂ to produce NO₂⁻. The resulting solution contains a mixture of a weak acid (HNO₂) and its conjugate base (NO₂⁻), which is a buffer solution. Net ionic equation: $\text{HNO}_2 + \text{OH}^- \rightarrow \text{NO}_2^- + \text{H}_2\text{O}$. 1 point earned for the recognition that the solution produced is a mixture of a weak acid and its conjugate base; 1 point earned for the correct net ionic equation.

Solution 3

(c)(ii)

Mark scheme

- The student should add 50.0 mL of 0.100 M NaOH(aq). Using the Henderson-Hasselbalch equation, $\text{pH} = \text{pK}_a + \log([\text{NO}_2^-]/[\text{HNO}_2])$, so $\text{pH} = \text{pK}_a$ exactly when $[\text{HNO}_2] = [\text{NO}_2^-]$; since the target pH (3.40) equals pK_a , a 1-to-1 ratio of HNO₂ to NO₂⁻ is required, i.e. half of the 10.0 mmol HNO₂ (100. mL × 0.100 M) must be converted, which needs 5.00 mmol NaOH = 50.0 mL of 0.100 M NaOH. 1 point earned for the correct volume; 1 point earned for clearly indicating a 1-to-1 ratio of HNO₂ and NO₂⁻ is required (calculation not required for this point).

Solution 3

(d)

Mark scheme

- The buffer made by the second student (0.100 mol NaNO_2 dissolved in 100. mL of 1.00 M HNO_2) is more resistant to changes in pH, because it contains a higher concentration of HNO_2 and NO_2^- available to react with added H^+ or OH^- ions (greater buffer capacity) than the buffer from part (c). 1 point earned for the correct choice and a valid justification.

Solution 3

(e)

Mark scheme

- The pH of the solution is less than 3.40. If $[\text{HNO}_2] = [\text{NO}_2^-]$, $\text{pH} = \text{pK}_a$ and the pH of the solution would be 3.40; since the particulate diagram shows more HNO_2 molecules than NO_2^- ions (i.e. $[\text{HNO}_2] > [\text{NO}_2^-]$), the solution has a pH less than 3.40 (equivalently, with the diagram's ratio of about 5 NO_2^- to 10 HNO_2 , $\text{pH} = 3.40 + \log(5/10) = 3.10$). 1 point earned for the correct choice; 1 point earned for a valid justification.