

Past-paper walk-through

Reaction Quotient and Le Chatelier's Principle ■ 7.10

eXercise

Questions in this set

- 2026 Q3
- 2025 Q1
- 2024 Q5
- 2022 Q2
- 2018 Q2
- 2018 Q5
- 2016 Q6
- 2014 Q4

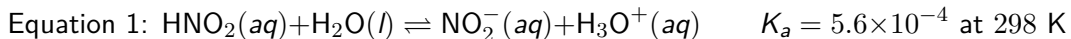
Reading the mark scheme

- **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 3

2026 ■ Q3

Nitrous acid, HNO_2 , is a weak acid that ionizes according to Equation 1.



(a) Identify a conjugate acid-base pair in the equation. Be sure to clearly label which is the acid and which is the base.

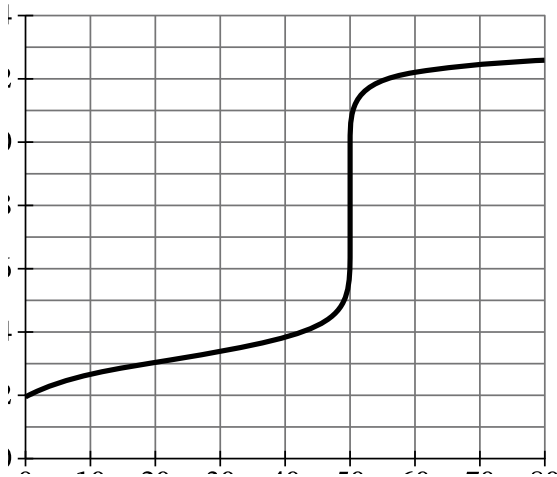
Table 1

Chemical Equation	Equilibrium Constant
$\text{HNO}_2(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NO}_2^-(aq) + \text{H}_3\text{O}^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$\text{H}_2\text{O}(l) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{OH}^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$\text{HNO}_2(aq) + \text{OH}^-(aq) \rightarrow \text{NO}_2^-(aq) + \text{H}_2\text{O}(l)$	$K_2 = ?$

Table 2

Indicator Name	Acid Color	pH Range of Color Change	Base Color
Methyl orange	Red	3.1–4.4	Yellow
Thymol blue	Yellow	8.0–9.6	Blue
Clayton yellow	Yellow	12.2–13.2	Orange

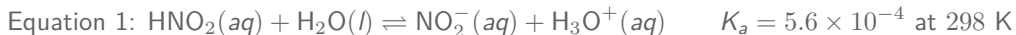
Question 3



Question 3

2026 ■ Q3

Nitrous acid, HNO_2 , is a weak acid that ionizes according to Equation 1.



(b)(i) A solution of $\text{HNO}_2(aq)$ with an initial concentration of 0.125 M has a pH of 2.09.

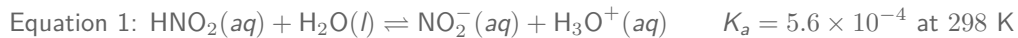
****Calculate**** the value of $[\text{H}_3\text{O}^+]$ in the solution. Show the work that leads to your answer.

(b)(ii) ****Calculate**** $[\text{HNO}_2]$ at equilibrium. Show the work that leads to your answer.

Question 3

2026 ■ Q3

Nitrous acid, HNO_2 , is a weak acid that ionizes according to Equation 1.



(c)(i) In an experiment, the solution of $0.125 \text{ M HNO}_2(aq)$ is heated to 333 K . The new equilibrium concentrations are determined to be $[\text{HNO}_2] = 0.114 \text{ M}$, $[\text{NO}_2^-] = 0.0109 \text{ M}$, and $[\text{H}_3\text{O}^+] = 0.0109 \text{ M}$.

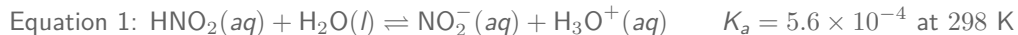
****Calculate**** the value of K_a for HNO_2 at 333 K . Show the work that leads to your answer.

(c)(ii) Is the reaction represented by Equation 1 endothermic or exothermic? **Justify** your answer by comparing K_a values at 298 K and 333 K .

Question 3

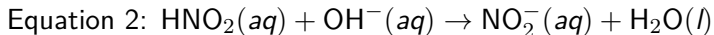
2026 ■ Q3

Nitrous acid, HNO_2 , is a weak acid that ionizes according to Equation 1.



(d) The following information applies to parts D, E, and F.

In a second experiment, a student is given a bottle containing HNO_2 with an unknown molarity. To determine the concentration of the $\text{HNO}_2(aq)$ in the bottle, the student titrates 35.0 mL of the $\text{HNO}_2(aq)$ with 0.16 M $\text{NaOH}(aq)$ at 298 K, which reacts according to Equation 2.



Question 3

The results of the titration are summarized in Figure 1.

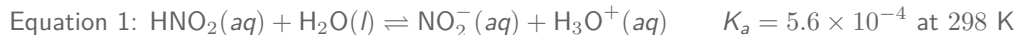
[Figure 1: Titration curve, pH vs. Volume of 0.16 M NaOH Added (mL); y-axis pH 0 to 14 in increments of 2, x-axis 0 to 80 mL in increments of 10; curve starts near (0, 2), rises gradually to about (40, 4), then rises steeply (equivalence point) between about 45-55 mL up to about pH 12, then levels off gradually to approximately (80, 12.7).]

Using Figure 1, **identify** the pH at the equivalence point.

Question 3

2026 ■ Q3

Nitrous acid, HNO_2 , is a weak acid that ionizes according to Equation 1.

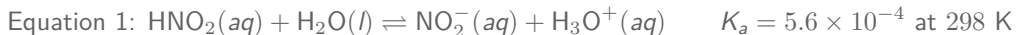


(e) Using Figure 1, ****calculate**** the molarity $\text{HNO}_2(aq)$ of in the bottle. Show the work that leads to your answer.

Question 3

2026 ■ Q3

Nitrous acid, HNO_2 , is a weak acid that ionizes according to Equation 1.

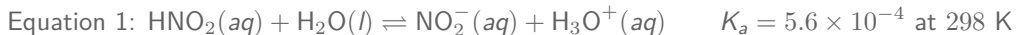


(f) ****Draw**** an X on Figure 1 to represent a point in the titration where $[\text{HNO}_2] > [\text{NO}_2^-]$ in the reaction mixture.

Question 3

2026 ■ Q3

Nitrous acid, HNO_2 , is a weak acid that ionizes according to Equation 1.



(g) Equilibrium constants at 298 K are shown in Table 1 for the acid ionization reaction represented by Equation 1, K_a ; the autoionization of water, K_w ; and the neutralization reaction represented by Equation 2, K_2 .

Chemical Equation	Equilibrium Constant
$\text{HNO}_2(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NO}_2^-(aq) + \text{H}_3\text{O}^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$\text{H}_2\text{O}(l) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{OH}^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$\text{HNO}_2(aq) + \text{OH}^-(aq) \rightarrow \text{NO}_2^-(aq) + \text{H}_2\text{O}(l)$	$K_2 = ?$

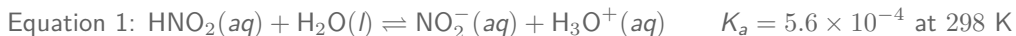
Question 3

****Calculate**** the value of K_2 for Equation 2 at 298 K. Show the work that leads to your answer.

Question 3

2026 ■ Q3

Nitrous acid, HNO_2 , is a weak acid that ionizes according to Equation 1.



(h) The student decides to repeat the experiment, this time using an indicator, and has access to the indicators in Table 2.

Indicator Name	Acid Color	pH Range of Color Change	Base Color	— — — —
Methyl orange	Red	3.1–4.4	Yellow	Thymol blue
				Yellow
				8.0–9.6
				Blue
Clayton yellow	Yellow	12.2–13.2	Orange	

Question 3

The student conducts a second titration by adding two drops of methyl orange indicator to 35.0 mL of the $\text{HNO}_2(aq)$ solution and titrating the solution with 0.16 M $\text{NaOH}(aq)$ until a color change from red to yellow occurs.

The student claims that methyl orange was the best choice for the indicator. Do you agree or disagree? ****Justify**** your answer.

Question 1

2025 ■ Q1

Answer the following questions about magnesium.

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

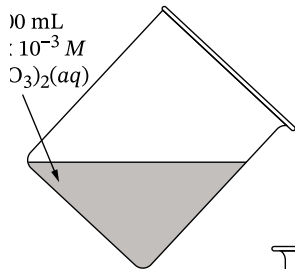
[Bar graph titled “Relative Abundance” vs. “Mass (amu)”]; y-axis from 0 to 100 in increments of 20; x-axis shows tick marks at 24, 25, 26; a single thick vertical bar is drawn at mass 24 reaching a relative abundance of about 79.]

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.

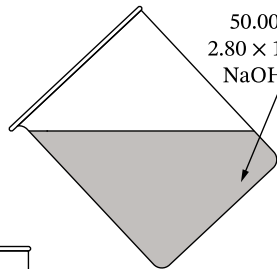
(a)(ii) Describe the difference in atomic structure that accounts for the difference in mass between magnesium-25 and magnesium-26.

Question 1



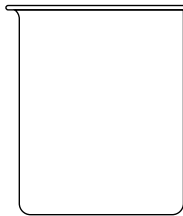
10.0 mL
 $1.0 \times 10^{-3} M$
 $\text{Ca}_3(\text{PO}_4)_2(aq)$

Beaker 1

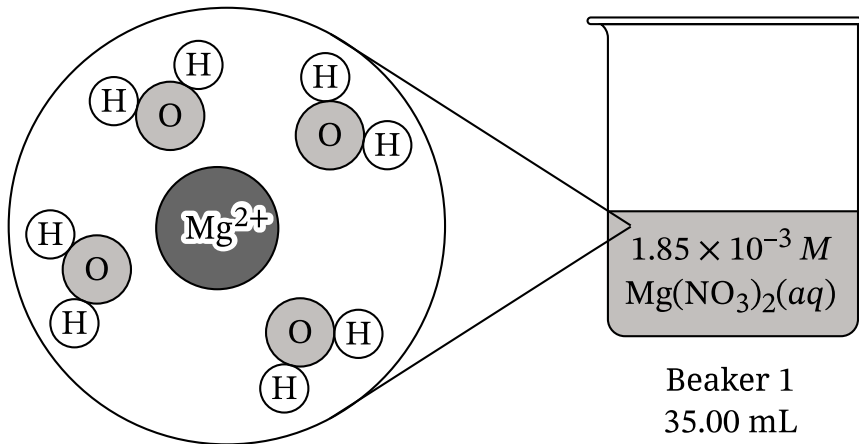


50.00 mL
 $2.80 \times 10^{-4} M$
 $\text{NaOH}(aq)$

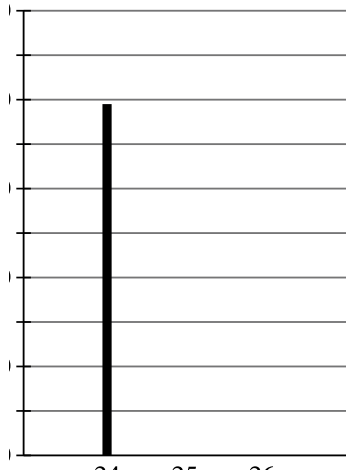
Beaker 2



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 $1.85 \times 10^{-3} \text{ M}$ $\text{Mg}(\text{NO}_3)_2(aq)$ with 50.00 mL of $2.80 \times 10^{-4} \text{ M}$ $\text{NaOH}(aq)$, 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.)

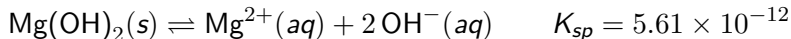
[Diagram of two conical/Erlenmeyer flasks being poured into an empty Beaker 3. Left flask: "35.00 mL", " $1.85 \times 10^{-3} \text{ M}$ ", " $\text{Mg}(\text{NO}_3)_2(aq)$ ", labeled "Beaker 1". Right flask: "50.00 mL", " $2.80 \times 10^{-4} \text{ M}$ ", " $\text{NaOH}(aq)$ ", labeled "Beaker 2". 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.



(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

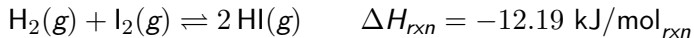
(f)

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 5

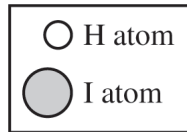
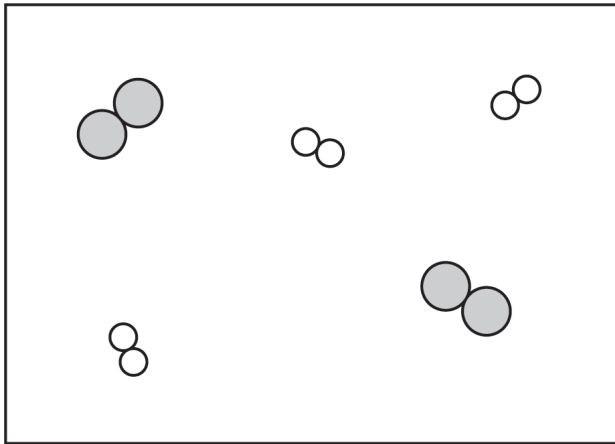
2024 ■ Q5



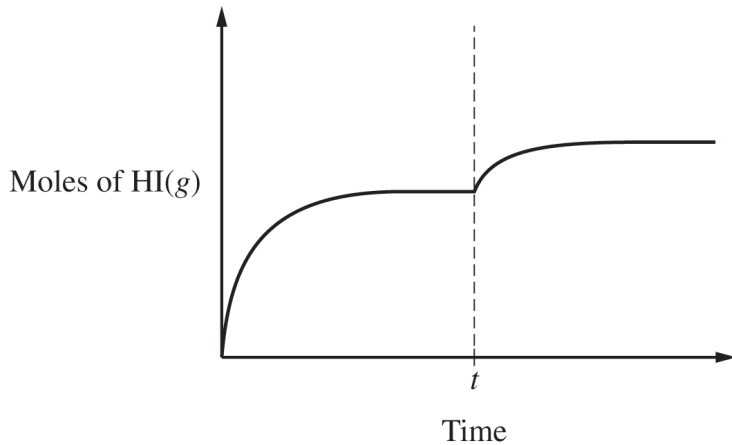
5. Hydrogen gas and iodine gas react to form hydrogen iodide at an elevated temperature, as represented by the following equation.

(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

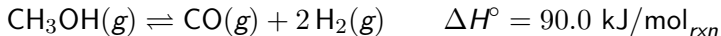
(b)(iii)

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

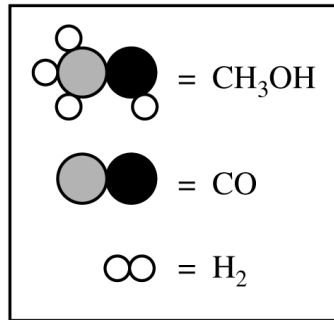
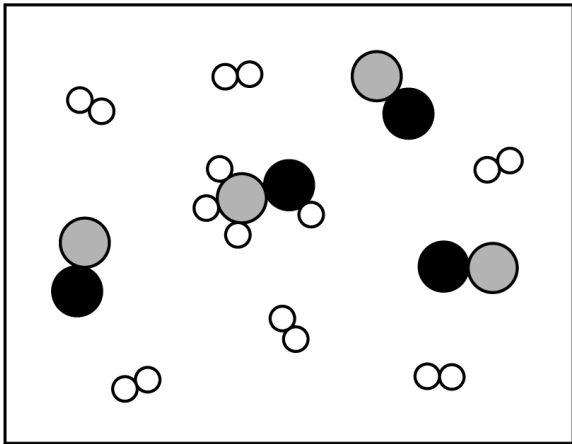
2022 ■ Q2



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.

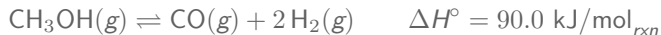
(a) Are the hydrogen atoms oxidized or are they reduced in the forward reaction? Justify your answer in terms of oxidation numbers.

Question 2



Question 2

2022 ■ Q2



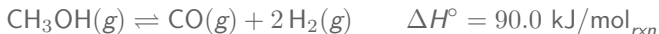
Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(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			

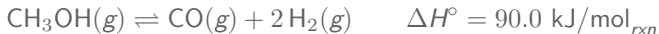
Use the data in the table to calculate the value of the standard entropy change, ΔS° , in J/(K · mol_{rxn}), for the reaction.

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 +

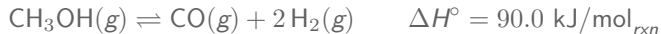
Question 2

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

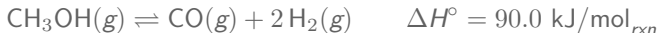


Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(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.

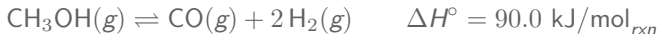
Question 2

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

- $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ = 90.0 \text{ kJ/mol}_{\text{rxn}} - (375 \text{ K})(0.220 \text{ kJ}/(\text{K} \cdot \text{mol}_{\text{rxn}})) = +7.5 \text{ kJ/mol}_{\text{rxn}}$ (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): $K_p = (P_{\text{CO}})(P_{\text{H}_2})^2 / (P_{\text{CH}_3\text{OH}}) = (4.2)(8.4)^2 / (2.7) = 110$.

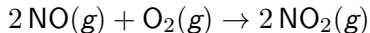
Solution 2

(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 $Q_p = [(P_{\text{CO}}/2)(P_{\text{H}_2}/2)^2] / (P_{\text{CH}_3\text{OH}}/2) = K_p/4$ $27 < K_p$. 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 2

2018 ■ Q2



A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

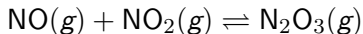
(a) The particle-level representation of the equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ in the flask at the completion of the reaction between $\text{NO}(g)$ and $\text{O}_2(g)$ is shown below in the box on the right. In the box below on the left, draw the particle-level representation of the reactant mixture of $\text{NO}(g)$ and $\text{O}_2(g)$ that would yield the product mixture shown in the box on the right. In your drawing, represent oxygen atoms and nitrogen atoms as indicated below.

Question 2

[Key: Oxygen atom = open (white) circle; Nitrogen atom = filled (gray) circle.]

[Two boxes side by side connected by an arrow. Left box labeled "Reactant Mixture" is empty (for the student to draw in). Right box labeled "Product Mixture" shows a particle-level representation containing 6 NO molecules (each one open circle bonded to one filled circle) and 6 NO₂ molecules (each one filled circle bonded to two open circles), scattered randomly in the box.]

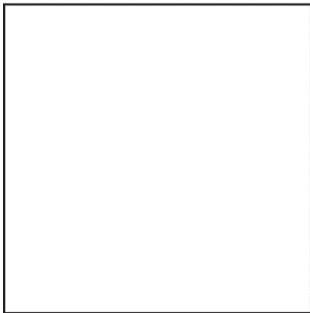
The student reads in a reference text that $\text{NO}(g)$ and $\text{NO}_2(g)$ will react as represented by the equation below. Thermodynamic data for the reaction are given in the table below the equation.



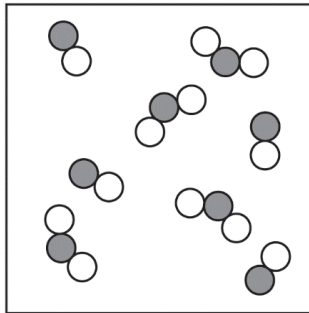
ΔH_{298}°	ΔS_{298}°	ΔG_{298}°	— — —	$-40.4 \text{ kJ/mol}_{rxn}$	$-138.5 \text{ J/(K} \cdot \text{mol}_{rxn})$	0.87
kJ/mol _{rxn}						

Question 2

Oxygen atom =  Nitrogen atom = 

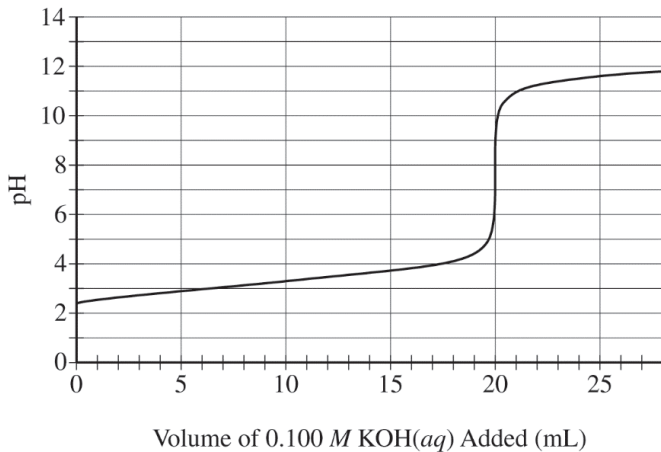


Reactant Mixture

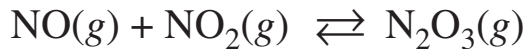


Product Mixture

Question 2



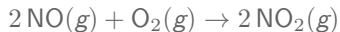
Question 2



ΔH_{298}°	ΔS_{298}°	ΔG_{298}°
$-40.4 \text{ kJ/mol}_{rxn}$	$-138.5 \text{ J/(K} \cdot \text{mol}_{rxn})$	$0.87 \text{ kJ/mol}_{rxn}$

Question 2

2018 ■ Q2



A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

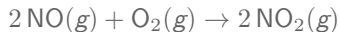
(b)(i) The student begins with an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.

Calculate the value of the equilibrium constant, K , for the reaction at 298 K.

(b)(ii) If both P_{NO} and P_{NO_2} in the vessel are initially 1.0 atm, will $P_{\text{N}_2\text{O}_3}$ at equilibrium be equal to 1.0 atm? Justify your answer.

Question 2

2018 ■ Q2

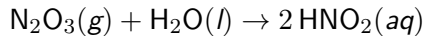


A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

(c) The student hypothesizes that increasing the temperature will increase the amount of $\text{N}_2\text{O}_3(g)$ in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.

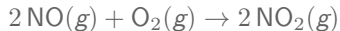
$\text{N}_2\text{O}_3(g)$ reacts with water to form nitrous acid, $\text{HNO}_2(aq)$, a compound involved in the production of acid rain. The reaction is represented below.

Question 2



Question 2

2018 ■ Q2



A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

(d)(i) The skeletal structure of the HNO_2 molecule is shown in the box below.

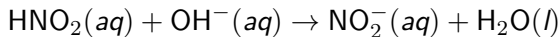
[Box showing the skeletal structure: H O N O, written left to right in a line.]

Complete the Lewis electron-dot diagram of the HNO_2 molecule in the box below, including any lone pairs of electrons.

(d)(ii) Based on your completed diagram above, identify the hybridization of the nitrogen atom in the HNO_2 molecule.

Question 2

To produce an aqueous solution of HNO_2 , the student bubbles $\text{N}_2\text{O}_3(g)$ into distilled water. Assume that the reaction goes to completion and that HNO_2 is the only species produced. To determine the concentration of $\text{HNO}_2(aq)$ in the resulting solution, the student titrates a 100. mL sample of the solution with 0.100 M $\text{KOH}(aq)$. The neutralization reaction is represented below.



The following titration curve shows the change in pH of the solution during the titration.

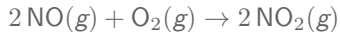
[Titration curve graph: Y-axis pH from 0 to 14 in increments of 2. X-axis "Volume of 0.100 M $\text{KOH}(aq)$ Added (mL)" from 0 to 25+ in increments of 5. The curve starts around pH 2.3 at 0 mL, rises very gradually and slightly through a small buffer region

Question 2

to about pH 4 near 15-18 mL, then rises steeply (equivalence point) around 20 mL up to about pH 12, then levels off gradually toward pH 12-13 by 25 mL.]

Question 2

2018 ■ Q2



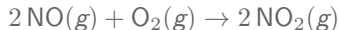
A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

(e)(i) Use the titration curve and the information above to determine the initial concentration of the $\text{HNO}_2(aq)$ solution.

(e)(ii) Use the titration curve and the information above to estimate the value of $\text{p}K_a$ for $\text{HNO}_2(aq)$.

Question 2

2018 ■ Q2



A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

(f) During the titration, after a volume of 15 mL of 0.100 *M* $\text{KOH}(aq)$ has been added, which species, $\text{HNO}_2(aq)$ or $\text{NO}_2^-(aq)$, is present at a higher concentration in the solution? Justify your answer.

Solution 2

(a)

Mark scheme

- The reactant mixture must contain 8 NO(g) molecules and 2 O₂(g) molecules. As $2 \text{NO(g)} + \text{O}_2\text{(g)} \rightarrow 2 \text{NO}_2\text{(g)}$ proceeds (O₂ limiting), 4 NO react with the 2 O₂ to form 4 NO₂, leaving 4 NO unreacted, giving the equimolar 4 NO : 4 NO₂ product mixture shown. 1 point is earned for correctly representing the molecules of NO and O₂ (8 NO + 2 O₂, drawn as separate diatomic particles using the given atom key); 1 point is earned for correctly representing atom conservation between the reactant and product boxes (same total number of N atoms and O atoms in both boxes).

Solution 2

(b)(i)

Mark scheme

- $\Delta G = -RT \ln K$, so $K = e^{(-\Delta G/RT)} = e^{[-870 \text{ J/mol} / ((8.314 \text{ J/(mol K)})(298 \text{ K}))]} = e^{-0.351} = 0.70$. 1 point is earned for the correct calculation of K .

Solution 2

(b)(ii)

Mark scheme

- No, $P(\text{N}_2\text{O}_3)$ will not equal 1.0 atm at equilibrium. $P(\text{N}_2\text{O}_3)$ would only equal 1.0 atm if the reaction went to completion; the value of K (0.70, not much greater than 1) indicates that a substantial amount of reactants (NO and NO_2) will remain at equilibrium, so $P(\text{N}_2\text{O}_3)$ will be less than 1.0 atm. 1 point is earned for the correct choice ('no') and a valid justification based on the value of K .

Solution 2

(c)

Mark scheme

- Disagree. Because the reaction $\text{NO(g)} + \text{NO}_2\text{(g)} \rightleftharpoons \text{N}_2\text{O}_3\text{(g)}$ is exothermic ($\Delta H_{298} = -40.4 \text{ kJ/mol}_{\text{rxn}}$), increasing the temperature will favor the formation of the reactants (shift left), according to Le Chatelier's principle, so the amount of $\text{N}_2\text{O}_3\text{(g)}$ will decrease, not increase. 1 point is earned for the correct choice (disagree) AND a correct justification.

Solution 2

(d)(i)

Mark scheme

- Completed Lewis structure of HNO_2 (skeleton H-O-N-O): H is single-bonded to O; that O is single-bonded to N and carries 2 lone pairs; N is double-bonded to the terminal O and carries 1 lone pair; the terminal O carries 2 lone pairs. Formal charges are all zero and every atom (except H) has a complete octet. 1 point is earned for a valid diagram showing all lone pairs and correct bonding (H-O-N=O with 2 lone pairs on each O and 1 lone pair on N).

Solution 2

(d)(ii)

Mark scheme

- The nitrogen atom is sp^2 hybridized (it is bonded to 2 O atoms and has 1 lone pair, i.e., 3 electron domains, giving trigonal planar / sp^2 geometry). 1 point is earned for the correct answer, sp^2 .

Solution 2

(e)(i)

Mark scheme

- At the equivalence point (from the titration curve), 20. mL of 0.100 M KOH has been added: $20. \text{ mL} \times 0.100 \text{ mol KOH}/1000 \text{ mL} = 0.0020 \text{ mol KOH}$ added, which equals 0.0020 mol HNO₂ originally present (1:1 stoichiometry of $\text{HNO}_2 + \text{OH}^- \rightarrow \text{NO}_2^- + \text{H}_2\text{O}$). Initial concentration = $0.0020 \text{ mol HNO}_2 / 0.100 \text{ L} = 0.020 \text{ M HNO}_2$. 1 point is earned for the correct calculation of the initial concentration.

Solution 2

(e)(ii)

Mark scheme

- pKa is approximately 3.4, read from the pH at the half-equivalence volume (10 mL) on the titration curve, where $\text{pH} = \text{pKa}$. 1 point is earned for an acceptable estimate of pKa (values near 3.4 accepted).

Solution 2

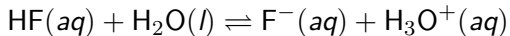
(f)

Mark scheme

- $\text{NO}_2\text{-(aq)}$ is present at the higher concentration. The equivalence point is at 20 mL, so the half-equivalence point is at 10 mL; after 15 mL of KOH has been added, the titration is past the half-equivalence point, so more of the conjugate base (NO_2^-) than the acid (HNO_2) is present. 1 point is earned for the correct choice AND a valid justification.

Question 5

2018 ■ Q5



The ionization of $\text{HF}(aq)$ in water is represented by the equation above. In a 0.0350 M $\text{HF}(aq)$ solution, the percent ionization of HF is 13.0 percent.

(a) Two particulate representations of the ionization of HF molecules in the 0.0350 M $\text{HF}(aq)$ solution are shown below in Figure 1 and Figure 2. Water molecules are not shown. Explain why the representation of the ionization of HF molecules in water in Figure 1 is more accurate than the representation in Figure 2. (The key below identifies the particles in the representations.)

[Key: filled black triple-particle cluster = H_3O^+ ; two-particle black-and-gray cluster = HF ; single gray circle = F^- .]

Question 5

[Figure 1: a circle containing a mixture of particles — approximately 2 H_3O^+ clusters, 2 F^- single circles, and 6 HF two-particle clusters, scattered with mostly HF molecules present and few ionized species, consistent with a small (13

[Figure 2: a circle containing a denser mixture of particles — approximately 6 H_3O^+ clusters, 6 F^- single circles, and 8 HF two-particle clusters, scattered with a much higher proportion of ionized species than Figure 1, inconsistent with only 13

Question 5

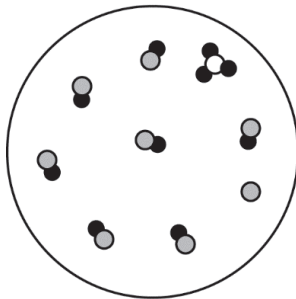
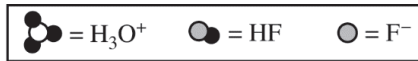


Figure 1

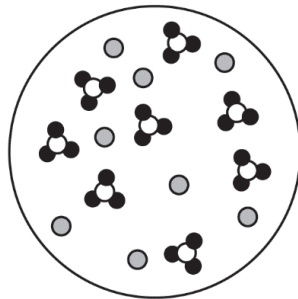
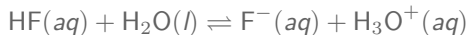


Figure 2

Question 5

2018 ■ Q5

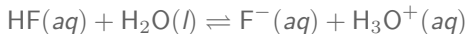


The ionization of $\text{HF}(aq)$ in water is represented by the equation above. In a 0.0350 M $\text{HF}(aq)$ solution, the percent ionization of HF is 13.0 percent.

(b) Use the percent ionization data above to calculate the value of K_a for HF.

Question 5

2018 ■ Q5



The ionization of $\text{HF}(aq)$ in water is represented by the equation above. In a $0.0350\text{ M HF}(aq)$ solution, the percent ionization of HF is 13.0 percent.

(c) If 50.0 mL of distilled water is added to 50.0 mL of $0.035\text{ M HF}(aq)$, will the percent ionization of $\text{HF}(aq)$ in the solution increase, decrease, or remain the same? Justify your answer with an explanation or calculation.

Solution 5

(a)

Mark scheme

- HF is a weak acid and is only partially ionized. This is consistent with Figure 1, which shows only one out of eight ($\sim 13\%$) HF particles ionized (forming one H_3O^+ and one F^-), matching the given 13.0% ionization. Figure 2, showing complete (100%) ionization of every HF molecule, cannot represent a weak acid like HF. 1 point is earned for a valid explanation.

Solution 5

(b)

Mark scheme

- Assume $[\text{H}_3\text{O}^+] = [\text{F}^-]$ in $\text{HF}(\text{aq})$. Since percent ionization is 13.0%:
 $[\text{H}_3\text{O}^+]/0.0350 \text{ M} = 0.130$, so $[\text{H}_3\text{O}^+] = 0.00455 \text{ M}$. ICE table: initial
 $[\text{HF}] = 0.0350$, change $-0.00455/+0.00455/+0.00455$, equilibrium
 $[\text{HF}] = 0.0304 \text{ M}$, $[\text{H}_3\text{O}^+] = [\text{F}^-] = 0.00455 \text{ M}$. $K_a = [\text{H}_3\text{O}^+][\text{F}^-]/[\text{HF}] =$
 $(0.00455)^2/(0.0304) = 6.81 \times 10^{-4}$. 1 point is earned for the correct
 calculation of $[\text{H}_3\text{O}^+]$; 1 point is earned for a value of K_a consistent with the
 calculated $[\text{H}_3\text{O}^+]$.

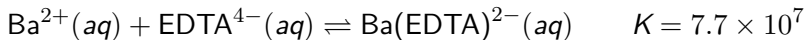
Solution 5

(c) Mark scheme

- The percent ionization would increase. Doubling the volume (adding an equal volume of water) halves the initial concentration of each species, so $Q = [(1/2[H_3O^+])_i(1/2[F^-])_i]/(1/2[HF])_i = 1/2 K_a$, i.e. $Q < K_a$, so the equilibrium shifts toward products, increasing percent ionization. (Confirmed by calculation: new $[HF]_i = 0.035/2 = 0.0175 \text{ M}$; solving $6.81 \times 10^{-4} = x^2/(0.0175-x)$ approximately $x^2/0.0175$ gives x approximately 0.00345 M ; percent ionization = $0.00345/0.0175 \times 100 = 20.0\%$, which is greater than the original 13.0% .) 1 point is earned for a correct answer (increase) AND a valid explanation or calculation.

Question 6

2016 ■ Q6



The polyatomic ion $\text{C}_{10}\text{H}_{12}\text{N}_2\text{O}_8^{4-}$ is commonly abbreviated as EDTA^{4-} . The ion can form complexes with metal ions in aqueous solutions. A complex of EDTA^{4-} with Ba^{2+} ion forms according to the equation above. A 50.0 mL volume of a solution that has an $\text{EDTA}^{4-}(\text{aq})$ concentration of 0.30 M is mixed with 50.0 mL of 0.20 M $\text{Ba}(\text{NO}_3)_2$ to produce 100.0 mL of solution.

- (a)** Considering the value of K for the reaction, determine the concentration of $\text{Ba}(\text{EDTA})^{2-}(\text{aq})$ in the 100.0 mL of solution. Justify your answer.
- (b)** The solution is diluted with distilled water to a total volume of 1.00 L. After equilibrium has been reestablished, is the number of moles of $\text{Ba}^{2+}(\text{aq})$ present in the

Question 6

solution greater than, less than, or equal to the number of moles of $\text{Ba}^{2+}(\text{aq})$ present in the original solution before it was diluted? Justify your answer.

Solution 6

(a) Mark scheme

- K is very large (7.7×10^7), so the reaction goes essentially to completion with $\text{Ba}^{2+}(\text{aq})$ as the limiting reactant. The concentration of Ba^{2+} when the two solutions are first mixed, before reaction, is $0.20 \text{ M} / 2 = 0.10 \text{ M}$ (50.0 mL diluted into 100.0 mL total). Since the reaction proceeds essentially to completion, the equilibrium concentration of $\text{Ba}(\text{EDTA})^{2-}(\text{aq})$ in the 100.0 mL of solution is 0.10 M. 1 point for indicating that the equilibrium concentration of $\text{Ba}(\text{EDTA})^{2-}$ equals the original (pre-reaction, post-mixing) concentration of Ba^{2+} , 1 point for the concentration (0.10 M) with appropriate supporting calculation.

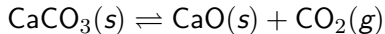
Solution 6

(b) Mark scheme

- The number of moles of $\text{Ba}^{2+}(\text{aq})$ will be greater than in the original solution. Justification: diluting from 100.0 mL to 1.00 L reduces the concentrations of all species to one tenth of their original values, so immediately after dilution $Q = (1/10[\text{Ba}(\text{EDTA})^{2-}]) / ((1/10[\text{Ba}^{2+}])(1/10[\text{EDTA}^{4-}])) = 10K$. Because $Q > K$, the reaction shifts toward reactants (more dissociation) to re-establish equilibrium, so the number of moles of $\text{Ba}^{2+}(\text{aq})$ increases relative to before dilution. (Equivalently: the percent dissociation of $\text{Ba}(\text{EDTA})^{2-}$ increases upon dilution.) 1 point for stating that the number of moles of $\text{Ba}^{2+}(\text{aq})$ will increase, 1 point for a valid justification (the $Q > K$ argument, or an equivalent percent-dissociation argument).

Question 4

2014 ■ Q4



When heated, calcium carbonate decomposes according to the equation above. In a study of the decomposition of calcium carbonate, a student added a 50.0 g sample of powdered $\text{CaCO}_3(s)$ to a 1.00 L rigid container. The student sealed the container, pumped out all the gases, then heated the container in an oven at 1100 K. As the container was heated, the total pressure of the $\text{CO}_2(g)$ in the container was measured over time. The data are plotted in the graph below.

[Graph of Pressure (atm) vs. Time (min); x-axis Time (min) 0 to 20 (gridlines at 0, 5, 10, 15, 20), y-axis Pressure (atm) 0 to 1.25 (gridlines at 0, 0.25, 0.50, 0.75, 1.00, 1.25); curve starts at (0, 0), rises steeply and roughly linearly to about (5, 0.65),

Question 4

continues rising with decreasing slope through about (10, 0.95), levels off and becomes essentially flat at a pressure of about 1.0-1.05 atm from about $t = 12$ min to $t = 20$ min.]

The student repeated the experiment, but this time the student used a 100.0 g sample of powdered $\text{CaCO}_3(s)$. In this experiment, the final pressure in the container was 1.04 atm, which was the same final pressure as in the first experiment.

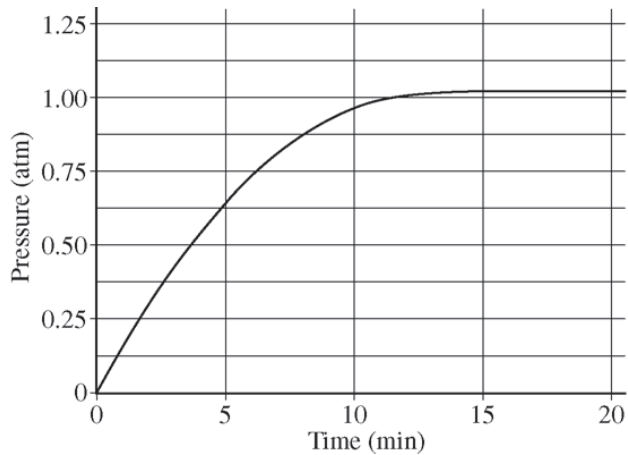
- (a)** Calculate the number of moles of $\text{CO}_2(g)$ present in the container after 20 minutes of heating.
- (b)** The student claimed that the final pressure in the container in each experiment became constant because all of the $\text{CaCO}_3(s)$ had decomposed. Based on the data in the experiments, do you agree with this claim? Explain.

Question 4

(c) After 20 minutes some $\text{CO}_2(g)$ was injected into the container, initially raising the pressure to 1.5 atm. Would the final pressure inside the container be less than, greater than, or equal to 1.04 atm? Explain your reasoning.

(d) Are there sufficient data obtained in the experiments to determine the value of the equilibrium constant, K_p , for the decomposition of $\text{CaCO}_3(s)$ at 1100 K? Justify your answer.

Question 4



Solution 4

(a)

Mark scheme

- Using the ideal gas law:

$$n = \frac{PV}{RT} = \frac{(1.04 \text{ atm})(1.00 \text{ L})}{(0.0821 \text{ L} \cdot \text{atm/mol} \cdot \text{K})(1100 \text{ K})} = 0.0115 \text{ mol CO}_2.$$

Solution 4

(b)

Mark scheme

- Do not agree with the claim. In experiment 1, moles of $\text{CaCO}_3 = 50.0 \text{ g} / 100.09 \text{ g/mol} = 0.500 \text{ mol CaCO}_3$; if the reaction had gone to completion, 0.500 mol of CO_2 would have been produced, but only 0.0115 mol was produced (part a), so the claim is false. Alternatively: the two experiments (50.0 g and 100.0 g of CaCO_3) both reached the same constant final pressure of 1.04 atm; since adding more reactant did not produce more product, not all of the CaCO_3 could have reacted — an equilibrium condition was reached instead, with some solid CaCO_3 remaining.

Solution 4

(c)

Mark scheme

- The final pressure would be equal to 1.04 atm. Equilibrium was reached in both experiments at this temperature, giving an equilibrium CO_2 pressure of 1.04 atm. Raising the pressure to 1.5 atm shifts the reaction toward the reactant (Le Chatelier's principle), and $\text{CO}_2(\text{g})$ is consumed until the pressure returns to the equilibrium value of 1.04 atm.

Solution 4

(d)

Mark scheme

- Yes. For this equilibrium, at a given temperature the equilibrium pressure of CO_2 determines the equilibrium constant. Since the measured pressure of CO_2 (1.04 atm) is the equilibrium pressure, $K_p = P_{\text{CO}_2} = 1.04$. (Alternate credit: if part (b) claimed all CaCO_3 decomposed, the point can instead be earned by stating that the system never reached equilibrium in either experiment, so K_p cannot be calculated from the data.)