Past-paper walk-through

Henderson-Hasselbalch Equation ▪ 8.9

eXercise

Questions in this set

- 2026 Q3
- 2025 Q2
- 2024 Q2
- 2023 Q4
- 2019 Q3
- 2017 Q3
- 2015 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 3

2026 ▪ Q3

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

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

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

Question 3

Table 1

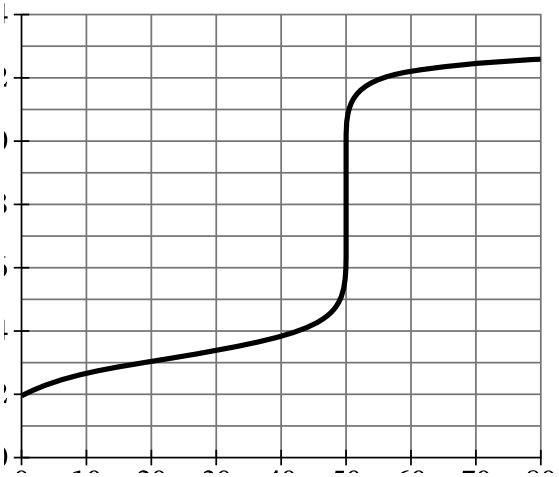
Chemical Equation	Equilibrium Constant
$HNO_2(aq) + H_2O(l) \rightleftarrows NO_2^-(aq) + H_3O^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$H_2O(l) + H_2O(l) \rightleftarrows H_3O^+(aq) + OH^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$	$K_2 =$?

Question 3

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.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\quad K_a = 5.6 \times 10^{-4}$ at 298 K

(b)(i) A solution of $HNO_2(aq)$ with an initial concentration of 0.125 M has a pH of 2.09.

Calculate the value of $[H_3O^+]$ in the solution. Show the work that leads to your answer.

(b)(ii) **Calculate** $[HNO_2]$ 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.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(c)(i) In an experiment, the solution of 0.125 *M* $HNO_2(aq)$ is heated to 333 K. The new equilibrium concentrations are determined to be $[HNO_2] = 0.114$ *M*, $[NO_2^-] = 0.0109$ *M*, and $[H_3O^+] = 0.0109$ *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.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(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 $HNO_2(aq)$ in the bottle, the student titrates 35.0 mL of the $HNO_2(aq)$ with 0.16 M $NaOH(aq)$ at 298 K, which reacts according to Equation 2.

Equation 2: $HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$

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.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(e) Using Figure 1, **calculate** the molarity $HNO_2(aq)$ 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.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(f) **Draw** an X on Figure 1 to represent a point in the titration where $[HNO_2] > [NO_2^-]$ in the reaction mixture.

Question 3

2026 ▪ Q3

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

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\quad K_a = 5.6 \times 10^{-4}$ at 298 K

(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 | |—|—| |
$HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ | $K_a = 5.6 \times 10^{-4}$ | |
$H_2O(l) + H_2O(l) \rightleftharpoons H_3O^+(aq) + OH^-(aq)$ | $K_w = 1.0 \times 10^{-14}$ | |
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$ | $K_2 = ?$ |

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.

Equation 1: $HNO_2(aq) + H_2O(l) \rightleftharpoons NO_2^-(aq) + H_3O^+(aq)$ $\qquad K_a = 5.6 \times 10^{-4}$ at 298 K

(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 $HNO_2(aq)$ solution and titrating the solution with 0.16 M 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 2

2025 ▪ Q2

Answer the following questions about ascorbic acid (vitamin C).

(a) A student combusts a sample of ascorbic acid, $C_xH_yO_x$, to determine its chemical composition. The only products of the reaction are 0.2400 mol of CO_2 and 2.883 g of H_2O.

(a)(i) Calculate the number of moles of H_2O produced.

(a)(ii) The mole ratio of carbon (C) to oxygen (O) is 1:1 in ascorbic acid. Based on this information and your answer to part A (i), determine the empirical formula of ascorbic acid.

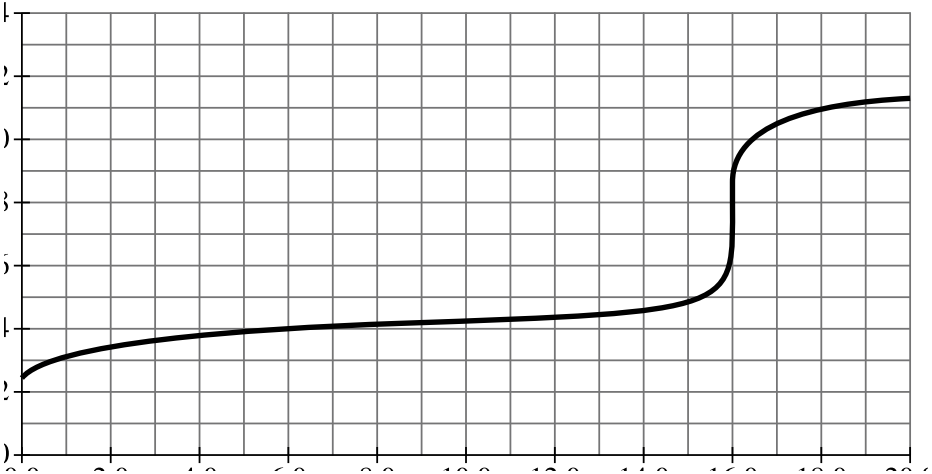
Question 2

Trial	[HAsc] (M)	$[I_3^-](M)$	Initial Rate of DHAsc Formation (M/s)
1	0.450	1.200	2.457×10^{-4}
2	0.450	0.600	1.229×10^{-4}
3	0.900	1.200	4.914×10^{-4}

i. The rate law for the reaction is $rate = k[\text{HAsc}][I_3^-]$. Explain how the data in the table support the conclusion that the reaction is first order with respect to $[\text{HAsc}]$.

ii. Calculate the value of the rate constant, k, for the reaction. Include units with your

Question 2



Question 2

2025 ▪ Q2

Answer the following questions about ascorbic acid (vitamin C).

(b) Ascorbic acid, HAsc(aq), acts as a weak acid, as shown in the equation.

$$\mathrm{HAsc}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{Asc^-}(aq)$$

The following titration curve was produced when a 10.0 mL sample of HAsc(aq) was titrated using 0.0550 M NaOH(aq).

[Titration curve graph: x-axis "Volume of 0.0550 M NaOH Added (mL)" from 0.0 to 20.0 in increments of 2.0; y-axis "pH" from 0 to 14 in increments of 2. The curve starts at about (0.0, 2.6), rises gradually and levels into a broad buffer region around pH 4 from about 2 mL to 14 mL, has a small inflection/bump near (14.0, 4.5)-(15.0,

Question 2

5.2), then rises steeply (equivalence point) through the region 15.0-16.5 mL up to about pH 10.5, then levels off gradually approaching about (20.0, 11.3).]

(b)(i) Calculate the molar concentration of the ascorbic acid solution.

(b)(ii) From the titration curve, determine the approximate pK_a of ascorbic acid.

(b)(iii) What is the value of the ratio $\frac{[\text{Asc}^-]}{[\text{HAsc}]}$ when the pH of the solution is 4.7?

Question 2

2025 ▪ Q2

Answer the following questions about ascorbic acid (vitamin C).

(c) Dehydroascorbic acid (DHAsc) can be produced by reacting ascorbic acid with the triiodide ion, I_3^-, as represented by the following equation.

$$HAsc + I_3^- \rightarrow DHAsc + 3\,I^- + 2\,H^+$$

The student runs three trials of the reaction with different initial concentrations of HAsc and I_3^-, producing the following data.

Trial	[HAsc] (M)	[I_3^-] (M)	Initial Rate of DHAsc Formation (M/s)
1	0.450	1.200	2.457×10^{-4}
2	0.450	0.600	1.229×10^{-4}
3	0.900	1.200	4.914×10^{-4}

Question 2

(c)(i) The rate law for the reaction is $rate = k[\text{HAsc}][\text{I}_3^-]$. Explain how the data in the table support the conclusion that the reaction is first order with respect to [HAsc].
(c)(ii) Calculate the value of the rate constant, k, for the reaction. Include units with your answer.

Question 2

2025 ▪ Q2

Answer the following questions about ascorbic acid (vitamin C).

(d) The triiodide ion, I_3^-, is significantly more soluble in water than elemental iodine, I_2, is. Identify an intermolecular force between I_3^- and water that is **not** present between I_2 and water, which could explain the difference in solubility. Lewis diagrams for I_2 and I_3^- are provided.

[Lewis structures: I_2 shown as two iodine atoms singly bonded together, each with three lone pairs. I_3^- shown in brackets with an overall negative charge, as three iodine atoms in a row connected by single bonds (I—I—I), each terminal iodine with three lone pairs and the central iodine with two lone pairs.]

Solution 2

(a)

Mark scheme

- No separate response required — this is the context/stem describing the combustion of ascorbic acid ($C_xH_yO_x$) producing 0.2400 mol CO_2 and 2.883 g H_2O, which parts (i) and (ii) below use.

(a)(i)

Mark scheme

- moles $H_2O = 2.883$ g $H_2O \times \dfrac{1 \text{ mol } H_2O}{18.02 \text{ g } H_2O} = 0.1600$ mol H_2O.

Solution 2

(a)(ii)

Mark scheme

- moles H $= 0.1600$ mol $H_2O \times \dfrac{2 \text{ mol H}}{1 \text{ mol } H_2O} = 0.3200$ mol H (this step may be left implicit). Using mol C $= 0.2400$ mol $CO_2 \times \dfrac{1 \text{ mol C}}{1 \text{ mol } CO_2} = 0.2400$ mol C and the given 1:1 C:O ratio:
  $x : y : z = (\text{mol C}) : (\text{mol H}) : (\text{mol O}) = 0.2400 : 0.3200 : 0.2400 = 3 : 4 : 3.$
  Therefore the empirical formula of ascorbic acid is $C_3H_4O_3$.

Solution 2

(b)

Mark scheme

- No separate response required — this is the context/stem describing HAsc(aq) as a weak acid and presenting the titration curve (10.0 mL HAsc titrated with 0.0550 M NaOH) that parts (i)–(iii) below refer to.

Solution 2

(b)(i)

Mark scheme

- Reading the volume of NaOH at the equivalence point (16.0 mL) from the curve:

$$0.0160 \text{ L NaOH} \times \frac{0.0550 \text{ mol NaOH}}{1 \text{ L NaOH}} \times \frac{1 \text{ mol HAsc}}{1 \text{ mol NaOH}} = 8.80 \times 10^{-4} \text{ mol HAsc.}$$

$$\text{Molarity} = \frac{8.80 \times 10^{-4} \text{ mol HAsc}}{0.0100 \text{ L}} = 0.0880 \ M \text{ HAsc.}$$

Solution 2

(b)(ii)

Mark scheme

- From the titration curve, the pK_a (the pH at the half-equivalence point) is approximately 4.1 (acceptable range 4.0–4.3).

Solution 2

(b)(iii)

Mark scheme

- Using the Henderson–Hasselbalch equation: $\mathrm{pH} = \mathrm{p}K_a + \log\left(\dfrac{[\mathrm{Asc}^-]}{[\mathrm{HAsc}]}\right)$.

  $4.7 = 4.1 + \log\left(\dfrac{[\mathrm{Asc}^-]}{[\mathrm{HAsc}]}\right)$, so $\dfrac{[\mathrm{Asc}^-]}{[\mathrm{HAsc}]} = 10^{0.6} = 4.0$.

Solution 2

(c)

Mark scheme

- No separate response required — this is the context/stem describing the reaction of ascorbic acid (HAsc) with triiodide (I_3^-) to form DHAsc, and the table of three trials' initial concentrations and rates, that parts (i) and (ii) below use.

Solution 2

(c)(i)

Mark scheme

- Comparing trials 1 and 3: $\frac{4.914 \times 10^{-4}}{2.457 \times 10^{-4}} = \left(\frac{0.900}{0.450}\right)^{a}$, thus $a = 1$. The rate doubles when [HAsc] is doubled while $[I_3^-]$ is held constant, indicating the reaction is first order with respect to [HAsc].

Solution 2

(c)(ii)

Mark scheme

- Using rate $= k[\text{HAsc}][\text{I}_3^-]$ and trial 1 data: $k = \dfrac{\text{rate}}{[\text{HAsc}][\text{I}_3^-]} = \dfrac{2.457 \times 10^{-4}\ M/\text{s}}{(0.450\ M)(1.200\ M)} = 4.55 \times 10^{-4}\ M^{-1}\text{s}^{-1}$. Units: $M^{-1}\text{s}^{-1}$.

Solution 2

(d)

Mark scheme

- Ion-dipole attractions are present between I_3^- ions and water but not between I_2 molecules and water. Because I_3^- is a charged ion, it attracts the polar water molecules via ion-dipole forces, giving it much greater solubility than the neutral, nonpolar I_2.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(a)(i) A student combines equal masses of $H_2C_4H_2O_4(s)$ chunks and $NaHCO_3(s)$ chunks with sufficient water at 20.0°C. The student determines that 0.0114 mol of $CO_2(g)$ is produced after the reaction goes to completion.

Calculate the number of grams of $CO_2(g)$ produced.

(a)(ii) The $CO_2(g)$ produced from the reaction at 20.0°C was collected and found to have a pressure of 1.25 atm. Calculate the volume of $CO_2(g)$, in liters.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(b)(i) The student performs a second experiment that is identical to the first except that the student grinds the chunks of $H_2C_4H_2O_4(s)$ and $NaHCO_3(s)$ into powder before combining the powder with water.

What happens to the surface area of the reactants when the student grinds the chunks into powder?

Question 2

(b)(ii) The rate-determining step for the overall reaction is the dissolving of the solids. Would the time required for the dissolving of the solids in the second experiment be longer than, shorter than, or the same as the time required in the first experiment? Justify your answer based on the collisions between particles.

(b)(iii) When the reaction is complete, will the volume of $CO_2(g)$ at the end of the second experiment be greater than, less than, or equal to the volume at the end of the first experiment? Justify your answer.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(c) The student conducts additional trials of the experiment and produces the following data table.

Trial	Mass of $H_2C_4H_2O_4$ (grams)	Mass of $NaHCO_3$ (grams)	Moles of CO_2 Produced (mol)
3	1.543	1.251	0.01489
4	1.543	1.686	0.02007

Based on the student's data, identify the limiting reactant in trial 3. Justify your answer.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(d) The reaction has a value of ΔS° greater than zero. Using particle-level reasoning, explain why the entropy increases as the reaction progresses.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(e) The student notices that the temperature of the reaction mixture decreases as the reaction takes place and correctly determines that the reaction is endothermic.
The student claims that the reaction is thermodynamically favorable at all temperatures because $\Delta S^\circ_{rxn} > 0$ and the reaction is endothermic. Do you agree or disagree with the student's claim? Justify your answer.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(f) Next, the student investigates the acid-base behavior of maleic acid. The student notes that maleic acid is a diprotic acid. The two acid dissociation processes that occur are represented by the following equations.

$$H_2C_4H_2O_4 + H_2O \rightleftharpoons HC_4H_2O_4^- + H_3O^+ \qquad K_{a_1} = 1.5 \times 10^{-2}$$

$$HC_4H_2O_4^- + H_2O \rightleftharpoons C_4H_2O_4^{2-} + H_3O^+ \qquad K_{a_2} = 8.5 \times 10^{-7}$$

Question 2

Calculate the pK_{a_2} value for the $HC_4H_2O_4^-$ ion.

Question 2

2024 ▪ Q2

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

(g) A buffer solution with a pH of 7.00 is prepared using $C_4H_2O_4^{2-}$ and $HC_4H_2O_4^-$. Calculate the ratio

$$\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]}$$

in this solution.

Solution 2

(a)(i)

Mark scheme

- 0.0114 mol $CO_2 \times \dfrac{44.01\ \text{g}}{1\ \text{mol}} = 0.502\ \text{g}\ CO_2$.

Solution 2

(a)(ii)

Mark scheme

- Using $PV = nRT$:
  $$V = \frac{nRT}{P} = \frac{(0.0114\ \text{mol})(0.08206\ \text{L} \cdot \text{atm}/(\text{mol} \cdot \text{K}))(293\ \text{K})}{1.25\ \text{atm}} = 0.219\ \text{L}.$$

Solution 2

(b)(i)

Mark scheme

- Claim: the surface area of the solid reactants increases when the chunks are ground into powder.

(b)(ii)

Mark scheme

- Shorter than. The powdered solids have a larger surface area than the solid chunks, so collisions between water molecules and the solid surface particles occur more frequently, resulting in a faster rate of dissolution and a shorter time to dissolve the solids.

Solution 2

(b)(iii)

Mark scheme

- Equal to. Both experiments begin with the same amount (mass) of reactants, so they produce the same number of moles of $CO_2(g)$ under the same conditions of pressure and temperature; therefore the final volume of CO_2 will be the same regardless of particle size (rate changes, but the final amount/volume does not).

Solution 2

(c) Mark scheme

- $NaHCO_3$ is the limiting reactant (accept either justification): changing the mass of $NaHCO_3$ alters the amount of CO_2 produced, OR $NaHCO_3$ has the smaller theoretical yield of CO_2:
  1.543 g $H_2C_4H_2O_4 \times \dfrac{1 \text{ mol}}{116.07 \text{ g}} \times \dfrac{2 \text{ mol } CO_2}{1 \text{ mol acid}} = 0.02659$ mol CO_2 (if acid were limiting) vs. 1.251 g $NaHCO_3 \times \dfrac{1 \text{ mol}}{84.01 \text{ g}} \times \dfrac{2 \text{ mol } CO_2}{2 \text{ mol } NaHCO_3} = 0.01489$ mol CO_2 (if $NaHCO_3$ limiting) — the smaller value ($NaHCO_3$) is the actual limiting reactant, matching the trial's observed 0.01489 mol CO_2.

Solution 2

(d)

Mark scheme

- The entropy change is positive because the aqueous/solid reactants produce 2 moles of gas (CO_2) particles, according to the balanced equation. Gases are far more dispersed (occupy many more microstates) than condensed (solid/aqueous) phases, so the entropy of the products is greater than that of the reactants.

Solution 2

(e)

Mark scheme

- Disagree. Accept either justification: (1) The reaction is endothermic ($\Delta H > 0$) with a positive entropy change ($\Delta S > 0$), so it is only thermodynamically favorable at a high enough temperature where the magnitude of $-T\Delta S$ exceeds ΔH — NOT at all temperatures. (2) For a reaction to be thermodynamically favorable ($\Delta G < 0$) at ALL temperatures, it must be exothermic ($\Delta H < 0$) AND have $\Delta S > 0$ — this reaction is endothermic, so it fails that requirement.

Solution 2

(f)

Mark scheme

- Given $K_{a_2} = 8.5 \times 10^{-7}$ for the second dissociation of maleic acid: $\mathrm{p}K_{a_2} = -\log(8.5 \times 10^{-7}) = 6.07$.

Solution 2

(g)

Mark scheme

- Using the Henderson–Hasselbalch equation: $\mathrm{pH} = \mathrm{p}K_{a_2} + \log \dfrac{[\mathrm{C_4H_2O_4^{2-}}]}{[\mathrm{HC_4H_2O_4^-}]}$.

  Solving: $\dfrac{[\mathrm{C_4H_2O_4^{2-}}]}{[\mathrm{HC_4H_2O_4^-}]} = 10^{(\mathrm{pH}-\mathrm{p}K_{a_2})} = 10^{(7.00-6.07)} = 8.5.$

Question 4

2023 ▪ Q4

A student is asked to prepare a buffer solution made with equimolar amounts of $CH_3NH_2(aq)$ and $CH_3NH_3Cl(s)$. The student uses 25.00 mL of 0.100 *M* $CH_3NH_2(aq)$, which contains 0.00250 mol of CH_3NH_2, to make the buffer.

(a) Calculate the mass of $CH_3NH_3Cl(s)$ that contains 0.00250 mol of CH_3NH_3Cl.

Question 4

2023 ▪ Q4

A student is asked to prepare a buffer solution made with equimolar amounts of $CH_3NH_2(aq)$ and $CH_3NH_3Cl(s)$. The student uses 25.00 mL of 0.100 M $CH_3NH_2(aq)$, which contains 0.00250 mol of CH_3NH_2, to make the buffer.

(b) The student has the following materials and equipment available.

- Distilled water - Electronic balance - 50 mL beaker - Pipets - 0.100 M $CH_3NH_2(aq)$ - Weighing paper - 10.0 mL graduated cylinder - pH meter - Solid CH_3NH_3Cl - 50.00 mL buret - Small spatula

The following table contains a partial procedure for making the buffer solution. Fill in steps 1 and 4 to complete the procedure using only materials and equipment selected from the choices given. (Not all materials listed will be used. Assume that all appropriate safety measures are already in place.)

Question 4

| Step | Procedure | |—|—| | 1 | | | 2 | Place the solid in the 50 mL beaker. | | 3 | Clean the buret and rinse with distilled water. | | 4 | | | 5 | Use the buret to add 25.00 mL of 0.100 M $CH_3NH_2(aq)$ to the beaker. | | 6 | Mix well. | | 7 | Check the pH with the pH meter. |

Question 4

2023 ▪ Q4

A student is asked to prepare a buffer solution made with equimolar amounts of $CH_3NH_2(aq)$ and $CH_3NH_3Cl(s)$. The student uses 25.00 mL of 0.100 *M* $CH_3NH_2(aq)$, which contains 0.00250 mol of CH_3NH_2, to make the buffer.

(c) The value of K_b for $CH_3NH_2(aq)$ is 4.4×10^{-4}, and the pH of the buffer the student prepared is 10.64.

The student prepares a second buffer solution. The student uses 25.00 mL of 0.050 *M* $CH_3NH_2(aq)$ instead of 25.00 mL of 0.100 *M* $CH_3NH_2(aq)$, and half the mass of $CH_3NH_3Cl(s)$ that was used in the first buffer. Is the pH of the second buffer greater than, less than, or equal to the pH of the first buffer? Justify your answer.

Solution 4

(a)

Mark scheme

- 0.00250 mol $CH_3NH_3Cl \times \dfrac{67.52\ \text{g}}{1\ \text{mol}} = 0.169\ \text{g}.$

Solution 4

(b)

Mark scheme

- Step 1: Use the spatula, balance, and weighing paper to measure out exactly 0.169 g of $CH_3NH_3Cl(s)$ — i.e., weigh out the mass of solid calculated in part (a) (1 point). Step 4: Rinse the buret with a small amount of 0.100 M $CH_3NH_2(aq)$, drain it, and refill the buret with 0.100 M $CH_3NH_2(aq)$ (1 point).

Solution 4

(c)

Mark scheme

- Equal to. The buffer's pH depends on the mole ratio of weak base (CH_3NH_2) to conjugate acid ($CH_3NH_3^+$); using half the volume/concentration of base and half the mass of salt keeps that ratio at 1:1, the same as in the first buffer, so the pH is unchanged.

Question 3

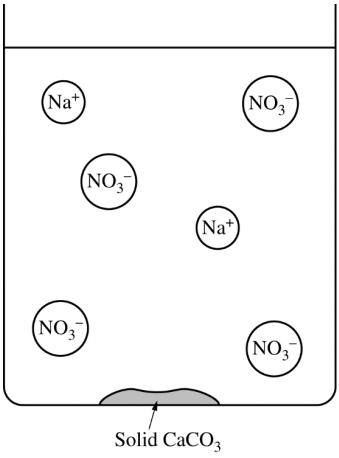
2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(a) Write the net ionic equation for the reaction that occurs when the solutions of Na_2CO_3 and $Ca(NO_3)_2$ are mixed.

Question 3



Question 3

Volume of Na_2CO_3 solution	50.0 mL
Volume of 1.0 *M* $Ca(NO_3)_2$ added	100.0 mL
Mass of $CaCO_3$ precipitate collected	0.93 g

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(b) The diagram below is incomplete. Draw in the species needed to accurately represent the major ionic species remaining in the solution after the reaction has been completed.

Question 3

[Diagram of a beaker of solution after reaction: floating ion labels Na^+, NO_3^-, NO_3^-, Na^+, NO_3^-, NO_3^- scattered above a layer of gray solid labelled "Solid $CaCO_3$" at the bottom of the beaker]

The student filters and dries the precipitate of $CaCO_3$ (molar mass 100.1 g/mol) and records the data in the table below.

Volume of Na_2CO_3 solution	50.0 mL
Volume of 1.0 *M* $Ca(NO_3)_2$ added	100.0 mL
Mass of $CaCO_3$ precipitate collected	0.93 g

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(c) Determine the number of moles of Na_2CO_3 in the original 50.0 mL of solution.

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(d) The student realizes that the precipitate was not completely dried and claims that as a result, the calculated Na_2CO_3 molarity is too low. Do you agree with the student's claim? Justify your answer.

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(e) After the precipitate forms and is filtered, the liquid that passed through the filter is tested to see if it can conduct electricity. What would be observed? Justify your answer.

Question 3

The student decides to determine the molarity of the same Na_2CO_3 solution using a second method. When Na_2CO_3 is dissolved in water, $CO_3^{2-}(aq)$ hydrolyzes to form $HCO_3^-(aq)$, as shown by the following equation.

$$CO_3^{2-}(aq) + H_2O(l) \rightleftharpoons HCO_3^-(aq) + OH^-(aq) \qquad K_b = \frac{[HCO_3^-][OH^-]}{[CO_3^{2-}]} = 2.1 \times 10^{-4}$$

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(f)(i) The student decides to first determine $[OH^-]$ in the solution, then use that result to calculate the initial concentration of $CO_3^{2-}(aq)$.
Identify a laboratory method (not titration) that the student could use to collect data to determine $[OH^-]$ in the solution.

Question 3

(f)(ii) Explain how the student could use the measured value in part (f)(i) to calculate the initial concentration of $CO_3^{2-}(aq)$. (Do not do any numerical calculations.)

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 M $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(g) In the original Na_2CO_3 solution at equilibrium, is the concentration of $HCO_3^-(aq)$ greater than, less than, or equal to the concentration of $CO_3^{2-}(aq)$? Justify your answer.

Question 3

2019 ▪ Q3

A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 *M* $Ca(NO_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.

$$Na_2CO_3(aq) + Ca(NO_3)_2(aq) \rightarrow 2\,NaNO_3(aq) + CaCO_3(s)$$

(h) The student needs to make a CO_3^{2-}/HCO_3^- buffer. Is the Na_2CO_3 solution suitable for making a buffer with a pH of 6? Explain why or why not.

Solution 3

(a)

Mark scheme

- Ca^2 (aq) + $CO3^2$ (aq) $\rightarrow$ CaCO3(s). 1 point for the correct net ionic equation (spectator ions Na and NO3 omitted).

Solution 3

(b)

Mark scheme

- The completed diagram should show one Ca^2 ion added among the floating Na and NO3 ions: Ca(NO3)2 was added in excess (100.0 mL of 1.0 M vs. only 50.0 mL of dilute Na2CO3), so some unreacted Ca^2 remains in solution along with the spectator Na and NO3 ions. 1 point for drawing a Ca^2 ion in the solution.

Solution 3

(c)

Mark scheme

- 0.93 g CaCO3 × (1 mol CaCO3 / 100.1 g) = 0.0093 mol CaCO3. Since the reaction is 1:1 (Na2CO3 : CaCO3), 0.0093 mol CaCO3 × (1 mol Na2CO3 / 1 mol CaCO3) = 0.0093 mol Na2CO3. 1 point for the correct answer (0.0093 mol).

Solution 3

(d)

Mark scheme

- Disagree. If the precipitate was not completely dried, residual water increases the measured mass of the 'CaCO3' precipitate above its true mass. This makes the calculated moles of CaCO3 (and therefore of Na2CO3) too high, not too low — so the calculated Na2CO3 molarity would actually be too HIGH, contrary to the student's claim. 1 point for disagreeing with valid justification.

Solution 3

(e)

Mark scheme

- The filtrate would conduct electricity, because dissolved ions remain in solution — specifically Na (aq), the excess Ca^2 (aq) (from the excess Ca(NO3)2 added), and NO3 (aq). 1 point for the correct answer (conducts) with valid justification listing the ions present.

Solution 3

(f)(i)

Mark scheme

- Measure the pH of the solution using a pH meter (a non-titration laboratory method for determining [OH]). 1 point for identifying a valid method.

Solution 3

(f)(ii)

Mark scheme

- From the measured pH: $pOH = 14 - pH$, then $[OH^-] = 10^{\wedge}(-pOH)$. 1 point for this valid method of determining $[OH^-]$ from the measured value. Then, using the Kb expression $Kb = [HCO3^-][OH^-]/[CO3^{2-}]$ with an ICE table (I: ci, 0, 0; C: $-x$, $+x$, $+x$; E: ci$-x$, x, x, where $x = [OH^-] = [HCO3^-]$ at equilibrium since they form in a 1:1 ratio from water), solve $ci = (x^2/Kb) + x$ for the initial concentration ci of $CO3^{2-}$ (equal to the sum of the equilibrium $[CO3^{2-}]$ and $[HCO3^-]$). 1 point for this valid method of determining the initial concentration of $CO3^{2-}$ from $[OH^-]$.

Solution 3

(g)

Mark scheme

HCO3 is less than [CO3^{2}]. The small value of Kb (2.1×10 , much less than 1) indicates that the reactants (H2O and CO3^{2}) are favored at equilibrium over the products, so only a small fraction of CO3^{2} hydrolyzes to HCO3 . 1 point for the correct answer (less than) with valid justification.

Solution 3

(h)

Mark scheme

- No, the Na2CO3 solution is not suitable for making a pH-6 buffer. The pKa of HCO3 (the conjugate acid in this $CO3^2$ /HCO3 system) is 10.32. A buffer is most effective when the desired pH is close to the pKa of its weak-acid component; pH 6 is far from pKa 10.32, so this system cannot buffer effectively at pH 6. 1 point for the correct answer (no) with a valid explanation referencing pKa.

Question 3

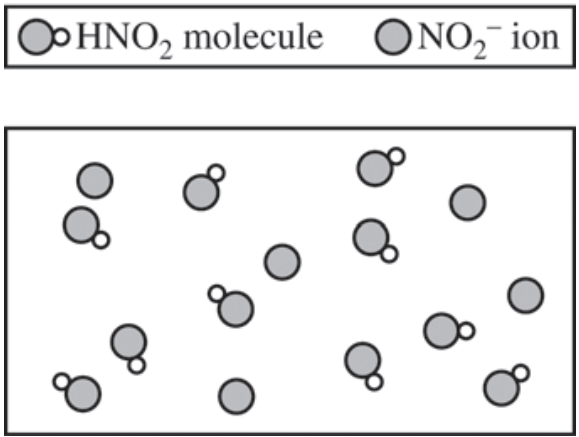
2017 ▪ Q3

$$N_2(g) + O_2(g) \rightleftharpoons 2\,NO(g)$$

At high temperatures, $N_2(g)$ and $O_2(g)$ can react to produce nitrogen monoxide, $NO(g)$, 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

$$N_2(g) + O_2(g) \rightleftharpoons 2\,NO(g)$$

At high temperatures, $N_2(g)$ and $O_2(g)$ can react to produce nitrogen monoxide, $NO(g)$, as represented by the equation above.

(b) A student injects $N_2(g)$ and $O_2(g)$ into a previously evacuated, rigid vessel and raises the temperature of the vessel to $2000°C$. At this temperature the initial partial pressures of $N_2(g)$ and $O_2(g)$ are 6.01 atm and 1.61 atm, respectively. The system is allowed to reach equilibrium. The partial pressure of $NO(g)$ at equilibrium is 0.122 atm. Calculate the value of K_p.

Question 3

2017 ▪ Q3

$$N_2(g) + O_2(g) \rightleftharpoons 2\,NO(g)$$

At high temperatures, $N_2(g)$ and $O_2(g)$ can react to produce nitrogen monoxide, $NO(g)$, as represented by the equation above.

(c)(i) Nitrogen monoxide, $NO(g)$, 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 pK_a of 3.40.

A student is asked to make a buffer solution with a pH of 3.40 by using 0.100 *M* $HNO_2(aq)$ and 0.100 *M* $NaOH(aq)$.

Explain why the addition of 0.100 *M* $NaOH(aq)$ to 0.100 *M* $HNO_2(aq)$ can result in the formation of a buffer solution. Include the net ionic equation for the reaction that occurs when the student adds the $NaOH(aq)$ to the $HNO_2(aq)$.

Question 3

(c)(ii) Determine the volume, in mL, of 0.100 *M* $NaOH(aq)$ the student should add to 100. mL of 0.100 *M* $HNO_2(aq)$ to make a buffer solution with a pH of 3.40. Justify your answer.

Question 3

2017 ▪ Q3

$$N_2(g) + O_2(g) \rightleftharpoons 2\,NO(g)$$

At high temperatures, $N_2(g)$ and $O_2(g)$ can react to produce nitrogen monoxide, $NO(g)$, as represented by the equation above.

(d) A second student makes a buffer by dissolving 0.100 mol of $NaNO_2(s)$ in 100. mL of 1.00 *M* $HNO_2(aq)$. 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

$$N_2(g) + O_2(g) \rightleftharpoons 2\,NO(g)$$

At high temperatures, $N_2(g)$ and $O_2(g)$ can react to produce nitrogen monoxide, $NO(g)$, as represented by the equation above.

(e) A new buffer is made using $HNO_2(aq)$ 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

- Kp = (P_NO)^2 / [(P_N2)(P_O2)]. 1 point earned for a correct Kp expression.

Solution 3

(b)

Mark scheme

- ICE table (atm): Initial N2 = 6.01, O2 = 1.61, 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_N2 = 5.95 atm and P_O2 = 1.55 atm. Kp = (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 Kp.

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: HNO2 + OH- -> NO2- + H2O. 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, pH = pKa + log([NO2-]/[HNO2]), so pH = pKa exactly when [HNO2] = [NO2-]; since the target pH (3.40) equals pKa, a 1-to-1 ratio of HNO2 to NO2- is required, i.e. half of the 10.0 mmol HNO2 (100. mL x 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 NaNO2 dissolved in 100. mL of 1.00 M HNO2) is more resistant to changes in pH, because it contains a higher concentration of HNO2 and NO2- 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 [HNO2] = [NO2-], pH = pKa and the pH of the solution would be 3.40; since the particulate diagram shows more HNO2 molecules than NO2- ions (i.e. [HNO2] > [NO2-]), the solution has a pH less than 3.40 (equivalently, with the diagram's ratio of about 5 NO2- to 10 HNO2, pH = 3.40 + log(5/10) = 3.10). 1 point earned for the correct choice; 1 point earned for a valid justification.

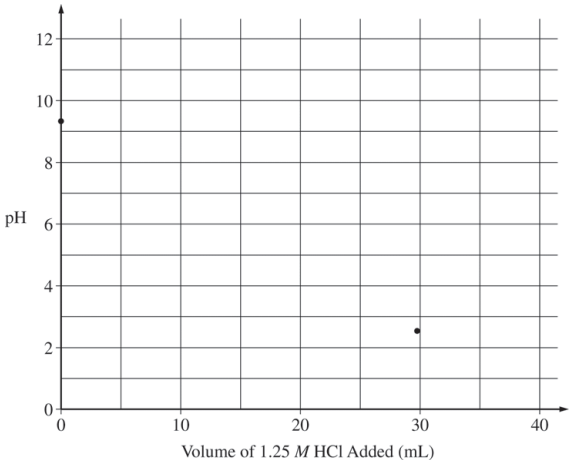
Question 3

2015 ▪ Q3

Potassium sorbate, $KC_6H_7O_2$ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of $KC_6H_7O_2(aq)$ of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 M $HCl(aq)$ using both an indicator and a pH meter. The value of K_a for sorbic acid, $HC_6H_7O_2$, is 1.7×10^{-5}.

(a) Write the net-ionic equation for the reaction between $KC_6H_7O_2(aq)$ and $HCl(aq)$.

Question 3



Question 3

Indicator	pK_a
Phenolphthalein	9.3
Bromothymol blue	7.0
Methyl red	5.0
Thymol blue	2.0
Methyl violet	0.80

Question 3

2015 ▪ Q3

Potassium sorbate, $KC_6H_7O_2$ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of $KC_6H_7O_2(aq)$ of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 *M* $HCl(aq)$ using both an indicator and a pH meter. The value of K_a for sorbic acid, $HC_6H_7O_2$, is 1.7×10^{-5}.

(b) A total of 29.95 mL of 1.25 *M* $HCl(aq)$ is required to reach the equivalence point. Calculate $[KC_6H_7O_2]$ in the stock solution.

Question 3

2015 ▪ Q3

Potassium sorbate, $KC_6H_7O_2$ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of $KC_6H_7O_2(aq)$ of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 *M* $HCl(aq)$ using both an indicator and a pH meter. The value of K_a for sorbic acid, $HC_6H_7O_2$, is 1.7×10^{-5}.

(c) The pH at the equivalence point of the titration is measured to be 2.54. Which of the following indicators would be the best choice for determining the end point of the titration? Justify your answer.

| Indicator | pK_a | |—|—| | Phenolphthalein | 9.3 | | Bromothymol blue | 7.0 | | Methyl red | 5.0 | | Thymol blue | 2.0 | | Methyl violet | 0.80 |

Question 3

2015 ▪ Q3

Potassium sorbate, $KC_6H_7O_2$ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of $KC_6H_7O_2(aq)$ of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 *M* $HCl(aq)$ using both an indicator and a pH meter. The value of K_a for sorbic acid, $HC_6H_7O_2$, is 1.7×10^{-5}.

(d) Calculate the pH at the half-equivalence point.

Question 3

2015 ▪ Q3

Potassium sorbate, $KC_6H_7O_2$ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of $KC_6H_7O_2(aq)$ of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 *M* HCl(aq) using both an indicator and a pH meter. The value of K_a for sorbic acid, $HC_6H_7O_2$, is 1.7×10^{-5}.

(e) The initial pH and the equivalence point are plotted on the graph below. Accurately sketch the titration curve on the graph below. Mark the position of the half-equivalence point on the curve with an X.

[Graph: x-axis "Volume of 1.25 *M* HCl Added (mL)" from 0 to 40 (gridlines every 2 mL); y-axis "pH" from 0 to 12 (gridlines every 0.5). Two points are plotted: one near (0, 9.4) representing the initial pH, and one at approximately (30, 2.54) representing the equivalence point. The curve connecting them (the titration curve) is NOT drawn — the student must sketch it.]

Question 3

2015 ▪ Q3

Potassium sorbate, $KC_6H_7O_2$ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of $KC_6H_7O_2(aq)$ of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 *M* $HCl(aq)$ using both an indicator and a pH meter. The value of K_a for sorbic acid, $HC_6H_7O_2$, is 1.7×10^{-5}.

(f) The pH of the soft drink is 3.37 after the addition of the $KC_6H_7O_2(aq)$. Which species, $HC_6H_7O_2$ or $C_6H_7O_2^-$, has a higher concentration in the soft drink? Justify your answer.

Solution 3

(a)

Mark scheme

- H+(aq) + C6H7O2-(aq) <-> HC6H7O2(aq). 1 point for the correct net-ionic equation (K+ and Cl- are spectator ions and are omitted).

Solution 3

(b)

Mark scheme

- At the equivalence point, moles HCl = moles KC6H7O2 originally present. mol HCl = 1.25 M x 0.02995 L = 0.0374 mol (1 point for the moles of HCl at the equivalence point). [KC6H7O2] = 0.0374 mol / 0.04500 L = 0.832 M (1 point for the correct concentration of the stock solution).

Solution 3

(c)

Mark scheme

- Thymol blue is the best choice, because its pKa (2.0) is closest to the measured pH at the equivalence point (2.54), so it will change color right around the equivalence point of the titration (1 point for selecting the correct indicator, thymol blue; 1 point for the correct justification that its pKa is close to the equivalence-point pH).

Solution 3

(d)

Mark scheme

- At the half-equivalence point, pH = pKa = -log(1.7 x 10^-5) = 4.77. 1 point for the correct pH.

Solution 3

(e) Mark scheme

- The titration curve starts at the given initial pH (~9.4 at V=0), decreases with a relatively flat/gently-sloped buffer region around the half-equivalence point (V ~ 15.0 mL, where pH = pKa = 4.77, consistent with part (d)), then drops with a steep negative slope through the equivalence point (V=29.95 mL, pH=2.54), and levels off again afterward as excess strong acid is added. The half-equivalence point should be marked with an X at V ~ 15 mL (half of 29.95 mL) and pH = 4.77. 1 point for a half-equivalence point (X) consistent with the answer to part (d) and located at the correct volume; 1 point for a curve that levels off to a relatively horizontal slope through the half-equivalence point; 1 point for a relatively steep negative slope through the equivalence point.

Solution 3

(f)

Mark scheme

- Using Ka = [H+][C6H7O2-]/[HC6H7O2], the ratio [C6H7O2-]/[HC6H7O2] = Ka/[H+] = (1.7x10^-5)/(10^-3.37) ~ 0.04, so [HC6H7O2] > [C6H7O2-] (equivalently: since pH 3.37 is below the half-equivalence-point pH of 4.77, the solution is more protonated than deprotonated, so the weak-acid form HC6H7O2 dominates). 1 point for identifying HC6H7O2 as the species with higher concentration AND making a comparison/argument involving the pH (with or without a full calculation).