Past-paper walk-through

Introduction to Titration ▪ 4.6

eXercise

Questions in this set

- 2026 Q3
- 2025 Q2
- 2019 Q7
- 2018 Q2
- 2018 Q3
- 2016 Q7
- 2015 Q3
- 2014 Q2

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

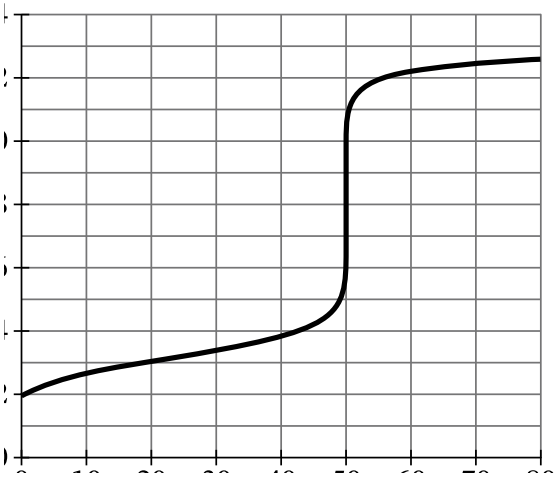
Chemical Equation	Equilibrium Constant
$HNO_2(aq) + H_2O(l) \rightleftarrows NO_2^-(aq) + H_3O^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$H_2O(l) + H_2O(l) \rightleftarrows H_3O^+(aq) + OH^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$	$K_2 =$?

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

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(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.

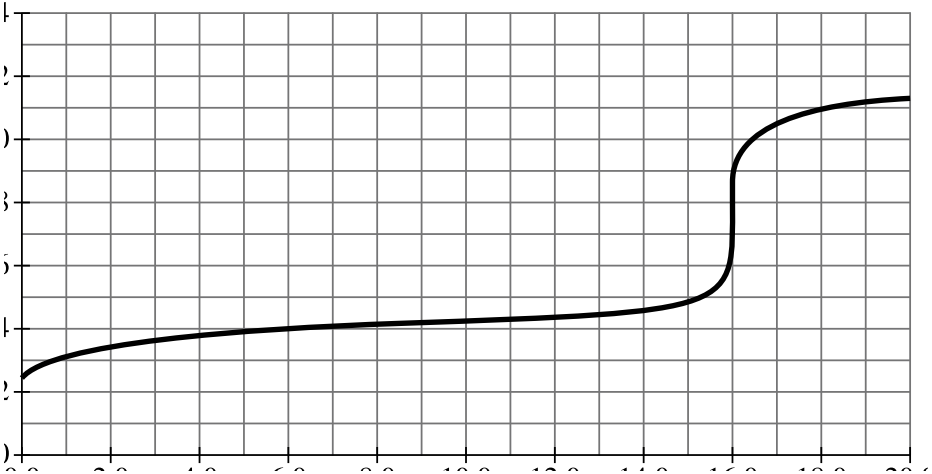
Question 2

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 7

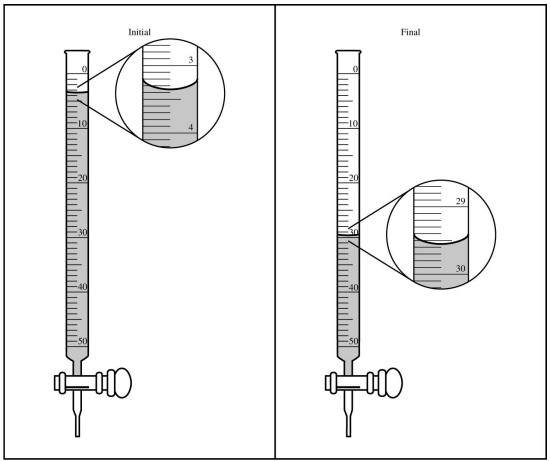
2019 ▪ Q7

$$6\,H^+(aq) + 2\,MnO_4^-(aq) + 5\,H_2C_2O_4(aq) \rightarrow 10\,CO_2(g) + 8\,H_2O(l) + 2\,Mn^{2+}(aq)$$

A student dissolved a 0.139 g sample of oxalic acid, $H_2C_2O_4$, in water in an Erlenmeyer flask. Then the student titrated the $H_2C_2O_4$ solution in the flask with a solution of $KMnO_4$, which has a dark purple color. The balanced chemical equation for the reaction that occurred during the titration is shown above.

(a) Identify the species that was reduced in the titration reaction. Justify your answer in terms of oxidation numbers.

Question 7



Question 7

2019 ▪ Q7

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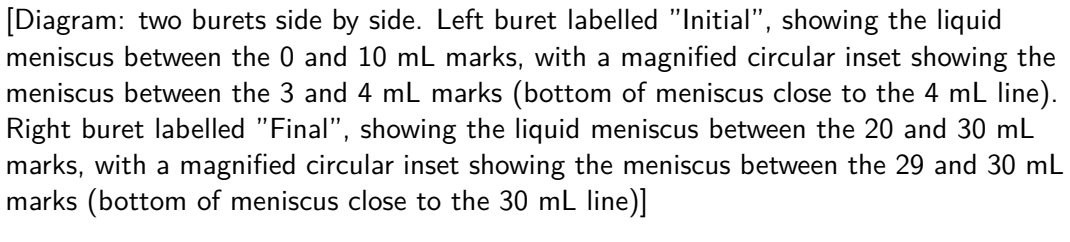
A student dissolved a 0.139 g sample of oxalic acid, $H_2C_2O_4$, in water in an Erlenmeyer flask. Then the student titrated the $H_2C_2O_4$ solution in the flask with a solution of $KMnO_4$, which has a dark purple color. The balanced chemical equation for the reaction that occurred during the titration is shown above.

(b) The student used a 50.0 mL buret to add the $KMnO_4(aq)$ to the $H_2C_2O_4(aq)$ until a faint lavender color was observed in the flask, an indication that the end point of the titration had been reached. The initial and final volume readings of the solution in the buret are shown below. Write down the initial reading and the final reading and use them to determine the volume of $KMnO_4(aq)$ that was added during the titration.

Question 7



[Diagram: two burets side by side. Left buret labelled "Initial", showing the liquid meniscus between the 0 and 10 mL marks, with a magnified circular inset showing the meniscus between the 3 and 4 mL marks (bottom of meniscus close to the 4 mL line). Right buret labelled "Final", showing the liquid meniscus between the 20 and 30 mL marks, with a magnified circular inset showing the meniscus between the 29 and 30 mL marks (bottom of meniscus close to the 30 mL line)]

Question 7

2019 ▪ Q7

$$6\,H^+(aq) + 2\,MnO_4^-(aq) + 5\,H_2C_2O_4(aq) \rightarrow 10\,CO_2(g) + 8\,H_2O(l) + 2\,Mn^{2+}(aq)$$

A student dissolved a 0.139 g sample of oxalic acid, $H_2C_2O_4$, in water in an Erlenmeyer flask. Then the student titrated the $H_2C_2O_4$ solution in the flask with a solution of $KMnO_4$, which has a dark purple color. The balanced chemical equation for the reaction that occurred during the titration is shown above.

(c) Given that the concentration of $KMnO_4(aq)$ was 0.0235 *M*, calculate the number of moles of MnO_4^- ions that completely reacted with the $H_2C_2O_4$.

Question 7

2019 ▪ Q7

$$6\,H^+(aq) + 2\,MnO_4^-(aq) + 5\,H_2C_2O_4(aq) \rightarrow 10\,CO_2(g) + 8\,H_2O(l) + 2\,Mn^{2+}(aq)$$

A student dissolved a 0.139 g sample of oxalic acid, $H_2C_2O_4$, in water in an Erlenmeyer flask. Then the student titrated the $H_2C_2O_4$ solution in the flask with a solution of $KMnO_4$, which has a dark purple color. The balanced chemical equation for the reaction that occurred during the titration is shown above.

(d) The student proposes to perform another titration using a 0.139 g sample of $H_2C_2O_4$, but this time using 0.00143 *M* $KMnO_4(aq)$ in the buret. Would this titrant concentration be a reasonable choice to use if the student followed the same procedure and used the same equipment as before? Justify your response.

Solution 7

(a)

Mark scheme

- MnO4 is reduced (to Mn^2). In MnO4 , Mn has oxidation number $+7$; in Mn^2 , Mn has oxidation number $+2$. This decrease in oxidation number ($+7 \rightarrow +2$, a gain of 5 electrons) indicates that Mn was reduced. 1 point for the correct answer with oxidation-number justification.

Solution 7

(b)

Mark scheme

- Volume of KMnO4 added = final reading − initial reading = 29.55 mL − 3.35 mL = 26.20 mL. 1 point for the correct answer.

Solution 7

(c)

Mark scheme

- Moles of MnO4 $=$ volume (L) $\times$ molarity $=$ (0.02620 L)(0.0235 mol/L) $=$ 0.000616 mol. 1 point for the correct answer.

Solution 7

(d)

Mark scheme

- No, this titrant concentration would not be reasonable. The 0.00143 M KMnO4 solution is far more dilute than the original (0.0235 M), so a much larger volume of titrant would be required to deliver the same moles of MnO4 needed to reach the endpoint — this volume would exceed the 50.0 mL capacity of the buret. 1 point for the correct answer (no) with this justification.

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\mathrm{NO}(g)$ and $\mathrm{NO_2}(g)$, which the student produces by using the reaction represented above.

(a) The particle-level representation of the equimolar mixture of $\mathrm{NO}(g)$ and $\mathrm{NO_2}(g)$ in the flask at the completion of the reaction between $\mathrm{NO}(g)$ and $\mathrm{O_2}(g)$ 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 $\mathrm{NO}(g)$ and $\mathrm{O_2}(g)$ 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.

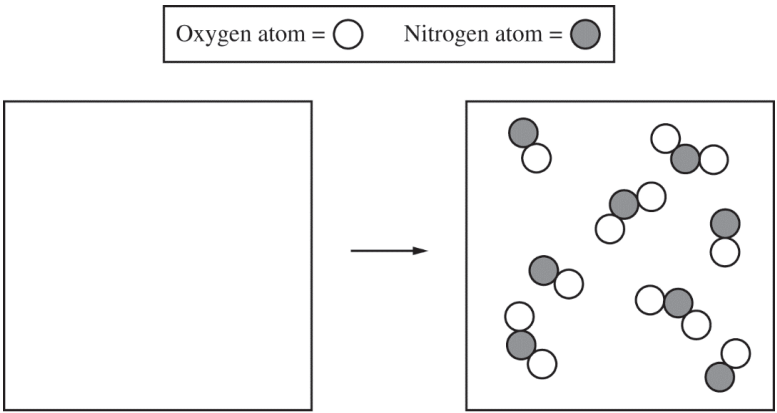
Question 2

[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 NO_2 molecules (each one filled circle bonded to two open circles), scattered randomly in the box.]
The student reads in a reference text that $NO(g)$ and $NO_2(g)$ will react as represented by the equation below. Thermodynamic data for the reaction are given in the table below the equation.

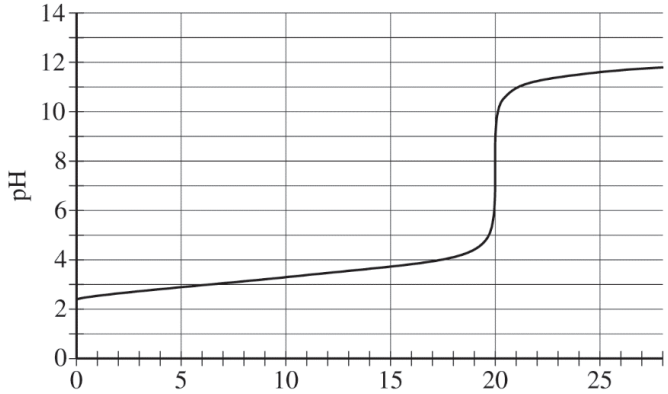
$$NO(g) + NO_2(g) \rightleftharpoons N_2O_3(g)$$

| ΔH°_{298} | ΔS°_{298} | ΔG°_{298} | |—|—|—| | -40.4 kJ/mol$_{rxn}$ | -138.5 J/(K $\cdot$ mol$_{rxn}$) | 0.87 kJ/mol$_{rxn}$ |

Question 2


Oxygen atom =
Nitrogen atom =
Reactant Mixture
Product Mixture

Question 2



Question 2

$$\mathrm{NO}(g) + \mathrm{NO_2}(g) \rightleftarrows \mathrm{N_2O_3}(g)$$

ΔH°_{298}	ΔS°_{298}	ΔG°_{298}
$-40.4\ \mathrm{kJ/mol}_{rxn}$	$-138.5\ \mathrm{J/(K \cdot mol}_{rxn})$	$0.87\ \mathrm{kJ/mol}_{rxn}$

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\mathrm{NO}(g)$ and $\mathrm{NO_2}(g)$, which the student produces by using the reaction represented above.

(b)(i) The student begins with an equimolar mixture of $\mathrm{NO}(g)$ and $\mathrm{NO_2}(g)$ 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 $P_{\mathrm{NO_2}}$ in the vessel are initially 1.0 atm, will $P_{\mathrm{N_2O_3}}$ at equilibrium be equal to 1.0 atm? Justify your answer.

Question 2

2018 ▪ Q2

$$2\,NO(g) + O_2(g) \rightarrow 2\,NO_2(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(c) The student hypothesizes that increasing the temperature will increase the amount of $N_2O_3(g)$ in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.

$N_2O_3(g)$ reacts with water to form nitrous acid, $HNO_2(aq)$, a compound involved in the production of acid rain. The reaction is represented below.

Question 2

$$N_2O_3(g) + H_2O(l) \rightarrow 2\,HNO_2(aq)$$

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\mathrm{NO}(g)$ and $\mathrm{NO_2}(g)$, which the student produces by using the reaction represented above.

(d)(i) The skeletal structure of the $\mathrm{HNO_2}$ 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 $\mathrm{HNO_2}$ 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 $\mathrm{HNO_2}$ molecule.

Question 2

To produce an aqueous solution of HNO_2, the student bubbles $N_2O_3(g)$ into distilled water. Assume that the reaction goes to completion and that HNO_2 is the only species produced. To determine the concentration of $HNO_2(aq)$ in the resulting solution, the student titrates a 100. mL sample of the solution with 0.100 M $KOH(aq)$. The neutralization reaction is represented below.

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

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 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

$$2\,NO(g) + O_2(g) \rightarrow 2\,NO_2(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $NO(g)$ and $NO_2(g)$, 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 $HNO_2(aq)$ solution.

(e)(ii) Use the titration curve and the information above to estimate the value of pK_a for $HNO_2(aq)$.

Question 2

2018 ▪ Q2

$$2\,\mathrm{NO}(g) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{NO_2}(g)$$

A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\mathrm{NO}(g)$ and $\mathrm{NO_2}(g)$, which the student produces by using the reaction represented above.

(f) During the titration, after a volume of 15 mL of 0.100 *M* $\mathrm{KOH}(aq)$ has been added, which species, $\mathrm{HNO_2}(aq)$ or $\mathrm{NO_2^-}(aq)$, 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 NO(g) + O2(g) -> 2 NO2(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

- DeltaG = -RT ln K, so K = e^(-DeltaG/RT) = e^[-870 J/mol / ((8.314 J/(mol K))(298 K))] = e^(-0.351) = 0.70. 1 point is earned for the correct calculation of K.

Solution 2

(b)(ii)

Mark scheme

- No, P(N2O3) will not equal 1.0 atm at equilibrium. P(N2O3) 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 NO2) will remain at equilibrium, so P(N2O3) 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 NO(g) + NO2(g) <=> N2O3(g) is exothermic (DeltaH_298 = -40.4 kJ/mol_rxn), increasing the temperature will favor the formation of the reactants (shift left), according to Le Chatelier's principle, so the amount of N2O3(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 HNO2 (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 sp2 hybridized (it is bonded to 2 O atoms and has 1 lone pair, i.e., 3 electron domains, giving trigonal planar / sp2 geometry). 1 point is earned for the correct answer, sp2.

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. mL x 0.100 mol KOH/1000 mL = 0.0020 mol KOH added, which equals 0.0020 mol HNO2 originally present (1:1 stoichiometry of HNO2 + OH- -> NO2- + H2O). Initial concentration = 0.0020 mol HNO2 / 0.100 L = 0.020 M HNO2. 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 pH = pKa. 1 point is earned for an acceptable estimate of pKa (values near 3.4 accepted).

Solution 2

(f)

Mark scheme

- NO2-(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 (NO2-) than the acid (HNO2) is present. 1 point is earned for the correct choice AND a valid justification.

Question 3

2018 ▪ Q3

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

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

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

Question 3

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

Question 3

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

Question 3

2018 ▪ Q3

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

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

Question 3

2018 ▪ Q3

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

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

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

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

Question 3

2018 ▪ Q3

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

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

Question 3

2018 ▪ Q3

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

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

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

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

Question 3

2018 ▪ Q3

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

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

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

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

Question 3

2018 ▪ Q3

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

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

Question 3

2018 ▪ Q3

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

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

Question 3

2018 ▪ Q3

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

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

Solution 3

(a)

Mark scheme

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

Solution 3

(b)

Mark scheme

- Both ions have the same nuclear charge (26 protons), but Fe^{2+} has one more electron in its outermost (3d) shell than Fe^{3+}. The greater number of electrons in that shell for Fe^{2+} results in greater electron-electron repulsion, which leads to a larger radius. 1 point is earned for a valid explanation.

Solution 3

(c)

Mark scheme

- By Coulomb's law, F is proportional to q1*q2/r^2 (need not be explicitly stated). Fe^{3+} has a higher charge than Fe^{2+}, so it attracts the partially negative O of water molecules more strongly. OR: the smaller ionic radius of Fe^{3+} allows it to get closer to a water molecule, increasing the force of attraction (smaller r increases F). 1 point is earned for a valid explanation using Coulomb's law.

Solution 3

(d)

Mark scheme

- Half-reaction: Fe2+(aq) -> Fe3+(aq) + e-. 1 point is earned for the correct half-reaction.

Solution 3

(e)

Mark scheme

- 17.48 mL x 0.0350 mol KMnO4/1000 mL = 0.000612 mol KMnO4. Using the stoichiometry 5 Fe2+ : 1 MnO4-: 0.000612 mol KMnO4 x (5 mol Fe2+/1 mol KMnO4) = 0.003059 mol Fe2+. [Fe2+] = 0.003059 mol / 0.0100 L = 0.306 M. 1 point is earned for calculating the number of moles of KMnO4 (may be implicit); 1 point is earned for the correct concentration of Fe2+.

Solution 3

(f)

Mark scheme

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

Solution 3

(g)

Mark scheme

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

Solution 3

(h)

Mark scheme

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

Solution 3

(i)

Mark scheme

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

Question 7

2016 ▪ Q7

A student is given a 25.0 mL sample of a solution of an unknown monoprotic acid and asked to determine the concentration of the acid by titration. The student uses a standardized solution of 0.110 M NaOH(aq), a buret, a flask, an appropriate indicator, and other laboratory equipment necessary for the titration.

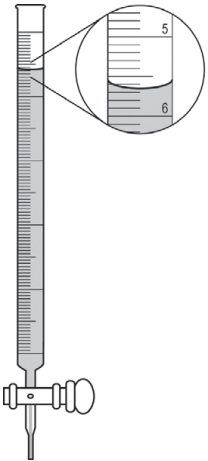
(a) The images below show the buret before the titration begins (below left) and at the end point (below right). What should the student record as the volume of NaOH(aq) delivered to the flask?

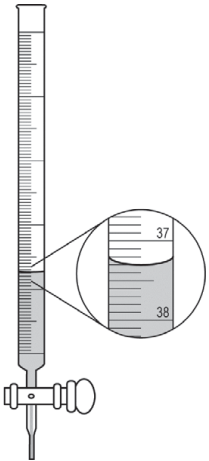
[Diagram: two burets side by side, each with a magnified circular inset showing the meniscus reading. Left buret (before titration): the magnified inset shows graduation marks labeled 5 (above) and 6 (below), with the liquid meniscus sitting between them, closer to the 6 mark (approximately 5.8 mL). Right buret (at end point): the

Question 7

magnified inset shows graduation marks labeled 37 (above) and 38 (below), with the liquid meniscus sitting between them, closer to the 38 mark (approximately 37.7 mL).]

Question 7





Question 7

2016 ▪ Q7

A student is given a 25.0 mL sample of a solution of an unknown monoprotic acid and asked to determine the concentration of the acid by titration. The student uses a standardized solution of 0.110 M NaOH(aq), a buret, a flask, an appropriate indicator, and other laboratory equipment necessary for the titration.

(b) Based on the given information and your answer to part (a), determine the value of the concentration of the acid that should be recorded in the student's lab report.

Question 7

2016 ▪ Q7

A student is given a 25.0 mL sample of a solution of an unknown monoprotic acid and asked to determine the concentration of the acid by titration. The student uses a standardized solution of 0.110 M NaOH(aq), a buret, a flask, an appropriate indicator, and other laboratory equipment necessary for the titration.

(c) In a second trial, the student accidentally added more NaOH(aq) to the flask than was needed to reach the end point, and then recorded the final volume. Would this error increase, decrease, or have no effect on the calculated acid concentration for the second trial? Justify your answer.

Solution 7

(a)

Mark scheme

- Volume of NaOH(aq) delivered = final buret reading − initial buret reading = 37.30 mL − 5.65 mL = 31.65 mL. 1 point for the correct delivered volume (≈31.65 mL, based on the two meniscus readings).

Solution 7

(b)

Mark scheme

- At the equivalence point, moles OH− added = moles H+ consumed (HA is monoprotic): Ma = (Mb × Vb) / Va = (0.110 M)(0.03165 L) / (0.0250 L) = 0.139 M. 1 point for the correct setup and molarity of the acid (≈0.139 M), consistent with the volume found in part (a).

Solution 7

(c)

Mark scheme

- The error would increase the calculated acid concentration. Adding more NaOH(aq) than needed to reach the true equivalence point gives a recorded volume larger than the actual volume needed to neutralize the acid; since the calculation assumes moles of acid = moles of base delivered, the larger (erroneous) volume of base leads to a calculated moles of base — and thus a calculated acid concentration — greater than the true value. 1 point for correctly indicating an increase, 1 point for a valid justification.

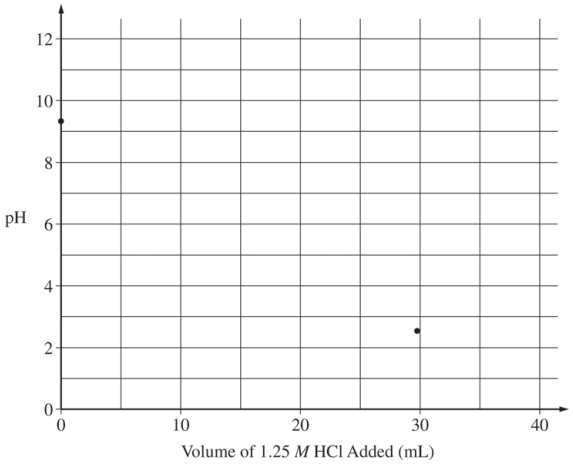
Question 3

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).

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 *M* CH_3CH_2COOH is 2.79.

(a) Identify a Brønsted-Lowry conjugate acid-base pair in the reaction. Clearly label which is the acid and which is the base.

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 *M* CH_3CH_2COOH is 2.79.

(b) Determine the value of K_a for propanoic acid at 25°C.

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 *M* CH_3CH_2COOH is 2.79.

(c)(i) For each of the following statements, determine whether the statement is true or false. In each case, explain the reasoning that supports your answer.

The pH of a solution prepared by mixing the 50.0 mL sample of 0.20 *M* CH_3CH_2COOH with a 50.0 mL sample of 0.20 *M* NaOH is 7.00.

(c)(ii) For each of the following statements, determine whether the statement is true or false. In each case, explain the reasoning that supports your answer.

Question 2

If the pH of a hydrochloric acid solution is the same as the pH of a propanoic acid solution, then the molar concentration of the hydrochloric acid solution must be less than the molar concentration of the propanoic acid solution.

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 *M* CH_3CH_2COOH is 2.79.

(d) A student is given the task of determining the concentration of a propanoic acid solution of unknown concentration. A 0.173 *M* NaOH solution is available to use as the titrant. The student uses a 25.00 mL volumetric pipet to deliver the propanoic acid solution to a clean, dry flask. After adding an appropriate indicator to the flask, the student titrates the solution with the 0.173 *M* NaOH, reaching the end point after 20.52 mL of the base solution has been added.

Calculate the molarity of the propanoic acid solution.

Question 2

2014 ▪ Q2

$$CH_3CH_2COOH(aq) + H_2O(l) \rightleftharpoons CH_3CH_2COO^-(aq) + H_3O^+(aq)$$

Propanoic acid, CH_3CH_2COOH, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 M CH_3CH_2COOH is 2.79.

(e) The student is asked to redesign the experiment to determine the concentration of a butanoic acid solution instead of a propanoic acid solution. For butanoic acid the value of pK_a is 4.83. The student claims that a different indicator will be required to determine the equivalence point of the titration accurately. Based on your response to part (b), do you agree with the student's claim? Justify your answer.

Solution 2

(a)

Mark scheme

- A valid Brønsted-Lowry conjugate acid-base pair: CH_3CH_2COOH (acid) and $CH_3CH_2COO^-$ (base); OR equivalently H_3O^+ (acid) and H_2O (base). Credit requires clearly labeling which species is the acid and which is the base.

Solution 2

(b) Mark scheme

- $[H_3O^+] = 10^{-pH} = 10^{-2.79} = 1.6 \times 10^{-3}$ *M* (1 point for solving for [H3O+]). Set up the Ka expression with $[CH_3CH_2COO^-] = [H_3O^+]$ and $[CH_3CH_2COOH] = 0.20 - [H_3O^+] \approx 0.20$ *M*: $K_a = \frac{[CH_3CH_2COO^-][H_3O^+]}{[CH_3CH_2COOH]}$ (1 point for the correct Ka expression or correct substitution). Solving: $K_a = \frac{(1.6 \times 10^{-3})^2}{0.20} = 1.3 \times 10^{-5}$ (1 point for the correct numeric Ka value).

Solution 2

(c)(i)

Mark scheme

- False. The conjugate base CH3CH2COO- formed at equivalence undergoes hydrolysis, $CH_3CH_2COO^- + H_2O \rightleftharpoons CH_3CH_2COOH + OH^-$, giving a solution with pH > 7, not exactly 7.00.

Solution 2

(c)(ii)

Mark scheme

- True. HCl is a strong acid that ionizes completely, so fewer moles of HCl are needed to produce the same [H3O+] (and hence the same pH) as the propanoic acid solution, which only partially ionizes; therefore the HCl solution's molar concentration must be less than the propanoic acid solution's.

Solution 2

(d)

Mark scheme

- At the equivalence point, moles acid = moles base delivered. Moles NaOH = 0.02052 L $\times$ 0.173 mol/L $= 3.55 \times 10^{-3}$ mol = moles propanoic acid (1 point for correctly finding moles of acid that reacted). Molarity of acid = 3.55×10^{-3} mol / 0.02500 L = 0.142 M (1 point for the correct molarity). Equivalent method: since the acid is monoprotic, $M_A V_A = M_B V_B \Rightarrow M_A = (0.173\ M)(20.52\ \text{mL})/(25.00\ \text{mL}) = 0.142\ M$.

Solution 2

(e)

Mark scheme

- Disagree with the student's claim (1 point for disagreeing with a valid justification). From part (b), pKa for propanoic acid $= -\log(1.3 \times 10^{-5}) = 4.89$. Because butanoic acid's pKa (4.83) is so close to propanoic acid's pKa (4.89), the pH at the equivalence point of the butanoic acid titration should be close enough to that of the propanoic acid titration that the original indicator remains appropriate (1 point for numerically comparing the two pKa, Ka, or equivalence-point pH values).