Past-paper walk-through

Acid-Base Titrations ▪ 8.5

eXercise

Questions in this set

- 2026 Q3
- 2025 Q2
- 2024 Q1
- 2022 Q1
- 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

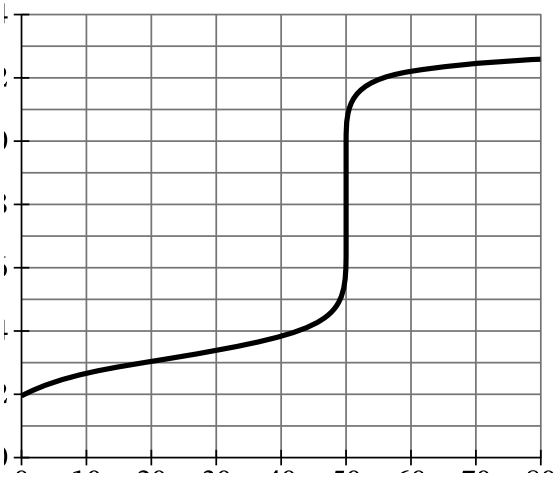
Chemical Equation	Equilibrium Constant
$HNO_2(aq) + H_2O(l) \rightleftarrows NO_2^-(aq) + H_3O^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$H_2O(l) + H_2O(l) \rightleftarrows H_3O^+(aq) + OH^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$HNO_2(aq) + OH^-(aq) \rightarrow NO_2^-(aq) + H_2O(l)$	$K_2 =$?

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

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.

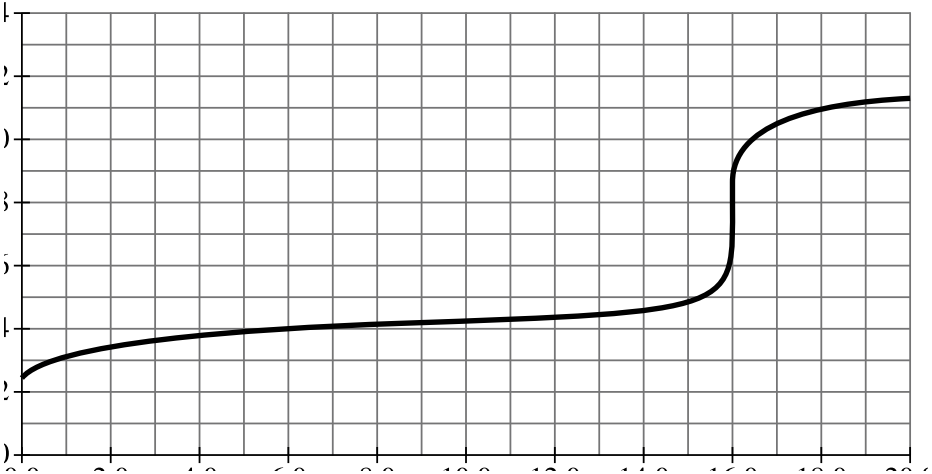
Question 2

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 1

2024 ▪ Q1

$$C_3H_6O_3(aq) + NaOH(aq) \rightarrow NaC_3H_5O_3(aq) + H_2O(l)$$

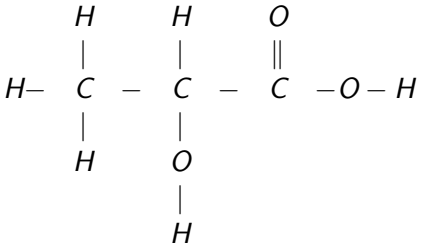
1. A student is studying the reaction between lactic acid, $C_3H_6O_3$, and sodium hydroxide, NaOH, as represented in the balanced equation above.

(a) The structural formula of lactic acid is shown in the following diagram. Circle the hydrogen atom that most readily participates in the chemical reaction with sodium hydroxide.

[Structural (Lewis) formula of lactic acid: a chain H—C—C—C(=O)—O—H, drawn as: Top row: H, H, O(double bond) The first carbon bears an H above, an H below, and a bond to the second carbon. The second carbon bears an OH group below it (O bonded down to an H). The third carbon is a carbonyl carbon (C=O, double bond to

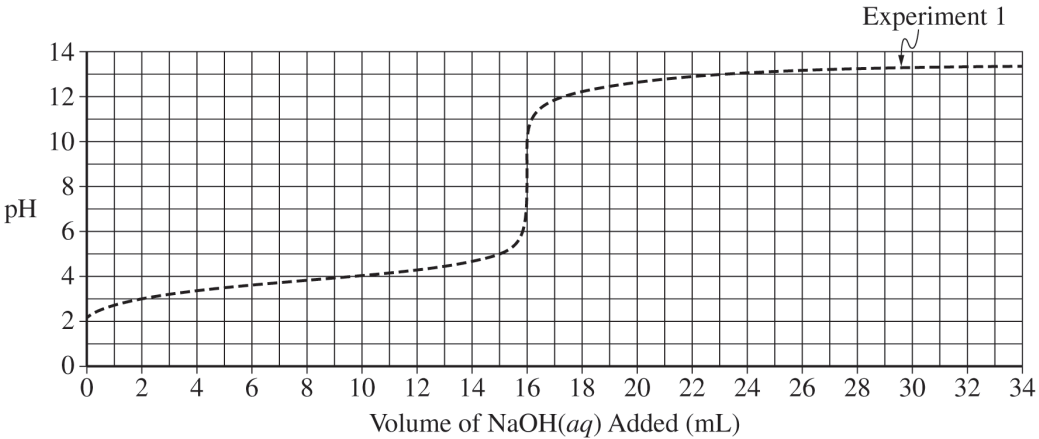
Question 1

O above) bonded to an —O—H (single-bonded hydroxyl oxygen then H) on the right. Full skeleton:

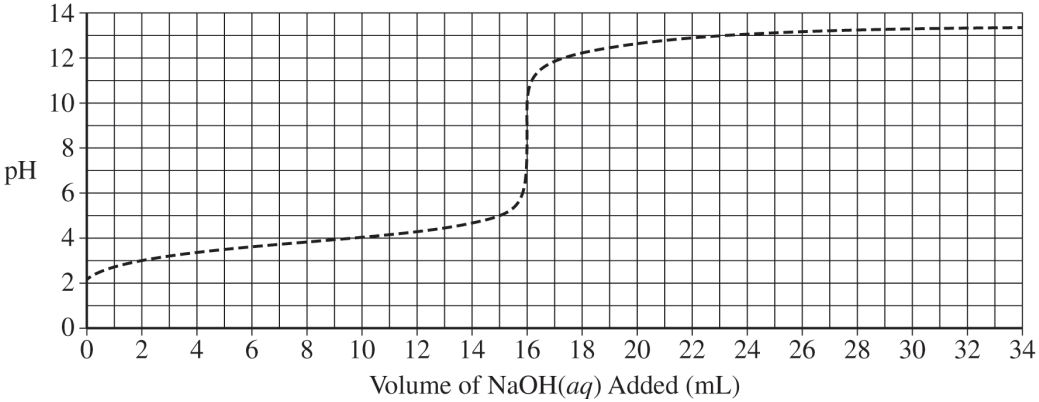


The hydrogen to circle is the one on the hydroxyl oxygen attached to the carbonyl carbon (the carboxylic acid —C(=O)—O—H proton).]

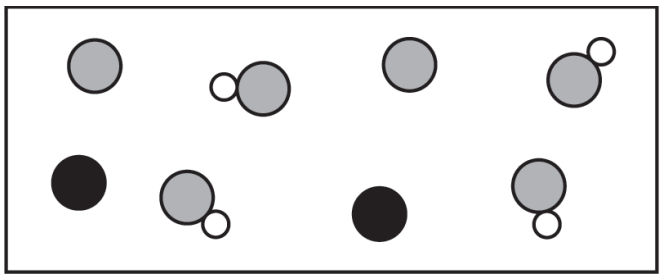
Question 1

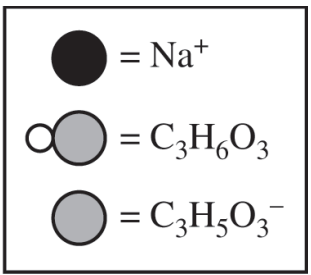

Experiment 1
pH
14
12
10
8
6
4
2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
Volume of NaOH(aq) Added (mL)

Question 1


pH
14
12
10
8
6
4
2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
Volume of NaOH(aq) Added (mL)

Question 1





Question 1

2024 ▪ Q1

$$C_3H_6O_3(aq) + NaOH(aq) \rightarrow NaC_3H_5O_3(aq) + H_2O(l)$$

1. A student is studying the reaction between lactic acid, $C_3H_6O_3$, and sodium hydroxide, NaOH, as represented in the balanced equation above.

(b) The student begins the experiment by dissolving 10.22 g of sodium hydroxide (molar mass 40.00 g/mol) in enough water to produce 500. mL of solution. Calculate the molarity of the sodium hydroxide solution.

Question 1

2024 ▪ Q1

$$C_3H_6O_3(aq) + NaOH(aq) \rightarrow NaC_3H_5O_3(aq) + H_2O(l)$$

1. A student is studying the reaction between lactic acid, $C_3H_6O_3$, and sodium hydroxide, NaOH, as represented in the balanced equation above.

(c) The student uses the sodium hydroxide solution from part (b), a buret, a pH meter, and a 100 mL Erlenmeyer flask to titrate a 25.0 mL sample of lactic acid. The student's data are shown in the following graph.

[Graph: titration curve of pH vs. Volume of NaOH(aq) Added (mL); x-axis 0 to 34 mL in increments of 2, y-axis pH 0 to 14 in increments of 2. Curve starts near pH 2-3 at V=0, rises slowly/gradually (buffer region) from about V=2 to V=14, then shows a

Question 1

steep equivalence-point jump between about V=15 and V=17 (pH rising sharply from about 4 to about 11-12), then levels off and rises slowly to about pH 13 by V=34.]
Use the information in the graph to determine the approximate pK_a of lactic acid.

_____

Question 1

2024 ▪ Q1

$$C_3H_6O_3(aq) + NaOH(aq) \rightarrow NaC_3H_5O_3(aq) + H_2O(l)$$

1. A student is studying the reaction between lactic acid, $C_3H_6O_3$, and sodium hydroxide, NaOH, as represented in the balanced equation above.

(d)(i) [Particle diagram box showing the relative amounts of major species in a sample of the solution in the flask at one point during the titration. Water molecules are omitted. Key: solid black circle = Na^+; circle half-white/half-gray (with a small white circle attached) = $C_3H_6O_3$; circle half-black/half-gray (with a small white circle attached) = $C_3H_5O_3^-$. The box contains 2 large gray/white two-tone circles (labeled as $C_3H_6O_3$-type), 2 large gray/black two-tone circles (labeled as $C_3H_5O_3^-$-type), and 2

Question 1

small solid black circles (Na^+), with small white circles attached to some of the larger circles.]

The preceding diagram represents the relative amounts of major species in a sample of the solution in the flask at one point during the titration. (Note that water molecules are omitted.)

Draw an X on the preceding titration curve at a point in the titration where the reaction mixture would be represented by this diagram.

(d)(ii) Justify your answer.

Question 1

2024 ▪ Q1

$$C_3H_6O_3(aq) + NaOH(aq) \rightarrow NaC_3H_5O_3(aq) + H_2O(l)$$

1. A student is studying the reaction between lactic acid, $C_3H_6O_3$, and sodium hydroxide, NaOH, as represented in the balanced equation above.

(e) The following table shows two experiments:

Experiment	**Mass of NaOH(s) (grams)**	**Volume of Solution (mL)**	**Titration Curve**
1	10.22	500.	Already shown on graph
2	20.44	500.	?

Question 1

The student repeats the experiment but uses a solution of NaOH(*aq*) with twice the concentration, as shown in the preceding table. On the following graph, draw the titration curve that would be expected for experiment 2.
[Blank graph titled "Experiment 1" with a faint curve of Experiment 1 shown as reference (pH vs. Volume of NaOH(aq) Added (mL), x-axis 0 to 34 mL, y-axis pH 0 to 14); student draws the Experiment 2 curve on the same axes.]

Question 1

2024 ▪ Q1

$$C_3H_6O_3(aq) + NaOH(aq) \rightarrow NaC_3H_5O_3(aq) + H_2O(l)$$

1. A student is studying the reaction between lactic acid, $C_3H_6O_3$, and sodium hydroxide, NaOH, as represented in the balanced equation above.

(f) In a third experiment, the student investigates the enthalpy of the reaction between lactic acid and sodium hydroxide. The student combines 100.0 mL of a 0.500 *M* lactic acid solution at 20.0°C with 100.0 mL of a 0.500 *M* NaOH solution at 20.0°C in a calorimeter. The final temperature of the resulting combined solution is 23.2°C. Assume the density of each solution before combining is 1.00 g/mL and that the specific heat capacity of the combined solution is 4.2 J/(g · °C).

Calculate the quantity of heat produced in the reaction, in J.

Question 1

(f)(ii) Calculate the molar enthalpy of reaction, in kJ/mol$_{rxn}$. Include the sign in your answer.

(f)(iii) The student claims that if heat is lost from the calorimeter to the surrounding air during the reaction, then the experimental value of the molar enthalpy of reaction will be smaller in magnitude than the actual value. Do you agree or disagree with the student's claim? Justify your answer.

Solution 1

(a)

Mark scheme

- Circle the rightmost hydrogen atom — the acidic O–H proton on the carboxylic acid group ($-\mathrm{C}(=\mathrm{O})-\mathrm{O}-\mathrm{H}$). This H is the most acidic (bonded to O, adjacent to the electron-withdrawing carbonyl) and is the one that reacts with NaOH in the acid–base neutralization.

Solution 1

(b)

Mark scheme

- Molarity $= \dfrac{(10.22\ \text{g})\left(\dfrac{1\ \text{mol}}{40.00\ \text{g}}\right)}{0.500\ \text{L}} = 0.511\ M.$

Solution 1

(c)

Mark scheme

- pK_a = 3.9 (acceptable range: 3.7–4.0), read as the pH at the half-equivalence point of the titration curve (where pH = pK_a).

Solution 1

(d)(i)

Mark scheme

- The particle diagram shows more lactic acid (HA) particles than lactate (A^-) particles present in solution at that point during the titration. The X should be placed on the titration curve (from part c) at a volume ≥ 3 mL and < 8 mL — i.e., before the half-equivalence point, consistent with acid predominating over conjugate base at that point.

Solution 1

(d)(ii)

Mark scheme

- Justification: more acid (HA) particles are present than conjugate base (A^-) particles, meaning the titration is before the half-equivalence point (where $[HA] = [A^-]$).

Solution 1

(e) Mark scheme

- Draw the titration curve expected for Experiment 2 (NaOH solution with twice the concentration titrating the same lactic acid sample). Two criteria are scored: (1) Equivalence point — doubling the NaOH concentration means HALF the volume is needed to deliver the same moles of base, so the new equivalence point should be at 8 mL (half of Experiment 1's 16 mL equivalence volume), NOT at 16 mL. (2) Shape — the drawn curve should begin at the same initial pH as Experiment 1's curve, rise gradually through a buffer region, rise sharply at a volume different from 16 mL (i.e., near 8 mL), and end (plateau) at a final pH similar to Experiment 1's curve.

Solution 1

(f)

Mark scheme

- $q = mc\Delta T = (200.0\ \text{g})(4.2\ \text{J/(g} \cdot {}^\circ\text{C}))(23.2{}^\circ\text{C} - 20.0{}^\circ\text{C}) = 2700\ \text{J}$ (heat absorbed by the combined solution).

Solution 1

(f)(ii)

Mark scheme

- $q_{rxn} = -q_{soln} = -2700\ \text{J} = -2.7\ \text{kJ}$.
  $\Delta H_{rxn} = \dfrac{q_{rxn}}{\text{mol}} = \dfrac{-2.7\ \text{kJ}}{(0.100\ \text{L})(0.500\ \text{mol/L})} = -54\ \text{kJ/mol}_{rxn}$. (Sign must be included: negative, exothermic.)

Solution 1

(f)(iii)

Mark scheme

- Agree. Heat lost from the system to the surroundings would result in a lower final (measured) temperature, which produces smaller measured values of ΔT, q_{soln}, and thus $|\Delta H_{rxn}|$ than the true (actual) value — so the experimental molar enthalpy will be smaller in magnitude than the actual value.

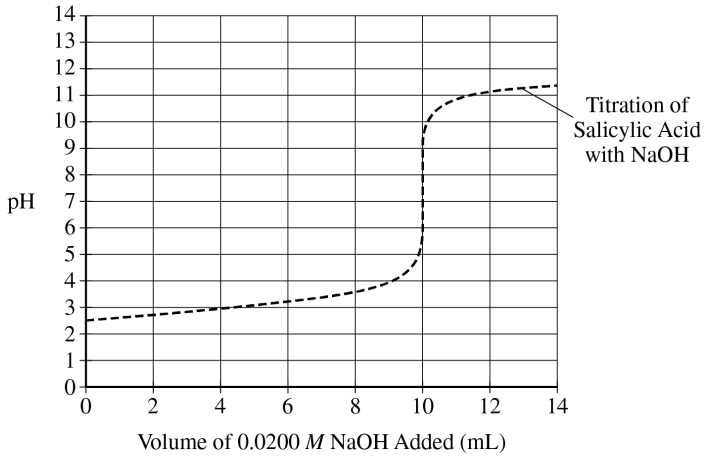
Question 1

2022 ▪ Q1

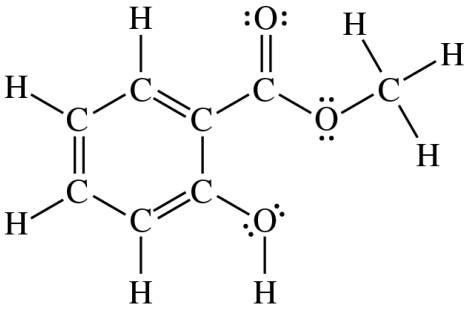
A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

(a) For every 1 mole of $C_8H_8O_3$ (molar mass 152.15 g/mol) reactant used, 1 mole of salicylic acid crystals ($HC_7H_5O_3$, molar mass 138.12 g/mol) is produced. Calculate the maximum mass, in grams, of $HC_7H_5O_3$ that could be produced in this reaction.

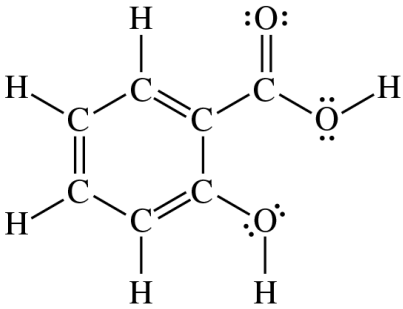
Question 1


14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
pH
0
2
4
6
8
10
12
14
Volume of 0.0200 *M* NaOH Added (mL)
Titration of
Salicylic Acid
with NaOH

Question 1

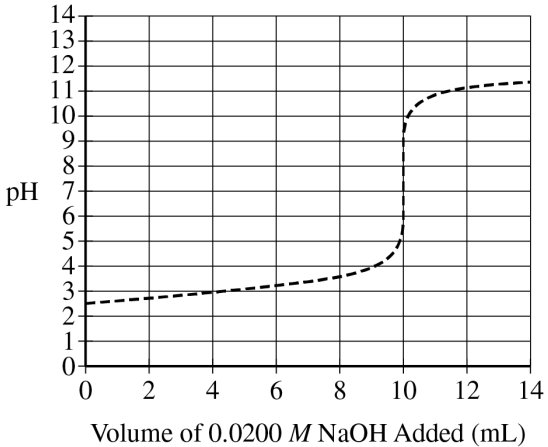


Methyl Salicylate
Melting Point: –9°C



Salicylic Acid
Melting Point: 159°C

Question 1


pH
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
14
Volume of 0.0200 *M* NaOH Added (mL)

Question 1

2022 ▪ Q1

A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

(b) As part of the experimental procedure to purify the $HC_7H_5O_3$ crystals after the reaction is complete, the crystals are filtered from the reaction mixture, rinsed with distilled water, and dried. Some physical properties of $HC_7H_5O_3$ are given in the following table.

Properties of Salicylic Acid ($HC_7H_5O_3$)	
Melting point	159°C
Solubility in H_2O at 25°C	2.2 g/L
Specific heat capacity	1.17 J/(g · °C)
Heat of fusion	27.1 kJ/mol

The student's experiment results in an 87

Question 1

2022 ▪ Q1

A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

(c) Given the physical properties in the table, calculate the quantity of heat that must be absorbed to increase the temperature of a 0.105 g sample of dry $HC_7H_5O_3$ (molar mass 138.12 g/mol) crystals from $25°C$ to the melting point $159°C$ and melt the crystals completely.

Question 1

2022 ▪ Q1

A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

(d) The structures and melting points for methyl salicylate and salicylic acid are shown.

[Two skeletal/Lewis structural formulas of benzene-ring compounds are shown side by side, drawn with explicit H atoms and lone pairs. Left: Methyl Salicylate, Melting Point: $-9°C$ — a benzene ring with an ester group $-C(=O)-O-CH_3$ and an adjacent $-O-H$ hydroxyl group on the ring. Right: Salicylic Acid, Melting Point: $159°C$ — the same benzene ring but with a carboxylic acid group $-C(=O)-O-H$ and the adjacent $-O-H$ hydroxyl group on the ring.]

The same three types of intermolecular forces (London dispersion forces, dipole-dipole interactions, and hydrogen bonding) exist among molecules of each substance. Explain why the melting point of salicylic acid is higher than that of methyl salicylate.

Question 1

The student titrates 20.0 mL of 0.0100 *M* $HC_7H_5O_3(aq)$ with 0.0200 *M* NaOH, using a probe to monitor the pH of the solution. The data are plotted producing the following titration curve.

[Titration curve graph: x-axis "Volume of 0.0200 M NaOH Added (mL)" from 0 to 14; y-axis "pH" from 0 to 14. The curve starts near pH 2-3 at 0 mL, rises gradually and gently through the buffer region, then shows a steep equivalence-point jump at approximately 10 mL (rising from about pH 7 to pH 11), then levels off near pH 12-13 as more NaOH is added.]

Question 1

2022 ▪ Q1

A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

(e) Using the information in the graph, estimate the pK_a of $HC_7H_5O_3$.

Question 1

2022 ▪ Q1

A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

(f) When the pH of the titration mixture is 4.00, is there a higher concentration of the weak acid, $HC_7H_5O_3$, or its conjugate base, $C_7H_5O_3^-$, in the flask? Justify your answer.

Question 1

2022 ▪ Q1

A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

(g) The student researches benzoic acid ($HC_7H_5O_2$) and finds that it has similar properties to salicylic acid ($HC_7H_5O_3$). The K_a for benzoic acid is 6.3×10^{-5}. Calculate the value of pK_a for benzoic acid.

Question 1

2022 ▪ Q1

A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

(h) The student performs a second titration, this time titrating 20.0 mL of a 0.0100 *M* benzoic acid solution with 0.0200 *M* NaOH. Sketch the curve that would result from this titration of benzoic acid on the following graph, which already shows the original curve from the titration of 20.0 mL of 0.0100 *M* salicylic acid. The initial pH of the benzoic acid solution is 3.11.

[A second copy of the titration curve graph, titled "Titration of Salicylic Acid with NaOH," showing the same original salicylic-acid curve as in part (d) (x-axis "Volume of 0.0200 M NaOH Added (mL)" from 0 to 14; y-axis "pH" from 0 to 14; gradual rise from about pH 2-3 through a buffer region, then a steep jump near 10 mL up to about

Question 1

pH 11, leveling off near pH 12-13), onto which the student is to sketch the new benzoic-acid titration curve.]

Solution 1

(a)

Mark scheme

- Maximum mass of HC7H5O3: 0.300 g C8H8O3 × (1 mol C8H8O3 / 152.15 g) × (1 mol HC7H5O3 / 1 mol C8H8O3) × (138.12 g / 1 mol HC7H5O3) = 0.272 g HC7H5O3.

Solution 1

(b)

Mark scheme

- Yes (consistent). Because the acid is soluble in water, some crystals may dissolve during rinsing, causing the mass of the collected precipitate to be lower than expected. This would lead to a percent yield less than 100%.

Solution 1

(c)

Mark scheme

- q_heat $= mc\Delta T = (0.105\ \text{g})(1.17\ \text{J/(g} \cdot \text{°C))(159°C} - 25°\text{C}) = 16.5\ \text{J}$ (1 point for either q value). q_melt $= 0.105\ \text{g} \times (1\ \text{mol} / 138.12\ \text{g}) \times (27{,}100\ \text{J} / 1\ \text{mol}) = 20.6\ \text{J}$ (1 point for the other q value and the total). q_total $=$ q_heat $+$ q_melt $= 16.5\ \text{J} + 20.6\ \text{J} = 37.1\ \text{J}$.

Solution 1

(d)

Mark scheme

- Molecules of salicylic acid have more hydrogen bonding sites than molecules of methyl salicylate have, which leads to stronger intermolecular forces and a higher melting point for salicylic acid.

Solution 1

(e)

Mark scheme

- The pKa is approximately 3, estimated from the titration curve graph at the half-equivalence point.

Solution 1

(f)

Mark scheme

- The conjugate base, $C_7H_5O_3^-$, is present at higher concentration. Justification (either accepted): at pH = 4.00 the titration is beyond the half-equivalence point, where $[HC_7H_5O_3] = [C_7H_5O_3^-]$; thus $[C_7H_5O_3^-]$ must be greater than $[HC_7H_5O_3]$. OR: because the pH of the solution is greater than the pKa of the acid, the majority of the molecules will be deprotonated.

Solution 1

(g)

Mark scheme

- $\text{pKa} = -\log(6.3 \times 10^{-5}) = 4.20$.

Solution 1

(h)

Mark scheme

- Sketch of the benzoic acid titration curve (consistent with part (g)): (1 point) the curve starts at pH $\approx$ 3.11 (the given initial pH) and passes through its pKa (4.20, from part (g)) at the half-equivalence volume of 5 mL. (1 point) the curve inflects vertically at 10 mL, showing the same volume of NaOH needed to reach the equivalence point as the original salicylic acid curve, since both are 20.0 mL of 0.0100 M acid titrated with the same 0.0200 M NaOH.

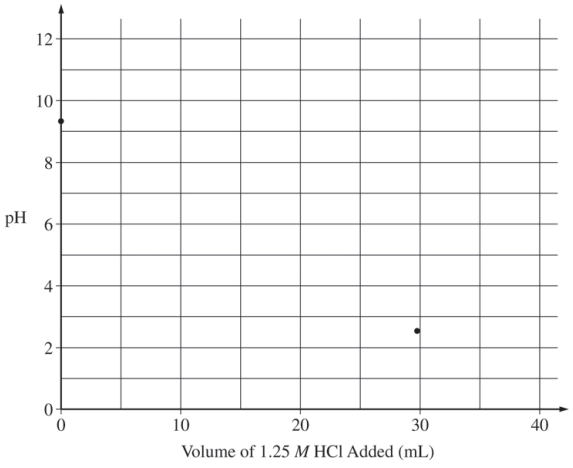
Question 3

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).