Past-paper walk-through

Acid-Base Reactions and Buffers ▪ 8.4

eXercise

Questions in this set

- 2025 Q2
- 2023 Q4
- 2022 Q1
- 2021 Q1
- 2019 Q3
- 2018 Q2
- 2017 Q3
- 2016 Q2
- 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 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.

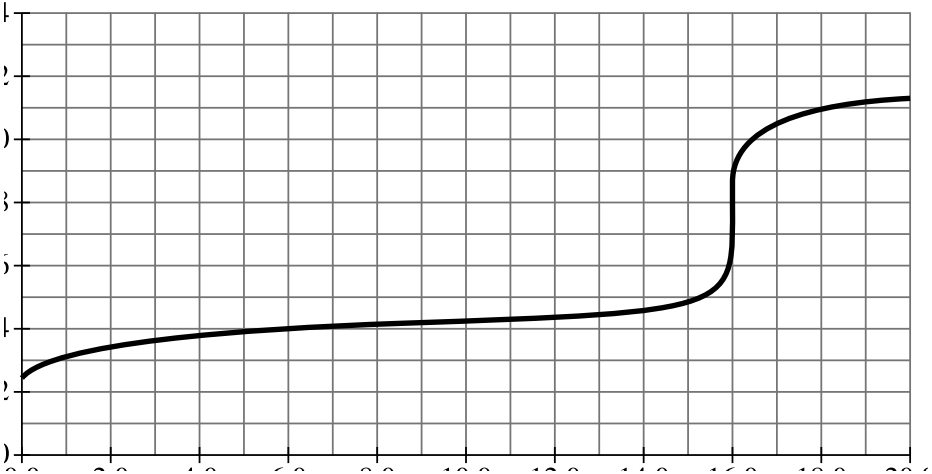
Question 2

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 4

2023 ▪ Q4

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

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

Question 4

2023 ▪ Q4

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

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

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

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

Question 4

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

Question 4

2023 ▪ Q4

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

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

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

Solution 4

(a)

Mark scheme

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

Solution 4

(b)

Mark scheme

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

Solution 4

(c)

Mark scheme

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

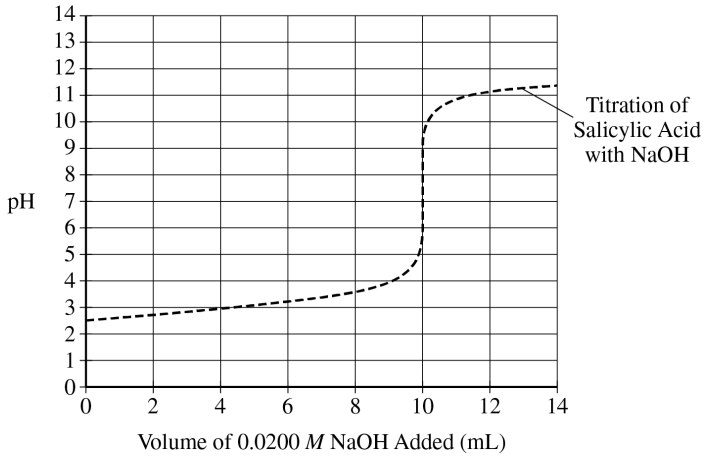
Question 1

2022 ▪ Q1

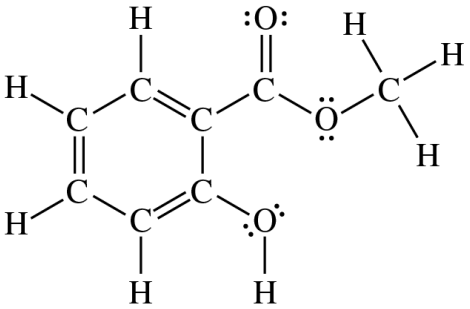
A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

(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.

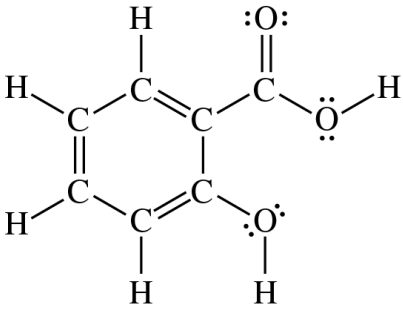
Question 1


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

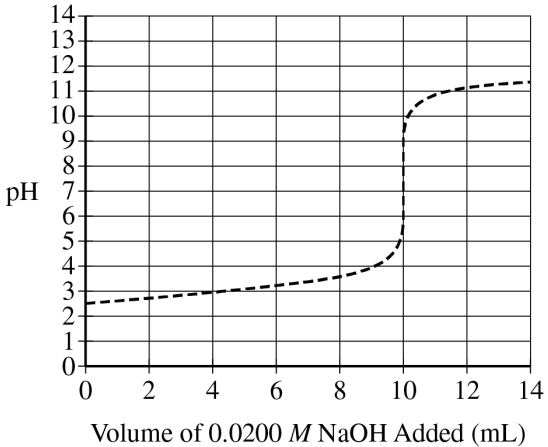


Methyl Salicylate
Melting Point: –9°C



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

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

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 1

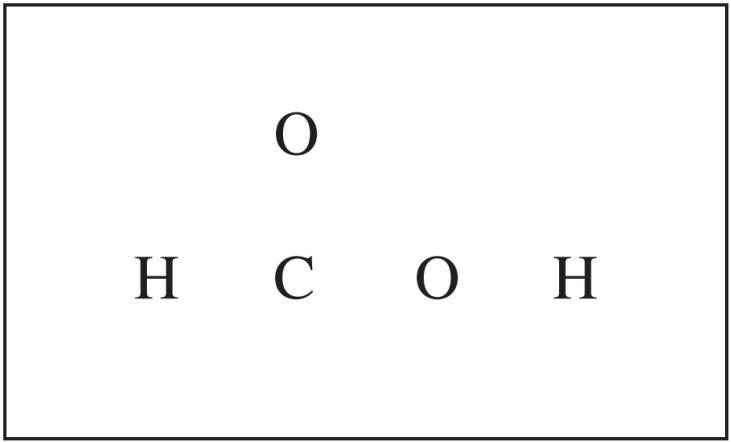
2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

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

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

Question 1



Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

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

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

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

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

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

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

```
        O
        |
H - C - O - H
```

Question 1

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

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

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

(d)(i)

$$H_2NNH_2(aq) + H_2O(l) \rightleftharpoons H_2NNH_3^+(aq) + OH^-(aq) \qquad K_b = 1.3 \times 10^{-6}$$

In aqueous solution, the compound H_2NNH_2 reacts according to the equation above. A 50.0 mL sample of 0.25 *M* $H_2NNH_2(aq)$ is combined with a 50.0 mL sample of 0.25 *M* $HCOOH(aq)$.

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

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

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

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

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

$$HCOOH(aq) \rightarrow H_2(g) + CO_2(g)$$

Is the reaction a redox reaction? Justify your answer.

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

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

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

The reaction occurs in a rigid 4.3 L vessel at 25°C, and the total pressure is monitored, as shown in the graph above. The vessel originally did not contain any gas. Calculate the number of moles of $CO_2(g)$ produced in the reaction. (Assume that the amount of $CO_2(g)$ dissolved in the solution is negligible.)

Question 1

2021 ▪ Q1

$$HCOOH(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + HCOO^-(aq) \qquad K_a = 1.8 \times 10^{-4}$$

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

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

Solution 1

(a)

Mark scheme

- $K_a = \dfrac{[H_3O^+][HCOO^-]}{[HCOOH]}$ — the correct equilibrium-constant expression for the dissociation of HCOOH (products over reactant; water omitted as pure liquid).

Solution 1

(b)

Mark scheme

- ICE table for HCOOH + H2O H3O+ + HCOO-, initial [HCOOH]=0.25 M: $K_a = 1.8 \times 10^{-4} = \dfrac{x^2}{0.25 - x}$. Assuming $x \ll 0.25$: $x^2 = (1.8 \times 10^{-4})(0.25) \Rightarrow x = [\mathrm{H_3O^+}] = 0.0067$ *M* (1 pt). Then $\mathrm{pH} = -\log[\mathrm{H_3O^+}] = -\log(0.0067) = 2.17$ (1 pt, consistent with the calculated concentration).

Solution 1

(c)

Mark scheme

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

Solution 1

(d)(i)

Mark scheme

- $H_2NNH_2(aq) + HCOOH(aq) \rightarrow H_2NNH_3^+(aq) + HCOO^-(aq)$ — the weak base H2NNH2 accepts a proton from the weak acid HCOOH; already balanced as written (state symbols not required).

Solution 1

(d)(ii)

Mark scheme

- Acidic. The resulting solution is a mixture of the conjugate acid H2NNH3+ and the conjugate base HCOO-. Because the K_a of $H_2NNH_3^+$ is greater than the K_b of $HCOO^-$, production of $H_3O^+(aq)$ occurs to a greater extent than production of $OH^-(aq)$, so the solution is acidic.

Solution 1

(e)

Mark scheme

- Yes, it is a redox reaction. Accept either valid justification: the oxidation number of hydrogen changes from $+1$ in HCOOH to 0 in H2 (reduction); or the oxidation number of carbon changes from $+2$ in HCOOH to $+4$ in CO2 (oxidation).

Solution 1

(f) Mark scheme

- Reaction HCOOH(aq) $\rightarrow$ H2(g) + CO2(g) produces H2 and CO2 in a 1:1 mole ratio, so each contributes half the total pressure: $P_{CO_2} = 24 \text{ atm} \times \frac{1 \text{ atm } CO_2}{2 \text{ atm product}} = 12 \text{ atm}$ (1 pt, may be implicit). Then using the ideal gas law $PV = nRT$ with V=4.3 L, T=298 K: $n = \frac{PV}{RT} = \frac{(12 \text{ atm})(4.3 \text{ L})}{(0.08206 \text{ L} \cdot \text{atm} \cdot \text{mol}^{-1}\text{K}^{-1})(298 \text{ K})} = 2.1 \text{ mol } CO_2$ (1 pt).

Solution 1

(g)

Mark scheme

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

Question 3

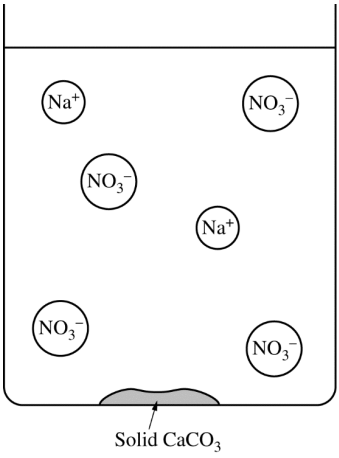
2019 ▪ Q3

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

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

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

Question 3



Question 3

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

Question 3

2019 ▪ Q3

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

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

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

Question 3

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

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

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

Question 3

2019 ▪ Q3

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

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

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

Question 3

2019 ▪ Q3

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

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

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

Question 3

2019 ▪ Q3

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

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

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

Question 3

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

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

Question 3

2019 ▪ Q3

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

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

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

Question 3

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

Question 3

2019 ▪ Q3

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

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

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

Question 3

2019 ▪ Q3

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

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

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

Solution 3

(a)

Mark scheme

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

Solution 3

(b)

Mark scheme

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

Solution 3

(c)

Mark scheme

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

Solution 3

(d)

Mark scheme

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

Solution 3

(e)

Mark scheme

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

Solution 3

(f)(i)

Mark scheme

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

Solution 3

(f)(ii)

Mark scheme

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

Solution 3

(g)

Mark scheme

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

Solution 3

(h)

Mark scheme

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

Question 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.

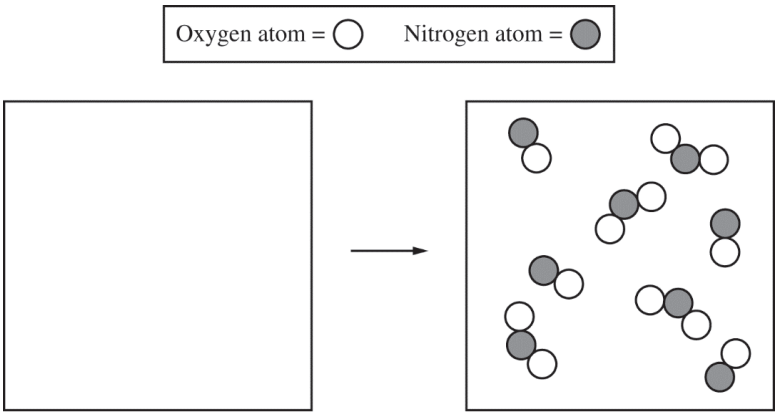
Question 2

[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.

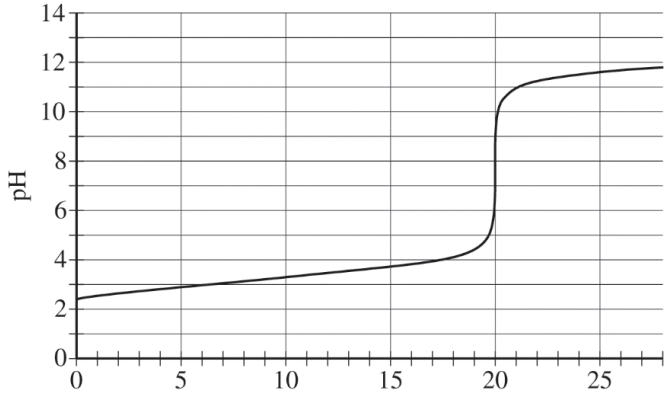
$$NO(g) + NO_2(g) \rightleftharpoons N_2O_3(g)$$

| 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

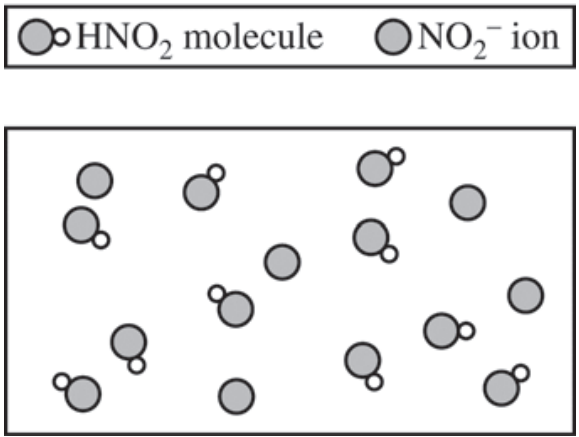
2017 ▪ Q3

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

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

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

Question 3



Question 3

2017 ▪ Q3

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

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

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

Question 3

2017 ▪ Q3

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

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

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

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

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

Question 3

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

Question 3

2017 ▪ Q3

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

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

(d) A second student makes a buffer by dissolving 0.100 mol of $NaNO_2(s)$ in 100. mL of 1.00 *M* $HNO_2(aq)$. Which is more resistant to changes in pH when a strong acid or a strong base is added, the buffer made by the second student or the buffer made by the first student in part (c) ? Justify your answer.

Question 3

2017 ▪ Q3

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

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

(e) A new buffer is made using $HNO_2(aq)$ as one of the ingredients. A particulate representation of a small representative portion of the buffer solution is shown below. (Cations and water molecules are not shown.) Is the pH of the buffer represented in the diagram greater than, less than, or equal to 3.40 ? Justify your answer.

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

Question 3

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

Solution 3

(a)

Mark scheme

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

Solution 3

(b)

Mark scheme

- ICE table (atm): Initial N2 = 6.01, O2 = 1.61, NO = 0; Change -x, -x, +2x; Equilibrium 6.01-x, 1.61-x, 0.122. Since 2x = 0.122 atm, x = 0.0610 atm, so at equilibrium P_N2 = 5.95 atm and P_O2 = 1.55 atm. Kp = (0.122)^2 / [(5.95)(1.55)] = 0.00161. 1 point earned for the correct equilibrium partial pressures of reactants and products (may be implicit); 1 point earned for the correct calculation of Kp.

Solution 3

(c)(i)

Mark scheme

- NaOH will neutralize some of the HNO2 to produce NO2-. The resulting solution contains a mixture of a weak acid (HNO2) and its conjugate base (NO2-), which is a buffer solution. Net ionic equation: HNO2 + OH- -> NO2- + H2O. 1 point earned for the recognition that the solution produced is a mixture of a weak acid and its conjugate base; 1 point earned for the correct net ionic equation.

Solution 3

(c)(ii)

Mark scheme

- The student should add 50.0 mL of 0.100 M NaOH(aq). Using the Henderson-Hasselbalch equation, pH = pKa + log([NO2-]/[HNO2]), so pH = pKa exactly when [HNO2] = [NO2-]; since the target pH (3.40) equals pKa, a 1-to-1 ratio of HNO2 to NO2- is required, i.e. half of the 10.0 mmol HNO2 (100. mL x 0.100 M) must be converted, which needs 5.00 mmol NaOH = 50.0 mL of 0.100 M NaOH. 1 point earned for the correct volume; 1 point earned for clearly indicating a 1-to-1 ratio of HNO2 and NO2- is required (calculation not required for this point).

Solution 3

(d)

Mark scheme

- The buffer made by the second student (0.100 mol NaNO2 dissolved in 100. mL of 1.00 M HNO2) is more resistant to changes in pH, because it contains a higher concentration of HNO2 and NO2- available to react with added H+ or OH- ions (greater buffer capacity) than the buffer from part (c). 1 point earned for the correct choice and a valid justification.

Solution 3

(e)

Mark scheme

- The pH of the solution is less than 3.40. If [HNO2] = [NO2-], pH = pKa and the pH of the solution would be 3.40; since the particulate diagram shows more HNO2 molecules than NO2- ions (i.e. [HNO2] > [NO2-]), the solution has a pH less than 3.40 (equivalently, with the diagram's ratio of about 5 NO2- to 10 HNO2, pH = 3.40 + log(5/10) = 3.10). 1 point earned for the correct choice; 1 point earned for a valid justification.

Question 2

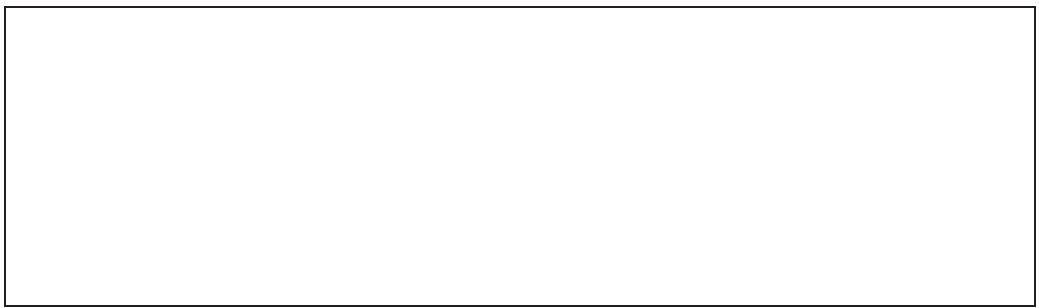
2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(a) Identify the reaction represented above as an acid-base reaction, precipitation reaction, or redox reaction. Justify your answer.

Question 2



Question 2

2016 ▪ Q2

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(b) Based on the information above, identify the limiting reactant. Justify your answer with calculations.

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 *M* $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(c) The student observes that the bubbling is rapid at the beginning of the reaction and gradually slows as the reaction continues. Explain this change in the reaction rate in terms of the collisions between reactant particles.

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 M $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(d)(i) In thermodynamic terms, a reaction can be driven by enthalpy, entropy, or both. Considering that the flask gets cooler as the reaction proceeds, what drives the chemical reaction between $NaHCO_3(s)$ and $HC_2H_3O_2(aq)$? Answer by drawing a circle around one of the choices below.

Enthalpy only Entropy only Both enthalpy and entropy

(d)(ii) Justify your selection in part (d)(i) in terms of ΔG°.

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 *M* $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(e) The HCO_3^- ion has three carbon-to-oxygen bonds. Two of the carbon-to-oxygen bonds have the same length and the third carbon-to-oxygen bond is longer than the other two. The hydrogen atom is bonded to one of the oxygen atoms. In the box below, draw a Lewis electron-dot diagram (or diagrams) for the HCO_3^- ion that is (are) consistent with the given information.

[Empty box provided for the student to draw the Lewis electron-dot diagram(s).]

Question 2

2016 ▪ Q2

$$NaHCO_3(s) + HC_2H_3O_2(aq) \rightarrow NaC_2H_3O_2(aq) + H_2O(l) + CO_2(g)$$

A student designs an experiment to study the reaction between $NaHCO_3$ and $HC_2H_3O_2$. The reaction is represented by the equation above. The student places 2.24 g of $NaHCO_3$ in a flask and adds 60.0 mL of 0.875 *M* $HC_2H_3O_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

(f) A student prepares a solution containing equimolar amounts of $HC_2H_3O_2$ and $NaC_2H_3O_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 *M* $HNO_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $HNO_3(aq)$ and the chemical species in the sample that is responsible for the pH remaining at 4.7.

Solution 2

(a)

Mark scheme

- It is an acid-base reaction: the weak acid HC2H3O2 reacts with the weak base HCO3−, with HC2H3O2 donating a proton. (Equivalently: no solid precipitates, so it is not a precipitation reaction; no oxidation numbers change, so it is not a redox reaction.) 1 point for identifying the reaction as acid-base, 1 point for a valid justification.

Solution 2

(b)

Mark scheme

- 2.24 g $NaHCO_3$ × (1 mol / 84.0 g) = 0.0267 mol $NaHCO_3$. 60.0 mL × (0.875 mol $HC_2H_3O_2$ / 1000 mL) = 0.0525 mol $HC_2H_3O_2$. $NaHCO_3$(s) and $HC_2H_3O_2$(aq) react in a 1:1 ratio, so the smaller mole amount, $NaHCO_3$(s), is the limiting reactant. 1 point for calculating the number of moles of each reactant, 1 point for correctly identifying $NaHCO_3$ as the limiting reactant, consistent with the calculation.

Solution 2

(c)

Mark scheme

- As the reaction proceeds, both reactants are consumed and their concentrations decrease; collisions between reactant particles become less frequent as concentrations decrease, so the reaction rate slows. 1 point for a valid explanation in terms of collision frequency between reactant particles.

Solution 2

(d)(i)

Mark scheme

- 'Entropy only' should be circled. Because the flask gets cooler as the reaction proceeds, the reaction is endothermic and cannot be driven by a favorable enthalpy change — it must be driven by entropy. 1 point for circling 'Entropy only'.

Solution 2

(d)(ii)

Mark scheme

- $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$; a reaction is thermodynamically favorable when ΔG° is negative. Since the reaction is endothermic (flask gets cooler, ΔH° is positive), enthalpy does not help make ΔG° negative, so the reaction is not driven by enthalpy. Because the reactants contain no gas while one product (CO_2) is a gas, ΔS° must be positive, which helps make ΔG° negative — so the reaction is entropy-driven. 1 point for a valid justification referencing the signs of ΔH°, ΔS°, and ΔG°.

Solution 2

(e) Mark scheme

- A correct Lewis structure for HCO3− has a central C bonded to three O atoms: one C=O double bond, one C−O single bond to an O bearing three lone pairs (charge −1 on that O), and one C−O single bond to the O−H oxygen (two lone pairs on that O), with the H attached to that same oxygen. Because two C-to-O bonds are equal length and the third (C−OH) is longer, resonance exists between the two equivalent non-OH oxygens — shown either as two resonance structures or as one structure with a double-headed resonance arrow between those two oxygens. 1 point for a correct Lewis structure of HCO3−, 1 point for indicating resonance between the two equivalent (non-OH) oxygens.

Solution 2

(f)

Mark scheme

- C2H3O2− + H3O+ → HC2H3O2 + H2O (equivalently: C2H3O2− + H+ → HC2H3O2). 1 point for a correct, balanced net-ionic equation showing the acetate ion neutralizing the added H3O+/H+, which is why the pH remains at 4.7 (buffer action).

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).