Past-paper walk-through

Introduction to Enthalpy of Reaction ▪ 6.6

eXercise

Questions in this set

- 2026 Q1
- 2026 Q7
- 2025 Q3
- 2024 Q1
- 2023 Q3
- 2018 Q1

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 1

2026 ▪ Q1

A student performs a calorimetry experiment with KCl.
(a)(i) Consider the K^+ ion in KCl.
Write the complete ground-state electron configuration for the potassium ion, K^+.
(a)(ii) Which has the larger radius, the K^+ ion or the K atom? **Explain** your reasoning using principles of atomic structure.

Question 1

Mass of water	97.5 g
Mass of $KCl\,(s)$	6.80 g
Initial temperature of water	24.5°C
Final temperature of solution	21.1°C

Question 1

2026 ▪ Q1

A student performs a calorimetry experiment with KCl.

(b) The following information applies to parts B, C, D, and E.

A student performs an experiment to determine the enthalpy of solution, ΔH_{soln}, of KCl. The student places water in a calorimeter, measures the initial temperature, adds KCl(s), and stirs until the KCl dissolves completely. The temperature is continuously monitored during the experiment. Data from the experiment are given in the following table.

Quantity	Value
Mass of water	97.5 g
Mass of KCl (s)	6.80 g
Initial temperature of water	$24.5°C$
Final temperature of solution	$21.1°C$

Describe how the student can use the temperature readings during the experiment to determine when the dissolution is complete.

Question 1

2026 ▪ Q1

A student performs a calorimetry experiment with KCl.

(c)(i) Use the data in the table to do the following.

Calculate the magnitude of the thermal energy, q, in joules, transferred during the dissolution. Show the work that leads to your answer. (Assume that the solution has a specific heat capacity of 3.95 J/(g · °C).)

(c)(ii) **Calculate** the value of the molar enthalpy of solution, ΔH_{soln}, in kJ/mol, for KCl given that 0.0912 mol of KCl dissolved. Show the work that leads to your answer. Include the sign with your answer.

Question 1

2026 ▪ Q1

A student performs a calorimetry experiment with KCl.

(d) The calorimeter is not perfectly insulated. Would this cause the magnitude of ΔH_{soln} calculated in part C (ii) to be greater than, less than, or equal to the accepted value? **Justify** your answer.

Question 1

2026 ▪ Q1

A student performs a calorimetry experiment with KCl.

(e) The student performs a second experiment using the same mass of water but 6.80 g of RbCl(s) instead of 6.80 g of KCl(s). The magnitude of the molar enthalpy of solution, ΔH_{soln}, of RbCl is approximately equal to that of KCl.
Is the magnitude of ΔT in the RbCl experiment greater than, less than, or equal to that in the KCl experiment? **Justify** your answer. (Assume that the specific heat capacities of the solutions are equal.)

Question 1

2026 ▪ Q1

A student performs a calorimetry experiment with KCl.

(f)(i) RbCl has a K_{sp} of 57 at $20°C$.

Write the net ionic equation for the dissolution of RbCl in pure water.

(f)(ii) **Calculate** the molar solubility of RbCl in a saturated solution at $20°C$. Show the work that leads to your answer.

(f)(iii) A second saturated solution is prepared by dissolving RbCl(s) in 1.0 M KCl(aq) at $20°C$ instead of in pure water. Will the molar solubility of RbCl in 1.0 M KCl(aq) be greater than, less than, or equal to the molar solubility calculated in part F (ii)? **Justify** your answer.

Question 7

2026 ▪ Q7

The following information applies to parts A and B.
Sodium metal reacts with oxygen gas according to Equation 1.

$$\text{Equation 1: } 4\,\mathrm{Na}(s) + \mathrm{O_2}(g) \rightarrow 2\,\mathrm{Na_2O}(s) \qquad \Delta H^{\circ}{}_{rxn} = -828 \text{ kJ/mol}_{rxn}$$

Standard enthalpies of formation are provided in Table 1.

Substance	$\Delta H^{\circ}{}_{f}$ (kJ/mol)
$Na(s)$	0
$O_2(g)$	0
$Na_2O(s)$	?

(a) Based on the information given, **calculate** the value of $\Delta H^{\circ}{}_{f}$ for $Na_2O(s)$. Show the work that leads to your answer.

(b) An 18.4 g sample of $Na(s)$ reacts with 12.8 g of $O_2(g)$ according to Equation 1. **Calculate** the total amount of heat, in kilojoules, released during this process. Show the work that leads to your answer.

Question 7

(c) Lattice enthalpy can be defined as the energy required to separate an ionic crystal into gaseous ions. $Rb_2O(s)$ and $Na_2O(s)$ have similar crystal structures, and their lattice enthalpies are given in Table 2.

Compound	Lattice Enthalpy (kJ/mol)
$Na_2O(s)$	2481
$Rb_2O(s)$	2163

Using Coulomb's law, **explain** why the lattice enthalpy of $Rb_2O(s)$ is smaller than that of $Na_2O(s)$.

Question 7

Table 2

Compound	Lattice Enthalpy (kJ/mol)
$Na_2O\,(s)$	2481
$Rb_2O\,(s)$	2163

Question 7

Table 1

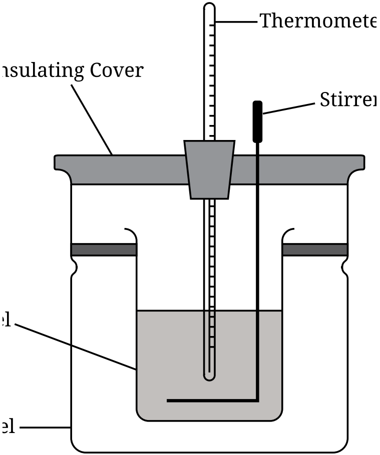
Substance	ΔH°_f (kJ/mol)
$Na\,(s)$	0
$O_2\,(g)$	0
$Na_2O\,(s)$	?

Question 3

2025 ▪ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.
[Left: a ball-and-stick tetrahedral structure of P_4, showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]
[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]
(a) In the box in part A, complete the Lewis diagram for P_4 by drawing the nonbonding electrons.

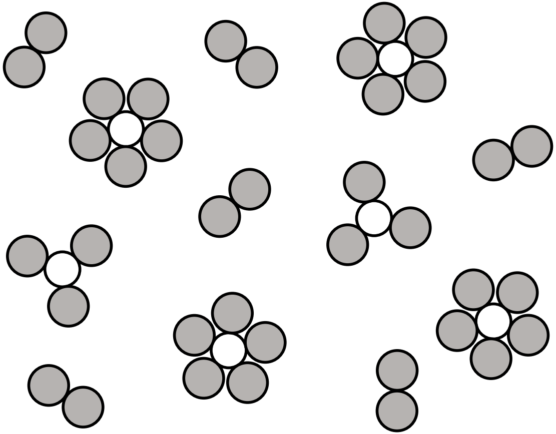
Question 3



Question 3

Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	$22.00°$ C
Final temperature	$22.38°$ C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g·°C)

Question 3



Question 3

2025 ▪ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4, showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]

(b) The reaction of white phosphorus with oxygen to form $P_4O_{10}(s)$ is thermodynamically favorable at 298 K. The reaction is represented by equation 1.

Equation 1: $P_4(s) + 5\,O_2(g) \rightarrow P_4O_{10}(s)$

Question 3

(b)(i) The entropy change of the reaction, ΔS°, is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.
(b)(ii) The enthalpy change of the reaction, ΔH°, is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** by entropy. Is the student's claim correct? Justify your answer by using the relationship between ΔG°, ΔH°, and ΔS°.

Question 3

2025 ▪ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4, showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]

(c) $P_4O_{10}(s)$ reacts exothermically with water to form phosphoric acid, as represented by equation 2.

Equation 2: $P_4O_{10}(s) + 6\,H_2O(l) \rightarrow 4\,H_3PO_4(aq)$

Question 3

A chemist uses a calorimetry experiment to determine the enthalpy change for the reaction, as represented by the following diagram.
[Calorimeter diagram: a coffee-cup-style calorimeter labeled "Thermometer" (inserted through the insulating cover), "Stirrer" (inserted alongside the thermometer), "Insulating Cover" (the lid), "Inner Vessel" (the cup holding the solution, shaded), and "Outer Vessel" (the outer supporting cup).]
The chemist carries out the calorimetry experiment and records the following information.

Quantity	Value
Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	$22.00°$C
Final temperature	$22.38°$C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g $\cdot °$ C)

(c)(i) Calculate the amount of heat, q, released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.

Question 3

(c)(ii) Calculate the value of ΔH°_{rxn} for equation 2 in kJ/mol$_{rxn}$. Include the sign in your answer.

Question 3

2025 ▪ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4, showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]

(d) The chemist weighed out 0.100 g P_4O_{10} of and 100.0 g of H_2O to perform a second trial. In the second trial, some of the solid P_4O_{10} stuck to the weighing paper and was not transferred to the calorimeter. Given that P_4O_{10} is the limiting reactant,

Question 3

would ΔT for the second trial be greater than, less than, or equal to the value in the first trial? Justify your answer.

$P_4(s)$ also reacts readily with $Cl_2(g)$ to produce phosphorus trichloride, $PCl_3(g)$, which in turn reacts with $Cl_2(g)$ in an equilibrium process to produce $PCl_5(g)$. The reactions are represented by equations 3 and 4.

Equation 3: $P_4(s) + 6\,Cl_2(g) \rightarrow 4\,PCl_3(g)$ $\quad \Delta H_1^\circ = -1148$ kJ/mol$_{rxn}$

Equation 4: $PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$ $\quad \Delta H_2^\circ = -88$ kJ/mol$_{rxn}$

Question 3

2025 ▪ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.
[Left: a ball-and-stick tetrahedral structure of P_4, showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]

(e) Calculate the standard enthalpy of formation of $PCl_5(g)$ represented by equation 5.

Equation 5: $\frac{1}{4}P_4(s) + \frac{5}{2}Cl_2(g) \rightarrow PCl_5(g) \qquad \Delta H_f^\circ = ?$

The following particle-level diagram represents the contents of the vessel in an equilibrium mixture at 546 K involving equation 4.

Question 3

[Particle diagram: a box containing multiple particles at random positions representing an equilibrium mixture; a key indicates two-atom particles (grey-grey) = Cl_2, four-atom tetrahedral-looking particles (grey with three white) = PCl_3, and six-atom particles (grey with five white) = PCl_5. The box shows several Cl_2 particles (pairs of grey circles), several PCl_3 particles (grey center with three white circles), and several PCl_5 particles (grey center with five white circles) scattered throughout.]

Question 3

2025 ▪ Q3

White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

[Left: a ball-and-stick tetrahedral structure of P_4, showing four P atoms (spheres) at the vertices of a tetrahedron connected by bonds (sticks).]

[Right: an incomplete Lewis diagram showing four P atoms arranged in a tetrahedral projection (one P at top, one P in the middle/front, two P at the bottom left and right), connected by single bonds forming the P4 skeleton, with no lone pairs drawn yet.]

(f) Equation 4 for the reaction that occurs is shown.

Equation 4: $PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g) \qquad \Delta H_2^\circ = -88$ kJ/mol$_{rxn}$

(f)(i) If each particle in the diagram represents a partial pressure of 1.00 atm, what is the value of K_p for the equilibrium mixture at 546 K?

Question 3

(f)(ii) Does the value of K_p increase, decrease, or remain the same when the temperature is increased to 596 K? Justify your answer based on ΔH_2°.

Solution 3

(a)

Mark scheme

- Complete Lewis diagram for P_4: the four P atoms form a tetrahedron, each bonded to the other three P atoms by single bonds, and each P atom bears one lone (nonbonding) pair of electrons — giving each P three bonding pairs plus one lone pair, satisfying the octet rule.

Solution 3

(b)

Mark scheme

- No separate response required — this is the context/stem presenting equation 1 ($P_4(s) + 5\,O_2(g) \rightarrow P_4O_{10}(s)$), thermodynamically favorable at 298 K, that parts (i) and (ii) below refer to.

(b)(i)

Mark scheme

- Because gas particles are more dispersed (have more accessible microstates) than solids, the entropy decreases as the reactants (which include a gas, O_2) convert into the solid product (P_4O_{10}).

Solution 3

(b)(ii)

Mark scheme

- Yes, the student's claim is correct. Given $\Delta G^\circ_{rxn} = \Delta H^\circ_{rxn} - T\Delta S^\circ_{rxn}$, the reaction must have $\Delta G^\circ_{rxn} < 0$ to be favorable. Because the reaction is exothermic, $\Delta H^\circ_{rxn} < 0$ and enthalpy contributes to favorability. $\Delta S^\circ_{rxn} < 0$, so entropy does NOT contribute to favorability — i.e., enthalpy alone drives it.

Solution 3

(c)

Mark scheme

- No separate response required — this is the context/stem describing the calorimetry experiment for the exothermic reaction of $P_4O_{10}(s)$ with water (equation 2: $P_4O_{10}(s) + 6\,H_2O(l) \rightarrow 4\,H_3PO_4(aq)$) that parts (i) and (ii) below use.

Solution 3

(c)(i)

Mark scheme

- $q = mc\Delta T = (100.1\ \text{g})(4.18\ \text{J}/(\text{g}\cdot{}^\circ\text{C}))(22.38^\circ\text{C} - 22.00^\circ\text{C}) = 160\ \text{J} = 0.16\ \text{kJ}$ (reported to the correct number of significant figures).

Solution 3

(c)(ii)

Mark scheme

- $q_{rxn} = -q_{surr} = -0.16$ kJ.
  $$\Delta H^\circ_{rxn} = \frac{-0.16\ \text{kJ}}{0.100\ \text{g}\ P_4O_{10}} \times \frac{283.9\ \text{g}\ P_4O_{10}}{1\ \text{mol}\ P_4O_{10}} \times \frac{1\ \text{mol}\ P_4O_{10}}{1\ \text{mol}_{rxn}} = -450\ \text{kJ/mol}_{rxn}.$$
  The correct (negative) sign must be included.

Solution 3

(d)

Mark scheme

- Less than. If less P_4O_{10} is present (some stuck to the weighing paper), less thermal energy will be transferred to the water during the reaction, causing the temperature increase (ΔT) to be less than it was with the full 0.100 g of P_4O_{10}.

Solution 3

(e)

Mark scheme

- Using Hess's law:
  $$\Delta H^\circ_{f,\mathrm{PCl_5}(g)} = \frac{1}{4}\Delta H^\circ_1 + \Delta H^\circ_2 = \frac{1}{4}(-1148) + (-88) = -375\ \text{kJ/mol}.$$

Solution 3

(f)

Mark scheme

- No separate response required — this is the context/stem presenting equation 4 ($PCl_3(g) + Cl_2(g) \rightleftharpoons PCl_5(g)$, $\Delta H_2^\circ = -88$ kJ/mol$_{rxn}$) that parts (i) and (ii) below refer to.

Solution 3

(f)(i)

Mark scheme

- Reading partial pressures of 1.00 atm per particle from the diagram (4 PCl_5, 2 PCl_3, 6 Cl_2 particles): $K_p = \dfrac{P_{PCl_5}}{(P_{PCl_3})(P_{Cl_2})} = \dfrac{4.00}{(2.00)(6.00)} = \dfrac{1}{3} = 0.333.$

Solution 3

(f)(ii)

Mark scheme

- Decrease. The negative value of ΔH_2° indicates the reaction is exothermic. Because exothermic reactions favor reactant formation at higher temperature (the equilibrium shifts toward reactants as heat is added), the value of K_p decreases.

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

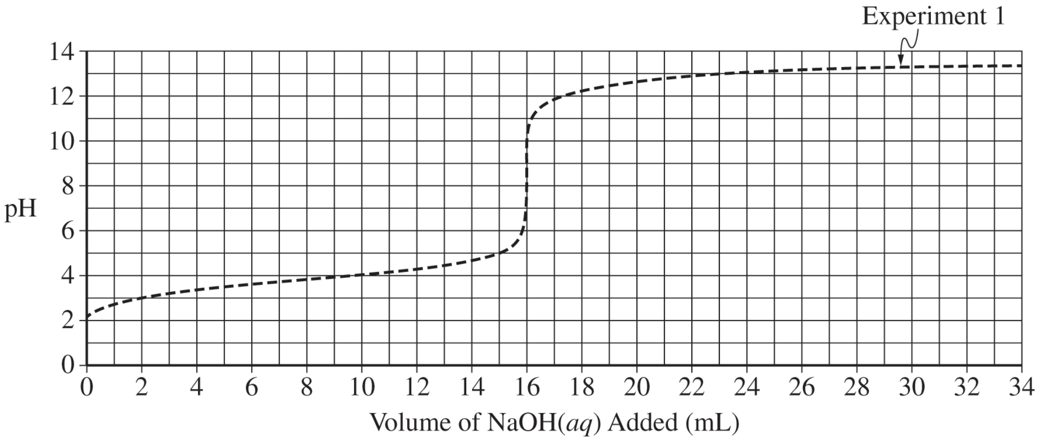
Question 1

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

$$\begin{array}{ccccccc}
 & H & & H & & O & \\
 & | & & | & & \| & \\
H- & C & - & C & - & C & -O-H \\
 & | & & | & & & \\
 & H & & O & & & \\
 & & & | & & & \\
 & & & H & & &
\end{array}$$

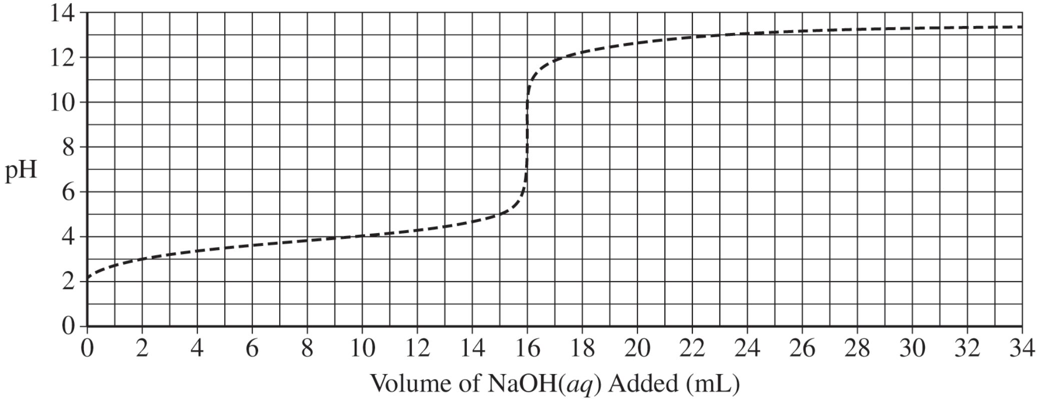
The hydrogen to circle is the one on the hydroxyl oxygen attached to the carbonyl carbon (the carboxylic acid —C(=O)—O—H proton).]

Question 1



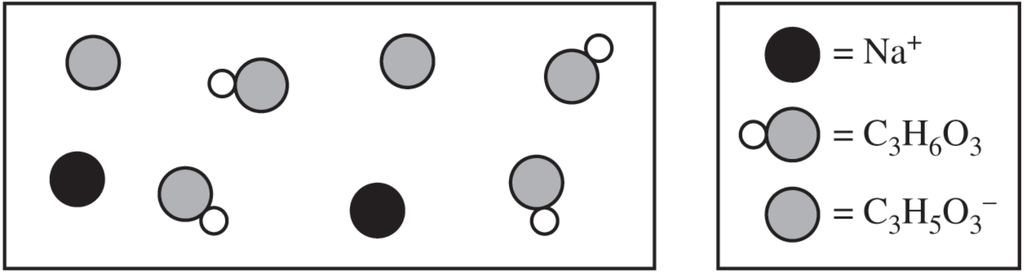
Experiment 1
pH
14
12
10
8
6
4
2
0
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34
Volume of NaOH(*aq*) Added (mL)

Question 1



14
12
10
8
6
4
2
0
pH
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 $(-C(=O)-O-H)$. 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

- $q = mc\Delta T = (200.0\ \text{g})(4.2\ \text{J}/(\text{g} \cdot {}^\circ\text{C}))(23.2^\circ\text{C} - 20.0^\circ\text{C}) = 2700\ \text{J}$ (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 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(a) Write the balanced net ionic equation for the reaction.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(b) A student performs an investigation to study factors that affect the rate of the reaction. In each trial the student combines 50.0 mL of $HCl(aq)$ at $21.2°C$ with 1.00 g of $CaCO_3(s)$ and measures the time required for the reaction to go to completion. The data are given in the following table.
| Trial | Concentration of $HCl(aq)$ (M) | Particle Size of $CaCO_3(s)$ | Time of Reaction (s) | |—|—|—|—| | 1 | 1.00 | Fine powder | 67 | | 2 | 1.00 | Small chunks | 112 | | 3 |

Question 3

1.00 | Large chunk | 342 | | 4 | 3.00 | Fine powder | 22 | | 5 | 3.00 | Small chunks | 227 | | 6 | 3.00 | Large chunk | 114 |

The student correctly identifies that trial 5 is inconsistent with the other trials. Explain why the student's claim is correct using the data in the table.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(c) Based on the reaction conditions and the collisions that occur between particles, explain the reason for the difference in the reaction times for trial 2 and trial 3.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(d) The student claims that the reaction is zero order with respect to $HCl(aq)$. Do you agree or disagree with the student's claim? Justify your answer using the student's data.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(e) The $HCl(aq)$ was present in excess in all trials of the experiment. Determine the molarity of the $HCl(aq)$ in the beaker after the reaction is complete in trial 2. Assume that the volume of the mixture remains constant at 50.0 mL throughout the trial. (The molar mass of $CaCO_3$ is 100.09 g/mol.)

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(f)

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

In order to measure the enthalpy of the reaction shown, the student repeats trial 1 by mixing 50.0 mL of $HCl(aq)$ with 1.00 g of $CaCO_3(s)$ using a coffee cup calorimeter. The student records the temperature of the system every 20 seconds. The data are given in the following table.

Question 3

Time (s)	Measured Temperature of Solution (°C)
0	21.20
20	21.51
40	21.70
60	21.85
80	21.90
100	21.90

Is the reaction endothermic or exothermic? Justify your answer using the information in the table.

Question 3

2023 ▪ Q3

Answer the following questions about an experiment in which $CaCO_3(s)$ is combined with $HCl(aq)$, represented by the following balanced equation.

$$CaCO_3(s) + 2\,HCl(aq) \rightarrow CaCl_2(aq) + CO_2(g) + H_2O(l)$$

(g)(i) Based on the experimental data, the mass of the system is 51.0 g, and the specific heat of the reaction mixture is 4.0 J/(g · °C).
Calculate the magnitude of heat transfer, *q*, in joules.
(g)(ii) Calculate the enthalpy of reaction in units of kJ/mol_{rxn}. Include the algebraic sign on your answer.

Solution 3

(a)

Mark scheme

- Balanced net ionic equation:
  $CaCO_3(s) + 2\,H^+(aq) \rightarrow Ca^{2+}(aq) + CO_2(g) + H_2O(l)$ (equivalently with hydronium: $CaCO_3(s) + 2\,H_3O^+(aq) \rightarrow Ca^{2+}(aq) + CO_2(g) + 3\,H_2O(l)$).
  State symbols not required.

Solution 3

(b)

Mark scheme

- Accept either explanation: (1) Even though [HCl] is greater in trial 5 than trial 2, the reaction time is significantly longer; trials 2 and 5 are otherwise identical, and the trend from trials 1 and 4 shows that a higher [HCl] gives a shorter reaction time, so concentration alone cannot explain trial 5 — particle size must be the cause. (2) The reaction time in trial 5 (small chunks) is longer than in trial 6 (large chunks), even though trials 5 and 6 are otherwise identical; the trend from trials 1, 2, and 3 shows that larger chunks of solid give a longer reaction time.

Solution 3

(c)

Mark scheme

- The reaction time in trial 2 is shorter than in trial 3 because the calcium carbonate in trial 2 has a larger surface area, meaning more $CaCO_3$ particles are exposed to H^+ particles in solution (1 point). A larger interface between the two reacting substances means more particle collisions occur per unit time, giving a higher frequency of successful collisions in which particles react to form products, i.e. a higher reaction rate (1 point).

Solution 3

(d)

Mark scheme

- Disagree. Accept either justification: (1) If the reaction were zeroth order with respect to HCl, changing [HCl] would not affect the reaction rate, so reaction time would be the same for trials differing only in [HCl] — but the data for trials 1 and 4 (and likewise 3 and 6) show that changing [HCl] significantly alters the time of reaction. (2) The reaction appears first order, not zeroth order, with respect to [HCl]: tripling [HCl] results in a reaction time that is $1/3$ of that when $[\mathrm{HCl}] = 1.00$ M, meaning the rate has also tripled, indicating a first-order process.

Solution 3

(e) Mark scheme

- Moles of HCl reacted: $1.00 \text{ g CaCO}_3 \times \dfrac{1 \text{ mol}}{100.09 \text{ g}} = 0.00999 \text{ mol CaCO}_3$; $0.00999 \text{ mol CaCO}_3 \times \dfrac{2 \text{ mol HCl}}{1 \text{ mol CaCO}_3} = 0.0200 \text{ mol HCl}$ reacted (1 point). Remaining [HCl]: initial HCl $= 0.0500 \text{ L} \times 1.00 \text{ mol/L} = 0.0500 \text{ mol}$; $0.0500 - 0.0200 = 0.0300$ mol remaining; $\dfrac{0.0300 \text{ mol}}{0.0500 \text{ L}} = 0.600\ M$ HCl remaining (1 point).

Solution 3

(f)

Mark scheme

- Exothermic. The solution temperature increases as the reaction proceeds (per the calorimeter data), indicating heat is released to the surroundings.

Solution 3

(g)(i)

Mark scheme

- $q_{surr} = mc\Delta T = (51.0\ \text{g})\left(4.0\ \frac{\text{J}}{\text{g}\cdot{}^\circ\text{C}}\right)(21.90^\circ\text{C} - 21.20^\circ\text{C}) = 140\ \text{J}$ (sign not required).

Solution 3

(g)(ii)

Mark scheme

- $q_{sys} = -q_{surr} = -140\ \text{J} = -0.14\ \text{kJ}$; moles reacted $= 1.00\ \text{g CaCO}_3 \times \dfrac{1\ \text{mol CaCO}_3}{100.09\ \text{g CaCO}_3} \times \dfrac{1\ \text{mol}_{rxn}}{1\ \text{mol CaCO}_3} = 0.00999\ \text{mol}_{rxn}$; $\Delta H^\circ_{rxn} = \dfrac{-0.14\ \text{kJ}}{0.00999\ \text{mol}_{rxn}} = -14\ \text{kJ/mol}_{rxn}$ (include the algebraic sign).

Question 1

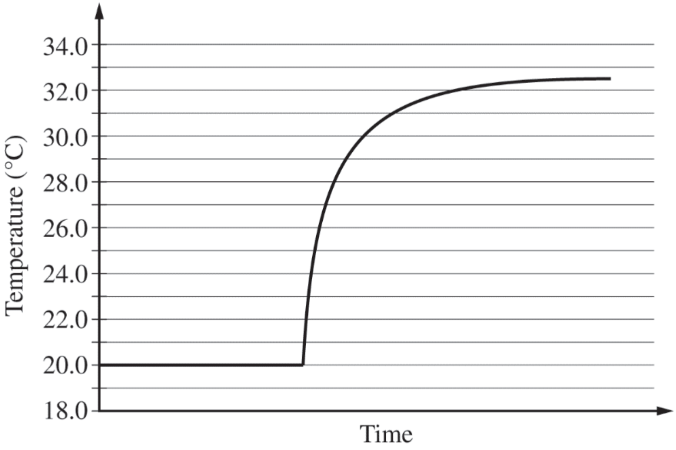
2018 ▪ Q1

$$Na_2S_2O_3(aq) + 4\,NaOCl(aq) + 2\,NaOH(aq) \rightarrow 2\,Na_2SO_4(aq) + 4\,NaCl(aq) + H_2O(l)$$

A student performs an experiment to determine the value of the enthalpy change, ΔH°_{rxn}, for the oxidation-reduction reaction represented by the balanced equation above.

(a) Determine the oxidation number of Cl in NaOCl.

Question 1



Question 1

Solution	Concentration (M)	Volume (mL)
$Na_2S_2O_3(aq)$	0.500	10.0
$NaOCl(aq)$	0.500	10.0
$NaOH(aq)$	0.500	10.0

Question 1

Solution	Concentration (M)	Volume (mL)
$Na_2S_2O_3(aq)$	0.500	5.00
$NaOCl(aq)$	0.500	5.00
$NaOH(aq)$	0.500	5.00

Question 1

2018 ▪ Q1

$$Na_2S_2O_3(aq) + 4\,NaOCl(aq) + 2\,NaOH(aq) \rightarrow 2\,Na_2SO_4(aq) + 4\,NaCl(aq) + H_2O(l)$$

A student performs an experiment to determine the value of the enthalpy change, ΔH°_{rxn}, for the oxidation-reduction reaction represented by the balanced equation above.

(b) Calculate the number of grams of $Na_2S_2O_3$ needed to prepare 100.00 mL of 0.500 *M* $Na_2S_2O_3(aq)$.

In the experiment, the student uses the solutions shown in the table below.

Solution	Concentration (*M*)	Volume (mL)
$Na_2S_2O_3(aq)$	0.500	5.00
$NaOCl(aq)$	0.500	5.00
$NaOH(aq)$	0.500	5.00

Question 1

2018 ▪ Q1

$$Na_2S_2O_3(aq) + 4\,NaOCl(aq) + 2\,NaOH(aq) \rightarrow 2\,Na_2SO_4(aq) + 4\,NaCl(aq) + H_2O(l)$$

A student performs an experiment to determine the value of the enthalpy change, ΔH°_{rxn}, for the oxidation-reduction reaction represented by the balanced equation above.

(c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

The solutions, all originally at 20.0°C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.

[Graph of Temperature (°C) vs. Time. Y-axis: Temperature (°C) from 18.0 to 34.0 in increments of 2.0. X-axis: Time (unlabeled scale). The curve starts flat at about 20.0°C, then rises steeply in an S-shaped curve, leveling off at approximately 32.5°C.]

Question 1

2018 ▪ Q1

$$Na_2S_2O_3(aq) + 4\,NaOCl(aq) + 2\,NaOH(aq) \rightarrow 2\,Na_2SO_4(aq) + 4\,NaCl(aq) + H_2O(l)$$

A student performs an experiment to determine the value of the enthalpy change, ΔH°_{rxn}, for the oxidation-reduction reaction represented by the balanced equation above.

(d) According to the graph, what is the temperature change of the reaction mixture?

Question 1

2018 ▪ Q1

$$Na_2S_2O_3(aq) + 4\,NaOCl(aq) + 2\,NaOH(aq) \rightarrow 2\,Na_2SO_4(aq) + 4\,NaCl(aq) + H_2O(l)$$

A student performs an experiment to determine the value of the enthalpy change, ΔH°_{rxn}, for the oxidation-reduction reaction represented by the balanced equation above.

(e)(i) The mass of the reaction mixture inside the calorimeter is 15.21 g. Calculate the magnitude of the heat energy, in joules, that is released during the reaction. Assume that the specific heat of the reaction mixture is 3.94 $J/(g \cdot {}^\circ C)$ and that the heat absorbed by the calorimeter is negligible.

(e)(ii) Using the balanced equation for the oxidation-reduction reaction and your answer to part (c), calculate the value of the enthalpy change of the reaction, ΔH°_{rxn}, in kJ/mol_{rxn}. Include the appropriate algebraic sign with your answer.

Question 1

The student repeats the experiment, but this time doubling the volume of each of the reactants, as shown in the table below.

Solution	Concentration (M)	Volume (mL)
$Na_2S_2O_3(aq)$	0.500	10.0
$NaOCl(aq)$	0.500	10.0
$NaOH(aq)$	0.500	10.0

Question 1

2018 ▪ Q1

$$Na_2S_2O_3(aq) + 4\,NaOCl(aq) + 2\,NaOH(aq) \rightarrow 2\,Na_2SO_4(aq) + 4\,NaCl(aq) + H_2O(l)$$

A student performs an experiment to determine the value of the enthalpy change, ΔH°_{rxn}, for the oxidation-reduction reaction represented by the balanced equation above.

(f) The magnitude of the enthalpy change, ΔH°_{rxn}, in kJ/mol$_{rxn}$, calculated from the results of the second experiment is the same as the result calculated in part (e)(ii). Explain this result.

Question 1

2018 ▪ Q1

$$Na_2S_2O_3(aq) + 4\,NaOCl(aq) + 2\,NaOH(aq) \rightarrow 2\,Na_2SO_4(aq) + 4\,NaCl(aq) + H_2O(l)$$

A student performs an experiment to determine the value of the enthalpy change, ΔH°_{rxn}, for the oxidation-reduction reaction represented by the balanced equation above.

(g) Write the balanced net ionic equation for the given reaction.

Solution 1

(a)

Mark scheme

- Oxidation number of Cl in NaOCl is $+1$. (Na is $+1$, O is -2, so Cl must be $+1$ for the compound to be neutral.) 1 point is earned for the correct answer of $+1$.

Solution 1

(b)

Mark scheme

- 100.00 mL x (0.500 mol $Na_2S_2O_3$/1000 mL) x (158.10 g $Na_2S_2O_3$/1 mol $Na_2S_2O_3$) = 7.90 g $Na_2S_2O_3$. 1 point for the correct number of moles of $Na_2S_2O_3$ (0.0500 mol, may be implicit); 1 point for the correct mass consistent with that number of moles.

Solution 1

(c)

Mark scheme

- NaOCl is the limiting reactant. Given that equal numbers of moles of each reactant (Na2S2O3, NaOCl, NaOH) were present initially (same concentration and volume), it follows from the coefficients of the balanced equation Na2S2O3 + 4 NaOCl + 2 NaOH -> 2 Na2SO4 + 4 NaCl + H2O (which requires NaOCl in the largest relative amount) that NaOCl will be depleted first. 1 point is earned for identifying the limiting reactant AND providing a valid justification.

Solution 1

(d)

Mark scheme

- From the graph, the final temperature is 32.5 degrees C and the initial temperature is 20.0 degrees C. Delta T = Tf - Ti = 32.5 - 20.0 = 12.5 degrees C. 1 point is earned for the correct value of Delta T.

Solution 1

(e)(i)

Mark scheme

- q = mcDeltaT = (15.21 g)(3.94 J/(g times degree C))(12.5 degrees C) = 749 J. 1 point is earned for the correct calculation of q, consistent with the Delta T value from part (d).

Solution 1

(e)(ii)

Mark scheme

- n(NaOCl) = 5.00 mL x 0.500 mol NaOCl/1000 mL = 0.00250 mol NaOCl. n_rxn = 0.00250 mol NaOCl x (1 mol_rxn/4 mol NaOCl) = 0.000625 mol_rxn (using the limiting reactant from part c). DeltaH_rxn = -0.749 kJ / 0.000625 mol_rxn = -1.20x10^3 kJ/mol_rxn. 1 point is earned for correctly calculating mol_rxn consistent with the limiting reactant in part (c); 1 point is earned for a negative DeltaH_rxn obtained by dividing the calculated q by the calculated mol_rxn.

Solution 1

(f)

Mark scheme

- By doubling the volumes, the number of moles of the reactants are doubled, which doubles the amount of energy produced. Therefore the amount of heat per mole (DeltaH_rxn) remains the same. Equivalently, DeltaH_rxn = (2mcDeltaT)/(2n) = mcDeltaT/n, so the magnitude is unchanged. 1 point is earned for a valid explanation.

Solution 1

(g)

Mark scheme

- Net ionic equation: S2O3^2-(aq) + 4 OCl^-(aq) + 2 OH^-(aq) -> 2 SO4^2-(aq) + 4 Cl^-(aq) + H2O(l). 1 point is earned for the correct net ionic equation (Na+ spectator ions removed, charge and atoms balanced).