

Past-paper walk-through

Resonance and Formal Charge ■ 2.6

eXercise

Questions in this set

- 2026 Q2
- 2023 Q2
- 2017 Q2
- 2016 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

2026 ■ Q2

Answer the following questions about the chromate ion, CrO_4^{2-} , and the dichromate ion, $\text{Cr}_2\text{O}_7^{2-}$.

(a)(i) The bonds between chromium and oxygen in CrO_4^{2-} can be represented as covalent bonds. One possible Lewis diagram for the CrO_4^{2-} ion is shown in Figure 1. [Figure 1: Lewis diagram of CrO_4^{2-} — a central Cr atom single-bonded to three O atoms (each with three lone pairs) and double-bonded to one O atom (with two lone pairs), the whole structure enclosed in brackets with a 2− charge.]

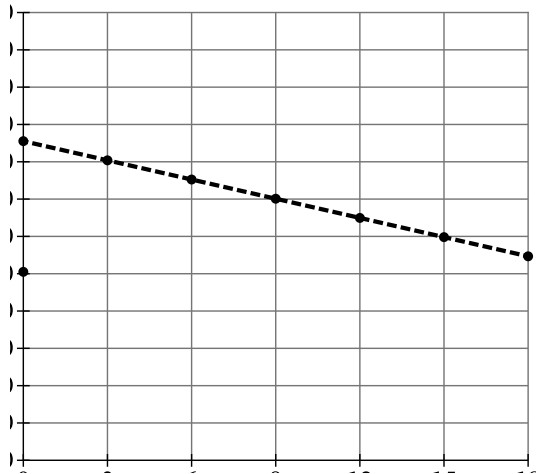
Based on VSEPR theory, ****predict**** the molecular geometry of the CrO_4^{2-} ion.

(a)(ii) On Figure 2, ****draw**** a complete Lewis diagram for a resonance structure of CrO_4^{2-} that results in a formal charge of zero on two of the O atoms and a formal charge of −1 on the other two O atoms. Your diagram should contain the same number of valence electrons as in Figure 1.

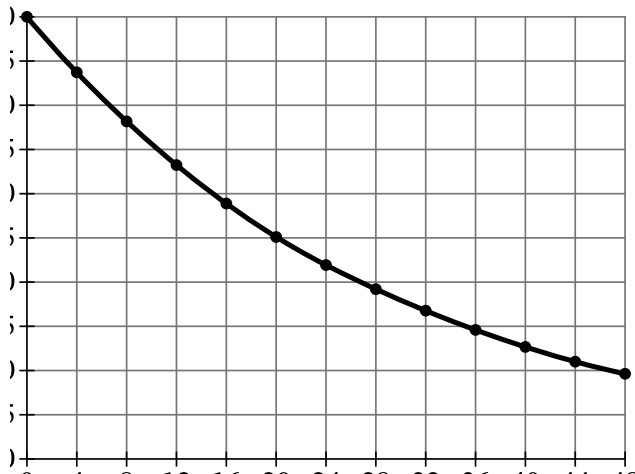
Question 2

[Figure 2: A blank template showing Cr in the center bonded to four O atoms arranged above, left, right, and below, enclosed in brackets with a 2[−] charge, for the student to complete.]

Question 2



Question 2



Question 2

2026 ■ Q2

Answer the following questions about the chromate ion, CrO_4^{2-} , and the dichromate ion, $\text{Cr}_2\text{O}_7^{2-}$.

(b)(i) When reacted with a strong acid like $\text{HNO}_3(\text{aq})$, $\text{CrO}_4^{2-}(\text{aq})$ can be converted to $\text{Cr}_2\text{O}_7^{2-}(\text{aq})$ and $\text{H}_2\text{O}(\text{l})$ in a reversible reaction.

****Write**** a balanced net ionic equation for the reaction between $\text{CrO}_4^{2-}(\text{aq})$ and a strong acid.

(b)(ii) Is the reaction a redox reaction? **Justify** your answer based on the oxidation number of Cr.

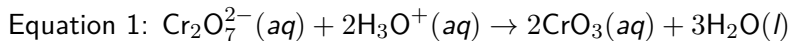
Question 2

2026 ■ Q2

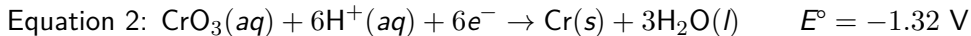
Answer the following questions about the chromate ion, CrO_4^{2-} , and the dichromate ion, $\text{Cr}_2\text{O}_7^{2-}$.

(c) The following information applies to parts C and D.

In acidic solutions, $\text{Cr}_2\text{O}_7^{2-}(\text{aq})$ reacts to form $\text{CrO}_3(\text{aq})$ according to Equation 1.



$\text{CrO}_3(\text{aq})$ can be electrolyzed to plate objects with a thin layer of chromium metal according to Equation 2.



Question 2

Is the reaction represented by Equation 2 thermodynamically favorable or unfavorable under standard conditions? ****Justify**** your answer with a calculation of ΔG° . Show the work that leads to your answer.

Question 2

2026 ■ Q2

Answer the following questions about the chromate ion, CrO_4^{2-} , and the dichromate ion, $\text{Cr}_2\text{O}_7^{2-}$.

(d) **Calculate** the number of grams of $\text{Cr}(s)$ that could be plated onto the surface of a steel rod when 15.0 A of current is applied for 3250 seconds. Show the work that leads to your answer.

Question 2

2026 ■ Q2

Answer the following questions about the chromate ion, CrO_4^{2-} , and the dichromate ion, $\text{Cr}_2\text{O}_7^{2-}$.

(e) In a separate experiment, an iron wire is placed directly in a solution of $0.50\text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$ with $\text{pH} = 1.99$. The concentration of $\text{Cr}_2\text{O}_7^{2-}(\text{aq})$ remaining is recorded over time, and the results are presented in Figure 3.

[Figure 3: Graph of $[\text{Cr}_2\text{O}_7^{2-}]$ (M) vs. Time (minutes); y-axis 0.00 to 0.50 in increments of 0.05, x-axis 0 to 48 in increments of 4; curve is concave up, decreasing from approximately (0, 0.50) through (4, 0.44), (8, 0.38), (12, 0.33), (16, 0.29), (20, 0.26), (24, 0.23), (28, 0.21), (32, 0.18), (36, 0.16), (40, 0.14), (44, 0.12), to approximately (48, 0.10).]

****Explain**** how the data in Figure 3 support the conclusion that the reaction is first order with respect to $\text{Cr}_2\text{O}_7^{2-}$.

Question 2

2026 ■ Q2

Answer the following questions about the chromate ion, CrO_4^{2-} , and the dichromate ion, $\text{Cr}_2\text{O}_7^{2-}$.

(f) The following information applies to parts F and G.

The student creates a plot of $\ln[\text{Cr}_2\text{O}_7^{2-}]$ versus time for a trial with an initial concentration of $0.50\text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$, as shown in Figure 4.

[Figure 4: Graph of $\ln[\text{Cr}_2\text{O}_7^{2-}]$ vs. Time (minutes); y-axis -2.40 to 0.00 in increments of 0.20 , x-axis 0 to 18 in increments of 3 ; dashed line of best fit through points starting near $(0, -0.65)$ decreasing roughly linearly to approximately $(18, -1.35)$.]

****Calculate**** the value of the rate constant, k , for the reaction. Report your answer in units of min^{-1} . Show the work that leads to your answer.

Question 2

2026 ■ Q2

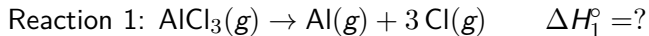
Answer the following questions about the chromate ion, CrO_4^{2-} , and the dichromate ion, $\text{Cr}_2\text{O}_7^{2-}$.

(g) The student then runs a second trial of the experiment under identical conditions but uses an initial concentration of $0.25 \text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$ instead of $0.50 \text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$. On Figure 4, carefully ****draw**** the plot of $\ln[\text{Cr}_2\text{O}_7^{2-}]$ versus time that would be expected for the second experiment. The point at time zero has already been plotted.

Question 2

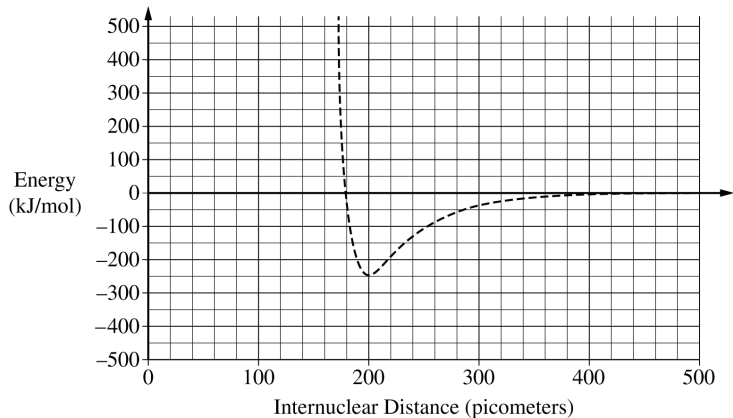
2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



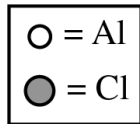
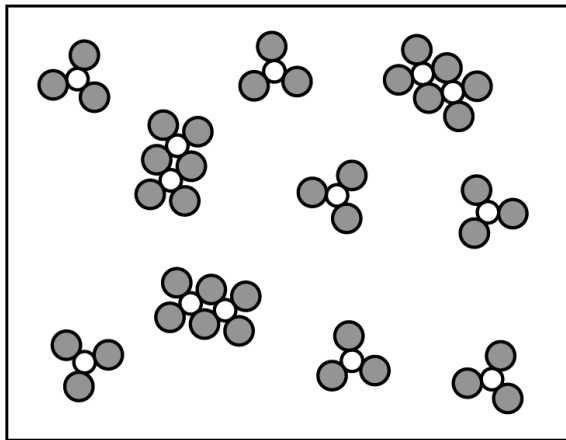
(a) How many grams of $\text{Cl}(g)$ can be formed from 1.25 mol of $\text{AlCl}_3(g)$?

Question 2



on the graph, what is the bond length, in picometers, for Cl_2 ? _____

Question 2



Question 2

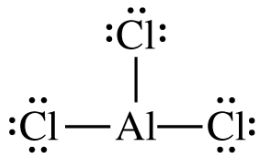


Diagram 1

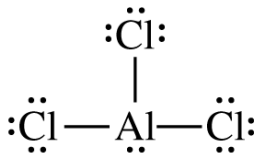


Diagram 2

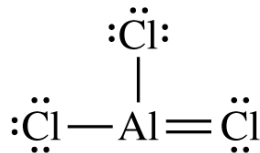


Diagram 3

Question 2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.

(b) Additional reactions that involve Al or Cl are shown in the following table.

Reaction Number	Equation	ΔH_{rxn}° (kJ/mol _{rxn})	2
	$\text{Al}(s) + \frac{3}{2}\text{Cl}_2(g) \rightarrow \text{AlCl}_3(g)$	-583	3
	$\text{Al}(s) \rightarrow \text{Al}(g)$	+326	4
	$\text{Cl}_2(g) \rightarrow 2\text{Cl}(g)$	+243	

Calculate the value of ΔH_1° , in kJ/mol_{rxn}, for reaction 1 above using reactions 2, 3, and 4.

Question 2

2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



(c)(i) A potential energy diagram for Cl_2 is shown in the following graph.

[Graph: potential energy (kJ/mol) vs. internuclear distance (picometers) for Cl_2 ; y-axis from -500 to 500 kJ/mol in steps of 100 ; x-axis from 0 to 500 picometers in steps of 100 ; dashed curve starts high near $x = 0$, plunges to a minimum of about -250 kJ/mol near $x \approx 200$ pm, then rises and levels off near 0 kJ/mol as x increases toward 500 pm.]
Based on the graph, what is the bond length, in picometers, for Cl_2 ?

Question 2

(c)(ii) A student finds that the average Al – Cl bond length is 220 picometers and the average bond energy is 425 kJ/mol. Draw the potential energy curve for the average Al – Cl bond on the preceding graph.

Question 2

2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



(d)(i) Three proposed Lewis diagrams for the $\text{AlCl}_3(g)$ molecule are shown.

[Diagram 1: Cl bonded to Al with a single bond above (Cl with 3 lone pairs) and two Cl atoms bonded to Al with single bonds on either side (each Cl with 3 lone pairs) — trigonal arrangement, all single Al–Cl bonds, Al with no lone pair shown.] [Diagram 2: same trigonal arrangement of three Cl atoms singly bonded to Al, each Cl shown with 3 lone pairs — visually similar layout to Diagram 1.] [Diagram 3: two Cl atoms singly bonded to Al (each with 3 lone pairs) and one Cl atom double-bonded to Al (shown with 2 lone pairs) — $\text{Cl}=\text{Al}$ on the right side.]

Diagram 1, Diagram 2, Diagram 3 (labeled beneath each structure).

Question 2

The $\text{AlCl}_3(g)$ molecule has a trigonal planar geometry. Which diagram (1, 2, or 3) can be eliminated based on geometry? Justify your choice based on VSEPR theory.

(d)(ii) Which of the three diagrams is the best representation for the bonding in AlCl_3 ? Justify your choice based on formal charges.

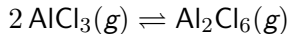
Question 2

2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



(e) AlCl_3 is known to dimerize reversibly in the gas phase. The dimerization equilibrium is represented by the following equation.



Write the expression for the equilibrium constant, K_p , for this reaction.

Question 2

2023 ■ Q2

In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



(f) A particle-level diagram of an equilibrium mixture of $\text{AlCl}_3(g)$ and $\text{Al}_2\text{Cl}_6(g)$ at 400°C in a 25 L closed container is shown.

[Particle diagram inside a rectangular box: several clusters of gray/white circles representing AlCl_3 monomers (isolated groupings of 1 white Al + 3 gray Cl) and Al_2Cl_6 dimers (larger fused clusters of 2 white Al + 6 gray Cl), scattered throughout the container. Legend: white circle = Al, gray circle = Cl.]

Using the particle-level diagram, calculate the value of K_p for the reaction if the total pressure in the container is 22.1 atm.

Solution 2

(a)

Mark scheme

$$\blacksquare 1.25 \text{ mol AlCl}_3 \times \frac{3 \text{ mol Cl}}{1 \text{ mol AlCl}_3} \times \frac{35.45 \text{ g Cl}}{1 \text{ mol Cl}} = 133 \text{ g Cl (3 sig figs)}.$$

Solution 2

(b) Mark scheme

- Apply Hess's law using reactions 2, 3, and 4: reverse reaction 2 ($\text{AlCl}_3(g) \rightarrow \text{Al}(s) + \frac{3}{2}\text{Cl}_2(g)$, $\Delta H = -(-583) = +583 \text{ kJ/mol}_{\text{rxn}}$) and multiply reaction 4 by $\frac{3}{2}$ ($\frac{3}{2}\text{Cl}_2(g) \rightarrow 3 \text{ Cl}(g)$, $\Delta H = 1.5(+243) = +365 \text{ kJ/mol}_{\text{rxn}}$), then add reaction 3 unchanged:
$$\Delta H_1^\circ = -\Delta H_2^\circ + \Delta H_3^\circ + 1.5(\Delta H_4^\circ) = -(-583) + 326 + 1.5(243) = 1274 \text{ kJ/mol}_{\text{rxn}}.$$

Solution 2

(c)(i)

Mark scheme

- Bond length ≈ 200 picometers (± 10 pm), read from the internuclear distance at the minimum (lowest potential energy point) of the Cl_2 curve shown.

Solution 2

(c)(ii)

Mark scheme

- Draw a new potential-energy curve for the Al–Cl bond with its minimum at an internuclear distance of 220 ± 10 pm — longer than Cl_2 's 200 pm bond length (1 point) — and a minimum energy value of -425 ± 20 kJ/mol that approaches zero as the internuclear distance approaches 500 pm — a shallower well than Cl_2 's since the Al–Cl bond energy (425 kJ/mol) is less than the Cl–Cl bond energy shown on the original curve (1 point).

Solution 2

(d)(i)

Mark scheme

- Diagram 2 is not a valid representation. In Diagram 2, Al has four electron domains (three single Al–Cl bonds plus one lone pair on Al), which would give a trigonal pyramidal (not trigonal planar) molecular geometry — inconsistent with the known trigonal planar geometry of $\text{AlCl}_3(\text{g})$.

Solution 2

(d)(ii)

Mark scheme

- Diagram 1 is the best representation. All atoms in Diagram 1 have a formal charge of zero, whereas atoms in Diagrams 2 and 3 have nonzero formal charges — the Lewis structure that minimizes (here, eliminates) formal charges is preferred.

Solution 2

(e)

Mark scheme

$$\blacksquare K_p = \frac{P_{\text{Al}_2\text{Cl}_6}}{(P_{\text{AlCl}_3})^2}.$$

Solution 2

(f) Mark scheme

- Using mole fractions read from the particle diagram ($\chi_{\text{AlCl}_3} = \frac{7}{10}$, $\chi_{\text{Al}_2\text{Cl}_6} = \frac{3}{10}$)
and total pressure 22.1 atm: $K_p = \frac{\chi_{\text{Al}_2\text{Cl}_6}(P_{\text{total}})}{(\chi_{\text{AlCl}_3}(P_{\text{total}}))^2} = \frac{\frac{3}{10}(22.1)}{(\frac{7}{10}(22.1))^2} = 0.0277$.

Question 2

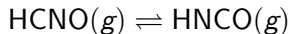
2017 ■ Q2

Answer the following questions about the isomers fulminic acid and isocyanic acid.

Two possible Lewis electron-dot diagrams for fulminic acid, HCNO, are shown below.

[Two Lewis structures side by side: Left: $\text{H}-\text{C}\equiv\text{N}-\ddot{\text{O}}:$ (H bonded to C by a single bond, C triple-bonded to N, N bonded to O by a single bond, O has two lone pairs) Right: $\text{H}-\text{C}=\text{N}=\ddot{\text{O}}:$ (H bonded to C by a single bond, C double-bonded to N, N double-bonded to O, C has one lone pair, O has two lone pairs)]

Fulminic acid can convert to isocyanic acid according to the equation below.



fulminic acid

isocyanic acid

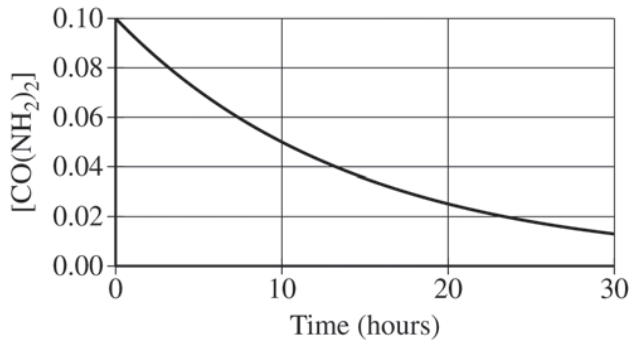
Question 2

| Fulminic Acid | Isocyanic Acid | $\text{H}-\text{C}\equiv\text{N}-\ddot{\text{O}}:$ (O has two lone pairs) |
 $\text{H}-\ddot{\text{N}}=\text{C}=\ddot{\text{O}}:$ (N has one lone pair, O has two lone pairs) |

(a) Explain why the diagram on the left is the better representation for the bonding in fulminic acid. Justify your choice based on formal charges.

Question 2

Time (hours)	$[\text{CO}(\text{NH}_2)_2]$
0	0.1000
5	0.0707
10	0.0500
15	0.0354
20	0.0250
25	0.0177
30	0.0125



Question 2

Fulminic Acid	Isocyanic Acid
$\text{H}-\text{C}\equiv\text{N}-\ddot{\text{O}}:$	$\text{H}-\ddot{\text{N}}=\text{C}=\ddot{\text{O}}:$

Question 2

Bond	Enthalpy (kJ/mol)		Bond	Enthalpy (kJ/mol)		Bond	Enthalpy (kJ/mol)
N–O	201		C=N	615		H–C	413
C=O	745		C≡N	891		H–N	391

Question 2

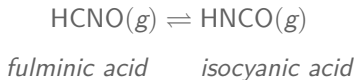
2017 ■ Q2

Answer the following questions about the isomers fulminic acid and isocyanic acid.

Two possible Lewis electron-dot diagrams for fulminic acid, HCNO, are shown below.

[Two Lewis structures side by side: Left: $\text{H}-\text{C}\equiv\text{N}-\ddot{\text{O}}:$ (H bonded to C by a single bond, C triple-bonded to N, N bonded to O by a single bond, O has two lone pairs) Right: $\text{H}-\text{C}=\text{N}=\ddot{\text{O}}:$ (H bonded to C by a single bond, C double-bonded to N, N double-bonded to O, C has one lone pair, O has two lone pairs)]

Fulminic acid can convert to isocyanic acid according to the equation below.



| Fulminic Acid | Isocyanic Acid | $|\text{—}| \text{—}|$ | $\text{H}-\text{C}\equiv\text{N}-\ddot{\text{O}}:$ (O has two lone pairs) | $\text{H}-\text{N}=\text{C}=\ddot{\text{O}}:$ (N has one lone pair, O has two lone pairs) |

Question 2

(b) Using the Lewis electron-dot diagrams of fulminic acid and isocyanic acid shown in the boxes above and the table of average bond enthalpies below, determine the value of ΔH° for the reaction of $\text{HCNO}(g)$ to form $\text{HNCO}(g)$.

Bond	Enthalpy (kJ/mol)	Bond	Enthalpy (kJ/mol)	Bond	Enthalpy (kJ/mol)
— — — — — —	N—O 201	C=N 615	H—C 413	C=O 745	C≡N 891
H—N 391					

Question 2

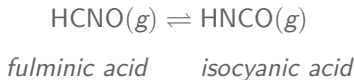
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Question 2

(c) A student claims that ΔS° for the reaction is close to zero. Explain why the student's claim is accurate.

Question 2

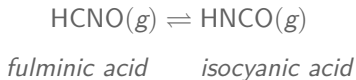
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Question 2

(d) Which species, fulminic acid (HCNO) or isocyanic acid (HNCO), is present in higher concentration at equilibrium at 298 K? Justify your answer in terms of thermodynamic favorability and the equilibrium constant.

Question 2

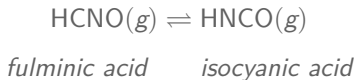
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Question 2

(e)(i) The ammonium salt of isocyanic acid is a product of the decomposition of urea, $\text{CO}(\text{NH}_2)_2$, represented below.



A student studying the decomposition reaction runs the reaction at 90°C . The student collects data on the concentration of urea as a function of time, as shown by the data table and the graph below.

Time (hours)	[CO(NH ₂) ₂]	— —	0	0.1000		5	0.0707		10	0.0500		15	
0.0354		20	0.0250		25	0.0177		30	0.0125				

[Graph: y-axis [CO(NH₂)₂] from 0.00 to 0.10 in increments of 0.02; x-axis "Time (hours)" from 0 to 30; a smooth exponential-decay curve starting at (0, 0.10) and decreasing to approximately (30, 0.0125), consistent with the data table above.]

Question 2

The student proposes that the rate law is $rate = k[CO(NH_2)_2]$.

Explain how the data support the student's proposed rate law.

(e)(ii) Using the proposed rate law and the student's results, determine the value of the rate constant, k . Include units with your answer.

Question 2

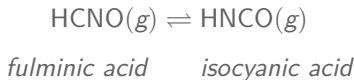
2017 ■ Q2

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Question 2

(f) The student learns that the decomposition reaction was run in a solution with a pH of 13. Briefly describe an experiment, including the initial conditions that you would change and the data you would gather, to determine whether the rate of the reaction depends on the concentration of $\text{OH}^{-}(\text{aq})$.

Solution 2

(a)

Mark scheme

- In the left diagram ($\text{H-C triple-bond N-O:}$ with O having 3 lone pairs... i.e. $\text{H-C}\equiv\text{N-O:}$), the C atom has a formal charge of 0 and the O atom has a formal charge of -1. In the right diagram ($\text{H-C(double bond)N(double bond)O:}$), the C atom has a formal charge of -1 and the O atom has a formal charge of 0. The diagram on the left is the better representation because it puts the negative formal charge on oxygen, which is more electronegative than carbon. 1 point earned for a correct assignment of formal charges in the two diagrams; 1 point earned for a correct explanation.

Solution 2

(b)

Mark scheme

- Sum bond enthalpies from each Lewis structure. HCNO (bonds broken): H-C (413) + C#N triple bond (891) + N-O (201) = 1505 kJ/mol. HNCO (bonds formed): H-N (391) + C=N (615) + C=O (745) = 1751 kJ/mol. ΔH (standard) = sum(enthalpies of bonds broken) - sum(enthalpies of bonds formed) = 1505 kJ/mol - 1751 kJ/mol = -246 kJ/mol_{rxn}. 1 point earned for subtracting the enthalpies of bonds formed from the enthalpies of bonds broken; 1 point earned for the correct determination of ΔH (standard).

Solution 2

(c)

Mark scheme

- The change from fulminic acid to isocyanic acid is a rearrangement of atoms (isomerization) with no change in phase and no change in the number of molecules, so there is essentially no change in the number of accessible microstates and ΔS (standard) is close to zero. 1 point earned for a correct explanation.

Solution 2

(d) Mark scheme

- Isocyanic acid (HNCO) is present in higher concentration at equilibrium. Delta G (standard) is essentially equal to delta H (standard) because delta S (standard) is essentially zero, so delta G (standard) is approximately $-246 \text{ kJ/mol}_{\text{rxn}}$, indicating the forward reaction ($\text{HCNO} \rightarrow \text{HNCO}$) is thermodynamically favorable. Since delta G (standard) is negative, $K > 1$ ($\Delta G_{\text{standard}} = -RT \ln K$), resulting in a higher equilibrium concentration of product (HNCO) than reactant (HCNO). 1 point earned for the correct choice WITH a valid justification (calculation of delta G standard is sufficient justification); 1 point earned for correctly connecting thermodynamic favorability to the equilibrium constant K.

Solution 2

(e)(i)

Mark scheme

- From inspecting the data table or the graph, the decomposition reaction has a constant half-life (the urea concentration approximately halves every 10 hours: 0.1000 to 0.0500 over the first 10 h, 0.0500 to 0.0250 over the next 10 h, etc.), which indicates the reaction is first order. 1 point earned for a correct explanation.

Solution 2

(e)(ii)

Mark scheme

- Since the reaction is first order: $k = 0.693 / t(1/2) = 0.693 / 10. \text{ h} = 0.069 \text{ h}^{-1}$ (equivalently $k = (\ln[A]_0 - \ln[A]_t)/t = (\ln 0.1000 - \ln 0.0500) / 10. \text{ h} = 0.069 \text{ h}^{-1}$). 1 point earned for the correct value of k with correct units.

Solution 2

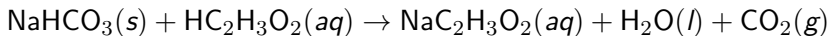
(f)

Mark scheme

- Perform the experiment again starting at a different initial concentration of $\text{OH}^-(\text{aq})$ (changing only $[\text{OH}^-]$, holding other variables such as temperature and initial urea concentration constant), and measure how the concentration of $\text{CO}(\text{NH}_2)_2$ changes over time; compare the resulting rate/rate constant to that obtained at pH 13. 1 point earned for the description of a valid experiment (correct changed initial condition and data to be gathered).

Question 2

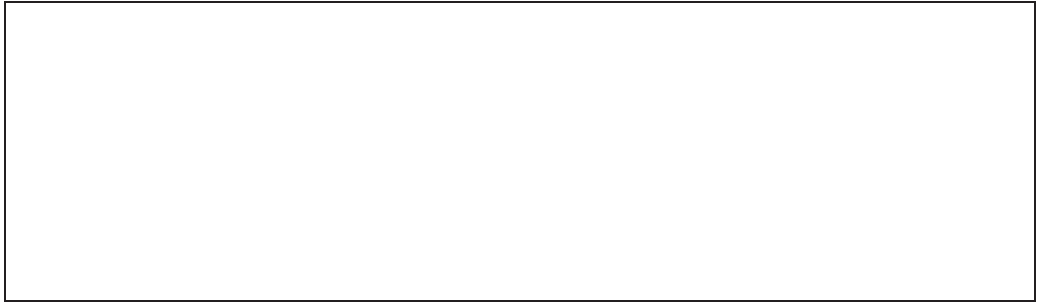
2016 ■ Q2



A student designs an experiment to study the reaction between NaHCO_3 and $\text{HC}_2\text{H}_3\text{O}_2$. 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 $\text{HC}_2\text{H}_3\text{O}_2$. 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

A large, empty rectangular box with a thin black border, intended for the user to provide their answer to the question.

Question 2

2016 ■ Q2



A student designs an experiment to study the reaction between NaHCO_3 and $\text{HC}_2\text{H}_3\text{O}_2$. 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 $\text{HC}_2\text{H}_3\text{O}_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

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

Question 2

2016 ■ Q2



A student designs an experiment to study the reaction between NaHCO_3 and $\text{HC}_2\text{H}_3\text{O}_2$. 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 $\text{HC}_2\text{H}_3\text{O}_2$. 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



A student designs an experiment to study the reaction between NaHCO_3 and $\text{HC}_2\text{H}_3\text{O}_2$. 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 $\text{HC}_2\text{H}_3\text{O}_2$. 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 $\text{NaHCO}_3(s)$ and $\text{HC}_2\text{H}_3\text{O}_2(aq)$? 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



A student designs an experiment to study the reaction between NaHCO_3 and $\text{HC}_2\text{H}_3\text{O}_2$. 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 $\text{HC}_2\text{H}_3\text{O}_2$. 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



A student designs an experiment to study the reaction between NaHCO_3 and $\text{HC}_2\text{H}_3\text{O}_2$. 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 $\text{HC}_2\text{H}_3\text{O}_2$. 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 $\text{HC}_2\text{H}_3\text{O}_2$ and $\text{NaC}_2\text{H}_3\text{O}_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 M $\text{HNO}_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $\text{HNO}_3(aq)$ 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 $\text{HC}_2\text{H}_3\text{O}_2$ reacts with the weak base HCO_3^- , with $\text{HC}_2\text{H}_3\text{O}_2$ 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

- $2.24 \text{ g NaHCO}_3 \times (1 \text{ mol} / 84.0 \text{ g}) = 0.0267 \text{ mol NaHCO}_3$. $60.0 \text{ mL} \times (0.875 \text{ mol HC}_2\text{H}_3\text{O}_2 / 1000 \text{ mL}) = 0.0525 \text{ mol HC}_2\text{H}_3\text{O}_2$. $\text{NaHCO}_3(\text{s})$ and $\text{HC}_2\text{H}_3\text{O}_2(\text{aq})$ react in a 1:1 ratio, so the smaller mole amount, $\text{NaHCO}_3(\text{s})$, 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 HCO_3^- has a central C bonded to three O atoms: one $\text{C}=\text{O}$ double bond, one $\text{C}-\text{O}$ single bond to an O bearing three lone pairs (charge -1 on that O), and one $\text{C}-\text{O}$ 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 ($\text{C}-\text{OH}$) 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 HCO_3^- , 1 point for indicating resonance between the two equivalent (non-OH) oxygens.

Solution 2

(f)

Mark scheme

- $\text{C}_2\text{H}_3\text{O}_2^- + \text{H}_3\text{O}^+ \rightarrow \text{HC}_2\text{H}_3\text{O}_2 + \text{H}_2\text{O}$ (equivalently: $\text{C}_2\text{H}_3\text{O}_2^- + \text{H}^+ \rightarrow \text{HC}_2\text{H}_3\text{O}_2$). 1 point for a correct, balanced net-ionic equation showing the acetate ion neutralizing the added $\text{H}_3\text{O}^+/\text{H}^+$, which is why the pH remains at 4.7 (buffer action).