Past-paper walk-through

VSEPR and Bond Hybridization ▪ 2.7

eXercise

Questions in this set

- 2026 Q2
- 2026 Q5
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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, $Cr_2O_7^{2-}$.

(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.]

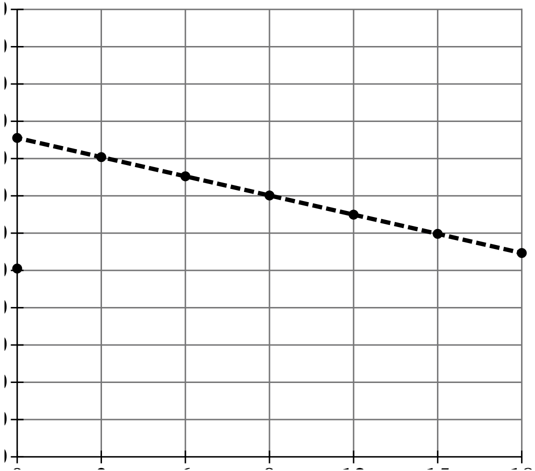
Based on VSEPR theory, **predict** the molecular geometry of the CrO_4^{2-} ion.

(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, $Cr_2O_7^{2-}$.

(b)(i) When reacted with a strong acid like $HNO_3(aq)$, $CrO_4^{2-}(aq)$ can be converted to $Cr_2O_7^{2-}(aq)$ and $H_2O(l)$ in a reversible reaction.
Write a balanced net ionic equation for the reaction between $CrO_4^{2-}(aq)$ 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, $Cr_2O_7^{2-}$.

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

In acidic solutions, $Cr_2O_7^{2-}(aq)$ reacts to form $CrO_3(aq)$ according to Equation 1.

$$\text{Equation 1: } Cr_2O_7^{2-}(aq) + 2H_3O^+(aq) \rightarrow 2CrO_3(aq) + 3H_2O(l)$$

$CrO_3(aq)$ can be electrolyzed to plate objects with a thin layer of chromium metal according to Equation 2.

$$\text{Equation 2: } CrO_3(aq) + 6H^+(aq) + 6e^- \rightarrow Cr(s) + 3H_2O(l) \qquad E^\circ = -1.32\ \text{V}$$

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, $Cr_2O_7^{2-}$.

(d) **Calculate** the number of grams of 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, $Cr_2O_7^{2-}$.

(e) In a separate experiment, an iron wire is placed directly in a solution of $0.50\ M$ $Cr_2O_7^{2-}(aq)$ with pH $= 1.99$. The concentration of $Cr_2O_7^{2-}(aq)$ remaining is recorded over time, and the results are presented in Figure 3.

[Figure 3: Graph of $[Cr_2O_7^{2-}]$ (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 $Cr_2O_7^{2-}$.

Question 2

2026 ▪ Q2

Answer the following questions about the chromate ion, CrO_4^{2-}, and the dichromate ion, $Cr_2O_7^{2-}$.

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

The student creates a plot of $\ln[Cr_2O_7^{2-}]$ versus time for a trial with an initial concentration of 0.50 *M* $Cr_2O_7^{2-}(aq)$, as shown in Figure 4.

[Figure 4: Graph of $\ln[Cr_2O_7^{2-}]$ 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, $Cr_2O_7^{2-}$.

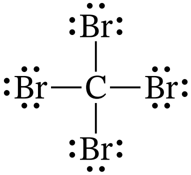
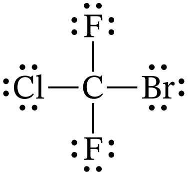
(g) The student then runs a second trial of the experiment under identical conditions but uses an initial concentration of 0.25 *M* $Cr_2O_7^{2-}(aq)$ instead of 0.50 *M* $Cr_2O_7^{2-}(aq)$. On Figure 4, carefully **draw** the plot of $\ln[Cr_2O_7^{2-}]$ versus time that would be expected for the second experiment. The point at time zero has already been plotted.

Question 5

2026 ▪ Q5

The following information applies to parts A and B.
The Lewis diagram of $CBrClF_2$ is shown.
[Lewis diagram of $CBrClF_2$: central C atom bonded to F (top, with three lone pairs), Cl (left, with three lone pairs), Br (right, with three lone pairs), and F (bottom, with three lone pairs).]
(a) Which of the bonds in $CBrClF_2$ (C–Br, C–Cl, or C–F) is the most polar? **Justify** your answer.

Question 5

Formula	CBr_4	$CBrClF_2$
Lewis diagram		
Boiling point	463 K	269 K

Question 5

2026 ▪ Q5

The following information applies to parts A and B.
The Lewis diagram of $CBrClF_2$ is shown.

[Lewis diagram of $CBrClF_2$: central C atom bonded to F (top, with three lone pairs), Cl (left, with three lone pairs), Br (right, with three lone pairs), and F (bottom, with three lone pairs).]

(b) In a molecule of $CBrClF_2$, the F–C–F bond angle is $106.8°$ and the Br–C–Cl bond angle is $112.3°$. **Explain** the difference in bond angles using principles of atomic structure and VSEPR theory.

Question 5

2026 ▪ Q5

The following information applies to parts A and B.
The Lewis diagram of $CBrClF_2$ is shown.

[Lewis diagram of $CBrClF_2$: central C atom bonded to F (top, with three lone pairs), Cl (left, with three lone pairs), Br (right, with three lone pairs), and F (bottom, with three lone pairs).]

(c)(i) Lewis diagrams and boiling points for CBr_4 and $CBrClF_2$ are given in the following table.

| Formula | CBr_4 | $CBrClF_2$ | |—|—|—| | Lewis diagram | [Central C bonded to four Br atoms, each Br bearing three lone pairs] | [Central C bonded to F (top), Cl (left), Br (right), F (bottom), each halogen bearing three lone pairs] | | Boiling point | 463 K | 269 K |

Clearly **identify** all the intermolecular forces in pure $CBr_4(l)$ and in pure $CBrClF_2(l)$.

Question 5

$CBr_4(l)$:
$CBrClF_2(l)$:
(c)(ii) In terms of the relative strengths of all the intermolecular forces, **explain** why pure $CBr_4(l)$ has a higher boiling point than pure $CBrClF_2(l)$ does.

Question 4

2025 ▪ Q4

A scientist is investigating the properties of a mixture of CH_3OH and H_2CO. The scientist generates the following diagram to represent the mixture.
[Diagram in a large box showing six Lewis-structure molecules scattered at different positions and orientations, representing a mixture of CH_3OH and H_2CO molecules: - Top-left: an H_2CO molecule, $\ddot{\mathrm{O}} = \mathrm{C}$ with two H atoms attached, two lone pairs on O. - Top-right: an H_2CO molecule (different orientation), H atoms attached to C, C double-bonded to O with two lone pairs. - Middle: a CH_3OH molecule, H—C(—H)(—H)—O(—H) with two lone pairs on O, drawn with C in the center bonded to three H atoms and one O, and the O bonded to one more H. - Middle-left: a CH_3OH molecule (different orientation) with O bonded to C and H, two lone pairs on O, C bonded to three H atoms. - Bottom-middle: an H_2CO molecule, C double-bonded to O (two lone pairs), C bonded to two H atoms below. -

Question 4

Bottom-right: an H_2CO molecule (different orientation), similar structure with O double-bonded to C bonded to two H atoms.]
(a) Identify the hybridization of the valence orbitals of the C atom in the H_2CO molecule.

Question 4

Substance	Melting Point (K)	Boiling Point (K)	Enthalpy of Vaporization (kJ/mol)
CH_3OH	176	338	37.6
H_2CO	181	254	24.2

Question 4

2025 ▪ Q4

A scientist is investigating the properties of a mixture of CH_3OH and H_2CO. The scientist generates the following diagram to represent the mixture.

[Diagram in a large box showing six Lewis-structure molecules scattered at different positions and orientations, representing a mixture of CH_3OH and H_2CO molecules: - Top-left: an H_2CO molecule, $\ddot{O} = C$ with two H atoms attached, two lone pairs on O. - Top-right: an H_2CO molecule (different orientation), H atoms attached to C, C double-bonded to O with two lone pairs. - Middle: a CH_3OH molecule, H—C(—H)(—H)—O(—H) with two lone pairs on O, drawn with C in the center bonded to three H atoms and one O, and the O bonded to one more H. - Middle-left: a CH_3OH molecule (different orientation) with O bonded to C and H, two lone pairs on O, C bonded to three H atoms. - Bottom-middle: an H_2CO molecule, C double-bonded to O (two lone pairs), C bonded to two H atoms below. - Bottom-right: an

Question 4

H_2CO molecule (different orientation), similar structure with O double-bonded to C bonded to two H atoms.]

(b) In the diagram provided, draw a SINGLE dashed line (---) to represent a strong hydrogen-bonding attraction between one CH_3OH molecule and one H_2CO molecule in the mixture.

Question 4

2025 ▪ Q4

A scientist is investigating the properties of a mixture of CH_3OH and H_2CO. The scientist generates the following diagram to represent the mixture.

[Diagram in a large box showing six Lewis-structure molecules scattered at different positions and orientations, representing a mixture of CH_3OH and H_2CO molecules: - Top-left: an H_2CO molecule, $\ddot{O} = C$ with two H atoms attached, two lone pairs on O. - Top-right: an H_2CO molecule (different orientation), H atoms attached to C, C double-bonded to O with two lone pairs. - Middle: a CH_3OH molecule, H—C(—H)(—H)—O(—H) with two lone pairs on O, drawn with C in the center bonded to three H atoms and one O, and the O bonded to one more H. - Middle-left: a CH_3OH molecule (different orientation) with O bonded to C and H, two lone pairs on O, C bonded to three H atoms. - Bottom-middle: an H_2CO molecule, C double-bonded to O (two lone pairs), C bonded to two H atoms below. - Bottom-right: an

Question 4

H_2CO molecule (different orientation), similar structure with O double-bonded to C bonded to two H atoms.]

(c) The scientist plans to cool a gaseous mixture of CH_3OH and H_2CO to form a liquid mixture and finds data on the two compounds. The data are summarized in the table.

Substance	Melting Point (K)	Boiling Point (K)	Enthalpy of Vaporization (kJ/mol)
CH_3OH	176	338	37.6
H_2CO	181	254	24.2

(c)(i) Propose a temperature to which the mixture should be cooled such that CH_3OH and H_2CO will both be liquids.

(c)(ii) The scientist analyzes the mixture after it is cooled and determines that 8.59 g of $CH_3OH(l)$ is present. Calculate the amount of thermal energy, in kJ, that was removed to condense the 8.59 g of CH_3OH (molar mass 32.04 g/mol) at its boiling point.

Solution 4

(a)

Mark scheme

- *sp*^{2} (the C atom in H_2CO is trigonal planar — one C=O double bond and two C–H single bonds, three electron domains, no lone pairs).

Solution 4

(b)

Mark scheme

- Draw a single dashed line from the H atom of the –OH group on one CH_3OH molecule to the O atom of one H_2CO molecule, representing a hydrogen bond between the H-bond donor (O–H of methanol) and the H-bond acceptor (C=O of formaldehyde).

Solution 4

(c)

Mark scheme

- No separate response required — this is the context/stem giving the melting point, boiling point, and enthalpy of vaporization data table for CH_3OH and H_2CO that parts (i) and (ii) below use.

Solution 4

(c)(i)

Mark scheme

- Propose any temperature in the range 181 K – 254 K, so that both CH_3OH (mp 176 K, bp 338 K) and H_2CO (mp 181 K, bp 254 K) are liquid — i.e., above the higher melting point (181 K, H_2CO) and below the lower boiling point (254 K, H_2CO).

Solution 4

(c)(ii)

Mark scheme

- $8.59 \text{ g CH}_3\text{OH} \times \dfrac{1 \text{ mol CH}_3\text{OH}}{32.04 \text{ g CH}_3\text{OH}} \times \dfrac{-37.6 \text{ kJ}}{1 \text{ mol CH}_3\text{OH}} = -10.1 \text{ kJ}$, so 10.1 kJ of thermal energy are removed (condensing the vapor releases this energy).

Question 5

2025 ▪ Q5

Complete Lewis diagrams and some physical properties for compounds X and Y are given.
| Compound | X | Y | |—|—|—| | Lewis diagram | [Lewis structure of compound X: a central chain of three C atoms; the left C is bonded to three H atoms and to the middle C; the middle C is bonded to an O atom above it (O has two lone pairs, drawn as :O:) and to the right C; the right C is bonded to three H atoms and to the middle C; the middle C is also bonded to a fourth C below it, which is bonded to two H atoms.] | [Lewis structure of compound Y: a central chain analogous to X but with a Si atom in place of the middle C; the left C is bonded to three H atoms and to Si; Si is bonded to an O atom above it (O has two lone pairs, drawn as :O:) and to the right C; the right C is bonded to three H atoms and to Si; Si is also bonded to a C below it,

Question 5

which is bonded to two H atoms.] | | Molar mass | 74.1 g/mol | 90.2 g/mol | | Boiling point | $82°$C | $98°$C |

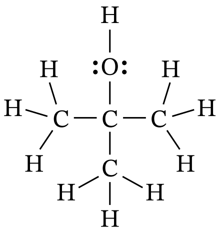
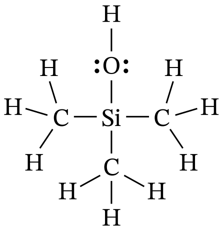
(a) Based on VSEPR theory, predict the geometry around the Si atom in compound Y.

(b) A student claims that compound Y has a higher boiling point than that of compound X because compound Y has stronger London dispersion forces. Do you agree or disagree? Justify your answer.

(c) An equimolar mixture of the two compounds is heated. When the mixture reaches $82°$C, which compound will have the higher vapor pressure? Justify your answer.

(d) The mixture is heated to $198°$C in a sealed, rigid 12.5 L container, at which point both substances are gases and the total pressure in the container is 2.30 atm. Calculate the number of moles of gas particles in the container.

Question 5

Compound	X	Y
Lewis diagram		
Molar mass	74.1 g/mol	90.2 g/mol
Boiling point	82°C	98°C

Solution 5

(a)

Mark scheme

- Tetrahedral (four bonding domains around the Si atom, no lone pairs, per VSEPR theory).

Solution 5

(b)

Mark scheme

- Agree. Compound Y (containing Si) has a larger, more polarizable electron cloud because the Si atom has more occupied electron shells than the C atom in compound X, giving compound Y stronger London dispersion forces and a higher boiling point than compound X.

Solution 5

(c)

Mark scheme

- Compound X will have the higher vapor pressure at $82°C$. Compound X has weaker intermolecular forces than compound Y, so molecules of X are more likely to be in the gas phase at $82°C$. Equivalently: at $82°C$ compound X has reached its boiling point but compound Y has not, so a much greater proportion of X molecules are in the vapor phase, giving X the higher vapor pressure.

Solution 5

(d)

Mark scheme

- Using $PV = nRT$: $n = \dfrac{PV}{RT} = \dfrac{(2.30\text{ atm})(12.5\text{ L})}{(0.08206\ \frac{\text{L·atm}}{\text{K·mol}})(471\text{ K})} = 0.744$ mol.

Question 6

2024 ▪ Q6

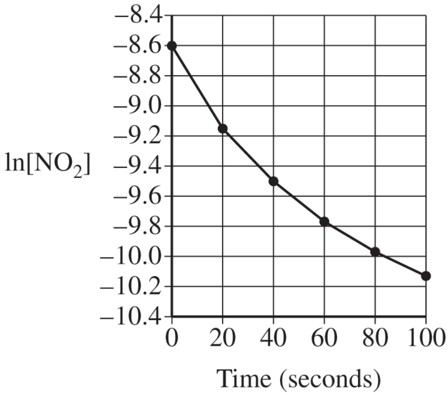
$$2\,\mathrm{NO_2} \rightarrow 2\,\mathrm{NO} + \mathrm{O_2}$$

6. At elevated temperatures, NO_2 undergoes decomposition in the gas phase, forming NO and O_2 as represented by the following equation.
A scientist measures the change in $[\mathrm{NO_2}]$ over the first 100. s of the reaction at 546°C. The scientist uses the data collected from the experiment to generate the following two graphs.
[Graph 1: $\ln[\mathrm{NO_2}]$ vs. Time (seconds); y-axis from -10.4 to -8.4 in increments of 0.2, x-axis 0 to 100 s in increments of 20. Data points (approximately): (0, -8.6), (20, -9.15), (40, -9.55), (60, -9.85), (80, -10.05), (100, -10.15); points connected by a

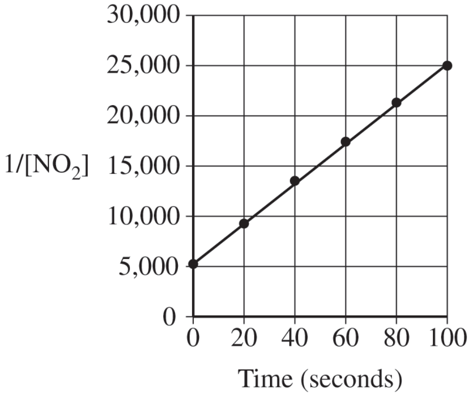
Question 6

smooth decreasing curve, concave up (linearizing downward but curving), consistent with a non-linear $\ln[NO_2]$ vs. t relationship.]
[Graph 2: $1/[NO_2]$ vs. Time (seconds); y-axis from 0 to 30,000 in increments of 5,000, x-axis 0 to 100 s in increments of 20. Data points (approximately): (0, 5000), (20, 9800), (40, 13800), (60, 18000), (80, 21800), (100, 25200); points lie on a straight line of constant positive slope.]
Based on these data, the scientist makes the claim that the rate law for the reaction is $\textit{rate} = k[NO_2]^2$.
(a) Explain how the graphs indicate that the reaction is second order with respect to NO_2.

Question 6

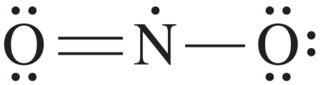


ln[NO_2]
−8.4
−8.6
−8.8
−9.0
−9.2
−9.4
−9.6
−9.8
−10.0
−10.2
−10.4
0 20 40 60 80 100
Time (seconds)



1/[NO_2]
30,000
25,000
20,000
15,000
10,000
5,000
0
0 20 40 60 80 100
Time (seconds)

Question 6



Question 6

2024 ▪ Q6

$$2\,NO_2 \rightarrow 2\,NO + O_2$$

6. At elevated temperatures, NO_2 undergoes decomposition in the gas phase, forming NO and O_2 as represented by the following equation.
A scientist measures the change in $[NO_2]$ over the first 100. s of the reaction at 546°C. The scientist uses the data collected from the experiment to generate the following two graphs.
[Graph 1: $\ln[NO_2]$ vs. Time (seconds); y-axis from -10.4 to -8.4 in increments of 0.2, x-axis 0 to 100 s in increments of 20. Data points (approximately): (0, -8.6), (20, -9.15), (40, -9.55), (60, -9.85), (80, -10.05), (100, -10.15); points connected by a smooth decreasing curve, concave up (linearizing downward but curving), consistent with a non-linear $\ln[NO_2]$ vs. t relationship.]

Question 6

[Graph 2: $1/[NO_2]$ vs. Time (seconds); y-axis from 0 to 30,000 in increments of 5,000, x-axis 0 to 100 s in increments of 20. Data points (approximately): (0, 5000), (20, 9800), (40, 13800), (60, 18000), (80, 21800), (100, 25200); points lie on a straight line of constant positive slope.]

Based on these data, the scientist makes the claim that the rate law for the reaction is $\mathit{rate} = k[NO_2]^2$.

(b) At a certain point in the reaction, the rate of disappearance of NO_2 is determined to be 6.52×10^{-7} M/s.

Determine the rate of appearance, in M/s, of O_2 at this same point in the reaction.

Question 6

2024 ▪ Q6

$$2\,NO_2 \rightarrow 2\,NO + O_2$$

6. At elevated temperatures, NO_2 undergoes decomposition in the gas phase, forming NO and O_2 as represented by the following equation.
A scientist measures the change in $[NO_2]$ over the first 100. s of the reaction at 546°C. The scientist uses the data collected from the experiment to generate the following two graphs.
[Graph 1: $\ln[NO_2]$ vs. Time (seconds); y-axis from -10.4 to -8.4 in increments of 0.2, x-axis 0 to 100 s in increments of 20. Data points (approximately): (0, -8.6), (20, -9.15), (40, -9.55), (60, -9.85), (80, -10.05), (100, -10.15); points connected by a smooth decreasing curve, concave up (linearizing downward but curving), consistent with a non-linear $\ln[NO_2]$ vs. t relationship.]

Question 6

[Graph 2: $1/[NO_2]$ vs. Time (seconds); y-axis from 0 to 30,000 in increments of 5,000, x-axis 0 to 100 s in increments of 20. Data points (approximately): (0, 5000), (20, 9800), (40, 13800), (60, 18000), (80, 21800), (100, 25200); points lie on a straight line of constant positive slope.]

Based on these data, the scientist makes the claim that the rate law for the reaction is $rate = k[NO_2]^2$.

(c) NO_2 is a molecule that contains an odd number of electrons and can be oxidized to form the NO_2^+ ion. In NO_2, the unpaired electron is presumed to be localized on the nitrogen atom, as shown in the Lewis diagram in the box on the left.

[Two boxes side by side. Left box: Lewis structure of NO_2 — O (with two lone pairs) double-bonded on the left to a central N (bearing an unpaired dot, single electron, above it), N single-bonded on the right to another O (bearing three lone pairs, i.e., a negative-type oxygen with full octet): $\ddot{O} = \dot{N} - \ddot{O}:$ with all lone pairs shown as dots. Right box: empty bracket template $[\ O \quad N \quad O\ ]^+$ for the student to complete with

Question 6

the Lewis structure of NO_2^+, showing atoms O, N, O in a row inside square brackets with a superscript plus charge, currently drawn with no bonds or lone pairs (blank template for the student to fill in).]

(c)(i) In the box on the right, complete the Lewis diagram for NO_2^+. Be sure to show all bonding and nonbonding electrons.

(c)(ii) A student makes the claim that the bond angles in NO_2 and NO_2^+ are different from each other. Do you agree or disagree with the student's claim? Justify your answer.

Solution 6

(a)

Mark scheme

- The plot of $1/[\mathrm{NO_2}]$ versus time is the most linear of the tested plots, which indicates that the reaction is second order with respect to NO_2 (a linear $1/[A]$ vs. t plot is the diagnostic signature of second-order kinetics).

Solution 6

(b)

Mark scheme

- Rate of appearance of O_2
  $= 6.52 \times 10^{-7}\ M/\text{s} \times \dfrac{1 \text{ mol } O_2}{2 \text{ mol } NO_2} = 3.26 \times 10^{-7}\ M/\text{s}.$

Solution 6

(c)

Mark scheme

- Context only — shows the given Lewis structure of NO_2 (O with two lone pairs double-bonded to a central N bearing one unpaired/nonbonding electron, N singly bonded to a second O with three lone pairs); sets up parts (c)(i) and (c)(ii). No separate scorable response for this leaf.

Solution 6

(c)(i)

Mark scheme

- Lewis diagram for NO_2^+ (isoelectronic with CO_2): linear $O = N = O$ structure, $[\ddot{O} = N = \ddot{O}]^+$, each O atom has two lone pairs, N has no lone pair and no unpaired electron (all 4 electron domains are used in the two double bonds), overall ion charge $+1$.

Solution 6

(c)(ii)

Mark scheme

- Agree. Accept either justification: (1) NO_2^+ no longer has a nonbonding/unpaired electron on the central N (unlike NO_2), so the two O atoms spread farther apart into a linear 180° geometry, different from NO_2's bent shape. (2) N in NO_2 is *sp*^{2} hybridized (bond angle $\approx 120°$), while N in NO_2^+ is *sp* hybridized (bond angle $= 180°$), so the bond angles differ.

Question 2

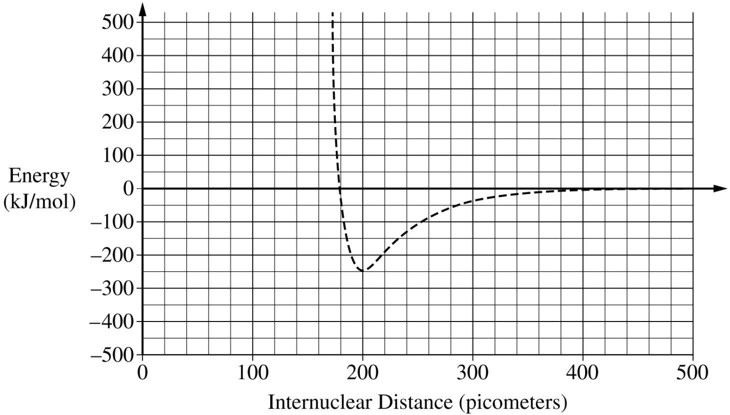
2023 ▪ Q2

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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

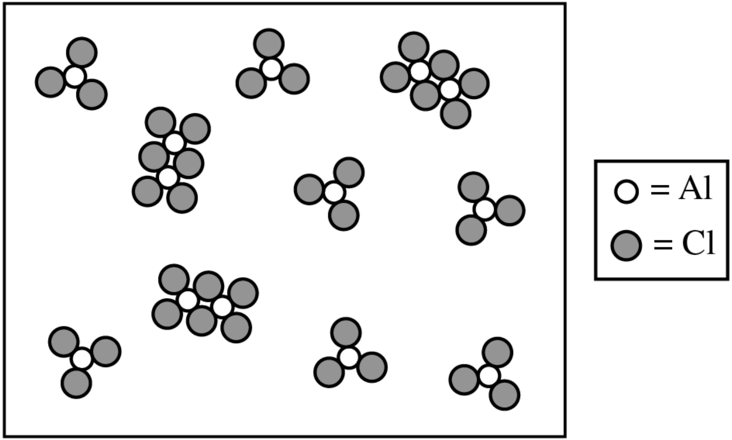
(a) How many grams of $Cl(g)$ can be formed from 1.25 mol of $AlCl_3(g)$?

Question 2



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

Question 2



Question 2

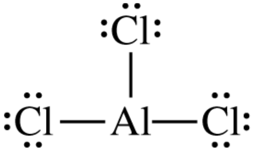


Diagram 1

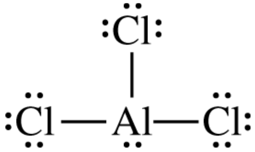


Diagram 2

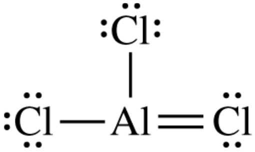


Diagram 3

Question 2

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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

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

Reaction Number	Equation	ΔH°_{rxn} (kJ/mol_{rxn})
2	$Al(s) + \frac{3}{2}Cl_2(g) \rightarrow AlCl_3(g)$	-583
3	$Al(s) \rightarrow Al(g)$	$+326$
4	$Cl_2(g) \rightarrow 2\,Cl(g)$	$+243$

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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(d)(i) Three proposed Lewis diagrams for the $AlCl_3(g)$ 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) — Cl=Al on the right side.]
Diagram 1, Diagram 2, Diagram 3 (labeled beneath each structure).

Question 2

The $AlCl_3(g)$ 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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

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

$$2\,AlCl_3(g) \rightleftharpoons Al_2Cl_6(g)$$

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.

Reaction 1: $AlCl_3(g) \rightarrow Al(g) + 3\,Cl(g) \qquad \Delta H_1^\circ = ?$

(f) A particle-level diagram of an equilibrium mixture of $AlCl_3(g)$ and $Al_2Cl_6(g)$ 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

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

Solution 2

(b) Mark scheme

- Apply Hess's law using reactions 2, 3, and 4: reverse reaction 2 ($AlCl_3(g) \rightarrow Al(s) + \frac{3}{2}Cl_2(g)$, $\Delta H = -(-583) = +583$ kJ/mol$_{rxn}$) and multiply reaction 4 by $\frac{3}{2}$ ($\frac{3}{2}Cl_2(g) \rightarrow 3\,Cl(g)$, $\Delta H = 1.5(+243) = +365$ kJ/mol$_{rxn}$), then add reaction 3 unchanged: $\Delta H_1^\circ = -\Delta H_2^\circ + \Delta H_3^\circ + 1.5(\Delta H_4^\circ) = -(-583) + 326 + 1.5(243) = 1274$ kJ/mol$_{rxn}$.

Solution 2

(c)(i)

Mark scheme

- Bond length $\approx$ 200 picometers ($\pm$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 $AlCl_3(g)$.

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

- $K_p = \dfrac{P_{\mathsf{Al_2Cl_6}}}{(P_{\mathsf{AlCl_3}})^2}$.

Solution 2

(f) Mark scheme

- Using mole fractions read from the particle diagram ($\chi_{AlCl_3} = \frac{7}{10}$, $\chi_{Al_2Cl_6} = \frac{3}{10}$) and total pressure 22.1 atm: $K_p = \frac{\chi_{Al_2Cl_6}(P_{total})}{(\chi_{AlCl_3}(P_{total}))^2} = \frac{\frac{3}{10}(22.1)}{(\frac{7}{10}(22.1))^2} = 0.0277.$

Question 7

2022 ▪ Q7

A Lewis electron-dot diagram of the oxalate ion, $C_2O_4^{2-}$, is shown.
[A Lewis electron-dot structure of the oxalate ion $C_2O_4^{2-}$: two carbon atoms singly bonded to each other, each carbon also double-bonded to one O atom and singly bonded to another O atom bearing a negative charge, with appropriate lone pairs shown on all oxygen atoms, consistent with the resonance-averaged/standard depiction of oxalate.]

(a) Identify the hybridization of the valence orbitals of either carbon atom in the oxalate ion.

(b) Silver oxalate, $Ag_2C_2O_4(s)$, is slightly soluble in water. The value of K_{sp} for $Ag_2C_2O_4$ is 5.40×10^{-12}.

(b)(i) Write the expression for the solubility-product constant, K_{sp}, for $Ag_2C_2O_4$.

(b)(ii) Calculate the molar solubility of $Ag_2C_2O_4$ in neutral distilled water.

Question 7

(b)(iii) The molar solubility of $Ag_2C_2O_4$ increases when it is dissolved in 0.5 *M* $HClO_4(aq)$ instead of neutral distilled water. Write a balanced, net-ionic equation for the process that occurs between species in solution that contributes to the increased solubility of $Ag_2C_2O_4(aq)$ in $HClO_4(aq)$.

Question 7

Solution 7

(a)

Mark scheme

- sp^2 — each carbon in the oxalate ion ($C2O4^{2}$) is trigonal planar (bonded to an O, a double-bonded/resonance O, and the other C), giving sp^2 hybridization of its valence orbitals.

Solution 7

(b)

Mark scheme

- This is the stem/introduction to part (b): silver oxalate, Ag2C2O4(s), is slightly soluble in water, with Ksp $= 5.40 \times 10^{12}$ for Ag2C2O4. No points are allocated to the stem itself — the graded sub-parts are 7bi, 7bii, and 7biii.

(b)(i)

Mark scheme

- Ksp $=$ [Ag]^2[C2O4^2].

Solution 7

(b)(ii)

Mark scheme

- Let molar solubility = s, so [Ag] = 2s and [C2O4^{2}] = s: 5.40 $\times$ 10 ^{12} = $(2s)^2(s)$ = $4s^3$, giving s = 1.11 $\times$ 10 M.

(b)(iii)

Mark scheme

- Balanced net-ionic equation for the process that increases solubility in acid (any one accepted, state symbols not required): C2O4^{2} (aq) + H3O (aq) $\rightarrow$ HC2O4 (aq) + H2O(l); or C2O4^{2} (aq) + H (aq) $\rightarrow$ HC2O4 (aq); or C2O4^{2} (aq) + 2H3O (aq) $\rightarrow$ H2C2O4(aq) + 2H2O(l); or C2O4^{2} (aq) + 2H (aq) $\rightarrow$ H2C2O4(aq).

Question 1

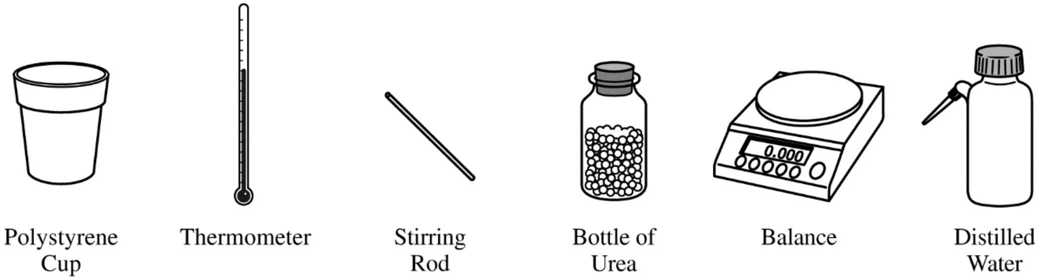
2019 ▪ Q1

[Complete Lewis electron-dot diagram of urea: H—N(H)—C(=O)—N(H)—H, with the carbon double-bonded to oxygen (two lone pairs on O), and each nitrogen bonded to two H atoms and bearing one lone pair, and the central carbon bonded to both nitrogens]

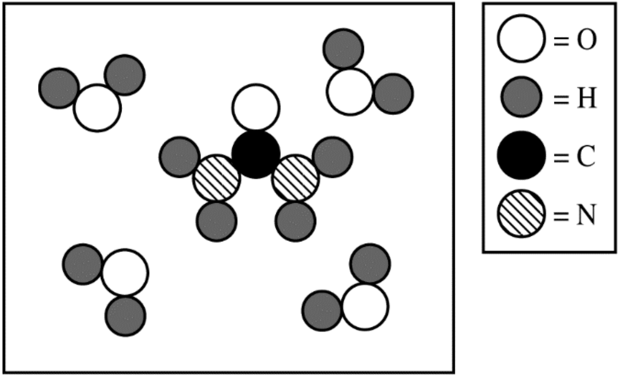
The compound urea, H_2NCONH_2, is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

(a) Identify the hybridization of the valence orbitals of the carbon atom in the urea molecule.

Question 1


Polystyrene Cup
Thermometer
Stirring Rod
Bottle of Urea
0.000
Balance
Distilled Water

Question 1



$$H_2NCONH_2(s) \rightleftarrows H_2NCONH_2(aq)$$

Question 1

	S° (J/(mol·K))
$H_2NCONH_2(s)$	104.6
$H_2NCONH_2(aq)$	?

Question 1

2019 ▪ Q1

[Complete Lewis electron-dot diagram of urea: H—N(H)—C(=O)—N(H)—H, with the carbon double-bonded to oxygen (two lone pairs on O), and each nitrogen bonded to two H atoms and bearing one lone pair, and the central carbon bonded to both nitrogens]

The compound urea, H_2NCONH_2, is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

(b) Urea has a high solubility in water, due in part to its ability to form hydrogen bonds. A urea molecule and four water molecules are represented in the box below. Draw ONE dashed line (—-) to indicate a possible location of a hydrogen bond between a water molecule and the urea molecule.

[Diagram: a box containing one urea molecule (drawn with spheres: white = O, gray = H, black = C, hatched = N) surrounded by four separate water molecules, each

Question 1

water molecule drawn as one white (O) sphere bonded to two gray (H) spheres; legend: white circle = O, gray circle = H, black circle = C, hatched circle = N]

$$H_2NCONH_2(s) \rightleftharpoons H_2NCONH_2(aq)$$

The dissolution of urea is represented by the equation above. A student determines that 5.39 grams of H_2NCONH_2 (molar mass 60.06 g/mol) can dissolve in water to make 5.00 mL of a saturated solution at 20.°C.

Question 1

2019 ▪ Q1

[Complete Lewis electron-dot diagram of urea: H—N(H)—C(=O)—N(H)—H, with the carbon double-bonded to oxygen (two lone pairs on O), and each nitrogen bonded to two H atoms and bearing one lone pair, and the central carbon bonded to both nitrogens]

The compound urea, H_2NCONH_2, is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

(c) Calculate the concentration of urea, in mol/L, in the saturated solution at 20.°C.

Question 1

2019 ▪ Q1

[Complete Lewis electron-dot diagram of urea: H—N(H)—C(=O)—N(H)—H, with the carbon double-bonded to oxygen (two lone pairs on O), and each nitrogen bonded to two H atoms and bearing one lone pair, and the central carbon bonded to both nitrogens]

The compound urea, H_2NCONH_2, is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

(d) The student also determines that the concentration of urea in a saturated solution at 25°C is 19.8 *M*. Based on this information, is the dissolution of urea endothermic or exothermic? Justify your answer in terms of Le Chatelier's principle.

[Diagram: row of laboratory equipment icons, labelled left to right: Polystyrene Cup, Thermometer, Stirring Rod, Bottle of Urea, Balance, Distilled Water]

Question 1

2019 ▪ Q1

[Complete Lewis electron-dot diagram of urea: H—N(H)—C(=O)—N(H)—H, with the carbon double-bonded to oxygen (two lone pairs on O), and each nitrogen bonded to two H atoms and bearing one lone pair, and the central carbon bonded to both nitrogens]

The compound urea, H_2NCONH_2, is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

(e) The equipment shown above is provided so that the student can determine the value of the molar heat of solution for urea. Knowing that the specific heat of the solution is 4.18 J/(g·°C), list the specific measurements that are required to be made during the experiment.

	S° (J/(mol·K))
$H_2NCONH_2(s)$	104.6
$H_2NCONH_2(aq)$	?

Question 1

2019 ▪ Q1

[Complete Lewis electron-dot diagram of urea: H—N(H)—C(=O)—N(H)—H, with the carbon double-bonded to oxygen (two lone pairs on O), and each nitrogen bonded to two H atoms and bearing one lone pair, and the central carbon bonded to both nitrogens]

The compound urea, H_2NCONH_2, is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

(f) The entropy change for the dissolution of urea, ΔS°_{soln}, is 70.1 J/(mol·K) at 25°C. Using the information in the table above, calculate the absolute molar entropy, S°, of aqueous urea.

Question 1

2019 ▪ Q1

[Complete Lewis electron-dot diagram of urea: H—N(H)—C(=O)—N(H)—H, with the carbon double-bonded to oxygen (two lone pairs on O), and each nitrogen bonded to two H atoms and bearing one lone pair, and the central carbon bonded to both nitrogens]

The compound urea, H_2NCONH_2, is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

(g) Using particle-level reasoning, explain why ΔS°_{soln} is positive for the dissolution of urea in water.

Question 1

2019 ▪ Q1

[Complete Lewis electron-dot diagram of urea: H—N(H)—C(=O)—N(H)—H, with the carbon double-bonded to oxygen (two lone pairs on O), and each nitrogen bonded to two H atoms and bearing one lone pair, and the central carbon bonded to both nitrogens]

The compound urea, H_2NCONH_2, is widely used in chemical fertilizers. The complete Lewis electron-dot diagram for the urea molecule is shown above.

(h) The student claims that ΔS° for the process contributes to the thermodynamic favorability of the dissolution of urea at 25°C. Use the thermodynamic information above to support the student's claim.

Solution 1

(a)

Mark scheme

- sp^2. The carbon atom in urea is bonded to three groups (two N atoms and one O atom, one bond of which is a double bond) with no lone pairs, giving trigonal-planar sp^2 hybridization. 1 point for stating sp^2.

Solution 1

(b)

Mark scheme

- A dashed line should connect a hydrogen atom of a water molecule to a nitrogen or oxygen atom of urea, OR an oxygen atom of a water molecule to a hydrogen atom of urea (an H-bond donor H drawn near an H-bond acceptor lone pair). 1 point is earned for any correctly placed dashed line matching this pattern.

Solution 1

(c)

Mark scheme

- Moles of urea: 5.39 g H2NCONH2 $\times$ (1 mol / 60.06 g) $=$ 0.0897 mol (1 point, may be implicit). Molarity: 0.0897 mol / 0.00500 L $=$ 17.9 M (1 point for the correct molarity).

Solution 1

(d)

Mark scheme

- Endothermic. The increased solubility at the higher temperature (19.8 M at 25°C vs. 17.9 M at 20.°C) implies the dissolution of urea is endothermic. By Le Chatelier's principle: heating a saturated solution stresses the equilibrium, and that stress is counteracted by more urea dissolving (the endothermic direction is favored). 1 point for the correct answer (endothermic) with this justification.

Solution 1

(e)

Mark scheme

- To determine the molar heat of solution calorimetrically, the student must measure: the mass of urea and the mass of water used (1 point); and the initial temperature of the water and the final temperature of the resulting solution (1 point). With the given specific heat 4.18 $J/(g \cdot {}^{\circ}C)$, these give $q = mc\Delta T$, which is then divided by moles of urea for the molar heat of solution.

Solution 1

(f)

Mark scheme

- $\Delta S°soln = S°(H2NCONH2(aq)) - S°(H2NCONH2(s))$; $70.1\ J/(mol \cdot K) = S°(aq) - 104.6\ J/(mol \cdot K)$; $S°(H2NCONH2(aq)) = 174.7\ J/(mol \cdot K)$. 1 point for the correct answer.

Solution 1

(g)

Mark scheme

- Urea molecules in aqueous solution have a much greater number of possible arrangements/microstates (free to move and interact throughout the solution) than in the ordered solid, so dissolution increases the number of accessible microstates, giving a positive $\Delta S°$soln. 1 point for a correct particle-level explanation along these lines.

Solution 1

(h)

Mark scheme

- Thermodynamic favorability at standard conditions is determined by the sign of $\Delta G°$, where $\Delta G° = \Delta H° - T\Delta S°$. Since $\Delta S°$ is positive, the $-T\Delta S°$ term is negative, making $\Delta G°$ smaller (more negative) and thus making the dissolution more thermodynamically favorable — supporting the student's claim. 1 point for this reasoning.

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 $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.
(a) The particle-level representation of the equimolar mixture of $NO(g)$ and $NO_2(g)$ in the flask at the completion of the reaction between $NO(g)$ and $O_2(g)$ 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 $NO(g)$ and $O_2(g)$ 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.

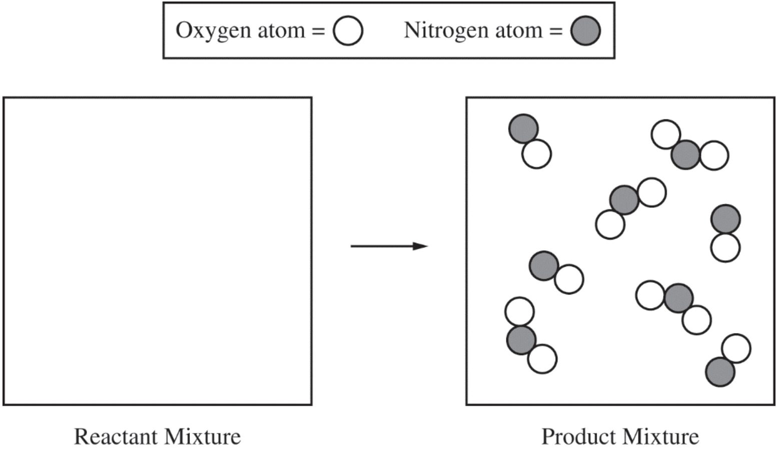
Question 2

[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.

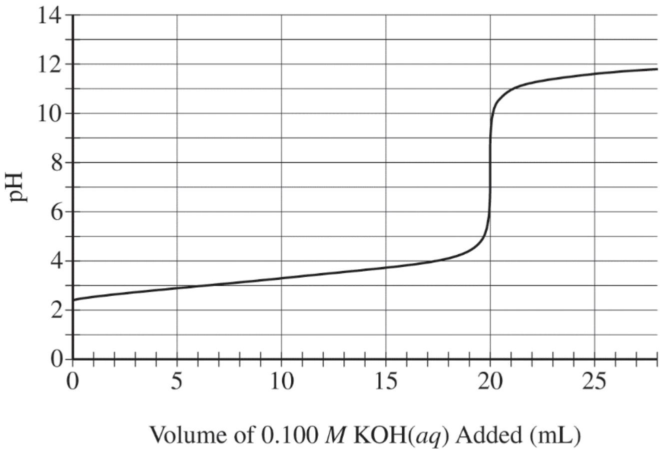
$$NO(g) + NO_2(g) \rightleftharpoons N_2O_3(g)$$

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

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

ΔH°_{298}	ΔS°_{298}	ΔG°_{298}
-40.4 kJ/mol_{rxn}	-138.5 J/(K·mol_{rxn})	0.87 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 $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(b)(i) The student begins with an equimolar mixture of $NO(g)$ and $NO_2(g)$ 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

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

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

(d)(i) The skeletal structure of the 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 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 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

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

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.

(e)(i) Use the titration curve and the information above to determine the initial concentration of the $\mathrm{HNO_2}(aq)$ solution.

(e)(ii) Use the titration curve and the information above to estimate the value of $\mathrm{p}K_a$ for $\mathrm{HNO_2}(aq)$.

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 $NO(g)$ and $NO_2(g)$, which the student produces by using the reaction represented above.

(f) During the titration, after a volume of 15 mL of 0.100 *M* $KOH(aq)$ has been added, which species, $HNO_2(aq)$ or $NO_2^-(aq)$, 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 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

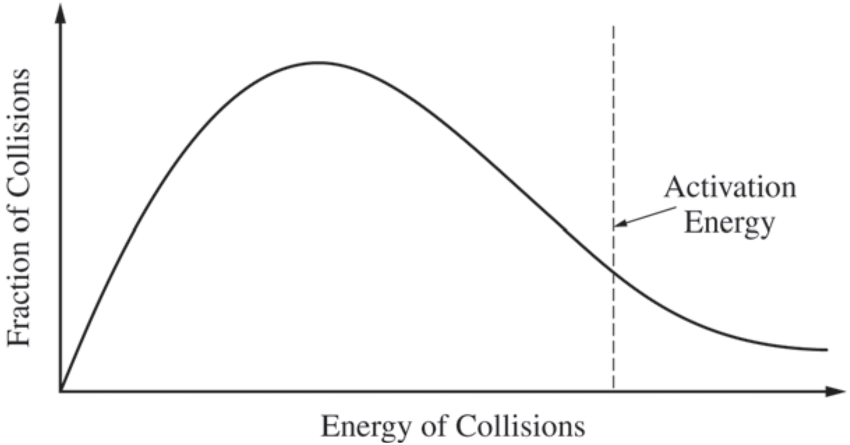
Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of $120°C$ in a rigid 25.0 L container.

(a)(i) Chlorine gas, $Cl_2(g)$, is initially present in the container at a pressure of 0.40 atm.

How many moles of $Cl_2(g)$ are in the container?

(a)(ii) How many grams of carbon disulfide, $CS_2(g)$, are needed to react completely with the $Cl_2(g)$?

Question 1



Fraction of Collisions
Activation
Energy
Energy of Collisions

Question 1

Cl S S Cl

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of $120°C$ in a rigid 25.0 L container.

(b)(i) At $30°C$ the reaction is thermodynamically favorable, but no reaction is observed to occur. However, at $120°C$, the reaction occurs at an observable rate. Explain how the higher temperature affects the collisions between the reactant molecules so that the reaction occurs at an observable rate at $120°C$.

(b)(ii) The graph below shows a distribution for the collision energies of reactant molecules at $120°C$. Draw a second curve on the graph that shows the distribution for the collision energies of reactant molecules at $30°C$.

Question 1

[Graph: Maxwell-Boltzmann-type distribution curve; y-axis "Fraction of Collisions" (unlabeled scale), x-axis "Energy of Collisions" (unlabeled scale); a single curve starts at the origin, rises to a peak, then decreases and levels off toward the x-axis; a vertical dashed line partway down the curve's descending portion is labeled "Activation Energy" with an arrow pointing to where it crosses the curve.]

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of 120°C in a rigid 25.0 L container.

(c)(i) S_2Cl_2 is a product of the reaction.

In the box below, complete the Lewis electron-dot diagram for the S_2Cl_2 molecule by drawing in all of the electron pairs.

[Box showing the unfinished skeletal structure: Cl S S Cl (four atoms in a row, single bonds implied between adjacent atoms, no lone pairs or additional dots drawn yet).]

(c)(ii) What is the approximate value of the Cl–S–S bond angle in the S_2Cl_2 molecule that you drew in part (c)(i) ? (If the two Cl–S–S bond angles are not equal, include both angles.)

Question 1

2017 ▪ Q1

$$CS_2(g) + 3\,Cl_2(g) \rightarrow CCl_4(g) + S_2Cl_2(g)$$

Carbon tetrachloride, $CCl_4(g)$, can be synthesized according to the reaction represented above. A chemist runs the reaction at a constant temperature of $120°C$ in a rigid 25.0 L container.

(d)(i) $CCl_4(g)$ can also be produced by reacting $CHCl_3(g)$ with $Cl_2(g)$ at $400°C$, as represented by the equation below.

$$CHCl_3(g) + Cl_2(g) \rightarrow CCl_4(g) + HCl(g)$$

At the completion of the reaction a chemist successfully separates the $CCl_4(g)$ from the $HCl(g)$ by cooling the mixture to $70°C$, at which temperature the $CCl_4(g)$ condenses while the $HCl(g)$ remains in the gaseous state.

Question 1

Identify all types of intermolecular forces present in HCl(l).

(d)(ii) What can be inferred about the relative strengths of the intermolecular forces in $CCl_4(l)$ and HCl(l) ? Justify your answer in terms of the information above.

Solution 1

(a)(i)

Mark scheme

- n = PV/RT = (0.40 atm x 25.0 L) / (0.08206 L*atm/(mol*K) x 393 K) = 0.31 mol Cl2. 1 point earned for the correct answer with supporting work.

(a)(ii)

Mark scheme

- 0.31 mol Cl2 x (1 mol CS2 / 3 mol Cl2) x (76.13 g CS2 / 1 mol CS2) = 7.9 g CS2. 1 point for using the correct mole ratio (may be implicit); 1 point for the correct mass of CS2.

Solution 1

(b)(i)

Mark scheme

- At the higher temperature the particles have a greater average kinetic energy than at the lower temperature. Thus there are more collisions with sufficient energy to overcome the activation energy. 1 point earned for an appropriate explanation that includes a reference to molecular collisions.

Solution 1

(b)(ii)

Mark scheme

- Draw a second curve on the graph for the 30C collision-energy distribution. 1 point earned for a curve that has a peak above and to the left of the given (120C) curve (lower T -> lower average kinetic energy, so the peak shifts to lower energy and is taller/narrower); 1 point earned for a curve that is below the given curve in the region beyond the activation energy (fewer molecules have collision energy exceeding Ea at the lower temperature).

Solution 1

(c)(i)

Mark scheme

- Completed Lewis structure: :Cl-S-S-Cl: with each Cl bearing 3 lone pairs and each S bearing 2 lone pairs, so every atom (C excluded, none here) satisfies the octet rule across the Cl-S-S-Cl skeleton with single bonds throughout. 1 point earned for a correctly drawn diagram (all electron pairs shown).

Solution 1

(c)(ii)

Mark scheme

- Any value between 104 degrees and 110 degrees is acceptable (bent/angular arrangement about each central S atom, which has 2 bonding pairs and 2 lone pairs, similar to the geometry around O in H2O2). 1 point earned for an acceptable angle that is consistent with the Lewis diagram drawn in part (c)(i).

Solution 1

(d)(i)

Mark scheme

- Dipole-dipole forces and London dispersion forces. 1 point earned for identifying both types of forces (HCl is a polar molecule, so dipole-dipole forces are present in addition to the London dispersion forces present between all molecules).

Solution 1

(d)(ii)

Mark scheme

- The intermolecular forces among CCl4 molecules must be stronger than those among HCl molecules, because the CCl4 condenses at a higher temperature (70C) than HCl, which remains gaseous at that temperature. 1 point earned for the correct answer with a valid justification.

Question 2

2015 ▪ Q2

Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH(g)$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below.
[Diagram of the lab synthesis setup: on the left, a test tube labeled "Test Tube" contains "Glass Wool with Ethanol" and "Solid Catalyst", heated from below by a "Bunsen Burner", both mounted on a stand. A delivery tube leads from the test tube on the right to a second, inverted test tube labeled "Ethene" that is collecting gas over water in a basin, also mounted on a stand.]

$$C_2H_5OH(g) \xrightarrow{\text{catalyst}} C_2H_4(g) + H_2O(g) \qquad \Delta H^\circ_{298} = 45.5\ \text{kJ/mol}_{rxn};\ \Delta S^\circ_{298} = 126\ \text{J/(K} \cdot \text{mol}$$

Question 2

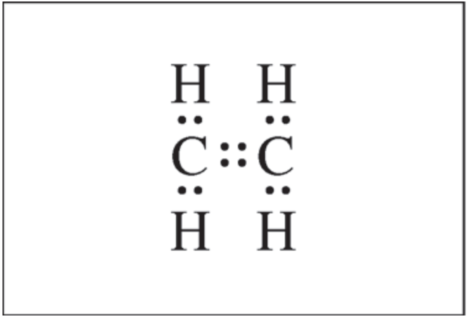
ethanol ethene water

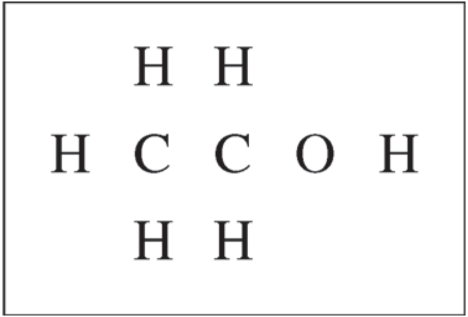
A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

(a)(i) Calculate the number of moles of $C_2H_4(g)$ that are actually produced in the experiment and measured in the gas collection tube.

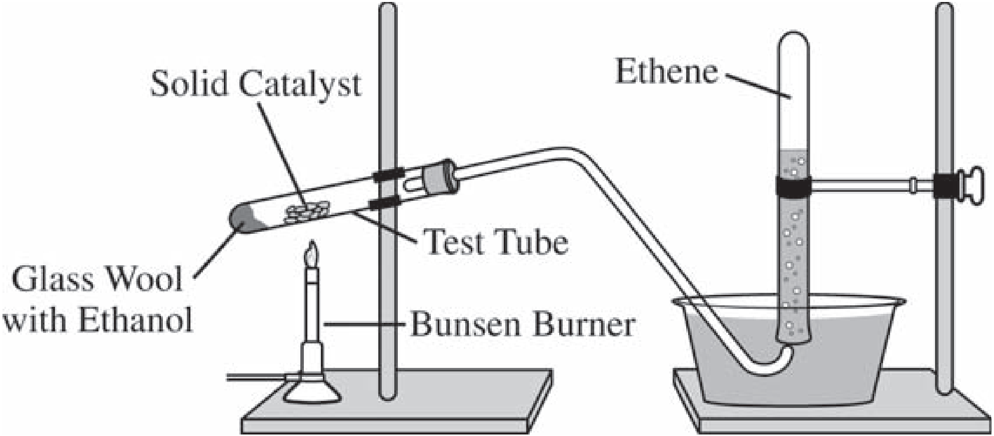
(a)(ii) Calculate the number of moles of $C_2H_4(g)$ that would be produced if the dehydration reaction went to completion.

Question 2





Question 2



Solid Catalyst
Ethene
Test Tube
Glass Wool
with Ethanol
Bunsen Burner

Question 2

2015 ▪ Q2

Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH(g)$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below. [Diagram of the lab synthesis setup: on the left, a test tube labeled "Test Tube" contains "Glass Wool with Ethanol" and "Solid Catalyst", heated from below by a "Bunsen Burner", both mounted on a stand. A delivery tube leads from the test tube on the right to a second, inverted test tube labeled "Ethene" that is collecting gas over water in a basin, also mounted on a stand.]

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ethanol ethene water

Question 2

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(b) Calculate the percent yield of $C_2H_4(g)$ in the experiment.

Question 2

2015 ▪ Q2

Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH(g)$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below. [Diagram of the lab synthesis setup: on the left, a test tube labeled "Test Tube" contains "Glass Wool with Ethanol" and "Solid Catalyst", heated from below by a "Bunsen Burner", both mounted on a stand. A delivery tube leads from the test tube on the right to a second, inverted test tube labeled "Ethene" that is collecting gas over water in a basin, also mounted on a stand.]

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ethanol ethene water

Question 2

A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

(c) Because the dehydration reaction is not observed to occur at 298 K, the student claims that the reaction has an equilibrium constant less than 1.00 at 298 K. Do the thermodynamic data for the reaction support the student's claim? Justify your answer, including a calculation of ΔG°_{298} for the reaction.

Question 2

2015 ▪ Q2

Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH(g)$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below. [Diagram of the lab synthesis setup: on the left, a test tube labeled "Test Tube" contains "Glass Wool with Ethanol" and "Solid Catalyst", heated from below by a "Bunsen Burner", both mounted on a stand. A delivery tube leads from the test tube on the right to a second, inverted test tube labeled "Ethene" that is collecting gas over water in a basin, also mounted on a stand.]

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ethanol ethene water

Question 2

A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

(d) The Lewis electron-dot diagram for C_2H_4 is shown below in the box on the left. In the box on the right, complete the Lewis electron-dot diagram for C_2H_5OH by drawing in all of the electron pairs.

[Two boxes side by side. Left box: the completed Lewis structure of C_2H_4 — two carbon atoms double-bonded to each other, each carbon also bonded to two hydrogen atoms (H H above, H H below), with all lone pairs and bonding pairs shown as dots. Right box: the skeletal (bonds-only, no lone pairs drawn) atom arrangement for C_2H_5OH — H H above the two carbons, "H C C O H" in a row, and H H below the first carbon — for the student to complete with electron pairs.]

Question 2

2015 ▪ Q2

Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH(g)$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below. [Diagram of the lab synthesis setup: on the left, a test tube labeled "Test Tube" contains "Glass Wool with Ethanol" and "Solid Catalyst", heated from below by a "Bunsen Burner", both mounted on a stand. A delivery tube leads from the test tube on the right to a second, inverted test tube labeled "Ethene" that is collecting gas over water in a basin, also mounted on a stand.]

$$C_2H_5OH(g) \xrightarrow{\text{catalyst}} C_2H_4(g) + H_2O(g) \qquad \Delta H^\circ_{298} = 45.5\ \text{kJ/mol}_{rxn};\ \Delta S^\circ_{298} = 126\ \text{J/(K} \cdot \text{mol}_{rxn})$$

ethanol ethene water

Question 2

A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

(e) What is the approximate value of the C–O–H bond angle in the ethanol molecule?

Question 2

2015 ▪ Q2

Ethene, $C_2H_4(g)$ (molar mass 28.1 g/mol), may be prepared by the dehydration of ethanol, $C_2H_5OH(g)$ (molar mass 46.1 g/mol), using a solid catalyst. A setup for the lab synthesis is shown in the diagram above. The equation for the dehydration reaction is given below. [Diagram of the lab synthesis setup: on the left, a test tube labeled "Test Tube" contains "Glass Wool with Ethanol" and "Solid Catalyst", heated from below by a "Bunsen Burner", both mounted on a stand. A delivery tube leads from the test tube on the right to a second, inverted test tube labeled "Ethene" that is collecting gas over water in a basin, also mounted on a stand.]

$$C_2H_5OH(g) \xrightarrow{\text{catalyst}} C_2H_4(g) + H_2O(g) \qquad \Delta H^\circ_{298} = 45.5 \text{ kJ/mol}_{rxn};\ \Delta S^\circ_{298} = 126 \text{ J/(K} \cdot \text{mol}_{rxn})$$

ethanol ethene water

Question 2

A student added a 0.200 g sample of $C_2H_5OH(l)$ to a test tube using the setup shown above. The student heated the test tube gently with a Bunsen burner until all of the $C_2H_5OH(l)$ evaporated and gas generation stopped. When the reaction stopped, the volume of collected gas was 0.0854 L at 0.822 atm and 305 K. (The vapor pressure of water at 305 K is 35.7 torr.)

(f) During the dehydration experiment, $C_2H_4(g)$ and unreacted $C_2H_5OH(g)$ passed through the tube into the water. The C_2H_4 was quantitatively collected as a gas, but the unreacted C_2H_5OH was not. Explain this observation in terms of the intermolecular forces between water and each of the two gases.

Solution 2

(a)(i)

Mark scheme

- First find the partial pressure of dry ethene by subtracting water's vapor pressure at 305 K from the total pressure: 35.7 torr x (1 atm / 760 torr) = 0.0470 atm; P_ethene = P_total - P_water = 0.822 atm - 0.0470 atm = 0.775 atm (1 point for this pressure calculation). Then apply the ideal gas law: n = PV/RT = (0.775 atm)(0.0854 L) / [(0.08206 L*atm*mol^-1*K^-1)(305 K)] = 0.00264 mol C2H4 actually produced and collected (1 point for the correct number of moles of ethene gas).

Solution 2

(a)(ii)

Mark scheme

- 0.200 g $C2H5OH$ x (1 mol $C2H5OH$ / 46.1 g $C2H5OH$) x (1 mol $C2H4$ / 1 mol $C2H5OH$) = 0.00434 mol $C2H4$ would be produced if the dehydration reaction went to completion. 1 point for the correct number of moles of ethene produced.

Solution 2

(b)

Mark scheme

- Percent yield = (actual yield / maximum possible yield) x 100 = (0.00264 mol / 0.00434 mol) x 100 = 60.8%. 1 point for the correct percent yield.

Solution 2

(c)

Mark scheme

- Yes, the thermodynamic data support the student's claim. DeltaG_298 = DeltaH - T*DeltaS = 45.5 kJ/mol_rxn - (298 K)(0.126 kJ/(K*mol_rxn)) = 8.0 kJ/mol_rxn (1 point for the correct calculation of DeltaG). Because DeltaG_298 > 0, K_p = e^(-DeltaG/RT) < 1.00, which confirms the equilibrium constant is less than 1.00 at 298 K, supporting the student's claim (1 point for a valid justification linking a positive DeltaG to K < 1).

Solution 2

(d)

Mark scheme

- The completed Lewis structure of C2H5OH (ethanol) must show all bonding pairs (the C-C bond, four C-H bonds, one C-O bond, and the O-H bond) plus the two nonbonding (lone) electron pairs on the oxygen atom; a line may be used in place of a dot pair. 1 point for a correct, complete diagram.

Solution 2

(e)

Mark scheme

- The C-O-H bond angle in ethanol is approximately 109 degrees, since the oxygen atom is roughly sp3-hybridized (bent/tetrahedral electron geometry) with two lone pairs. 1 point is earned for any answer from 100 degrees to 115 degrees.

Solution 2

(f) Mark scheme

- Ethene (C_2H_4) is nonpolar, so it can only interact with polar water molecules through weak dipole/induced-dipole forces, making it only slightly soluble in water (1 point for comparing the solubility of ethene in water with the solubility of ethanol in water in terms of their difference in polarity). Ethanol (C_2H_5OH) is polar and its -OH group can form hydrogen bonds with water molecules as it dissolves, making ethanol much more soluble in water; this is why the $C_2H_4(g)$ passing through the tube was quantitatively collected as a gas while the unreacted $C_2H_5OH(g)$ was not (1 point for describing the intermolecular forces between ethene and water as weak dipole/induced-dipole forces AND attributing ethanol's

Solution 2

solubility in water to the hydrogen bonds formed between ethanol and water molecules).

Question 5

2014 ▪ Q5

[Table:]

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Some binary compounds that form between fluorine and various nonmetals are listed in the table above. A student examines the data in the table and poses the following hypothesis: the number of F atoms that will bond to a nonmetal is always equal to 8 minus the number of valence electrons in the nonmetal atom.

(a) Based on the student's hypothesis, what should be the formula of the compound that forms between chlorine and fluorine?

Question 5

Question 5

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Question 5

Halogen	Formula(s)
F	F_2
Cl	
Br	BrF, BrF_3 , BrF_5
I	IF, IF_3 , IF_5 , IF_7

Question 5

2014 ▪ Q5

[Table:]

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Some binary compounds that form between fluorine and various nonmetals are listed in the table above. A student examines the data in the table and poses the following hypothesis: the number of F atoms that will bond to a nonmetal is always equal to 8 minus the number of valence electrons in the nonmetal atom.

(b) In an attempt to verify the hypothesis, the student researches the fluoride compounds of the other halogens and finds the formula ClF_3. In the box below, draw a complete Lewis electron-dot diagram for a molecule of ClF_3.

[A blank rectangular box provided for the student to draw the Lewis structure.]

Question 5

2014 ▪ Q5

[Table:]

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Some binary compounds that form between fluorine and various nonmetals are listed in the table above. A student examines the data in the table and poses the following hypothesis: the number of F atoms that will bond to a nonmetal is always equal to 8 minus the number of valence electrons in the nonmetal atom.

(c) Two possible geometric shapes for the ClF_3 molecule are trigonal planar and T-shaped. The student does some research and learns that the molecule has a dipole moment. Which of the two shapes is consistent with the fact that the ClF_3 molecule has a dipole moment? Justify your answer in terms of bond polarity and molecular structure.

Question 5

2014 ▪ Q5

[Table:]

Nonmetal	C	N	O	Ne	Si	P	S	Ar
Formula of Compound	CF_4	NF_3	OF_2	No compound	SiF_4	PF_3	SF_2	No compound

Some binary compounds that form between fluorine and various nonmetals are listed in the table above. A student examines the data in the table and poses the following hypothesis: the number of F atoms that will bond to a nonmetal is always equal to 8 minus the number of valence electrons in the nonmetal atom.

(d) In an attempt to resolve the existence of the ClF_3 molecule with the hypothesis stated above, the student researches the compounds that form between halogens and fluorine, and assembles the following list.

Halogen	Formula(s)
F	F_2
Cl	
Br	BrF, BrF_3, BrF_5
I	IF, IF_3, IF_5, IF_7

Question 5

Based on concepts of atomic structure and periodicity, propose a modification to the student's previous hypothesis to account for the compounds that form between halogens and fluorine.

Solution 5

(a)

Mark scheme

- ClF (chlorine has 7 valence electrons, so by the hypothesis $8 - 7 = 1$ F atom bonds to it).

Solution 5

(b)

Mark scheme

- A complete Lewis structure for ClF3: a central Cl atom single-bonded to three F atoms, with two nonbonding (lone) electron pairs on Cl and three nonbonding pairs on each F atom (T-shaped arrangement: F–Cl(F)(F) with Cl bearing 2 lone pairs and each F bearing 3 lone pairs). Full credit requires a central Cl surrounded by three bonding pairs to F atoms and two nonbonding pairs on Cl, plus three nonbonding pairs on each F (dots or line/dash notation both acceptable).

Solution 5

(c)

Mark scheme

- The molecule is T-shaped. A T-shaped structure is asymmetric, so its bond dipoles do not cancel and the molecule has a net dipole moment (polar). A trigonal planar structure would be symmetric, with the three Cl–F bond dipoles canceling to give a net dipole of zero (nonpolar), which is inconsistent with the observation that ClF3 has a dipole moment.

Solution 5

(d)

Mark scheme

- An acceptable modified hypothesis must address both atomic structure and periodicity, e.g.: the number of F atoms bonded to a halogen is always an odd number (reflecting the odd number of valence/unpaired electrons available for bonding), and as the atomic number (size) of the central halogen atom increases going down the group, the number of F atoms that can bond to it increases (consistent with Cl forming only ClF and ClF3, while the larger Br and I form progressively more fluorides: BrF/BrF3/BrF5 and IF/IF3/IF5/IF7).