Past-paper walk-through

Intermolecular and Interparticle Forces ▪ 3.1

eXercise

Questions in this set

- 2026 Q5
- 2025 Q2
- 2025 Q4
- 2025 Q5
- 2023 Q5
- 2023 Q6
- 2022 Q1
- 2022 Q4
- 2021 Q2
- 2019 Q1

Questions in this set

- 2019 Q2
- 2018 Q4

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 5

2026 ▪ Q5

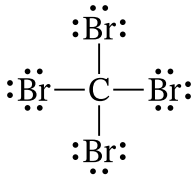
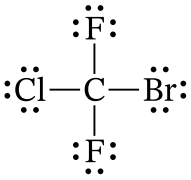
The following information applies to parts A and B.

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 2

2025 ▪ Q2

Answer the following questions about ascorbic acid (vitamin C).

(a) A student combusts a sample of ascorbic acid, $C_xH_yO_x$, to determine its chemical composition. The only products of the reaction are 0.2400 mol of CO_2 and 2.883 g of H_2O.

(a)(i) Calculate the number of moles of H_2O produced.

(a)(ii) The mole ratio of carbon (C) to oxygen (O) is 1:1 in ascorbic acid. Based on this information and your answer to part A (i), determine the empirical formula of ascorbic acid.

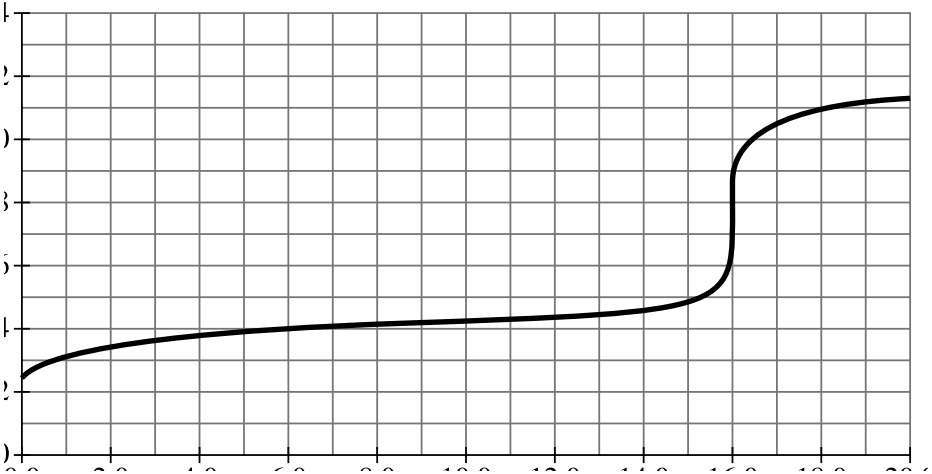
Question 2

Trial	[HAsc] (M)	$[I_3^-](M)$	Initial Rate of DHAsc Formation (M/s)
1	0.450	1.200	2.457×10^{-4}
2	0.450	0.600	1.229×10^{-4}
3	0.900	1.200	4.914×10^{-4}

i. The rate law for the reaction is $rate = k[\text{HAsc}][I_3^-]$. Explain how the data in the table support the conclusion that the reaction is first order with respect to $[\text{HAsc}]$.

ii. Calculate the value of the rate constant, k, for the reaction. Include units with your

Question 2



Question 2

2025 ▪ Q2

Answer the following questions about ascorbic acid (vitamin C).

(b) Ascorbic acid, HAsc(aq), acts as a weak acid, as shown in the equation.

$$\mathrm{HAsc}(aq) + \mathrm{H_2O}(l) \rightleftharpoons \mathrm{H_3O^+}(aq) + \mathrm{Asc^-}(aq)$$

The following titration curve was produced when a 10.0 mL sample of HAsc(aq) was titrated using 0.0550 M NaOH(aq).

[Titration curve graph: x-axis "Volume of 0.0550 M NaOH Added (mL)" from 0.0 to 20.0 in increments of 2.0; y-axis "pH" from 0 to 14 in increments of 2. The curve starts at about (0.0, 2.6), rises gradually and levels into a broad buffer region around pH 4 from about 2 mL to 14 mL, has a small inflection/bump near (14.0, 4.5)-(15.0,

Question 2

5.2), then rises steeply (equivalence point) through the region 15.0-16.5 mL up to about pH 10.5, then levels off gradually approaching about (20.0, 11.3).]

(b)(i) Calculate the molar concentration of the ascorbic acid solution.

(b)(ii) From the titration curve, determine the approximate pK_a of ascorbic acid.

(b)(iii) What is the value of the ratio $\frac{[\text{Asc}^-]}{[\text{HAsc}]}$ when the pH of the solution is 4.7?

Question 2

2025 ▪ Q2

Answer the following questions about ascorbic acid (vitamin C).

(c) Dehydroascorbic acid (DHAsc) can be produced by reacting ascorbic acid with the triiodide ion, I_3^-, as represented by the following equation.

$$HAsc + I_3^- \rightarrow DHAsc + 3\,I^- + 2\,H^+$$

The student runs three trials of the reaction with different initial concentrations of HAsc and I_3^-, producing the following data.

Trial	[HAsc] (M)	[I_3^-] (M)	Initial Rate of DHAsc Formation (M/s)
1	0.450	1.200	2.457×10^{-4}
2	0.450	0.600	1.229×10^{-4}
3	0.900	1.200	4.914×10^{-4}

Question 2

(c)(i) The rate law for the reaction is $rate = k[\text{HAsc}][\text{I}_3^-]$. Explain how the data in the table support the conclusion that the reaction is first order with respect to [HAsc].
(c)(ii) Calculate the value of the rate constant, k, for the reaction. Include units with your answer.

Question 2

2025 ▪ Q2

Answer the following questions about ascorbic acid (vitamin C).

(d) The triiodide ion, I_3^-, is significantly more soluble in water than elemental iodine, I_2, is. Identify an intermolecular force between I_3^- and water that is **not** present between I_2 and water, which could explain the difference in solubility. Lewis diagrams for I_2 and I_3^- are provided.

[Lewis structures: I_2 shown as two iodine atoms singly bonded together, each with three lone pairs. I_3^- shown in brackets with an overall negative charge, as three iodine atoms in a row connected by single bonds (I—I—I), each terminal iodine with three lone pairs and the central iodine with two lone pairs.]

Solution 2

(a)

Mark scheme

- No separate response required — this is the context/stem describing the combustion of ascorbic acid ($C_xH_yO_x$) producing 0.2400 mol CO_2 and 2.883 g H_2O, which parts (i) and (ii) below use.

(a)(i)

Mark scheme

- moles $H_2O = 2.883$ g $H_2O \times \dfrac{1 \text{ mol } H_2O}{18.02 \text{ g } H_2O} = 0.1600$ mol H_2O.

Solution 2

(a)(ii)

Mark scheme

- moles H $= 0.1600$ mol $H_2O \times \dfrac{2 \text{ mol H}}{1 \text{ mol } H_2O} = 0.3200$ mol H (this step may be left implicit). Using mol C $= 0.2400$ mol $CO_2 \times \dfrac{1 \text{ mol C}}{1 \text{ mol } CO_2} = 0.2400$ mol C and the given 1:1 C:O ratio:
  $x : y : z = (\text{mol C}) : (\text{mol H}) : (\text{mol O}) = 0.2400 : 0.3200 : 0.2400 = 3 : 4 : 3.$
  Therefore the empirical formula of ascorbic acid is $C_3H_4O_3$.

Solution 2

(b)

Mark scheme

- No separate response required — this is the context/stem describing HAsc(aq) as a weak acid and presenting the titration curve (10.0 mL HAsc titrated with 0.0550 M NaOH) that parts (i)–(iii) below refer to.

Solution 2

(b)(i)

Mark scheme

- Reading the volume of NaOH at the equivalence point (16.0 mL) from the curve:

$$0.0160 \text{ L NaOH} \times \frac{0.0550 \text{ mol NaOH}}{1 \text{ L NaOH}} \times \frac{1 \text{ mol HAsc}}{1 \text{ mol NaOH}} = 8.80 \times 10^{-4} \text{ mol HAsc.}$$

$$\text{Molarity} = \frac{8.80 \times 10^{-4} \text{ mol HAsc}}{0.0100 \text{ L}} = 0.0880 \ M \text{ HAsc.}$$

Solution 2

(b)(ii)

Mark scheme

- From the titration curve, the pK_a (the pH at the half-equivalence point) is approximately 4.1 (acceptable range 4.0–4.3).

Solution 2

(b)(iii)

Mark scheme

- Using the Henderson–Hasselbalch equation: $\mathrm{pH} = \mathrm{p}K_a + \log\left(\dfrac{[\mathrm{Asc}^-]}{[\mathrm{HAsc}]}\right)$.

  $4.7 = 4.1 + \log\left(\dfrac{[\mathrm{Asc}^-]}{[\mathrm{HAsc}]}\right)$, so $\dfrac{[\mathrm{Asc}^-]}{[\mathrm{HAsc}]} = 10^{0.6} = 4.0$.

Solution 2

(c)

Mark scheme

- No separate response required — this is the context/stem describing the reaction of ascorbic acid (HAsc) with triiodide (I_3^-) to form DHAsc, and the table of three trials' initial concentrations and rates, that parts (i) and (ii) below use.

Solution 2

(c)(i)

Mark scheme

- Comparing trials 1 and 3: $\frac{4.914 \times 10^{-4}}{2.457 \times 10^{-4}} = \left(\frac{0.900}{0.450}\right)^{a}$, thus $a = 1$. The rate doubles when [HAsc] is doubled while $[I_3^-]$ is held constant, indicating the reaction is first order with respect to [HAsc].

Solution 2

(c)(ii)

Mark scheme

- Using rate $= k[\text{HAsc}][\text{I}_3^-]$ and trial 1 data: $k = \dfrac{\text{rate}}{[\text{HAsc}][\text{I}_3^-]} = \dfrac{2.457 \times 10^{-4}\ M/\text{s}}{(0.450\ M)(1.200\ M)} = 4.55 \times 10^{-4}\ M^{-1}\text{s}^{-1}$. Units: $M^{-1}\text{s}^{-1}$.

Solution 2

(d)

Mark scheme

- Ion-dipole attractions are present between I_3^- ions and water but not between I_2 molecules and water. Because I_3^- is a charged ion, it attracts the polar water molecules via ion-dipole forces, giving it much greater solubility than the neutral, nonpolar I_2.

Question 4

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. -

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

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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

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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 g $CH_3OH \times \dfrac{1 \text{ mol } CH_3OH}{32.04 \text{ g } CH_3OH} \times \dfrac{-37.6 \text{ kJ}}{1 \text{ mol } CH_3OH} = -10.1$ 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 |

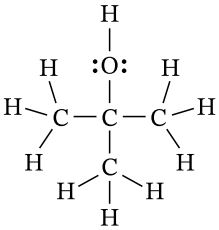
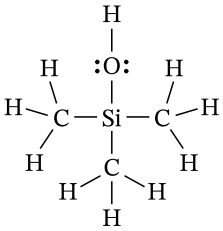
(a) Based on VSEPR theory, predict the geometry around the Si atom in compound Y.

(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

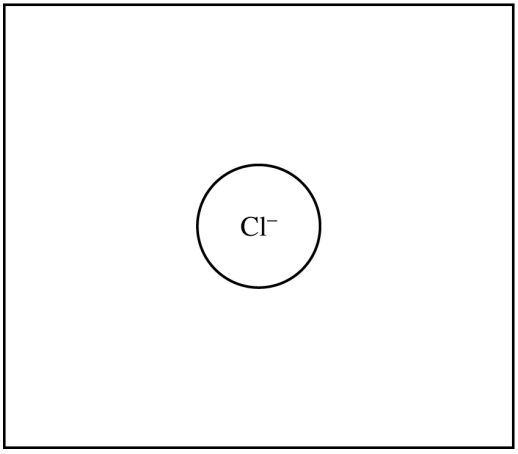
- Using $PV = nRT$: $n = \dfrac{PV}{RT} = \dfrac{(2.30\ \text{atm})(12.5\ \text{L})}{(0.08206\ \frac{\text{L·atm}}{\text{K·mol}})(471\ \text{K})} = 0.744\ \text{mol}.$

Question 5

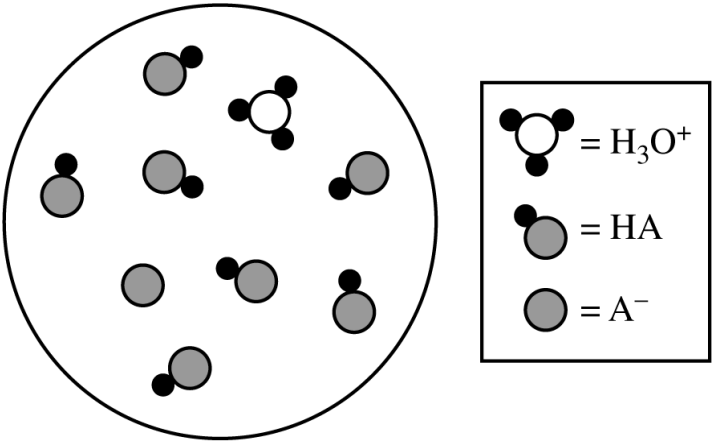
2023 ▪ Q5

HCl is a molecular gas as a pure substance but acts as an acid in aqueous solution.
(a)(i) A sample of HCl(g) is stored in a rigid 6.00 L container at 7.45 atm and 296 K. Calculate the number of moles of HCl(g) in the container.
(a)(ii) The rigid 6.00 L container of HCl(g) is cooled to a temperature of 271 K. Calculate the new pressure, in atm, of the HCl(g).

Question 5



Question 5



Question 5

2023 ▪ Q5

HCl is a molecular gas as a pure substance but acts as an acid in aqueous solution.

(b) When HCl ionizes in aqueous solution, $Cl^-(aq)$ ions are formed. In the following box, draw three water molecules with proper orientation around the Cl^- ion. Use [a water-molecule symbol: a large circle (O) with two small circles (H) attached] to represent water molecules.

[Empty square box with a small circle labeled Cl^- at its center, for the student to draw three water molecules around.]

Question 5

2023 ▪ Q5

HCl is a molecular gas as a pure substance but acts as an acid in aqueous solution.

(c) | Acid (HA) | Anion (A^-) | K_a Value | |—|—|—| | HNO_2 | NO_2^- | 5.6×10^{-4} | | HCl | Cl^- | 2.0×10^7 | | $HClO_4$ | ClO_4^- | 1.6×10^{15} |

The K_a values for three acids are shown in the preceding table.

The following particulate diagram represents the ionization of one of the acids in the data table. Water molecules have been omitted for clarity. Which acid (HNO_2, HCl, or $HClO_4$) is represented in the diagram? Justify your answer using the information in the table.

[Particle diagram: a large circle containing several small particle pairs; legend shows three symbols: a three-circle cluster (two small white circles bonded to one larger white circle) = H_3O^+; a gray circle with a small black dot attached = HA; a plain gray circle = A^-. Inside the large circle: two H_3O^+-like clusters, several HA (gray-with-dot)

Question 5

particles, and several bare A^- (plain gray) particles scattered about — roughly equal numbers of HA and A^- particles with two H_3O^+ clusters, suggesting near-complete/extensive ionization.]

Solution 5

(a)(i)

Mark scheme

- Ideal gas law: $n = \dfrac{PV}{RT} = \dfrac{(7.45\ \text{atm})(6.00\ \text{L})}{\left(0.08206\ \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}}\right)(296\ \text{K})} = 1.84\ \text{mol}.$

Solution 5

(a)(ii)

Mark scheme

- At constant volume and moles, $\frac{P_1}{T_1} = \frac{P_2}{T_2} \Rightarrow P_2 = \frac{P_1 T_2}{T_1} = \frac{(7.45\ \text{atm})(271\ \text{K})}{296\ \text{K}} = 6.82\ \text{atm}$ (equivalently via $P = nRT/V$ using $n = 1.84$ mol).

Solution 5

(b)

Mark scheme

- Draw three water molecules arranged around the central Cl^- ion with the partially-positive hydrogen (H) atom of each water molecule pointed inward, toward the Cl^- ion — reflecting the ion-dipole attraction between the negative Cl^- and the $\delta+$ H atoms of water.

Solution 5

(c)

Mark scheme

- HNO_2. The particulate diagram shows most of the acid molecules still in un-ionized (molecular) form, indicating a weak acid with a K_a value less than 1 — much less than the fully-dissociated strong acids HCl or $HClO_4$ in the table — which is consistent with HNO_2.

Question 6

2023 ▪ Q6

Answer the following questions related to HBr(l) and HF(l).

(a) In the following table, list all of the types of intermolecular forces present in pure samples of HBr(l) and HF(l).

Liquid	HBr(l)	HF(l)
Intermolecular forces present		

(b)(i) The enthalpy of vaporization, ΔH°_{vap}, for each liquid is provided in the following table.

Liquid	HBr(l)	HF(l)
ΔH°_{vap}	17.3 kJ/mol	25.2 kJ/mol

Based on the types and relative strengths of intermolecular forces, explain why ΔH°_{vap} of HF(l) is greater than that of HBr(l).

(b)(ii) Calculate the amount of thermal energy, in kJ, required to vaporize 6.85 g of HF(l).

Question 6

(c) Based on the arrangement of electrons in the Br and F atoms, explain why the bond length in an HBr molecule is greater than that in an HF molecule.

Solution 6

(a)

Mark scheme

- HBr(l): London dispersion forces and dipole-dipole attractions. HF(l): London dispersion forces, dipole-dipole attractions, and hydrogen bonding.

Solution 6

(b)(i)

Mark scheme

- ΔH°_{vap} is greater for HF(l) than HBr(l) because the overall intermolecular forces in HF(l) are stronger than those in HBr(l), due to the hydrogen bonding present in HF(l) (in addition to dispersion and dipole-dipole forces), so more energy is required to separate the HF(l) molecules.

Solution 6

(b)(ii)

Mark scheme

- $6.85\ \text{g HF} \times \dfrac{1\ \text{mol}}{20.01\ \text{g}} \times \dfrac{25.2\ \text{kJ}}{1\ \text{mol}} = 8.63\ \text{kJ}.$

Solution 6

(c)

Mark scheme

- Br has two additional occupied electron shells (n = 3 and n = 4) compared to F (n = 2). These extra electron shells increase the distance between the H and Br nuclei (larger atomic/covalent radius for Br), giving the H–Br bond a greater bond length than the H–F bond.

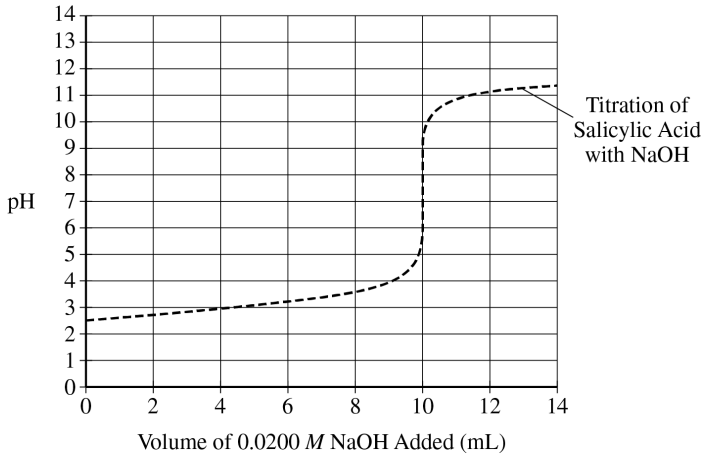
Question 1

2022 ▪ Q1

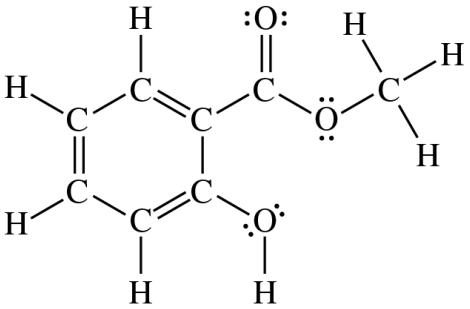
A student reacts 0.300 g of methyl salicylate ($C_8H_8O_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($HC_7H_5O_3$).

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

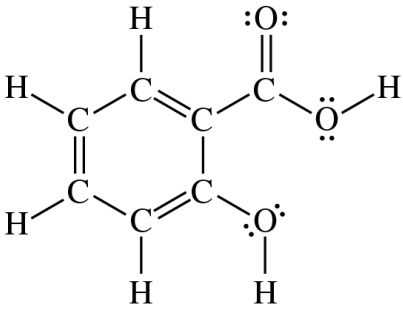
Question 1


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

Question 1

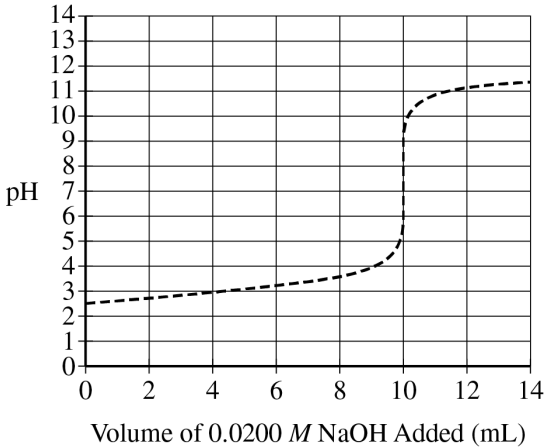


Methyl Salicylate
Melting Point: –9°C



Salicylic Acid
Melting Point: 159°C

Question 1


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

Question 1

2022 ▪ Q1

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

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

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

The student's experiment results in an 87

Question 1

2022 ▪ Q1

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

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

Question 1

2022 ▪ Q1

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

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

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

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

Question 1

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

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

Question 1

2022 ▪ Q1

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

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

Question 1

2022 ▪ Q1

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

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

Question 1

2022 ▪ Q1

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

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

Question 1

2022 ▪ Q1

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

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

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

Question 1

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

Solution 1

(a)

Mark scheme

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

Solution 1

(b)

Mark scheme

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

Solution 1

(c)

Mark scheme

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

Solution 1

(d)

Mark scheme

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

Solution 1

(e)

Mark scheme

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

Solution 1

(f)

Mark scheme

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

Solution 1

(g)

Mark scheme

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

Solution 1

(h)

Mark scheme

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

Question 4

2022 ▪ Q4

Answer the following questions about the compounds NH_2Cl and NCl_3. The Lewis electron-dot diagrams of the two compounds are shown.

[Two Lewis electron-dot structures shown side by side. Left (NH_2Cl): a central N atom bonded to two H atoms and one Cl atom, with one lone pair on N and three lone pairs on Cl — drawn as H–N(–H)–Cl with the lone pair over N and three lone pairs around Cl. Right (NCl_3): a central N atom bonded to three Cl atoms, with one lone pair on N and three lone pairs on each Cl atom — drawn as Cl–N(–Cl)–Cl with a lone pair over N and three lone pairs around each Cl.]

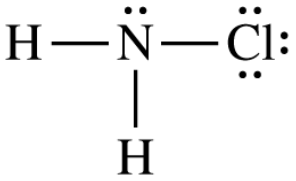
(a) Calculate the number of moles of NH_2Cl (molar mass 51.48 g/mol) present in 1.0 L of a solution in which the concentration of NH_2Cl is 0.0016 g/L.

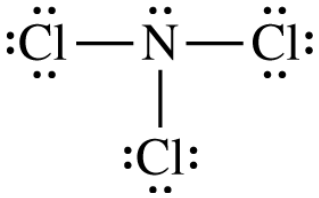
Question 4

(b) NH_2Cl is highly soluble in water, whereas NCl_3 is nearly insoluble. Explain this observation in terms of the types and relative strengths of the intermolecular forces between each of the solutes and water.

(c) The value of $\Delta H^{\circ}_{vaporization}$ for $NCl_3(l)$ is 32.9 kJ/mol. Calculate the amount of energy required to vaporize a 15.0 g sample of NCl_3 (molar mass 120.36 g/mol).

Question 4





Solution 4

(a)

Mark scheme

- 1 L $\times$ (0.0016 g / 1 L) $\times$ (1 mol / 51.48 g) $= 3.1 \times 10$ mol.

Solution 4

(b)

Mark scheme

- Identification of intermolecular forces (1 point): both NH2Cl and NCl3 can participate in hydrogen bonding with water (or equivalently, both have dipole-dipole attractions to water). Explanation (1 point): the intermolecular forces between NH2Cl molecules and water are stronger than those between NCl3 molecules and water, which leads to the greater solubility of NH2Cl in water.

Solution 4

(c)

Mark scheme

- 15.0 g NCl_3 $\times$ (1 mol / 120.36 g) $\times$ (32.9 kJ / 1 mol) $=$ 4.10 kJ.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

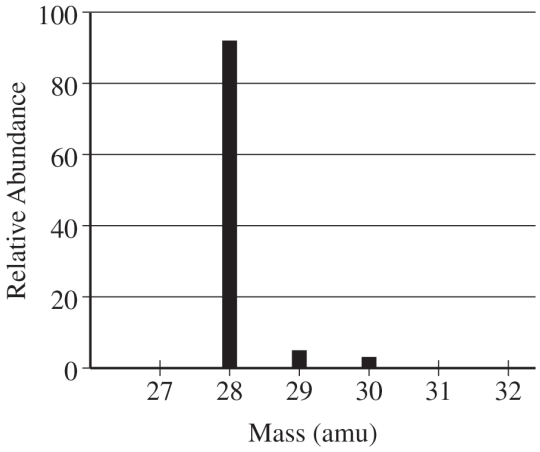
(a)(i) The mass spectrum of a pure sample of Si is shown below.

[Bar graph: Relative Abundance (y-axis, 0 to 100) vs. Mass (amu) (x-axis, 27 to 32). A tall bar of relative abundance ~92 at mass 28; a very small bar at mass 29 (~3); a very small bar at mass 30 (~4); negligible/no bars at 27, 31, 32.]

How many protons and how many neutrons are in the nucleus of an atom of the most abundant isotope of Si?

(a)(ii) Write the ground-state electron configuration of Si.

Question 2



Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(b) Two compounds that contain Si are SiO_2 and SiH_4.

At 161 K, SiH_4 boils but SiO_2 remains as a solid. Using principles of interparticle forces, explain the difference in boiling points.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(c) At high temperatures, SiH_4 decomposes to form solid silicon and hydrogen gas. Write a balanced equation for the reaction.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(d) A table of absolute entropies of some substances is given below.

Substance	S° (J/(mol $\cdot$ K))
$H_2(g)$	131
$Si(s)$	18
$SiH_4(g)$	205

Explain why the absolute molar entropy of $Si(s)$ is less than that of $H_2(g)$.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(e) Calculate the value, in J/(mol $\cdot$ K), of ΔS° for the reaction.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(f) The reaction is thermodynamically favorable at all temperatures. Explain why the reaction occurs only at high temperatures.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(g) A partial photoelectron spectrum of pure Si is shown below. On the spectrum, draw the missing peak that corresponds to the electrons in the $3p$ sublevel.

[Photoelectron spectrum: Relative Number of Electrons (y-axis) vs. Binding Energy (MJ/mol) (x-axis, logarithmic scale decreasing left to right: 1,000, 100, 10, 1, 0.1). Peaks shown (from left to right, i.e. highest to lowest binding energy): a small peak near ~180 (between 1,000 and 100), a small peak near ~20 (between 100 and 10), a tall peak near ~10, and a small peak near ~1.5 (between 1 and 0.1). No peak is shown corresponding to the $3p$ sublevel — the student must draw it in at the appropriate position and relative height.]

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(h) Using principles of atomic structure, explain why the first ionization energy of Ge is lower than that of Si.

Question 2

2021 ▪ Q2

Answer the following questions about the element Si and some of its compounds.

(i) A single photon with a wavelength of 4.00×10^{-7} m is absorbed by the Si sample. Calculate the energy of the photon in joules.

Solution 2

(a)(i)

Mark scheme

- The mass spectrum's tallest peak (highest relative abundance, ~92%) is at mass 28, so Si-28 is the most abundant isotope. Silicon's atomic number is 14, so this isotope has 14 protons and $(28 - 14 =)$ 14 neutrons.

(a)(ii)

Mark scheme

- Accept either equivalent form of the ground-state electron configuration of Si: $1s^2 2s^2 2p^6 3s^2 3p^2$, or the noble-gas-core notation $[\text{Ne}]3s^2 3p^2$.

Solution 2

(b)

Mark scheme

- SiH4 is composed of discrete molecules, so the only intermolecular forces between SiH4 molecules are (relatively weak) London dispersion forces. SiO2, by contrast, is a network covalent solid with strong covalent Si–O bonds extending throughout the entire structure. Because London dispersion forces are much weaker than covalent bonds, SiH4 boils at a much lower temperature (it is already a gas at 161 K) while SiO2 remains solid.

Solution 2

(c)

Mark scheme

- $SiH_4(g) \rightarrow Si(s) + 2\,H_2(g)$ (state symbols not required; equation is already balanced).

Solution 2

(d)

Mark scheme

- H2(g) molecules are more highly dispersed (able to move freely and occupy a much larger volume) than Si(s) atoms, and therefore have higher absolute molar entropy. Silicon is a solid, so its atoms are held in fixed positions within the lattice, are far less dispersed, and consequently have lower absolute molar entropy than H2(g).

Solution 2

(e)

Mark scheme

- $\Delta S^\circ_{rxn} = S^\circ_{\text{products}} - S^\circ_{\text{reactants}} = [18 + 2(131)] - 205 = +75$ J/(mol$_{rxn}$ · K), using S°: Si(s)=18, H2(g)=131 ($\times$2 mol), SiH4(g)=205, all in J/(mol · K).

Solution 2

(f)

Mark scheme

- High temperature is required so the reactant SiH4 molecules have sufficient thermal (kinetic) energy to overcome the activation energy barrier of the reaction. A negative ΔG° (thermodynamic favorability) only indicates the reaction is spontaneous, not that it proceeds at an appreciable rate at low temperature — reaction rate is a kinetic property governed separately by activation energy.

Solution 2

(g)

Mark scheme

- The missing peak (representing the Si 3p electrons) should be drawn as the rightmost peak on the spectrum — i.e., at the lowest binding energy (below the existing 1 MJ/mol region), since 3p electrons are Si's outermost/valence electrons and thus the most weakly bound. Its height should reach the second gridline above the horizontal axis, reflecting that the 3p sublevel holds 2 electrons.

Solution 2

(h)

Mark scheme

- The valence electrons of a Ge atom occupy a higher principal energy level/shell (n=4) than those of a Si atom (n=3), so the average distance between the nucleus and the valence electrons is greater in Ge than in Si. This greater separation results in weaker Coulombic attraction between the Ge nucleus and its valence electrons, making them less tightly bound and therefore easier to remove — giving Ge a lower first ionization energy than Si.

Solution 2

(i)

Mark scheme

- $E = h\nu = h\dfrac{c}{\lambda} = (6.626 \times 10^{-34}\ \text{J} \cdot \text{s})\left(\dfrac{2.998 \times 10^{8}\ \text{m/s}}{4.00 \times 10^{-7}\ \text{m}}\right) = 4.97 \times 10^{-19}\ \text{J}.$

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

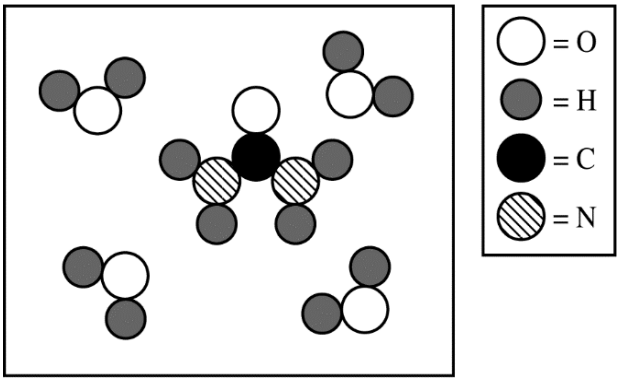
Stirring Rod

Bottle of Urea

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 $J/(g \cdot °C)$, 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 ΔS°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 ΔG°, where $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$. Since ΔS° is positive, the $-T\Delta S^\circ$ term is negative, making ΔG° smaller (more negative) and thus making the dissolution more thermodynamically favorable — supporting the student's claim. 1 point for this reasoning.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(a) The molecular formulas of diatomic bromine, chlorine, fluorine, and iodine are written below. Circle the formula of the molecule that has the longest bond length. Justify your choice in terms of atomic structure.

$$Br_2 \qquad Cl_2 \qquad F_2 \qquad I_2$$

A chemistry teacher wants to prepare Br_2. The teacher has access to the following three reagents: $NaBr(aq)$, $Cl_2(g)$, and $I_2(s)$.

| Half-Reaction | E° at 25°C (V) | |—|—| | $Br_2 + 2\,e^- \rightarrow 2\,Br^-$ | 1.07 | | $Cl_2 + 2\,e^- \rightarrow 2\,Cl^-$ | 1.36 | | $I_2 + 2\,e^- \rightarrow 2\,I^-$ | 0.53 |

Question 2

Half-Reaction	$E°$ at 25°C (V)
$Br_2 + 2\ e^- \rightarrow 2\ Br^-$	1.07
$Cl_2 + 2\ e^- \rightarrow 2\ Cl^-$	1.36
$I_2 + 2\ e^- \rightarrow 2\ I^-$	0.53

Question 2

Bond	Bond Energy (kJ/mol)
Br – Br	193
Cl – Cl	243
Br – Cl	?

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(b) Using the data in the table above, write the balanced equation for the thermodynamically favorable reaction that will produce Br_2 when the teacher combines two of the reagents. Justify that the reaction is thermodynamically favorable by calculating the value of E° for the reaction.

Br_2 and Cl_2 can react to form the compound BrCl.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(c) The boiling point of Br_2 is 332 K, whereas the boiling point of BrCl is 278 K. Explain this difference in boiling point in terms of all the intermolecular forces present between molecules of each substance.

The compound BrCl can decompose into Br_2 and Cl_2, as represented by the balanced chemical equation below.

$$2\,BrCl(g) \rightleftharpoons Br_2(g) + Cl_2(g) \qquad \Delta H^\circ = 1.6 \text{ kJ/mol}_{rxn}$$

A 0.100 mole sample of pure $BrCl(g)$ is placed in a previously evacuated, rigid 2.00 L container at 298 K. Eventually the system reaches equilibrium according to the equation above.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(d) Calculate the pressure in the container before equilibrium is established.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(e) Write the expression for the equilibrium constant, K_{eq}, for the decomposition of BrCl.

After the system has reached equilibrium, 42 percent of the original BrCl sample has decomposed.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(f) Determine the value of K_{eq} for the decomposition reaction of BrCl at 298 K.

Question 2

2019 ▪ Q2

Answer the following questions relating to the chemistry of the halogens.

(g) Calculate the bond energy of the Br-Cl bond, in kJ/mol, using ΔH° for the reaction (1.6 kJ/mol_{rxn}) and the information in the following table.

Bond	Bond Energy (kJ/mol)
$Br-Br$	193
$Cl-Cl$	243
$Br-Cl$	?

Solution 2

(a)

Mark scheme

- I2 (circled). I2 has the longest bond length because the atomic radius of I is greater than the radii of the other halogen atoms (Br, Cl, F), so the internuclear distance between the two bonded I atoms is greater than in the other diatomic halogens. 1 point for circling I2 with a valid atomic-structure justification.

Solution 2

(b)

Mark scheme

- Balanced equation (Cl2 is a strong enough oxidizer to oxidize Br since E°(Cl2/Cl)=1.36 V > E°(Br2/Br)=1.07 V, whereas I2 cannot): 2 Br (aq) + Cl2(g) → Br2 + 2 Cl (aq). 1 point for the correct balanced equation. E° = E°(reduced species) − E°(oxidized species) = 1.36 V − 1.07 V = +0.29 V; a positive E° confirms the reaction is thermodynamically favorable. 1 point for the correct E° calculation.

Solution 2

(c)

Mark scheme

- Br2(l) has only London dispersion forces between its nonpolar molecules. BrCl(l) is polar, so it has both London forces and dipole-dipole forces. 1 point for correctly identifying the IMFs present in each substance. However, Br2 has a larger, more polarizable electron cloud than BrCl, so the London forces in Br2(l) are stronger than the combined (London + dipole-dipole) forces in BrCl(l); this is why Br2's boiling point (332 K) is higher than BrCl's (278 K) despite BrCl being polar. 1 point for this valid explanation invoking polarizability.

Solution 2

(d)

Mark scheme

- $P = nRT/V = (0.100\ \text{mol})(0.08206\ \text{L} \cdot \text{atm} \cdot \text{mol}^{-1} \cdot \text{K}^{-1})(298\ \text{K}) / (2.00\ \text{L})$ $= 1.22$ atm. 1 point for the correct pressure with consistent units.

Solution 2

(e)

Mark scheme

- Keq = [Br2][Cl2] / $[BrCl]^2$ (equivalently, in terms of partial pressures: Keq = P(Br2) · P(Cl2) / $P(BrCl)^2$). 1 point for a correct equilibrium expression.

Solution 2

(f)

Mark scheme

- ICE table (partial pressures, atm) for 2 BrCl(g) $\rightleftharpoons$ Br2(g) + Cl2(g): Initial 1.22, 0, 0; Change $-2x$, $+x$, $+x$; Equilibrium 0.71, 0.26, 0.26. Since 42% of BrCl decomposed, P(BrCl decomposed) $= (0.42)(1.22\ \text{atm}) = 0.51\ \text{atm} = 2x$, so $x = 0.26$ atm. 1 point for the correct stoichiometric (ICE) values at equilibrium. Keq $= (0.26)(0.26)/(0.71)^2 = 0.13$. 1 point for a Keq value consistent with the student's ICE table (a molar-concentration-based solution also earns full credit).

Solution 2

(g)

Mark scheme

- $\Delta H^\circ = \Sigma$(bond energies)broken $-$ Σ(bond energies)formed. 1.6 kJ/mol $=$ 2(Br—Cl bond energy) $-$ (193 kJ/mol $+$ 243 kJ/mol); (436 $+$ 1.6) kJ/mol $=$ 2(Br—Cl bond energy); Br—Cl bond energy $=$ 219 kJ/mol. 1 point for the correct calculation.

Question 4

2018 ▪ Q4

[Key: Sulfur atom = large gray circle; Carbon atom = small black circle; Oxygen atom = small white circle.]

| Compound | Molecular Structure | Boiling Point at 1 atm (K) | |—|—|—| | CS_2 | gray–black–gray (S=C=S, linear, symmetric) | 319 | | COS | gray–black–white (S=C=O, linear, asymmetric) | 223 |

The table above gives the molecular structures and boiling points for the compounds CS_2 and COS.

(a) In terms of the types and relative strengths of all the intermolecular forces in each compound, explain why the boiling point of $CS_2(l)$ is higher than that of $COS(l)$.

(b) A 10.0 g sample of $CS_2(l)$ is put in an evacuated 5.0 L rigid container. The container is sealed and heated to 325 K, at which temperature all of the $CS_2(l)$ has vaporized. What is the pressure in the container once all of the $CS_2(l)$ has vaporized?

Question 4

Sulfur atom = ● Carbon atom = ● Oxygen atom = ○

Compound	Molecular Structure	Boiling Point at 1 atm (K)
CS_2		319
COS		223

Solution 4

(a)

Mark scheme

- CS2 is nonpolar (linear, symmetric) and has only London dispersion forces. COS is polar (asymmetric) and has both London dispersion forces and dipole-dipole forces. However, the London dispersion forces in CS2 (larger, more polarizable S atoms on both ends) are stronger than the combined London dispersion + dipole-dipole forces in COS, so CS2 has the higher boiling point. 1 point is earned for correctly identifying all of the intermolecular forces in both molecules; 1 point is earned for a valid explanation of why CS2's IMFs are stronger overall.

Solution 4

(b)

Mark scheme

- 10.0 g CS2 x (1 mol CS2/76.13 g CS2) = 0.131 mol CS2. Using PV = nRT: P = nRT/V = (0.131 mol)(0.08206 L atm/(mol K))(325 K)/5.0 L = 0.70 atm. 1 point is earned for the correct number of moles of CS2; 1 point is earned for the correct calculation of pressure with appropriate units.