Past-paper walk-through

Energy of Phase Changes ▪ 6.5

eXercise

Questions in this set

- 2025 Q4
- 2023 Q6
- 2022 Q1
- 2022 Q4
- 2015 Q7

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 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

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

Question 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.

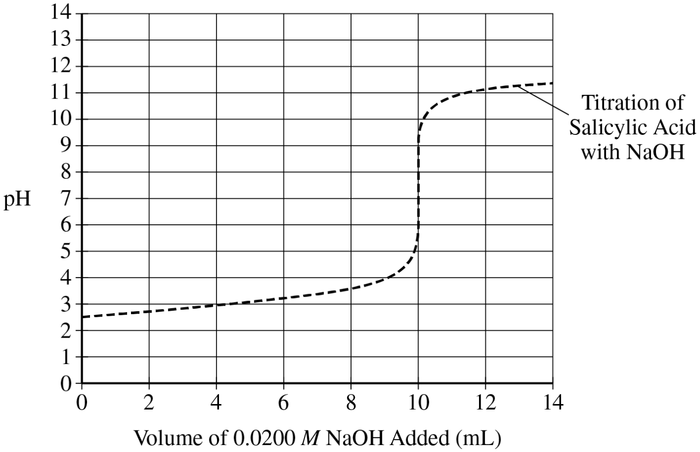
Question 1

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
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3
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pH
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2
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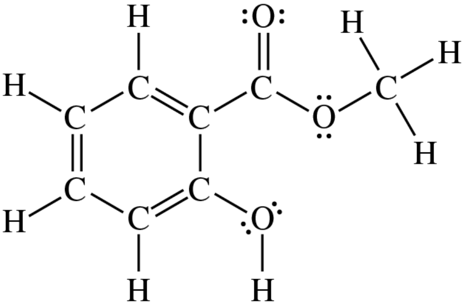
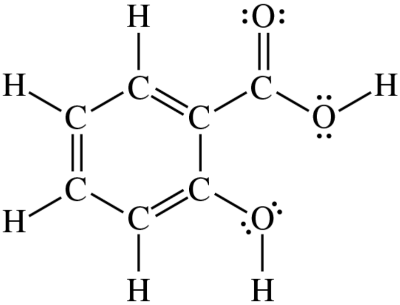
14
Volume of 0.0200 M NaOH Added (mL)
Titration of
Salicylic Acid
with NaOH

Question 1

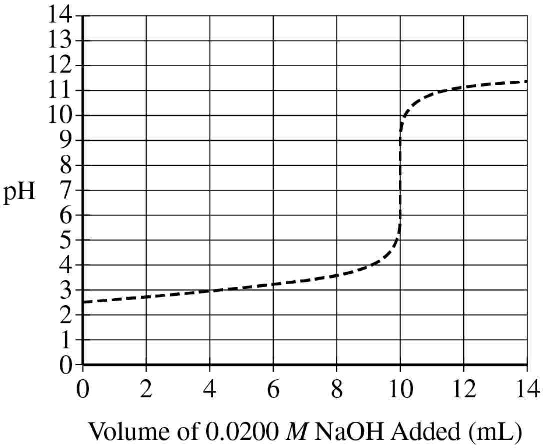


Methyl Salicylate
Melting Point: –9°C



Salicylic Acid
Melting Point: 159°C

Question 1



14
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pH
7
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3
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0
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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 $C8H8O3$ $\times$ (1 mol $C8H8O3$ / 152.15 g) $\times$ (1 mol $HC7H5O3$ / 1 mol $C8H8O3$) $\times$ (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 = $mc\Delta T$ = $(0.105\text{ g})(1.17\text{ J}/(\text{g}\cdot{}^\circ\text{C}))(159^\circ\text{C} - 25^\circ\text{C}) = 16.5\text{ J}$ (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, C7H5O3 , is present at higher concentration. Justification (either accepted): at pH $= 4.00$ the titration is beyond the half-equivalence point, where [HC7H5O3] $=$ [C7H5O3]; thus [C7H5O3] must be greater than [HC7H5O3]. 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

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

Solution 1

(h)

Mark scheme

- Sketch of the benzoic acid titration curve (consistent with part (g)): (1 point) the curve starts at pH ≈ 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

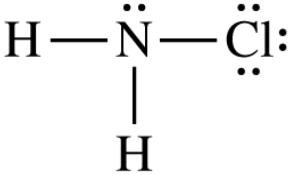
Answer the following questions about the compounds NH_2Cl and NCl_3. The Lewis electron-dot diagrams of the two compounds are shown.
[Two Lewis electron-dot structures shown side by side. Left (NH_2Cl): a central N atom bonded to two H atoms and one Cl atom, with one lone pair on N and three lone pairs 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.

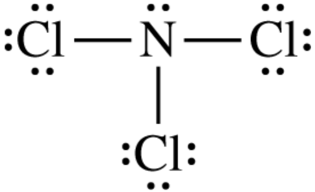
Question 4

(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

- $1\ \text{L} \times (0.0016\ \text{g} / 1\ \text{L}) \times (1\ \text{mol} / 51.48\ \text{g}) = 3.1 \times 10$ 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 NCl3 $\times$ (1 mol / 120.36 g) $\times$ (32.9 kJ / 1 mol) $=$ 4.10 kJ.

Question 7

2015 ▪ Q7

Aluminum metal can be recycled from scrap metal by melting the metal to evaporate impurities.

(a) Calculate the amount of heat needed to purify 1.00 mole of Al originally at 298 K by melting it. The melting point of Al is 933 K. The molar heat capacity of Al is 24 J/(mol · K), and the heat of fusion of Al is 10.7 kJ/mol.

(b) The equation for the overall process of extracting Al from Al_2O_3 is shown below. Which requires less energy, recycling existing Al or extracting Al from Al_2O_3? Justify your answer with a calculation.

$$\mathrm{Al_2O_3}(s) \rightarrow 2\mathrm{Al}(s) + \frac{3}{2}\mathrm{O_2}(g) \qquad \Delta H^\circ = 1675 \text{ kJ/mol}_{rxn}$$

Solution 7

(a)

Mark scheme

- To raise the temperature of 1.00 mol Al from 298 K to its melting point, 933 K: q = 24 J/(mol*K) x 1.00 mol x (933-298) K = 24 J/(mol*K) x 1.00 mol x 635 K = 15,000 J = 15 kJ (1 point for correctly calculating the heat needed to raise the temperature to 933 K). Then add the heat of fusion needed to melt the Al once at its melting point: 15 kJ + 10.7 kJ = 26 kJ total heat needed to purify (melt) the 1.00 mol Al (1 point for adding the heat of fusion to the previous result to reach the final answer, 26 kJ).

Solution 7

(b)

Mark scheme

- For extracting Al from Al2O3: the given reaction produces 2 mol Al per mol_rxn releasing/requiring 1675 kJ, so per mole of Al: 1675 kJ/mol_rxn x (1 mol rxn / 2 mol Al) = 837.5 kJ per mole of Al (1 point for a calculation that puts recycling and extraction on the same per-mole-Al basis for a fair comparison). Because 26 kJ (the recycling/melting energy from part (a)) is far less than 837.5 kJ (the energy to extract 1 mol Al from Al2O3), recycling existing Al requires less energy than extracting Al from its ore (1 point for the correct comparison and conclusion).