Past-paper walk-through

Solubility ▪ 3.10

eXercise

Questions in this set

- 2022 Q1
- 2021 Q6
- 2019 Q1

Reading the mark scheme

- **B1** a mark that stands on its own – the point is either made or not.
- **M1** a *method* mark: the right approach, even if the number is wrong.
- **A1** an *answer* mark, and it usually needs its M mark first.
- **C1** a working mark on the way to the answer.
- // separates answers the examiner accepts equally.
- **ecf** = error carried forward: a later part is marked on your own earlier answer.
- **owtte** = "or words to that effect" – the wording need not match.

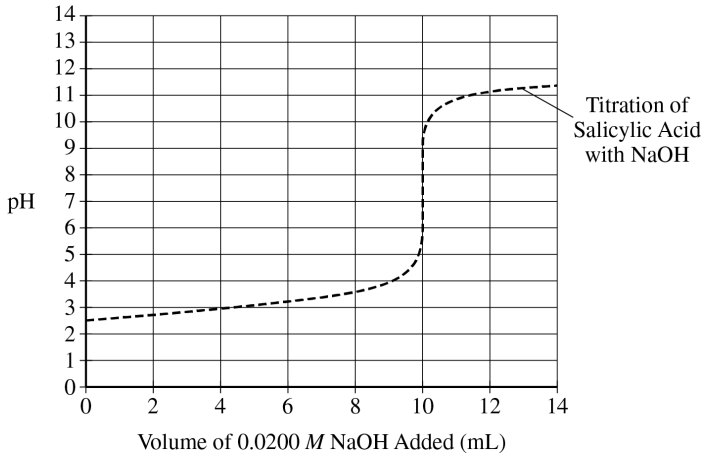
Question 1

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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12
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3
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pH
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2
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8
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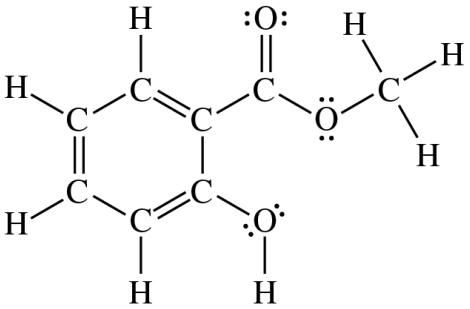
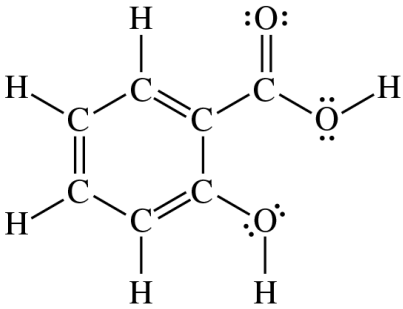
12
14
Volume of 0.0200 *M* NaOH Added (mL)
Titration of
Salicylic Acid
with NaOH

Question 1

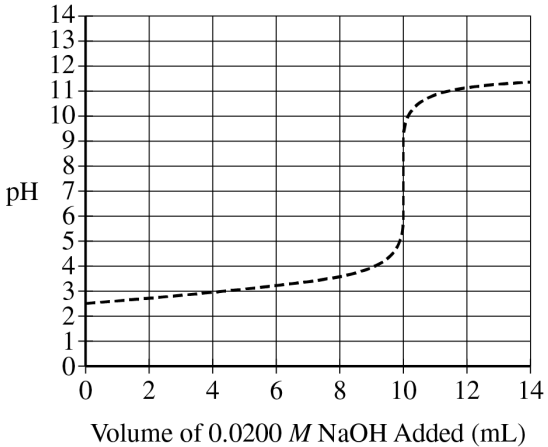


Methyl Salicylate
Melting Point: –9°C



Salicylic Acid
Melting Point: 159°C

Question 1


pH
14
13
12
11
10
9
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7
6
5
4
3
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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 $= mc\Delta T = (0.105\ \text{g})(1.17\ \text{J/(g} \cdot \text{°C}))(159\text{°C} - 25\text{°C}) = 16.5\ \text{J}$ (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 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.

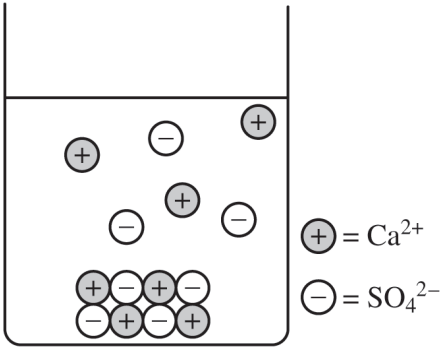
Question 6

2021 ▪ Q6

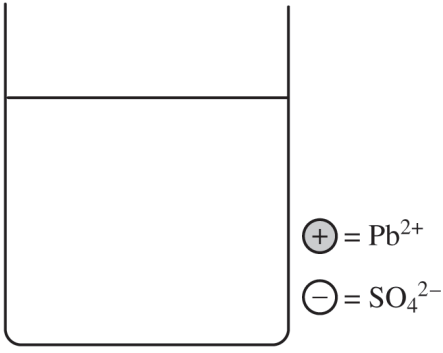
A student is studying the properties of $CaSO_4$ and $PbSO_4$. The student has samples of both compounds, which are white powders.

(a) The student tests the electrical conductivity of each solid and observes that neither solid conducts electricity. Describe the structures of the solids that account for their inability to conduct electricity.

Question 6



Higher Conductivity Solution



Lower Conductivity Solution

Question 6

2021 ▪ Q6

A student is studying the properties of $CaSO_4$ and $PbSO_4$. The student has samples of both compounds, which are white powders.

(b) The student places excess $CaSO_4(s)$ in a beaker containing 100 mL of water and places excess $PbSO_4(s)$ in another beaker containing 100 mL of water. The student stirs the contents of the beakers and then measures the electrical conductivity of the solution in each beaker. The student observes that the conductivity of the solution in the beaker containing the $CaSO_4(s)$ is higher than the conductivity of the solution in the beaker containing the $PbSO_4(s)$.

Which compound is more soluble in water, $CaSO_4(s)$ or $PbSO_4(s)$? Justify your answer based on the results of the conductivity test.

Question 6

2021 ▪ Q6

A student is studying the properties of $CaSO_4$ and $PbSO_4$. The student has samples of both compounds, which are white powders.

(c) The left side of the diagram below shows a particulate representation of the contents of the beaker containing the $CaSO_4(s)$ from the solution conductivity experiment.

[Diagram: two beakers side by side, each containing liquid. Left beaker, labeled "Higher Conductivity Solution": scattered small circles marked "+" (labeled Ca^{2+}) and "−" (labeled SO_4^{2-}) floating individually in the liquid (several of each, dispersed), plus a small cluster of undissolved solid at the bottom made of alternating "+" and "−" circles packed together. Right beaker, labeled "Lower Conductivity Solution": empty/blank, to be filled in by the student, with the same legend $+ = Pb^{2+}$, $- = SO_4^{2-}$.]

Question 6

Draw a particulate representation of $PbSO_4(s)$ and the ions dissolved in the solution in the beaker on the right in the diagram. Draw the particles to look like those shown to the right of the beaker. Draw an appropriate number of dissolved ions relative to the number of dissolved ions in the beaker on the left.

Question 6

2021 ▪ Q6

A student is studying the properties of $CaSO_4$ and $PbSO_4$. The student has samples of both compounds, which are white powders.

(d) The student attempts to increase the solubility of $CaSO_4(s)$ by adding 10.0 mL of 2 M $H_2SO_4(aq)$ to the beaker, and observes that additional precipitate forms in the beaker. Explain this observation.

Solution 6

(a)

Mark scheme

- Ionic solids do not have free-moving (mobile) ions — the ions are locked in fixed positions within the rigid crystal lattice — so there are no charge carriers able to move through the solid. Therefore there is no conduction of electricity.

Solution 6

(b)

Mark scheme

- CaSO4. The greater electrical conductivity of the CaSO4(aq) solution relative to the PbSO4(aq) solution implies a higher concentration of dissolved ions, which comes from CaSO4 dissolving/dissociating to a greater extent than PbSO4 — i.e., CaSO4 is more soluble than PbSO4.

Solution 6

(c)

Mark scheme

- The particulate diagram for the (lower-conductivity) PbSO4 beaker should show solid PbSO4 undissolved at the bottom (drawn similarly to the solid CaSO4 shown in the higher-conductivity beaker), together with fewer dissociated Pb2+ and SO4^2- ions dispersed in the solution than are shown in the CaSO4 beaker — reflecting PbSO4's lower solubility — while still showing an equal number of Pb2+ cations and SO4^2- anions in solution (1:1 stoichiometry / charge balance).

Solution 6

(d)

Mark scheme

- The additional precipitate is CaSO4 that forms in response to the increased [SO4^2-] introduced by the added H2SO4(aq). By Le Chatelier's principle (the reaction quotient Q now exceeds Ksp), the added common ion SO4^2- shifts the dissolution equilibrium of CaSO4 toward the solid, forming more CaSO4(s) — the common-ion effect.

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

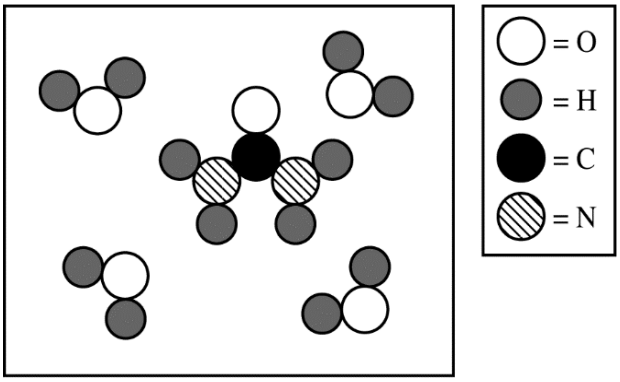
Stirring Rod

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.