2022

AP CollegeBoard

AP® Chemistry

Sample Student Responses and Scoring Commentary

Inside:

Free-Response Question 1

☑ Scoring Guidelines

☑ Student Samples

☑ Scoring Commentary

Question 1: Long Answer — 10 points

(a) For the correct calculated value: **1 point**

$$0.300 \text{ g } C_8H_8O_3 \times \frac{1 \text{ mol } C_8H_8O_3}{152.15 \text{ g}} \times \frac{1 \text{ mol } HC_7H_5O_3}{1 \text{ mol } C_8H_8O_3} \times \frac{138.12 \text{ g}}{1 \text{ mol } HC_7H_5O_3} = 0.272 \text{ g } HC_7H_5O_3$$

(b) For the correct answer and a valid justification: **1 point**

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%.

(c) For the correct calculated value of either q: **1 point**

Accept one of the following:

- $q_{heat} = mc\Delta T = (0.105 \text{ g})(1.17 \text{ J/(g} \cdot {}^\circ\text{C}))(159^\circ\text{C} - 25^\circ\text{C}) = 16.5 \text{ J}$
- $q_{melt} = 0.105 \text{ g} \times \frac{1 \text{ mol}}{138.12 \text{ g}} \times \frac{27{,}100 \text{ J}}{1 \text{ mol}} = 20.6 \text{ J}$

For the correct calculated value of the other q and the total heat: **1 point**

$q_{total} = q_{heat} + q_{melt} = 16.5 \text{ J} + 20.6 \text{ J} = 37.1 \text{ J}$

Total for part (c) — 2 points

(d) For a correct explanation: **1 point**

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.

(e) For the correct answer: **1 point**

The pK_a *is approximately 3.*

(f) For the correct answer and a valid justification, consistent with part (e): **1 point**

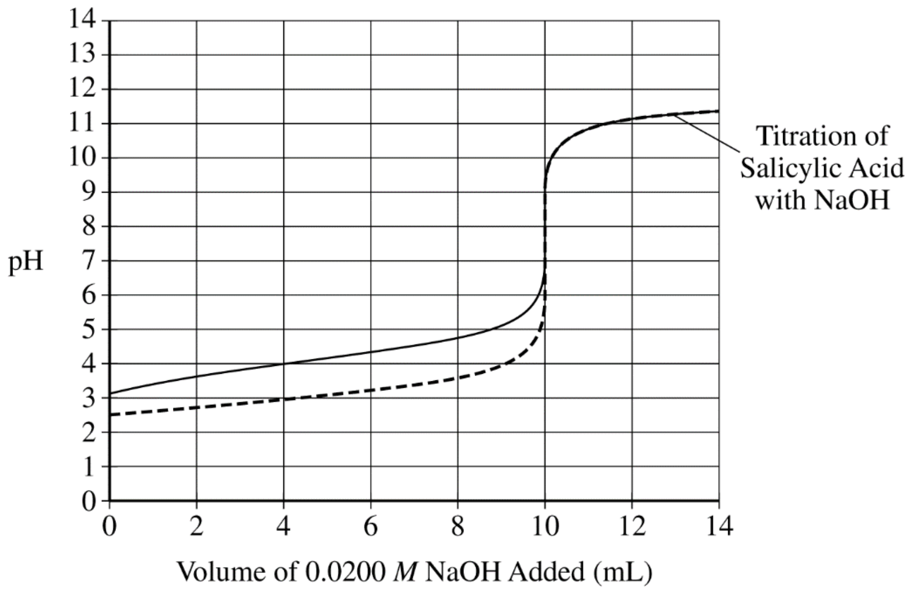
Accept one of the following:

- *The conjugate base,* $C_7H_5O_3^-$. *When* $pH = 4$, *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* $[HC_7H_5O_3]$.
- *The conjugate base,* $C_7H_5O_3^-$. *Because the* pH *of the solution is greater than the* pK_a *of the acid, the majority of the molecules will be deprotonated.*

(g) For the correct calculated value: **1 point**

$pK_a = -\log(6.3 \times 10^{-5}) = 4.20$

(h)	For a curve that shows a correct starting and half-equivalence point, consistent with part (g):	**1 point**
	The curve starts at $pH \approx 3.11$ *and passes through the* pK_a *calculated in part (g) at* 5 *mL*. *See example response below.*	
	For a curve that shows the correct equivalence point:	**1 point**
	The curve inflects vertically at 10 *mL showing the same volume of base needed to reach the equivalence point.*	



Total for part (h) 2 points

Total for question 1 10 points

Question 1

Begin your response to **QUESTION 1** on this page.

CHEMISTRY

SECTION II

Time—1 hour and 45 minutes

7 Questions

YOU MAY USE YOUR CALCULATOR FOR THIS SECTION.

Directions: Questions 1–3 are long free-response questions that require about 23 minutes each to answer and are worth 10 points each. Questions 4–7 are short free-response questions that require about 9 minutes each to answer and are worth 4 points each.

For each question, show your work for each part in the space provided after that part. Examples and equations may be included in your responses where appropriate. For calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer. Pay attention to significant figures.

1. 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.

$$0.300\,g \left| \frac{1\text{ mol } C_8H_8O_3}{152.15\text{ g}} \right| \frac{1\text{ mol } HC_7H_5O_3}{1\text{ mol } C_8H_8O_3} \left| \frac{138.12\text{ g}}{1\text{ mol } HC_7H_5O_3} \right| = \boxed{0.272\text{ g}}$$

GO ON TO THE NEXT PAGE.

Question 1

Continue your response to **QUESTION 1** on this page.

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

(b) The student's experiment results in an 87% yield of dry $HC_7H_5O_3$. The student suggests that some of the $HC_7H_5O_3$ crystals dissolved in the distilled water during the rinsing step. Is the student's claim consistent with the calculated percent yield value? Justify your answer.

Yes. The dissolution of $HC_7H_5O_3$ explains why the percent yield is less than 100%.

$HC_7H_5O_3$ is soluble in water (2.2 g/L)

(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 of 159°C and melt the crystals completely.

$q = mC\Delta T$

$q = \underset{g}{(0.105)}\underset{\frac{J}{g\cdot°C}}{(1.17)}\underset{°C}{(159-25)} = 16.5\ J$

$q = \text{mol}\,\Delta H°$

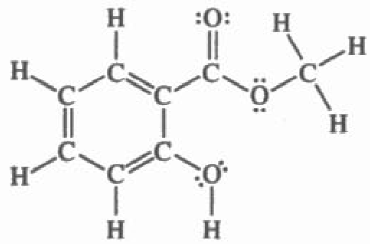
$= (0.105)\left(\frac{1}{138.12}\right)(27.1)(1000\ J) = 20.6\ J$

Total: **37.1 J**

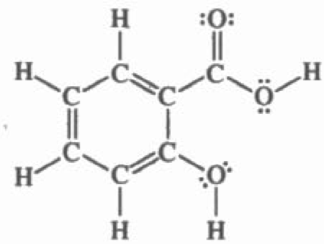
Question 1

Continue your response to **QUESTION 1** on this page.

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



Methyl Salicylate
Melting Point: –9°C

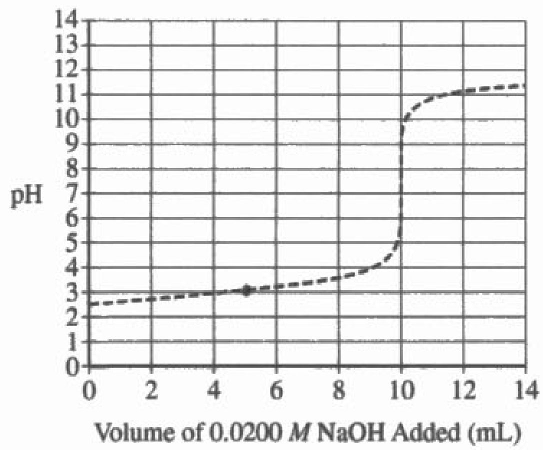


Salicylic Acid
Melting Point: 159°C

(d) 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.

The salicylic acid can hydrogen bond in two places whereas methyl salicylate can only ~~in~~ one.

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.



Question 1

Continue your response to **QUESTION 1** on this page.

(e) Using the information in the graph, estimate the pK_a of $HC_7H_5O_3$. 3

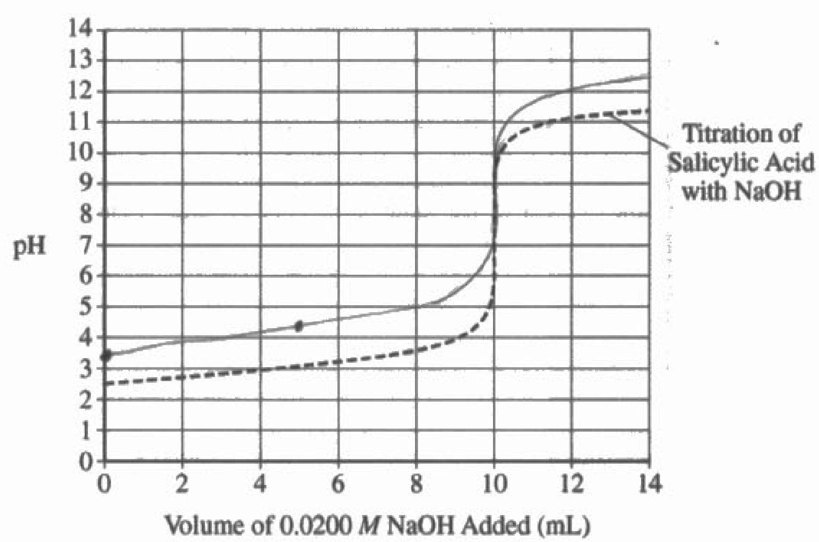
(f) When the pH of the titration mixture is 4.00, is there a higher concentration of the weak acid, $HC_7H_5O_3$, or its conjugate base, $C_7H_5O_3^-$, in the flask? Justify your answer.

Higher concentration of $C_7H_5O_3^-$ because pH of 4 is past the half-equivalence point, so more NaOH was added, leading to more conjugate base formed.

(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.

$-\log(K_a) = -\log(6.3 \times 10^{-5}) = 4.2$

(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.



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0078806

Q5119/5

Question 1

Begin your response to **QUESTION 1** on this page.

CHEMISTRY

SECTION II

Time—1 hour and 45 minutes

7 Questions

1:20
-2:50

YOU MAY USE YOUR CALCULATOR FOR THIS SECTION.

20

Directions: Questions 1–3 are long free-response questions that require about 23 minutes each to answer and are worth 10 points each. Questions 4–7 are short free-response questions that require about 9 minutes each to answer and are worth 4 points each.

For each question, show your work for each part in the space provided after that part. Examples and equations may be included in your responses where appropriate. For calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer. Pay attention to significant figures.

1. 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.

$$0.300\text{ g } C_8H_8O_3 \times \frac{1\text{ mol } C_8H_8O_3}{152.15\text{ g } C_8H_8O_3} = 0.00197\text{ mol } C_8H_8O_3$$

$$0.00197\text{ mol } C_8H_8O_3 \times \frac{1\text{ mol } HC_7H_5O_3}{1\text{ mol } C_8H_8O_3} \times \frac{138.12\text{ g } HC_7H_5O_3}{1\text{ mol } HC_7H_5O_3} = 0.272\text{ g } HC_7H_5O_3$$

0.272 g $HC_7H_5O_3$

Question 1

Continue your response to QUESTION 1 on this page.

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

(b) The student's experiment results in an 87% yield of dry $HC_7H_5O_3$. The student suggests that some of the $HC_7H_5O_3$ crystals dissolved in the distilled water during the rinsing step. Is the student's claim consistent with the calculated percent yield value? Justify your answer.

$HC_7H_5O_3$ has a high solubility and therefore the student's claim is inconsistent as very little to no $HC_7H_5O_3$ would have dissolved when placed with water.

(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 of 159°C and melt the crystals completely.

$q = mc\Delta T = 0.105\text{g} \times \frac{1.17\text{J}}{\text{g}\cdot{}^\circ\text{C}} \times (159^\circ\text{C} - 25^\circ\text{C}) = \boxed{16.5\text{ J}}$

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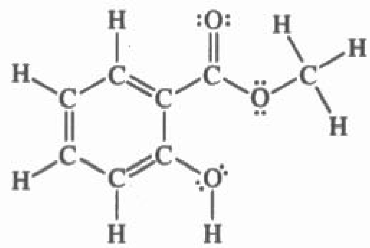
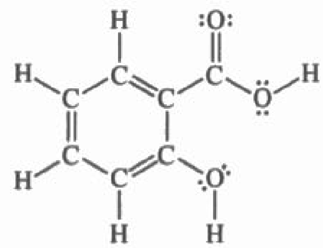
Question 1

Continue your response to QUESTION 1 on this page.

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



Methyl Salicylate
Melting Point: –9°C

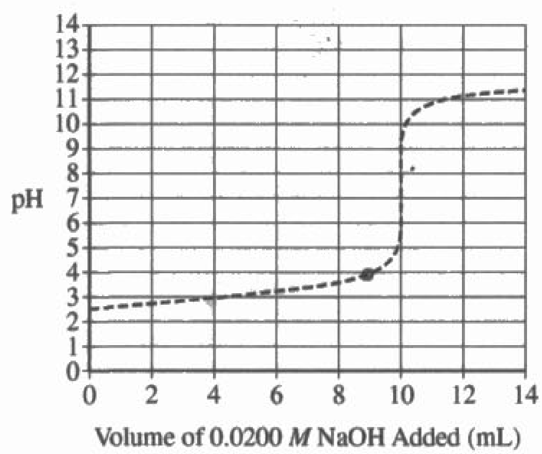


Salicylic Acid
Melting Point: 159°C

(d) 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.

Salicylic acid is more polarizeable because it has a larger electron cloud near the O atoms and therefore has stronger London dispersion forces than methyl salicylate.
Therefore salicylic acid has a higher melting point.

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.



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Question 1

Continue your response to **QUESTION 1** on this page.

(e) Using the information in the graph, estimate the pK_a of $HC_7H_5O_3$. 3.1

(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.

$HC_7H_5O_3$ and $C_7H_5O_3^-$ have ~~the~~ same stoichiometric coefficients. Since the pH <7, there is a higher concentration of the weak acid $HC_7H_5O_3$

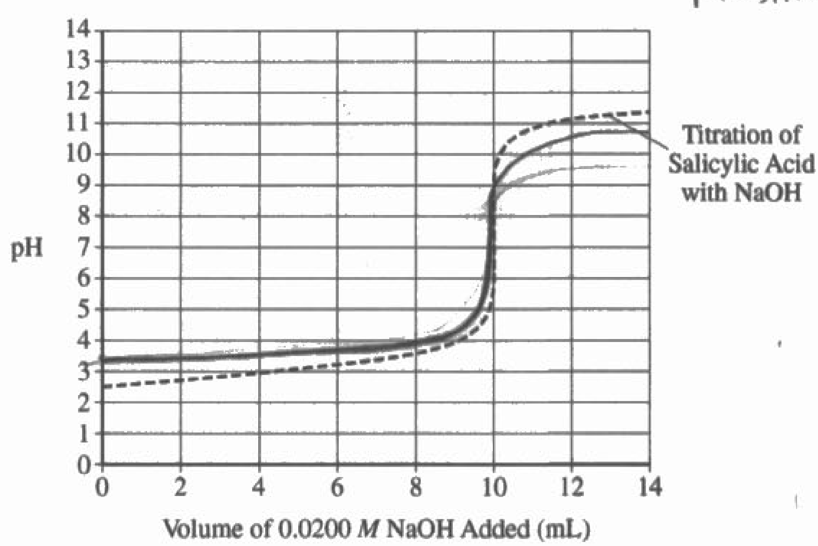
weak acid + strong base → weak base + strong acid

(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.

$pK_a = -\log K_a = -\log(6.3\times10^{-5}) = \boxed{4.2}$

(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.

14-3.11= 10.89



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0069138

Q5119/5

Question 1

Begin your response to **QUESTION 1** on this page.

CHEMISTRY

SECTION II

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7 Questions

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   (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.

$$0.300\,g\,C_8H_8O_3\left(\frac{1\,mol\,C_8H_8O_3}{152.15\,g/mol\,C_8H_8O_3}\right)\left(\frac{1\,mol\,HC_7H_5O_3}{1\,mol\,C_8H_8O_3}\right)\left(\frac{138.12\,g/mol\,HC_7H_5O_3}{1\,mol\,HC_7H_5O_3}\right)$$

$$= 0.272\,g\,HC_7H_5O_3$$

Question 1

Continue your response to **QUESTION 1** on this page.

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

(b) The student's experiment results in an 87% yield of dry $HC_7H_5O_3$. The student suggests that some of the $HC_7H_5O_3$ crystals dissolved in the distilled water during the rinsing step. Is the student's claim consistent with the calculated percent yield value? Justify your answer.

no, although it is clear that there was an error in the experiment it is unlikely that 13% of the $HC_7H_5O_3$ crystals dissolved in water.

(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 of 159°C and melt the crystals completely.

$q = mc\Delta t$

$q = (0.105g)(1.17J(g \cdot c))(159° - 25°)$

$q = 16.5J$

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Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

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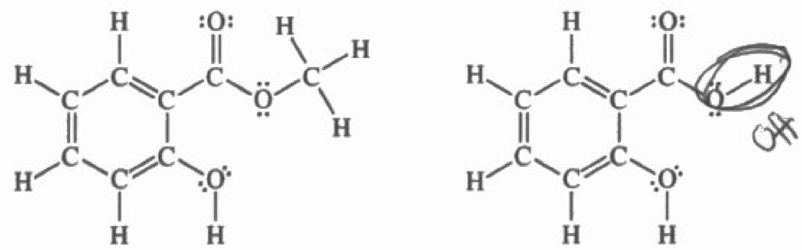
Q5119/3

Question 1

Continue your response to QUESTION 1 on this page.

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



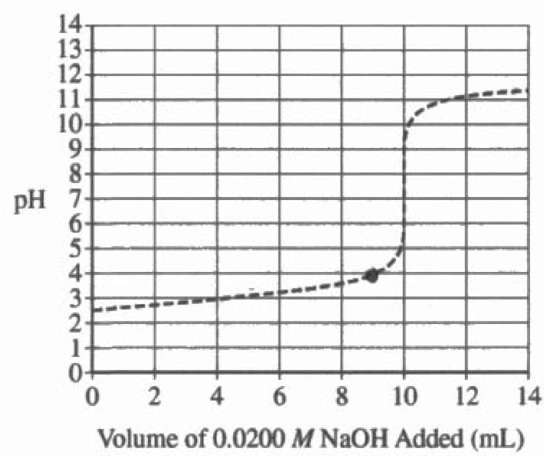
Methyl Salicylate
Melting Point: –9°C

Salicylic Acid
Melting Point: 159°C

(d) 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.

Salicylic acid has one more OH group than the structure shown for Methyl salicylate causing it to have a higher melting point

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.



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Question 1

Continue your response to **QUESTION 1** on this page.

(e) Using the information in the graph, estimate the pK_a of $HC_7H_5O_3$. 6

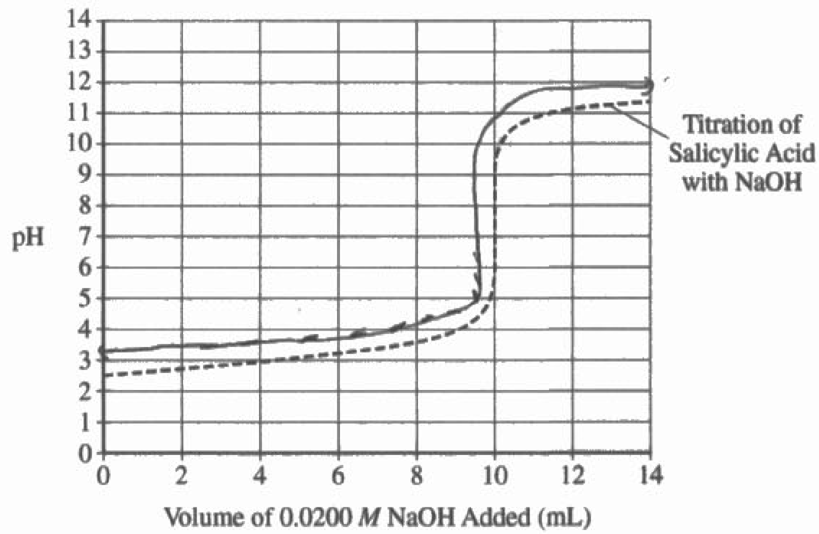
(f) When the pH of the titration mixture is 4.00, is there a higher concentration of the weak acid, $HC_7H_5O_3$, or its conjugate base, $C_7H_5O_3^-$, in the flask? Justify your answer.

The higher conentration is with $HC_7H_5O_3$ becaye the Ph is four the reaction is not basic enough to hold more $C_7H_5O_3$

(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.

$pK_a = 5$

(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.



Use a pencil or a pen with black or dark blue ink. Do NOT write your name. Do NOT write outside the box.

Question 1

Note: Student samples are quoted verbatim and may contain spelling and grammatical errors.

Overview

Question 1 presented students with a variety of questions concerning salicylic acid ($HC_7H_5O_3$).

Part (a) of this question required students to apply the concepts of stoichiometry (Learning Objective SPQ-4.A, Science Practice 5.F from the *AP Chemistry Course and Exam Description*) to predict the mass of salicylic acid produced from a given mass of methyl salicylate along with the mole ratio between the two substances.

Part (b) asked to justify a claim regarding the percent yield of the reaction in part (a) (SPQ-4.A, 6.G). The response expected students to justify that the loss of mass of the acid during the filtration process could be due to the solubility of the acid.

The intent of part (c) was for students to recognize that the amount of heat required to melt a sample of solid salicylic acid involves the sum of two quantities to determine the total heat required to complete the change of state: heat required to increase the temperature of the solid to the melting point and the heat required to melt the solid into the liquid phase (ENE-2.D, 5.F). Part (c) was worth 2 points. The first point was earned for the correct calculation of either the amount of energy required to heat the acid up to its melting point or the amount of energy required to melt the acid at its melting temperature. The second point was earned for correctly determining the other energy quantity and the sum of the energies for the two heating processes.

Part (d) required students to analyze the molecular structures of methyl salicylate and salicylic acid to explain the difference in the melting point of each substance based on the magnitudes of the given types of intermolecular forces present in each molecule (SAP-5.B, 4.C).

The students were provided a titration curve for the titration of a salicylic acid solution with NaOH in part (e). The students were asked to estimate the pK_a of the acid (SAP-9.C, 2.D).

Part (f) asked students to determine the relative concentrations of the species in a conjugate acid–base pair for salicylic acid at a point during the titration where the pH value is higher (more) than the pK_a determined in part (e) (SAP-9.D, 4.A).

Part (g) required that the students calculate the pK_a of benzoic acid given the K_a value (SAP-9.C, 5.F).

The titration curve of salicylic acid from part (e) was presented to the students in part (h). Given an initial pH of the benzoic acid solution and using the calculated pK_a value from part (g), students were asked to draw a representative titration curve for benzoic acid. Part (h) consisted of 2 points. The first point was earned for starting the curve at the correct initial pH of the benzoic acid (pH = 3.11) and drawing the curve through the pK_a of 4.2 at the half-equivalence point of the titration (5 mL). The second point was earned for indicating that the equivalence point is reached after 10 mL of NaOH has been added and that the overall shape of the titration curve is consistent with a weak acid/strong base titration. Both points align to SPQ-4.B and 3.A.

Question 1 (continued)

Sample: 1A
Score: 9

This response earned 9 points. In part (a) the point was earned for the correct answer with the correct number of significant figures. In part (b) the point was earned for relating the loss of yield to the solid dissolving in the rinse water. In part (c) the first point was earned for correctly calculating the heat absorbed as the temperature increased. The second point was earned for correctly calculating the heat absorbed during the phase change and the total amount of heat absorbed. In part (d) no point was earned because the response does not indicate that the intermolecular forces for salicylic acid are stronger because it has more hydrogen bonding than methyl salicylate does. In part (e) the point was earned for correctly identifying the pK_a to be approximately 3. In part (f) the point was earned for correctly indicating that the concentration of the base is higher than the concentration of the acid. This is true because the titration had passed the half-equivalence point, where the concentration of the acid and the conjugate base are equal. In part (g) the point was earned for correctly calculating the pK_a value. In part (h) the first point was earned for starting the curve near 3.11 and passing through pH 4.2 at 5 mL of NaOH added. The second point was earned for drawing the equivalence point at 10 mL of NaOH added.

Sample: 1B
Score: 5

This response earned 5 points. In part (a) the point was earned for calculating the correct answer with the correct number of significant figures. In part (b) no point was earned because the response states that the student's claim is inconsistent with the calculated percent yield because "very little to no" acid would dissolve. In part (c) the first point was earned for the correct calculation of the heat absorbed as the temperature increased. The second point was not earned because the heat of fusion and the total heat for the process are not calculated. In part (d) no point was earned because the response refers to electron cloud size and London dispersion forces to justify the difference in intermolecular force strength instead of the difference in hydrogen bonding. In part (e) the point was earned for indicating that the pK_a is approximately 3.1. In part (f) no point was earned because the response incorrectly identifies the weak acid as having the higher concentration. In part (g) the point was earned for correctly calculating the pK_a value. In part (h) the first point was not earned because the titration curve does not pass through pH 4.2 at 5 mL. The second point was earned for drawing the equivalence point at 10 mL of NaOH added.

Sample: 1C
Score: 2

This response earned 2 points. In part (a) the point was earned for the correct answer with the correct number of significant figures. In part (b) the point was not earned because the response does not agree that the loss of percent yield is related to the solid dissolving during the rinse. In part (c) the first point was earned for correctly calculating the amount of heat absorbed as the temperature increased. The second point was not earned because there is no heat of fusion calculation and no total heat calculation. In part (d) the point was not earned because the fact that salicylic acid is identified as having more OH groups is not related to hydrogen bonding or stronger intermolecular forces.

Question 1 (continued)

In part (e) the point was not earned because the pK_a is incorrectly estimated to be 6. In part (f) the point was not earned because there is no correct justification for a higher acid concentration, even though a higher acid concentration is consistent with part (e). In part (g) the point was not earned because the pK_a is incorrectly calculated. In part (h) the first point was not earned because the titration curve does not pass through pH 4.2 at 5 mL. The second point was not earned because the equivalence point is not at 10 mL of NaOH added.