2024

AP

AP® Chemistry

Sample Student Responses and Scoring Commentary

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Free-Response Question 2

☑ Scoring Guidelines

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Question 2: Long Answer — 10 points

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

$$0.0114 \text{ mol } CO_2 \times \frac{44.01 \text{ g}}{1 \text{ mol}} = 0.502 \text{ g } CO_2$$

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

$PV = nRT$

$$V = \frac{nRT}{P} = \frac{(0.0114 \text{ mol})(0.08206 \ \frac{\text{L·atm}}{\text{mol·K}})(293 \text{ K})}{1.25 \text{ atm}} = 0.219 \text{ L}$$

Total for part (a) — 2 points

(b) (i) For a correct claim: **1 point**

The surface area of the solid reactants increases.

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

Shorter than. The powdered solids have a larger surface area than the solid chunks, thus collisions between water and the surface particles occur more frequently, resulting in a faster rate of dissolution and a shorter amount of time to dissolve the solids.

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

Equal to. Both experiments begin with the same amount of reactants, so they will produce the same number of moles of $CO_2(g)$ *under the same conditions of pressure and temperature; therefore, the final volume will be the same.*

Total for part (b) — 3 points

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

Accept one of the following:

- $NaHCO_3$ *is the limiting reactant because changing the mass of* $NaHCO_3$ *alters the amount of* CO_2 *produced.*
- $NaHCO_3$ *is the limiting reactant because the amount present has a smaller theoretical yield of the* CO_2 *product.*

$$1.543 \text{ g } H_2C_4H_2O_4 \times \frac{1 \text{ mol } H_2C_4H_2O_4}{116.07 \text{ g}} \times \frac{2 \text{ mol } CO_2}{1 \text{ mol } H_2C_4H_2O_4} = 0.02659 \text{ mol } CO_2$$

$$1.251 \text{ g } NaHCO_3 \times \frac{1 \text{ mol } NaHCO_3}{84.01 \text{ g}} \times \frac{2 \text{ mol } CO_2}{2 \text{ mol } NaHCO_3} = 0.01489 \text{ mol } CO_2$$

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

The entropy change is positive because the aqueous reactants produce 2 moles of gas particles, according to the balanced chemical equation. Gases are far more dispersed (occupy a greater number of microstates) than condensed phases, so the entropy of the products is greater than that of the reactants.

(e)	For the correct answer and a valid justification: Accept one of the following: • *Disagree. The reaction is endothermic and has a positive entropy change. Thus, the reaction is only thermodynamically favorable at a high enough temperature such that the magnitude of* $-T\Delta S$ *is greater than that of* ΔH. • *Disagree. For the reaction to be thermodynamically favorable* $(\Delta G < 0)$ *at all temperatures, the reaction must be exothermic* $(\Delta H < 0)$ *and have a positive entropy change* $(\Delta S > 0)$.	**1 point**
(f)	For the correct calculated value: $pK_{a_2} = -\log(8.5 \times 10^{-7}) = 6.07$	**1 point**
(g)	For the correct calculated value: $pH = pK_{a_2} + \log\frac{[C_4H_2O_4^{\ 2-}]}{[HC_4H_2O_4^{\ -}]}$ $\frac{[C_4H_2O_4^{\ 2-}]}{[HC_4H_2O_4^{\ -}]} = 10^{(pH - pK_{a_2})} = 10^{(7.00-6.07)} = 8.5$	**1 point**

Total for question 2 10 points

Question 2

Begin your response to **QUESTION 2** on this page.

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

(a) A student combines equal masses of $H_2C_4H_2O_4(s)$ chunks and $NaHCO_3(s)$ chunks with sufficient water at 20.0°C. The student determines that 0.0114 mol of $CO_2(g)$ is produced after the reaction goes to completion.

(i) Calculate the number of grams of $CO_2(g)$ produced.

$.0114 \text{ mol } CO_2 \cdot \frac{44.01 \text{ g } CO_2}{\text{mol } CO_2} = .502 \text{ g } CO_2$

(ii) The $CO_2(g)$ produced from the reaction at 20.0°C was collected and found to have a pressure of 1.25 atm. Calculate the volume of $CO_2(g)$, in liters.

$20.0°C = 293°K$

$PV = nRT \qquad V = \frac{nRT}{P}$

$V = \frac{.0114 \text{ mol} \cdot .08206 \text{ L}\cdot\text{atm}\cdot\text{mol}^{-1}\cdot\text{K}^{-1} \cdot 293\text{K}}{1.25 \text{ atm}} = .219 \text{ L}$

(b) The student performs a second experiment that is identical to the first except that the student grinds the chunks of $H_2C_4H_2O_4(s)$ and $NaHCO_3(s)$ into powder before combining the powder with water.

(i) What happens to the surface area of the reactants when the student grinds the chunks into powder?

By grinding to a powder, the surface area increases.

(ii) The rate-determining step for the overall reaction is the dissolving of the solids. Would the time required for the dissolving of the solids in the second experiment be longer than, shorter than, or the same as the time required in the first experiment? Justify your answer based on the collisions between particles.

The time required for dissolving will be shorter in the second experiment because by increasing the surface area of the reactants, there is more area available for the reactants and water molecules to collide. This will increase the rate of collisions between the water and reactant particles and, thus, increase speed of dissolution.

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Question 2

Continue your response to **QUESTION 2** on this page.

(iii) When the reaction is complete, will the volume of $CO_2(g)$ at the end of the second experiment be greater than, less than, or equal to the volume at the end of the first experiment? Justify your answer.

The volume of CO_2 will be the same for both experiments because the amount of CO_2 produced is dependent on the molar quantities of the reactants, not the reaction rate. Since the molar quantities of the reactants are identical in both experiments, the amount of CO_2 produced will be the same.

The student conducts additional trials of the experiment and produces the following data table.

Trial	Mass of $H_2C_4H_2O_4$ (grams)	Mass of $NaHCO_3$ (grams)	Moles of CO_2 Produced (mol)
3	1.543	1.251	0.01489
4	1.543	1.686	0.02007

(c) Based on the student's data, identify the limiting reactant in trial 3. Justify your answer.

The limiting reactant in trial 3 is the $NaHCO_3$. When more $NaHCO_3$ was added in the 4th trial, the amount of CO_2 increased. Thus, $NaHCO_3$ was consumed before the $H_2C_4H_2O_4$ in trial 3 and was the limiting reactant.

(d) The reaction has a value of $\Delta S°$ greater than zero. Using particle-level reasoning, explain why the entropy increases as the reaction progresses.

The entropy increases due to the production of gas molecules. These gas molecules have greater particle microstates as they have greater freedoms of movement than only dissolved particles, leading to an increase in entropy as the reaction progresses.

Question 2

Continue your response to **QUESTION 2** on this page.

The student notices that the temperature of the reaction mixture decreases as the reaction takes place and correctly determines that the reaction is endothermic.

(e) The student claims that the reaction is thermodynamically favorable at all temperatures because $\Delta S^\circ_{rxn} > 0$ and the reaction is endothermic. Do you agree or disagree with the student's claim? Justify your answer.

I disagree, because the reaction is endothermic while $\Delta S^\circ_{rxn} > 0$, the reaction is only thermodynamically favorable at high temperatures. Based on the equation $\Delta G = \Delta H - T\Delta S$, with ΔH being positive, ΔG is only negative when $\Delta H < T\Delta S$, which occurs at high temperatures.

Next, the student investigates the acid-base behavior of maleic acid. The student notes that maleic acid is a diprotic acid. The two acid dissociation processes that occur are represented by the following equations.

$$H_2C_4H_2O_4 + H_2O \rightleftarrows HC_4H_2O_4^- + H_3O^+ \qquad K_{a_1} = 1.5 \times 10^{-2}$$

$$HC_4H_2O_4^- + H_2O \rightleftarrows C_4H_2O_4^{2-} + H_3O^+ \qquad K_{a_2} = 8.5 \times 10^{-7}$$

(f) Calculate the pK_{a_2} value for the $HC_4H_2O_4^-$ ion.

$pKa_2 = -\log(Ka_2)$

$pKa_2 = -\log(8.5 \cdot 10^{-7}) = 6.07$

(g) A buffer solution with a pH of 7.00 is prepared using $C_4H_2O_4^{2-}$ and $HC_4H_2O_4^-$. Calculate the ratio $\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]}$ in this solution.

A = $HC_4H_2O_4^-$
CB = $C_4H_2O_4^{2-}$

$pH = pKa + \log \frac{[CB]}{[A]}$

pKa = 6.07

$7.00 = 6.07 + \log \frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]}$

$.93 = \log \frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]}$ $\quad \frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]} = 8.5$

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Question 2

Begin your response to **QUESTION 2** on this page.

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

(a) A student combines equal masses of $H_2C_4H_2O_4(s)$ chunks and $NaHCO_3(s)$ chunks with sufficient water at 20.0°C. The student determines that 0.0114 mol of $CO_2(g)$ is produced after the reaction goes to completion.

(i) Calculate the number of grams of $CO_2(g)$ produced.

0.0114 mol × 44.01 g/mol = 0.502 g CO_2

C 1 × 12.01 = 12.01
O 2 × 16.00 = 32.00
+ 44.01

(ii) The $CO_2(g)$ produced from the reaction at 20.0°C was collected and found to have a pressure of 1.25 atm. Calculate the volume of $CO_2(g)$, in liters.

20° C → 293 K

PV = nRT

1.25V = (0.0114 mol)(0.08206)(293)

1.25 V = .274096812

V = .219 L

(b) The student performs a second experiment that is identical to the first except that the student grinds the chunks of $H_2C_4H_2O_4(s)$ and $NaHCO_3(s)$ into powder before combining the powder with water.

(i) What happens to the surface area of the reactants when the student grinds the chunks into powder?

when the student grinds the chunks into powder, the surface area of the reactants increases.

(ii) The rate-determining step for the overall reaction is the dissolving of the solids. Would the time required for the dissolving of the solids in the second experiment be longer than, shorter than, or the same as the time required in the first experiment? Justify your answer based on the collisions between particles.

The time would be greater because of an increased number of collisions. The increased number of collisions is a result of a greater surface area from breaking the chunks up into powder.

Question 2

Continue your response to **QUESTION 2** on this page.

(iii) When the reaction is complete, will the volume of $CO_2(g)$ at the end of the second experiment be greater than, less than, or equal to the volume at the end of the first experiment? Justify your answer.

The volume of CO_2 in the second experiment will be less than the volume of CO_2 in the first experiment because the powder takes up less volume than the chunks.

The student conducts additional trials of the experiment and produces the following data table.

Trial	Mass of $H_2C_4H_2O_4$ (grams)	Mass of $NaHCO_3$ (grams)	Moles of CO_2 Produced (mol)
3	1.543	1.251	0.01489
4	1.543	1.686	0.02007

$NaHCO_3 + H_2C_4H_2O_4 \rightarrow$

(c) Based on the student's data, identify the limiting reactant in trial 3. Justify your answer.

$NaHCO_3$ was the limiting reactent in Trial 3

(d) The reaction has a value of $\Delta S°$ greater than zero. Using particle-level reasoning, explain why the entropy increases as the reaction progresses.

Entropy, which is a measure of the disorder in a reaction, increases as the reaction progresses because there is an increase in volume & temperature which increase kinetic energy and ultimately entropy.

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Question 2

Continue your response to **QUESTION 2** on this page.

The student notices that the temperature of the reaction mixture decreases as the reaction takes place and correctly determines that the reaction is endothermic.

(e) The student claims that the reaction is thermodynamically favorable at all temperatures because $\Delta S^\circ_{rxn} > 0$ and the reaction is endothermic. Do you agree or disagree with the student's claim? Justify your answer.

I agree with the student's claim. In order for ΔS to be positive, ΔG must be negative & if ΔG is negative, the reaction is thermodynamically favored.

Next, the student investigates the acid-base behavior of maleic acid. The student notes that maleic acid is a diprotic acid. The two acid dissociation processes that occur are represented by the following equations.

$$H_2C_4H_2O_4 + H_2O \rightleftarrows HC_4H_2O_4^- + H_3O^+ \qquad K_{a_1} = 1.5 \times 10^{-2}$$

$$HC_4H_2O_4^- + H_2O \rightleftarrows C_4H_2O_4^{2-} + H_3O^+ \qquad K_{a_2} = 8.5 \times 10^{-7}$$

(f) Calculate the pK_{a_2} value for the $HC_4H_2O_4^-$ ion.

$pK_{a_2} = -\log K_{a_2}$

$pK_{a_2} = -\log(8.5 \times 10^{-7})$

$pK_{a_2} = 6.07$

(g) A buffer solution with a pH of 7.00 is prepared using $C_4H_2O_4^{2-}$ and $HC_4H_2O_4^-$. Calculate the ratio $\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]}$ in this solution.

The ratio of $C_4H_2O_4^{-2}$ & $HC_4H_2O_4^-$ would be equal in this scenario since the solution has a neutral pH of 7.

Question 2

Begin your response to **QUESTION 2** on this page.

2. A chemical reaction between maleic acid ($H_2C_4H_2O_4$) and sodium bicarbonate ($NaHCO_3$) occurs in the presence of water to produce carbon dioxide and sodium maleate ($Na_2C_4H_2O_4$), as represented by the following equation.

$$H_2C_4H_2O_4(aq) + 2\,NaHCO_3(aq) \rightarrow 2\,CO_2(g) + 2\,H_2O(l) + Na_2C_4H_2O_4(aq)$$

(a) A student combines equal masses of $H_2C_4H_2O_4(s)$ chunks and $NaHCO_3(s)$ chunks with sufficient water at 20.0°C. The student determines that 0.0114 mol of $CO_2(g)$ is produced after the reaction goes to completion.

(i) Calculate the number of grams of $CO_2(g)$ produced.

$\frac{.0114\,mol\,CO_2 \mid 44\,g\,CO_2}{\mid 2\,mol\,CO_2} = .25\,g\,CO_2$

(ii) The $CO_2(g)$ produced from the reaction at 20.0°C was collected and found to have a pressure of 1.25 atm. Calculate the volume of $CO_2(g)$, in liters.

PV=nRT

$(1.25\,atm)x = (.0114\,mol)(.08206\,L\,atm\,mol^{-}\,k^{-})(20°C)$

.015L

(b) The student performs a second experiment that is identical to the first except that the student grinds the chunks of $H_2C_4H_2O_4(s)$ and $NaHCO_3(s)$ into powder before combining the powder with water.

(i) What happens to the surface area of the reactants when the student grinds the chunks into powder?

The surface area of the reactants increases

(ii) The rate-determining step for the overall reaction is the dissolving of the solids. Would the time required for the dissolving of the solids in the second experiment be longer than, shorter than, or the same as the time required in the first experiment? Justify your answer based on the collisions between particles.

shorter b/c you are increasing the surface area by grinding up the chunks causing a quicker rate of dissolving allowing more collisions between particles

Question 2

Continue your response to **QUESTION 2** on this page.

(iii) When the reaction is complete, will the volume of $CO_2(g)$ at the end of the second experiment be greater than, less than, or equal to the volume at the end of the first experiment? Justify your answer.

greater than b/c more collisions meaning more product

The student conducts additional trials of the experiment and produces the following data table.

Trial	Mass of $H_2C_4H_2O_4$ (grams)	Mass of $NaHCO_3$ (grams)	Moles of CO_2 Produced (mol)
3	1.543	1.251	0.01489
4	1.543	1.686	0.02007

(c) Based on the student's data, identify the limiting reactant in trial 3. Justify your answer.

Na b/c it is fully used up at the end of the trial

(d) The reaction has a value of $\Delta S°$ greater than zero. Using particle-level reasoning, explain why the entropy increases as the reaction progresses.

entropy increases b/c product (CO_2) increases as the rxn progresses

Question 2

Continue your response to **QUESTION 2** on this page.

The student notices that the temperature of the reaction mixture decreases as the reaction takes place and correctly determines that the reaction is endothermic.

(e) The student claims that the reaction is thermodynamically favorable at all temperatures because $\Delta S^\circ_{rxn} > 0$ and the reaction is endothermic. Do you agree or disagree with the student's claim? Justify your answer.

agree b/c ΔH = + ΔS = + ΔG = + meaning all temps will be favored & endothermic creates more collisons at high heat resulting in more Product

Next, the student investigates the acid-base behavior of maleic acid. The student notes that maleic acid is a diprotic acid. The two acid dissociation processes that occur are represented by the following equations.

$$H_2C_4H_2O_4 + H_2O \rightleftarrows HC_4H_2O_4^- + H_3O^+ \qquad K_{a_1} = 1.5 \times 10^{-2}$$

$$HC_4H_2O_4^- + H_2O \rightleftarrows C_4H_2O_4^{2-} + H_3O^+ \qquad K_{a_2} = 8.5 \times 10^{-7}$$

(f) Calculate the pK_{a_2} value for the $HC_4H_2O_4^-$ ion.

pKa2 = −log(8.5×10−7)

pka2 = 6.07

(g) A buffer solution with a pH of 7.00 is prepared using $C_4H_2O_4^{2-}$ and $HC_4H_2O_4^-$. Calculate the ratio $\frac{[C_4H_2O_4^{2-}]}{[HC_4H_2O_4^-]}$ in this solution.

$\frac{[114g\,C_4H_2O_4^{2}]}{[115g\,C_4H_2O_4^{-}]}$ = .99

1:1 ratio

Question 2

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

Overview

Question 2 presents students with a series of questions concerning a reaction involving solid sodium bicarbonate and maleic acid.

Part (a)(i) requires students to calculate the mass of $CO_2(g)$ from the moles of $CO_2(g)$ produced in the reaction (Learning Objective SPQ-1.A/1.1A, Skill 5.F from the *AP Chemistry Course and Exam Description*).

Part (a)(ii) requires students to calculate the volume of $CO_2(g)$ produced in the reaction using the moles of $CO_2(g)$, the temperature, and the pressure, assuming ideal behavior (SAP-7.A/3.4.A, 5.F).

Part (b)(i) requires students to identify what happens to the surface area of chunks of $H_2C_4H_2O_4(s)$ and $NaHCO_3(s)$ when these are ground into powders. The intent was for students to identify that a ground up solid will have a larger surface area than solid chunks (TRA-3.A/5.1.A, 6.A).

Part (b)(ii) requires students to compare the dissolving time of the powdered and chunk solids. Students were required to make a claim about which dissolved faster and justify the claim. The intent of the question was for students to explain how the surface area of a solid affects the rate of dissolving in terms of the collisions of the particles (TRA-3.A/5.1.A, 6.E).

Part (b)(iii) requires students to make and justify a claim regarding what will happen to the volume of $CO_2(g)$ formed when the solids are ground into a powder. The intent was for students to explain that since the amount of reactants didn't change, the volume of $CO_2(g)$ wouldn't either (SPQ-4.A/4.5.A, 2.F).

Part (c) requires students to analyze a data table containing the initial masses of $H_2C_4H_2O_4(s)$ and $NaHCO_3(s)$ and the moles of $CO_2(g)$ produced and determine the limiting reagent and justify their choice. Students could justify the choice mathematically with stoichiometry or by stating that if the mass of $H_2C_4H_2O_4(s)$ is held constant, increasing the mass of $NaHCO_3(s)$ also increases the moles of $CO_2(g)$ produced (SPQ-4.A/4.5.A, 6.D).

Part (d) requires students to explain why the reaction between $H_2C_4H_2O_4(aq)$ and $NaHCO_3(aq)$ has a $\Delta S°$ value greater than 0. The intent was for students to give a particulate level explanation that entropy increases because a gas, CO_2, is produced, and gases are more dispersed or occupy many more microstates (ENE-4.A/9.1.A, 4.C).

Part (e) requires students to assess a claim that an endothermic reaction is thermodynamically favorable at all temperatures. The intent was for students to state that an endothermic reaction (positive $\Delta H°$) with a positive $\Delta S°$ is only thermodynamically favorable at high temperatures (ENE-4.4.A/9.3.A, 6.D).

Question 2 (continued)

Part (f) requires students to calculate the pK_{a2} of $HC_4H_2O_4^-(aq)$. To do this, students first had to choose the correct K_a from the successive ionizations of diprotic maleic acid (SAP-9.C/8.3.A, 5.F).

Part (g) requires students to calculate the ratio of $[C_4H_2O_4^{2-}]$ to $[HC_4H_2O_4^-]$ in a pH 7.00 solution. The intent was for students to use the pK_{a2} from part (f) and the Henderson-Hasselbalch equation to find the quantitative value of the ratio (SAP-10.C/8.9.A, 5.F).

Sample: 2A
Score: 10

This response earned 10 points. In part (a)(i) the point was earned for the correctly calculated mass of CO_2. In part (a)(ii) the point was earned for a correctly calculated volume of CO_2 using $PV = nRT$. The point was earned in part (b)(i) for a correct claim about surface area. In part (b)(ii) the point was earned for an explanation that more collisions were possible, resulting in a shorter reaction time. The point was earned in part (b)(iii) for a correct claim that a change in reaction rate will not alter the final volume of product formed, given that the initial reactant quantities are the same in both experiments. In part (c) the point was earned for identifying $NaHCO_3$ as the limiting reactant by comparing trials 3 and 4 and observing that the change in $NaHCO_3$ corresponds to the change in CO_2 production. The point was earned in part (d) for relating the increase in entropy to the formation of gas particles and the corresponding increase in microstates of the system. In part (e) the point was earned for a correct claim and explanation of the temperature dependence of the thermodynamic favorability of the system. The point was earned in part (f) for a correctly calculated pK_a. In part (g) the point was earned for a correct calculation of the ratio of conjugate base to acid.

Sample: 2B
Score: 4

This response earned 4 points. In part (a)(i) the point was earned for a correct calculation using the molar mass of CO_2. The point was earned in part (a)(ii) for a correctly calculated volume of CO_2 using $PV = nRT$. In part (b)(i) the point was earned for a correct claim about surface area, but a point was not earned in part (b)(ii) for an incorrect claim about reaction time, which would be less than, not greater than, the reaction time in the first experiment. The point was not earned in part (b)(iii) for an incorrect claim that the volume of CO_2 would be less in the second trial. In part (c) the point was not earned because although $NaHCO_3$ is correctly identified as the limiting reactant, there is no justification provided to support this claim. In part (d) the point was not earned because while it is correct that an increase in temperature would cause an increase in entropy, this reaction is endothermic, and the temperature would decrease as the reaction proceeds. Therefore, the explanation does not relate to this reaction, nor does it discuss the formation of gas particles and their relation to the increase in microstates or the dispersal of particles in the system. The point was not earned in part (e) for an incorrect claim about the conditions of thermodynamic favorability, leading to an incorrect conclusion. In part (f) the point was earned for a correct calculation of pK_a, but in part (g) the point was not earned for an incorrect explanation of the relative concentrations of conjugate base to acid.

Question 2 (continued)

Sample: 2C
Score: 3

The response earned 3 points. For part (a)(i) the point was not earned because the coefficient for CO_2 from the balanced equation was used, resulting in an incorrect calculation of the mass of the sample. The point was not earned in part (a)(ii) because temperature is not correctly converted to Kelvin, resulting in a miscalculated volume of CO_2. In part (b)(i) the point was earned for a correct claim about the increasing surface area, and a point was earned in part (b)(ii) for an explanation that more collisions were possible, resulting in a shorter reaction time. In part (b)(iii) the point was not earned due to the incorrect claim that increasing the number of collisions would increase the volume of CO_2 produced. The point was not earned in part (c) for an incorrect claim about the limiting reactant being the spectator sodium ion. In part (d) the point was not earned for an incorrect explanation regarding particle entropy. The response does not include a particle-level explanation, but only discusses the amount of CO_2 produced. The point was not earned in part (e) for an incorrect claim about the conditions of thermodynamic favorability, leading to an incorrect conclusion. In part (f) the point was earned for a correct calculation of $\mathrm{p}K_a$, but in part (g) the point was not earned for an incorrect calculation of the ratio of conjugate base to acid, where masses are used to determine the conjugate base/acid ratio rather than pH and $\mathrm{p}K_a$.