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.

(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.

(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?

(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.

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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 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.

(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.

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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.

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.

(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.

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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: **1 point**

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* $(\Delta S > 0)$.

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

$$pK_{a_2} = -\log\left(8.5 \times 10^{-7}\right) = 6.07$$

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

$$pH = pK_{a_2} + \log\frac{[C_4H_2O_4{}^{2-}]}{[HC_4H_2O_4{}^{-}]}$$

$$\frac{[C_4H_2O_4{}^{2-}]}{[HC_4H_2O_4{}^{-}]} = 10^{(pH - pK_{a_2})} = 10^{(7.00 - 6.07)} = 8.5$$

Total for question 2 10 points