2024

AP® Chemistry

Sample Student Responses and Scoring Commentary

Inside:

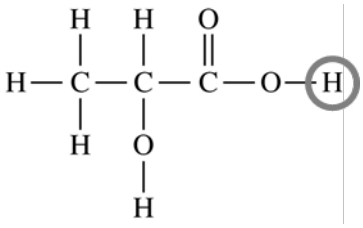
Free-Response Question 1

- ☑ **Scoring Guidelines**
- ☑ **Student Samples**
- ☑ **Scoring Commentary**

Question 1: Long Answer — 10 points

(a) For the correct circled atom: **1 point**

The rightmost hydrogen atom should be circled.



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

$$\frac{(10.22\text{ g})\left(\frac{1\text{ mol}}{40.00\text{ g}}\right)}{0.500\text{ L}} = 0.511\ M$$

(c) For the correct pK_a: **1 point**

3.9 *(acceptable range: 3.7 – 4.0)*

(d) (i) For the X at the correct point: **1 point**

The X should be at a point greater than or equal to 3 mL *and less than* 8 mL.

(ii) For a correct justification: **1 point**

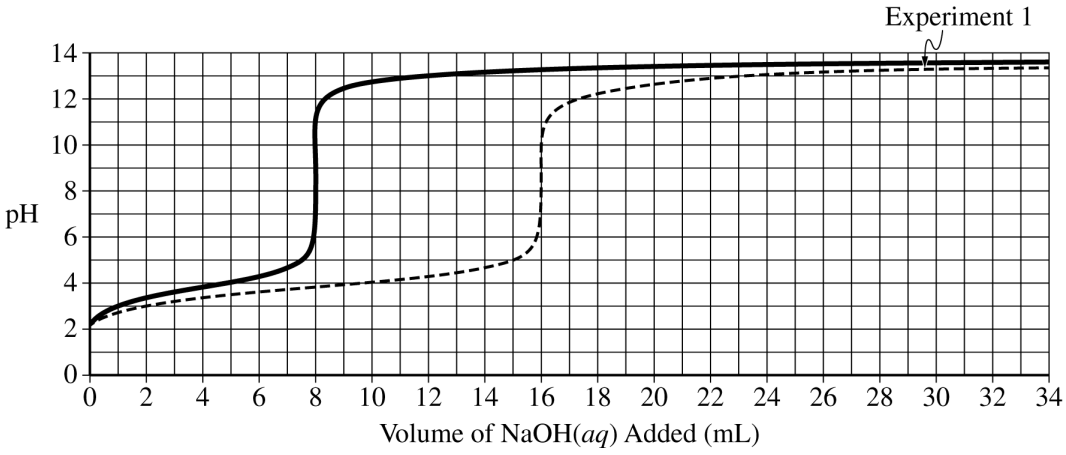
More acid particles are present than conjugate base particles, meaning that the titration is before the half-equivalence point.

(iii) For a curve showing the correct equivalence point: **1 point**

The equivalence point should be at 8 mL. *See example response below.*

For a curve with appropriate initial and final pH with a correct shape: **1 point**

The drawn curve should begin at the same pH, *gradually increase, rise sharply at a volume different than* 16 mL, *and end at a* pH *similar to the first curve.*



Total for part (d) 4 points

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

$q = mc\Delta T = (200.0\text{ g})(4.2\text{ J/(g} \cdot \text{°C)})(23.2\text{°C} - 20.0\text{°C}) = 2700\text{ J}$

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

$q_{rxn} = -q_{soln} = -2700\text{ J} = -2.7\text{ kJ}$

$\Delta H_{rxn} = \frac{q_{rxn}}{\text{mol}} = \frac{-2.7\text{ kJ}}{(0.100\text{ L})(0.500\text{ mol/L})} = -54\text{ kJ/mol}_{rxn}$

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

Agree. The heat lost from the system would result in a lower final temperature, which results in values of ΔT, q_{soln}, *and* ΔH *that are smaller than the actual value.*

Total for part (e) 3 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

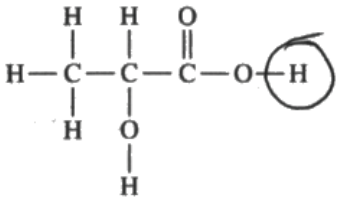
Directions: Questions 1–3 are long free-response questions that require about 23 minutes each to answer and are worth 10 points each. Questions 4–7 are short free-response questions that require about 9 minutes each to answer and are worth 4 points each.

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.

$$C_3H_6O_3(aq) + NaOH(aq) \rightarrow NaC_3H_5O_3(aq) + H_2O(l)$$

1. A student is studying the reaction between lactic acid, $C_3H_6O_3$, and sodium hydroxide, NaOH, as represented in the balanced equation above.

   (a) The structural formula of lactic acid is shown in the following diagram. Circle the hydrogen atom that most readily participates in the chemical reaction with sodium hydroxide.



   (b) The student begins the experiment by dissolving 10.22 g of sodium hydroxide (molar mass 40.00 g / mol) in enough water to produce 500. mL of solution. Calculate the molarity of the sodium hydroxide solution.

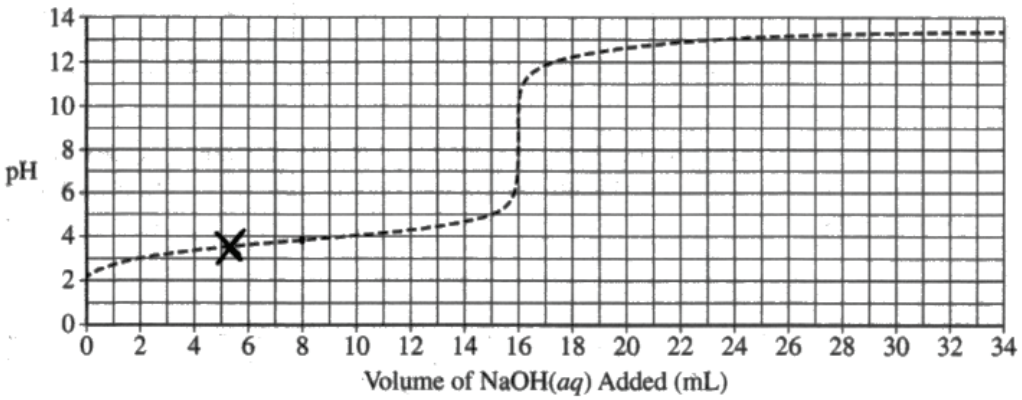
$10.22\text{g NaOH} \cdot \frac{1\text{ mol NaOH}}{40.00\text{g NaOH}} \cdot \frac{1}{500\text{mL}} \cdot \frac{1000\text{mL}}{1\text{L}} = 0.511\text{M NaOH solution}$

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

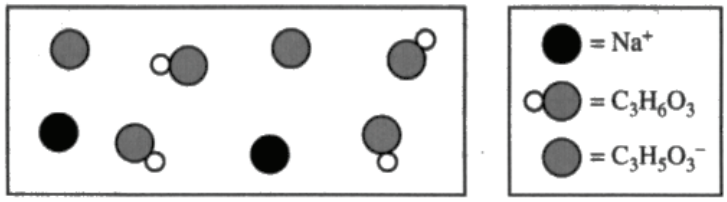
Continue your response to **QUESTION 1** on this page.

The student uses the sodium hydroxide solution from part (b), a buret, a pH meter, and a 100 mL Erlenmeyer flask to titrate a 25.0 mL sample of lactic acid solution. The student's data are shown in the following graph.



(c) Use the information in the graph to determine the approximate pK_a of lactic acid. 3.8

pKa is midpoint between start and equivalence point, which is at 8 mL NaOH



2:1 ratio of lactic acid to $C_3H_5O_3^-$

(d) The preceding diagram represents the relative amounts of major species in a sample of the solution in the flask at one point during the titration. (Note that water molecules are omitted.)

(i) Draw an X on the preceding titration curve at a point in the titration where the reaction mixture would be represented by this diagram.

(ii) Justify your answer.

(i) around 5.3 mL NaOH added.

(ii) Since there is a 2:1 ratio of $C_3H_6O_3$ to $C_3H_5O_3^-$, about $\frac{1}{3}$ of the original ~~$C_3H_6O_3$~~ $C_3H_6O_3$ was consumed. Since it takes 16 mL of NaOH to consume all of the $C_3H_6O_3$, $\frac{1}{3}$ is consumed when about 5.3 mL of ~~Na~~ NaOH is added.

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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.

0132232

Q5233/3

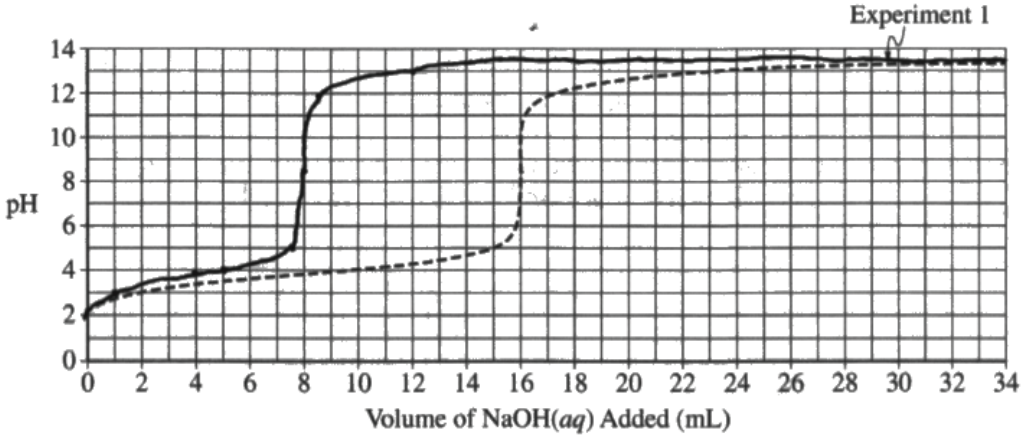
Question 1

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

Experiment	Mass of NaOH(*s*) (grams)	Volume of Solution (mL)	Titration Curve
1	10.22	500.	Already shown on graph
2	20.44	500.	?

(iii) The student repeats the experiment but uses a solution of NaOH(*aq*) with twice the concentration, as shown in the preceding table. On the following graph, draw the titration curve that would be expected for experiment 2.

Should take half as much NaOH to be added



(e) In a third experiment, the student investigates the enthalpy of the reaction between lactic acid and sodium hydroxide. The student combines 100.0 mL of a 0.500 *M* lactic acid solution at 20.0°C with 100.0 mL of a 0.500 *M* NaOH solution at 20.0°C in a calorimeter. The final temperature of the resulting combined solution is 23.2°C. Assume that the density of each solution before combining is 1.00 g / mL and that the specific heat capacity of the combined solution is 4.2 J / (g · °C).

(i) Calculate the quantity of heat produced in the reaction, in J.

Total mass of solution (m): $(100mL + 100mL) \cdot \frac{1g}{1mL} = 200g$

$c = 4.2 \frac{J}{g°C}$

$\Delta T = 23.2 - 20.0 = 3.2°C$

$q = cm\Delta T = 4.2 \frac{J}{g°C} \cdot 200g \cdot 3.2°C = 2700\ J$

$2.7 \cdot 10^3$ J were produced

Question 1

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

(ii) Calculate the molar enthalpy of reaction, in kJ / mol_{rxn}. Include the sign in your answer.

moles that were reacted: $100\,mL \cdot \frac{1\,L}{1000\,mL} \cdot 0.500\,M = 0.0500\,mol$

sign is negative because solution warmed up

$$\frac{-2700\,J}{0.0500\,mol} = -54000\,J/mol_{rxn} = -54.\,kJ/mol_{rxn}$$

(iii) The student claims that if heat is lost from the calorimeter to the surrounding air during the reaction, then the experimental value of the molar enthalpy of reaction will be smaller in magnitude than the actual value. Do you agree or disagree with the student's claim? Justify your answer.

I agree with the student's claim. If heat is lost to surrounding during the reaction, then ΔT will be smaller than it should be.* This would result in q being of smaller magnitude than it should be, which would mean the molar enthalpy of reaction would be smaller in magnitude than the actual value.

* as not all energy would get transferred to the water.

Question 1

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

CHEMISTRY

SECTION II

Time—1 hour and 45 minutes

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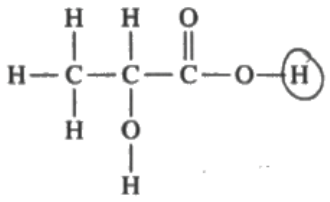
$$C_3H_6O_3(aq) + NaOH(aq) \rightarrow NaC_3H_5O_3(aq) + H_2O(l)$$

1. A student is studying the reaction between lactic acid, $C_3H_6O_3$, and sodium hydroxide, NaOH, as represented in the balanced equation above.

   (a) The structural formula of lactic acid is shown in the following diagram. Circle the hydrogen atom that most readily participates in the chemical reaction with sodium hydroxide.



   (b) The student begins the experiment by dissolving 10.22 g of sodium hydroxide (molar mass 40.00 g / mol) in enough water to produce 500. mL of solution. Calculate the molarity of the sodium hydroxide solution.

$\frac{10.22\text{g}}{40.00\text{g}} = 0.256\text{ mol NaOH} = \boxed{0.511\text{ M}}$
0.5L

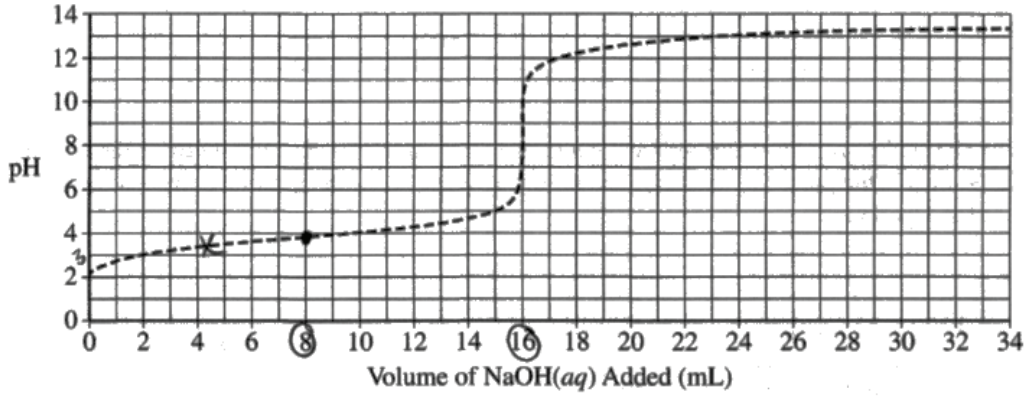
$\frac{500\text{mL}}{1000} = 0.5\text{L}$

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

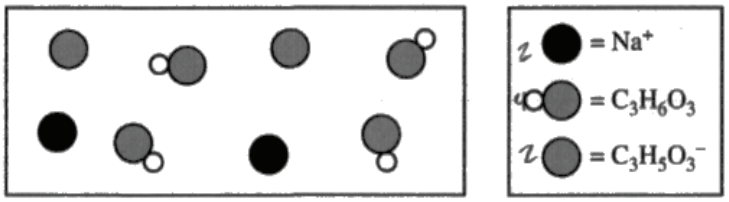
Question 1

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

The student uses the sodium hydroxide solution from part (b), a buret, a pH meter, and a 100 mL Erlenmeyer flask to titrate a 25.0 mL sample of lactic acid solution. The student's data are shown in the following graph.



(c) Use the information in the graph to determine the approximate pK_a of lactic acid. 3.80



(d) The preceding diagram represents the relative amounts of major species in a sample of the solution in the flask at one point during the titration. (Note that water molecules are omitted.)

(i) Draw an X on the preceding titration curve at a point in the titration where the reaction mixture would be represented by this diagram. $C_3H_6O_3 > C_3H_5O_3^-$

(ii) Justify your answer.

At half equivalence point, the amount of $C_3H_6O_3$ equals the amount of $C_3H_5O_3^-$ because $pH = pK_a$. Because there is more $C_3H_6O_3$ molecules in the diagram, $pH < pK_a$ and the X would be placed before the half equivalence point.

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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.

0143655

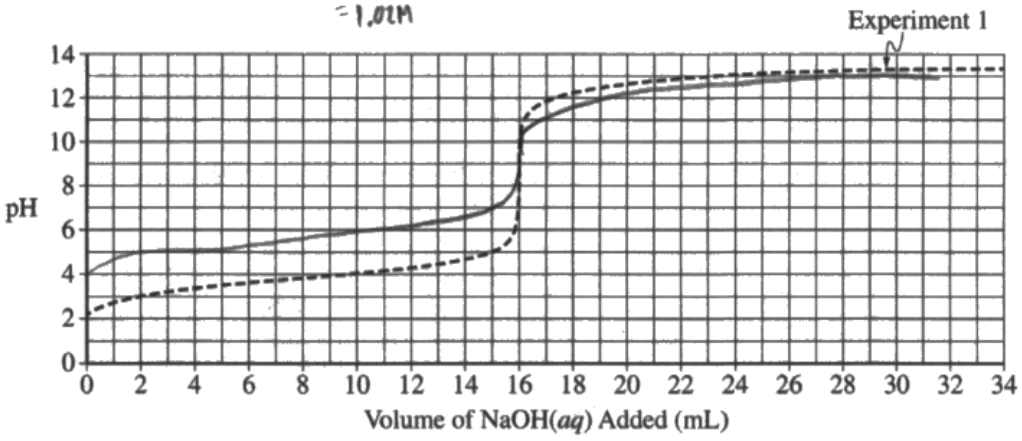
Question 1

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

Experiment	Mass of NaOH(*s*) (grams)	Volume of Solution (mL)	Titration Curve
1	10.22	500.	Already shown on graph
2	20.44	500.	?

*(iii) The student repeats the experiment but uses a solution of NaOH(*aq*) with twice the concentration, as shown in the preceding table. On the following graph, draw the titration curve that would be expected for experiment 2. $\frac{20.44\,g}{39.99\,g} = \frac{.511}{.5L}$ $HA + OH^- \rightarrow H_2O + A^-$ 1.02

$= 1.01M$



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(i) Calculate the quantity of heat produced in the reaction, in J.

$.1 \times .5 = .05\,mol\ lactic\ acid \cdot 96.1\,g/mol = 4.50\,g\ lactic\ acid$

$.1 \times .5 = .05\,mol\ NaOH \cdot 39.99\,g/mol = 2.00\,g\ NaOH$

$6.50\,g$

$q = 6.50\,g\left(4.2\,\frac{J}{g°C}\right)(23.2 - 20.0)$

$q = \boxed{87.4\,J}$

Question 1

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

(ii) Calculate the molar enthalpy of reaction, in kJ / mol_{rxn}. Include the sign in your answer.

$q_{sys} = q_{surr}$

$\frac{87.4\,J}{1000} = 0.0874\,kJ$

$\frac{0.0874\,kJ}{0.05 + 0.05\,mol} \rightarrow \frac{0.0874\,kJ}{0.1\,mol} = \boxed{0.874\,\frac{kJ}{mol}}$

(iii) The student claims that if heat is lost from the calorimeter to the surrounding air during the reaction, then the experimental value of the molar enthalpy of reaction will be smaller in magnitude than the actual value. Do you agree or disagree with the student's claim? Justify your answer.

I disagree. The magnitude of the molar enthalpy will be greater than the actual value.

GO ON TO THE NEXT PAGE.

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

0143655

Q5233/5

Question 1

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

CHEMISTRY

SECTION II

Time—1 hour and 45 minutes

7 Questions

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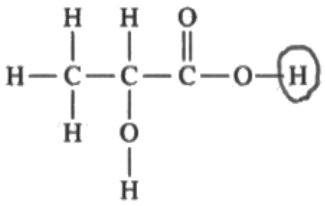

   (b) The student begins the experiment by dissolving 10.22 g of sodium hydroxide (molar mass 40.00 g / mol) in enough water to produce 500. mL of solution. Calculate the molarity of the sodium hydroxide solution.

$$\frac{10.22\text{ g}}{40.00\text{ g}} \left| \frac{1\text{ mol}}{1\text{ g}} \right| \frac{1}{500\text{ mL}} = 5.11 \times 10^{-4}\text{ M}$$

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Question 1

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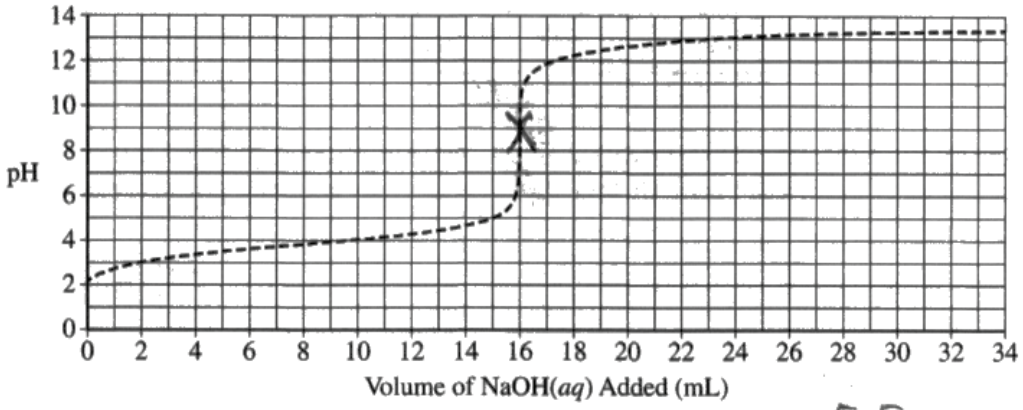
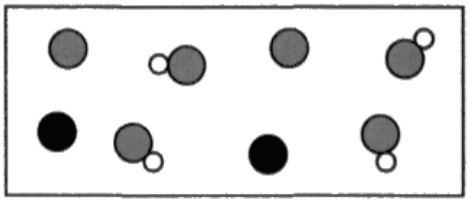


(c) Use the information in the graph to determine the approximate pK_a of lactic acid. 5.5



(d) The preceding diagram represents the relative amounts of major species in a sample of the solution in the flask at one point during the titration. (Note that water molecules are omitted.)

(i) Draw an X on the preceding titration curve at a point in the titration where the reaction mixture would be represented by this diagram.

(ii) Justify your answer.

because that is the location which the reaction reached equilibrium, meaning there'd be an equal amount of products and reactants, which is what is demonstrated in the diagram above

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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.

0137628

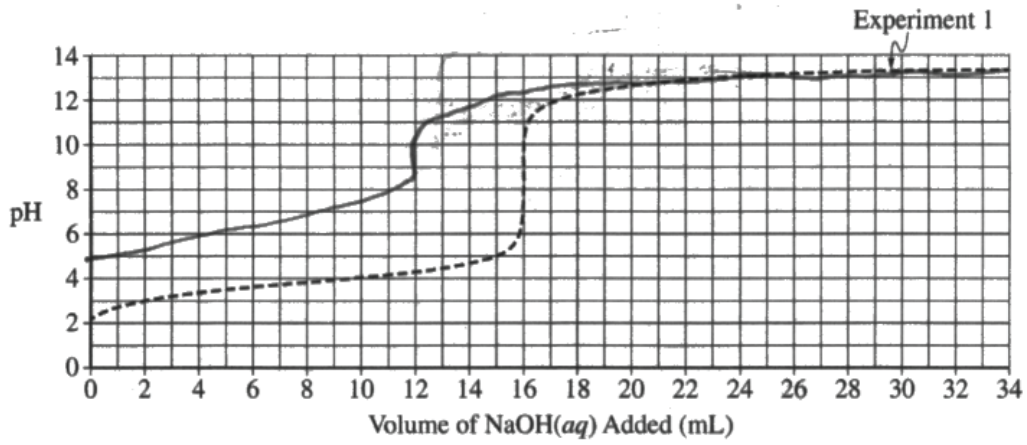
Q5233/3

Question 1

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

Experiment	Mass of NaOH(s) (grams)	Volume of Solution (mL)	Titration Curve
1	10.22	500.	Already shown on graph
2	20.44	500.	?

(iii) The student repeats the experiment but uses a solution of NaOH(aq) with twice the concentration, as shown in the preceding table. On the following graph, draw the titration curve that would be expected for experiment 2.



(e) In a third experiment, the student investigates the enthalpy of the reaction between lactic acid and sodium hydroxide. The student combines 100.0 mL of a 0.500 *M* lactic acid solution at 20.0°C with 100.0 mL of a 0.500 *M* NaOH solution at 20.0°C in a calorimeter. The final temperature of the resulting combined solution is 23.2°C. Assume that the density of each solution before combining is 1.00 g / mL and that the specific heat capacity of the combined solution is 4.2 J / (g · °C).

(i) Calculate the quantity of heat produced in the reaction, in J.

$q = mc\Delta T$

$q = (100_0)(4.2)(23.2 - 20)$

$q = 1344\ J$

GO ON TO THE NEXT PAGE.

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

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

(ii) Calculate the molar enthalpy of reaction, in kJ / mol_{rxn}. Include the sign in your answer.

$\frac{0.5\ mol}{90.09} \mid\mid \frac{1\ mol}{81.081}$

$\frac{0.5\ mol}{1\ mol} \mid\mid \frac{40}{20}$

$81.081 - 20 = \boxed{+61.081}$

(iii) The student claims that if heat is lost from the calorimeter to the surrounding air during the reaction, then the experimental value of the molar enthalpy of reaction will be smaller in magnitude than the actual value. Do you agree or disagree with the student's claim? Justify your answer.

I, agree because if there was a loss of heat to surrounding air, the final temperature reading would be lower than it should be, meaning the ΔT value would be lower than it should be, causing an inaccurate reading of the molar enthalpy, making it seem smaller than it should be

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

0137628

Q5233/5

Question 1

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

Overview

Question 1 presents students with a series of questions concerning multiple experiments involving lactic acid and sodium hydroxide.

Part (a) requires students to circle the hydrogen atom in the provided structural formula of lactic acid that most readily participates in the chemical reaction with sodium hydroxide. The intent was for students to identify and circle the hydrogen atom on the carboxyl group (Learning Objective SAP-9.F/8.6.A, Skill 1.A from the *AP Chemistry Course and Exam Description*).

Part (b) requires students to calculate the molarity of a sodium hydroxide solution given the mass of NaOH and volume of the solution (SPQ-3.A/3.7.A, 5.F).

Part (c) requires students to approximate the pK_a of lactic acid based on the information from a weak acid-strong base titration curve. The intent of the question was for students to identify the half-equivalence point from the titration curve and recognize that the pH is equal to the pK_a at this point (SAP-9.E/8.5.A, 5.D).

Part (d)(i) requires students to draw an X on the area of the titration curve represented by a given particle diagram. The intent of the question was for students to recognize that there were more lactic acid particles compared to lactate ions (conjugate base) in the particle diagram and recognize that the diagram represents an area of the curve prior to the half-equivalence point (SAP-9.E/8.5.A, 3.A).

Part (d)(ii) requires students to justify the location of the X drawn on the titration curve. The intent of the question was for the students to explain the position of their X on the titration curve based on the particle diagram containing more lactic acid particles than lactate ions (conjugate base), which indicates that the pH is less than the pK_a, a condition that is only true before the half-equivalence point (SAP-10.A/8.7.A, 6.F).

Part (d)(iii) requires students to draw a weak acid-strong base titration curve for a second experiment on top of the titration curve from the first experiment. Experiment 2 uses a sodium hydroxide solution with twice the concentration, which would reach the equivalence point with half the volume of NaOH(*aq*) required in experiment 1. The question's intent was for students to adjust the expected titration curve based on changing one variable of the experiment (SAP-9.E/8.5.A, 3.A).

Part (e)(i) requires students to calculate the quantity of heat produced when solutions of lactic acid and sodium hydroxide are combined. This may be quantified by the equation $q = mc\Delta T$ (ENE-2.D/6.4.A, 5.F).

Part (e)(ii) requires students to calculate the molar enthalpy of the reaction based on the information and calculated response in part (e)(i), including the appropriate algebraic sign. The intent of the question was to relate the heat (q_{soln}) absorbed by the solution in part (e)(i) to the molar enthalpy of the reaction in kJ/mol$_{rxn}$ (ENE-2.F/6.6.A, 5.F).

Question 1 (continued)

Part (e)(iii) requires students to agree or disagree with a student's claim that if heat is lost from the calorimeter to the surrounding air during the reaction, then the experimental value of the molar enthalpy would be smaller due to a smaller observed change in solution temperature. The intent of the question was to have students predict the effect heat loss would have on measurable observations (ENE-2.D/6.4.A, 6.G).

Sample: 1A
Score: 10

The response earned 10 points. In part (a) the hydrogen atom on the carboxyl group is circled and therefore earned the point. In part (b) the point was earned because the grams of sodium hydroxide is correctly converted to moles of sodium hydroxide and divided by the volume in liters to calculate the correct molarity of the solution. In part (c) the response gives a pK_a value of 3.8, which is in the proper range of 3.7-4.0 and earned the point. In part (d)(i) the X placement is in the correct range (greater than or equal to 3 mL and less than 8 mL) and therefore earned the point. The point was earned in part (d)(ii) for indicating the correct ratio of $C_3H_6O_3$ to $C_3H_5O_3^-$ and recognizing that the reaction is one-third of the way to the equivalence point. In part (d)(iii) 1 point was earned for indicating the correct equivalence point at 8 mL, and 1 point was earned for beginning the curve at the correct pH, ending it at the correct pH, and having a shape like a characteristic weak acid-strong base titration curve. The point was earned in part (e)(i) for the correct amount of heat produced, in joules. The point was earned in part (e)(ii) for the correct molar enthalpy value calculated with the negative sign indicated. The point was earned in part (e)(iii) because the response agrees with the student's claim that the observed change in temperature will be smaller because not all energy is transferred to the water, resulting in a smaller molar enthalpy value.

Sample: 1B
Score: 5

The response earned a total of 5 points. In part (a) the point was earned for circling the correct H on the carboxyl group. In part (b) the point was earned because the correct molarity is calculated with the appropriate work shown. In part (c) the point was earned for a correct pK_a value of 3.80, which is within the acceptable range of 3.7-4.0. In part (d)(i) the point was earned for the correct placement of X on the graph in a position greater than or equal to 3 mL and less than 8 mL. In part (d)(ii) the point was earned because the response correctly identifies the amount of $C_3H_6O_3$ as greater than $C_3H_5O_3^-$, indicating that the position in the titration is before the half-equivalence point. In part (d)(iii) the first point was not earned because the equivalence point is not at 8 mL, and the second point was not earned because the curve starts at a pH of 4 (not ~2) and has the same equivalence point as experiment 1. In part (e)(i) the point was not earned because the response uses 6.50 grams of NaOH instead of 200.0 grams of solution to determine the heat produced in the reaction. In part (e)(ii) the point was not earned because the response uses 0.1 mole instead of 0.0500 mole to determine the molar enthalpy and also lacks the required negative sign. The point was not earned in part (e)(iii) because the response incorrectly indicates that the magnitude of the experimental molar enthalpy of reaction would be larger, not smaller, than the actual value.

Question 1 (continued)

Sample: 1C
Score: 2

The response earned a total of 2 points. In part (a) the point was earned for circling the correct H atom on the carboxyl group. In part (b) the point was not earned because 500 mL is used to calculate the molarity instead of the correct 0.500 L. In part (c) the point was not earned for the incorrect pK_a approximation of 5.5. In part (d)(i) the point was not earned because X is located at the equivalence point of the titration curve instead of a position greater than or equal to 3 mL and less than 8 mL. In part (d)(ii) the point was not earned because the response does not indicate that the ratio of weak acid to conjugate base in the particulate diagram represents a scenario before the half-equivalence point. In part (d)(iii) the first point was not earned because the equivalence point drawn is at 12 mL instead of 8 mL, and the second point was not earned because the curve starts at an incorrect pH of 5. In part (e)(i) the point was not earned because the response uses the incorrect mass of 100 grams of solution instead of 200.0 grams of solution to calculate the heat produced. In part (e)(ii) the point was not earned because the value from part (e)(i) is not carried forward, nor does the end result have a negative value. In part (e)(iii) the point was earned because the response agrees with the student's claim and states that the final temperature reading would be lower, making the change in temperature "lower than it should be," resulting in a smaller experimental molar enthalpy.