

Week 18

AP Chemistry

Homework bundle for this week

本周作业合集

exercises.lol

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6. Thermochemistry

Starter Quiz · 课前小测

AP Chemistry

Name: _____ Score: _____

1. An exothermic reaction has a ΔH that is...
☐ negative
☐ positive
☐ always zero
2. On an energy diagram, products below reactants means the reaction is...
☐ exothermic
☐ endothermic
☐ at equilibrium
3. Heat flows from...
☐ hot to cold
☐ cold to hot
☐ high to low pressure
4. Heat 100 g of water ($c = 4.18$) by 5 degrees. The heat (in J)?
_____ J
5. The temperature stays constant during a phase change.
☐ True ☐ False
6. If burning 1 mol releases 500 kJ, how much does burning 3 mol release (in kJ)?
_____ kJ
7. Bonds broken total 600 kJ; bonds formed total 700 kJ. Estimate ΔH (in kJ).
_____ kJ
8. Products' $\sum \Delta H_f = -300$; reactants' $= -100$. Find ΔH_{rxn} (in kJ).
_____ kJ
9. Two steps have $\Delta H = -120$ kJ and $+30$ kJ. Their sum (in kJ)?
_____ kJ
10. A reaction that makes its container feel cold is...
☐ endothermic
☐ exothermic

☐ neither

6. Thermochemistry

Answers · 答案

AP Chemistry

1. negative

Releasing heat makes ΔH negative.

2. exothermic

Lower products mean energy was released – exothermic.

3. hot to cold

Heat always flows from the hotter object to the colder one.

4. 2090 J

$$q = mc\Delta T = 100 \times 4.18 \times 5 = 2090 \text{ J.}$$

5. True

Heat breaks attractions instead of raising the temperature.

6. 1500 kJ

ΔH scales with amount, so $3 \times 500 = 1500 \text{ kJ}$.

7. -100 kJ

$$\Delta H \approx 600 - 700 = -100 \text{ kJ (exothermic).}$$

8. -200 kJ

$$\Delta H_{rxn} = -300 - (-100) = -200 \text{ kJ.}$$

9. -90 kJ

$$-120 + 30 = -90 \text{ kJ.}$$

10. endothermic

Absorbing heat from your hand feels cold – endothermic.

AP CHEMISTRY · EXERCISE SHEET

6.1 Endothermic and Exothermic Processes

Name: _____ Class: _____ Date: _____

Total: 9 marks

KEY WORDS endothermic 吸热 • exothermic 放热 • heat 热量

Objective

Build the skills to answer exam questions on **endothermic and exothermic processes**.

You must be able to:

- classify a process as **exothermic** 放热 ($\Delta H < 0$) or **endothermic** 吸热 ($\Delta H > 0$)
- link the sign of ΔH to heat released or absorbed
- relate bond breaking/forming to energy

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Exo vs endo

- **Exothermic** — releases heat to the surroundings; $\Delta H < 0$; surroundings warm up.
- **Endothermic** — absorbs heat from the surroundings; $\Delta H > 0$; surroundings cool down.

■ Bonds and energy

Breaking bonds **absorbs** energy; **forming** bonds **releases** energy. If more energy is released (forming) than absorbed (breaking), the reaction is exothermic.

■ A worked judgement

Combustion feels hot → releases heat → **exothermic**, $\Delta H < 0$. A cold pack that gets cold when mixed → absorbs heat → **endothermic**, $\Delta H > 0$.

■ Sign convention

ΔH is written from the system's view: negative when the system **loses** energy (exothermic), positive when it **gains** energy (endothermic).

2 Practice

Now apply the methods above.

2.1 State the sign of ΔH for an exothermic reaction. [1]

2.2 A reaction makes the beaker feel cold. Classify it. [1]

2.3 Does breaking a bond absorb or release energy? [1]

3 Exam-style questions

3.1 An endothermic reaction has [1]

- **A** $\Delta H < 0$ and releases heat
 - **B** $\Delta H > 0$ and absorbs heat
 - **C** $\Delta H = 0$
 - **D** no energy change
-

3.2 When ammonium nitrate dissolves in water, the solution gets colder.

(a) Classify the process and give the sign of ΔH . [2]

(b) State the direction of heat flow (system $\leftrightarrow$ surroundings). [1]

3.3 Explain, in terms of bond breaking and forming, why combustion is exothermic. [2]

Solutions

2.1 Negative ($\Delta H < 0$).

2.2 Endothermic.

2.3 Absorbs energy.

3.1 **B** — $\Delta H > 0$ and absorbs heat.

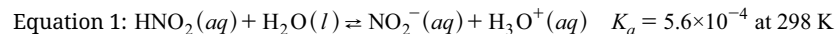
3.2 (a) Endothermic; $\Delta H > 0$. (b) Heat flows from the surroundings into the system.

3.3 Combustion forms strong bonds in CO_2 and H_2O , releasing more energy than is absorbed breaking the fuel and O_2 bonds, so the net ΔH is negative.

Question 3: Version J

The following information applies to all parts.

3. Nitrous acid, HNO_2 , is a weak acid that ionizes according to Equation 1.

**Part A**

Identify a conjugate acid-base pair in the equation. Be sure to clearly label which is the acid and which is the base.

Part B

A solution of $\text{HNO}_2(aq)$ with an initial concentration of 0.125 M has a pH of 2.09.

- Calculate** the value of $[\text{H}_3\text{O}^+]$ in the solution. Show the work that leads to your answer.
- Calculate** $[\text{HNO}_2]$ at equilibrium. Show the work that leads to your answer.

Part C

In an experiment, the solution of 0.125 M $\text{HNO}_2(aq)$ is heated to 333 K. The new equilibrium concentrations are determined to be $[\text{HNO}_2] = 0.114 \text{ M}$, $[\text{NO}_2^-] = 0.0109 \text{ M}$, and $[\text{H}_3\text{O}^+] = 0.0109 \text{ M}$.

- Calculate** the value of K_a for HNO_2 at 333 K. Show the work that leads to your answer.
- Is the reaction represented by Equation 1 endothermic or exothermic? **Justify** your answer by comparing K_a values at 298 K and 333 K.

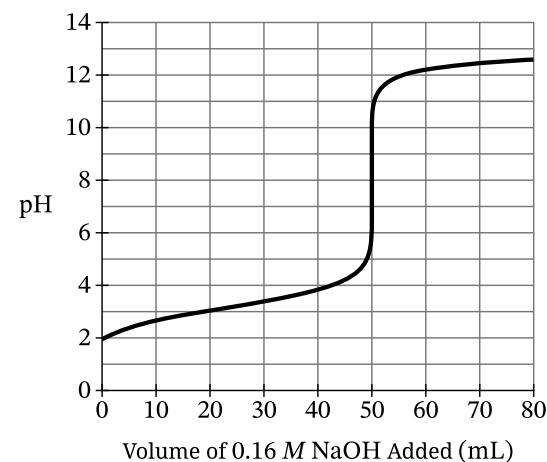
The following information applies to parts D, E, and F.

In a second experiment, a student is given a bottle containing HNO_2 with an unknown molarity. To determine the concentration of the $\text{HNO}_2(aq)$ in the bottle, the student titrates 35.0 mL of the $\text{HNO}_2(aq)$ with 0.16 M $\text{NaOH}(aq)$ at 298 K, which reacts according to Equation 2.



The results of the titration are summarized in Figure 1.

Figure 1

**Part D**

Using Figure 1, **identify** the pH at the equivalence point.

Part E

Using Figure 1, **calculate** the molarity $\text{HNO}_2(aq)$ of in the bottle. Show the work that leads to your answer.

Part F

Draw an X on Figure 1 to represent a point in the titration where $[\text{HNO}_2] > [\text{NO}_2^-]$ in the reaction mixture.

Part G

Equilibrium constants at 298 K are shown in Table 1 for the acid ionization reaction represented by Equation 1, K_a ; the autoionization of water, K_w ; and the neutralization reaction represented by Equation 2, K_2 .

Table 1

Chemical Equation	Equilibrium Constant
$\text{HNO}_2(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{NO}_2^-(aq) + \text{H}_3\text{O}^+(aq)$	$K_a = 5.6 \times 10^{-4}$
$\text{H}_2\text{O}(l) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{OH}^-(aq)$	$K_w = 1.0 \times 10^{-14}$
$\text{HNO}_2(aq) + \text{OH}^-(aq) \rightarrow \text{NO}_2^-(aq) + \text{H}_2\text{O}(l)$	$K_2 = ?$

Calculate the value of K_2 for Equation 2 at 298 K. Show the work that leads to your answer.

Part H

The student decides to repeat the experiment, this time using an indicator, and has access to the indicators in Table 2.

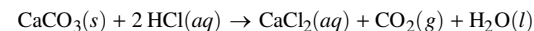
Table 2

Indicator Name	Acid Color	pH Range of Color Change	Base Color
Methyl orange	Red	3.1–4.4	Yellow
Thymol blue	Yellow	8.0–9.6	Blue
Clayton yellow	Yellow	12.2–13.2	Orange

The student conducts a second titration by adding two drops of methyl orange indicator to 35.0 mL of the $\text{HNO}_2(aq)$ solution and titrating the solution with 0.16 M $\text{NaOH}(aq)$ until a color change from red to yellow occurs.

The student claims that methyl orange was the best choice for the indicator. Do you agree or disagree? **Justify** your answer.

Answer the following questions about an experiment in which $\text{CaCO}_3(s)$ is combined with $\text{HCl}(aq)$, represented by the following balanced equation.



(a) Write the balanced net ionic equation for the reaction.

A student performs an investigation to study factors that affect the rate of the reaction. In each trial the student combines 50.0 mL of $\text{HCl}(aq)$ at 21.2°C with 1.00 g of $\text{CaCO}_3(s)$ and measures the time required for the reaction to go to completion. The data are given in the following table.

Trial	Concentration of $\text{HCl}(aq)$ (M)	Particle Size of $\text{CaCO}_3(s)$	Time of Reaction (s)
1	1.00	Fine powder	67
2	1.00	Small chunks	112
3	1.00	Large chunk	342
4	3.00	Fine powder	22
5	3.00	Small chunks	227
6	3.00	Large chunk	114

(b) The student correctly identifies that trial 5 is inconsistent with the other trials. Explain why the student's claim is correct using the data in the table.

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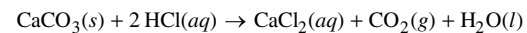
Continue your response to **QUESTION 3** on this page.

- (c) Based on the reaction conditions and the collisions that occur between particles, explain the reason for the difference in the reaction times for trial 2 and trial 3.

- (d) The student claims that the reaction is zero order with respect to $\text{HCl}(aq)$. Do you agree or disagree with the student's claim? Justify your answer using the student's data.

- (e) The $\text{HCl}(aq)$ was present in excess in all trials of the experiment. Determine the molarity of the $\text{HCl}(aq)$ in the beaker after the reaction is complete in trial 2. Assume that the volume of the mixture remains constant at 50.0 mL throughout the trial. (The molar mass of CaCO_3 is 100.09 g/mol.)

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

In order to measure the enthalpy of the reaction shown, the student repeats trial 1 by mixing 50.0 mL of $\text{HCl}(aq)$ with 1.00 g of $\text{CaCO}_3(s)$ using a coffee cup calorimeter. The student records the temperature of the system every 20 seconds. The data are given in the following table.

Time (s)	Measured Temperature of Solution ($^{\circ}\text{C}$)
0	21.20
20	21.51
40	21.70
60	21.85
80	21.90
100	21.90

- (f) Is the reaction endothermic or exothermic? Justify your answer using the information in the table.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

(g) Based on the experimental data, the mass of the system is 51.0 g, and the specific heat of the reaction mixture is $4.0 \text{ J / (g} \cdot ^\circ\text{C)}$.

(i) Calculate the magnitude of heat transfer, q , in joules.

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

GO ON TO THE NEXT PAGE.

6.2 Energy Diagrams

Name: _____ Class: _____ Date: _____

Total: 9 marks**KEY WORDS** endothermic 吸热 • exothermic 放热

Objective

Build the skills to answer exam questions on **energy diagrams** for reactions.**You must be able to:**

- draw/read an energy diagram showing reactants, products, and E_a
- show ΔH as products minus reactants
- compare exothermic and endothermic diagrams

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ The exothermic diagram

Reactants start **high**, climb over the activation-energy barrier, and end **lower** as products. Energy is released, so $\Delta H < 0$ (the arrow points down from reactants to products).

■ The endothermic diagram

Reactants start **low**, climb the barrier, and end **higher** as products. Energy is absorbed, so $\Delta H > 0$ (the arrow points up).

■ Reading E_a and ΔH

 E_a = height of the peak above the **reactants**. ΔH = (product level) – (reactant level).

■ A worked comparison

Same E_a but different ΔH : an exothermic reaction's products sit below the reactants; an endothermic reaction's products sit above. The barrier position is the same idea in both.

2 Practice

Now apply the methods above.

2.1 On an energy diagram, how is ΔH found? [1]

2.2 For an exothermic reaction, are the products higher or lower than the reactants? [1]

2.3 Where is E_a measured to on the diagram? [1]

3 Exam-style questions

3.1 On an **endothermic** energy diagram, the products are [1]

- A lower than the reactants
 - B higher than the reactants
 - C at the same level
 - D at the peak
-

3.2 An energy diagram shows reactants at 30 kJ, peak at 110 kJ, products at 70 kJ.

(a) Find E_a . [1]

(b) Find ΔH and classify the reaction. [2]

3.3 Two reactions have the same ΔH but different E_a . Explain which reacts faster and why. [2]

Solutions

2.1 Products' energy minus reactants' energy.

2.2 Lower.

2.3 From the reactants up to the peak.

3.1 B — higher than the reactants.

3.2 (a) $E_a = 110 - 30 = 80$ kJ. (b) $\Delta H = 70 - 30 = +40$ kJ, endothermic.

3.3 The one with the **lower** E_a reacts faster, because a larger fraction of collisions exceed the smaller barrier.

6.3 Heat Transfer and Thermal Equilibrium

Name: _____ Class: _____ Date: _____ **Total: 9 marks****KEY WORDS** thermal equilibrium 热平衡 • heat 热量 • specific heat 比热容

Objective

Build the skills to answer exam questions on **heat transfer and thermal equilibrium**.**You must be able to:**

- state that heat flows from **hot to cold** until **thermal equilibrium** 热平衡
- apply conservation of energy ($q_{\text{lost}} = q_{\text{gained}}$)
- reason about the final temperature

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Heat flows hot to cold

When two objects touch, heat flows from the **hotter** to the **cooler** one until they reach the **same temperature** — thermal equilibrium. Then net heat flow stops.

■ Conservation of energy

In an isolated system, the heat **lost** by the hot object equals the heat **gained** by the cold object:

$$q_{\text{lost}} = q_{\text{gained}} \quad (\text{equal magnitudes, opposite signs}).$$

■ A worked direction

Drop a hot metal into cool water: the metal cools (loses heat), the water warms (gains the same heat), and both settle at one final temperature between the two starting values.

■ Where the final temperature lands

The final temperature is **closer** to the object with the larger heat capacity (more mass or higher specific heat) — it changes temperature less for the same heat.

2 Practice

Now apply the methods above.

2.1 In which direction does heat flow between a hot and a cold object? [1]**2.2** What is thermal equilibrium? [1]**2.3** If a hot metal loses 500 J to water (isolated), how much does the water gain? [1]

3 Exam-style questions

3.1 Two objects reach thermal equilibrium when they have the same [1]

- A** mass
- B** temperature
- C** heat capacity
- D** volume

3.2 A 200 g block of hot metal is placed in 200 g of cool water.

(a) State the direction of heat flow. [1]

(b) Explain why the final temperature is closer to the water's starting temperature (water has a higher specific heat). [2]

3.3 Write the energy-conservation equation relating the heat lost by the metal to the heat gained by the water. [2]

Solutions

2.1 From hot to cold.

2.2 When both objects reach the same temperature and net heat flow stops.

2.3 500 J.

3.1 B — the same temperature.

3.2 (a) From the hot metal to the cool water. (b) Water's higher specific heat means it takes more energy to change its temperature, so it warms less than the metal cools — the final temperature ends up nearer the water's start.

3.3 $q_{\text{metal}} = -q_{\text{water}}$ (the heat lost by the metal equals the heat gained by the water).

Name:

AP Chemistry: 2018

CHEMISTRY

Section II

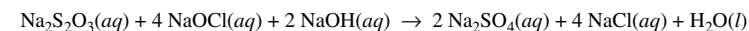
Time—1 hour and 45 minutes

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.

Write your response in the space provided following each question. 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 performs an experiment to determine the value of the enthalpy change, $\Delta H_{\text{rxn}}^\circ$, for the oxidation-reduction reaction represented by the balanced equation above.

(a) Determine the oxidation number of Cl in NaOCl.

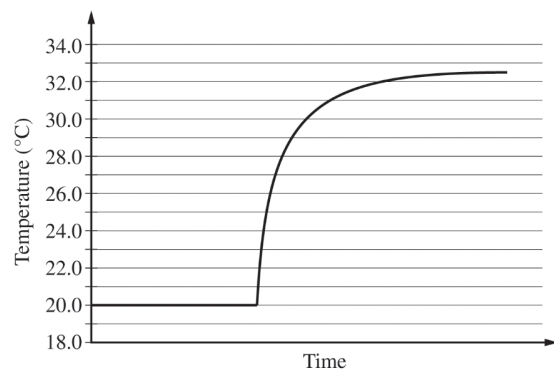
(b) Calculate the number of grams of $\text{Na}_2\text{S}_2\text{O}_3$ needed to prepare 100.00 mL of 0.500 M $\text{Na}_2\text{S}_2\text{O}_3(aq)$.

In the experiment, the student uses the solutions shown in the table below.

Solution	Concentration (M)	Volume (mL)
$\text{Na}_2\text{S}_2\text{O}_3(aq)$	0.500	5.00
$\text{NaOCl}(aq)$	0.500	5.00
$\text{NaOH}(aq)$	0.500	5.00

- (c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

The solutions, all originally at 20.0°C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.



- (d) According to the graph, what is the temperature change of the reaction mixture?
- (e) The mass of the reaction mixture inside the calorimeter is 15.21 g.
- Calculate the magnitude of the heat energy, in joules, that is released during the reaction. Assume that the specific heat of the reaction mixture is 3.94 J/(g·°C) and that the heat absorbed by the calorimeter is negligible.
 - Using the balanced equation for the oxidation-reduction reaction and your answer to part (c), calculate the value of the enthalpy change of the reaction, ΔH_{rxn}° , in kJ/mol_{rxn}. Include the appropriate algebraic sign with your answer.

The student repeats the experiment, but this time doubling the volume of each of the reactants, as shown in the table below.

Solution	Concentration (M)	Volume (mL)
Na ₂ S ₂ O ₃ (aq)	0.500	10.0
NaOCl(aq)	0.500	10.0
NaOH(aq)	0.500	10.0

- (f) The magnitude of the enthalpy change, ΔH_{rxn}° , in kJ/mol_{rxn}, calculated from the results of the second experiment is the same as the result calculated in part (e)(ii). Explain this result.
- (g) Write the balanced net ionic equation for the given reaction.

AP CHEMISTRY • EXERCISE SHEET

6.4 Heat Capacity and Calorimetry

Name: _____ Class: _____ Date: _____

Total: 14 marks

KEY WORDS specific heat 比热容 • calorimetry 量热法 • heat 热量 • exothermic 放热
• endothermic 吸热

Objective

Build the skills to answer exam questions on **heat capacity and calorimetry**.

You must be able to:

- use $q = mc\Delta T$
- carry out a **calorimetry** 量热法 calculation
- find a specific heat or a heat of reaction from data

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ The heat equation

$$q = mc\Delta T,$$

where q is heat (J), m mass (g), c **specific heat** 比热容 (J g⁻¹°C⁻¹), and $\Delta T = T_{\text{final}} - T_{\text{initial}}$.

■ A worked heat

Heat 50 g of water ($c = 4.18$) from 20 to 30°C:

$$q = (50)(4.18)(10) = 2090 \text{ J.}$$

■ Calorimetry

In a calorimeter, the heat released by a reaction is absorbed by the water: $q_{\text{reaction}} = -q_{\text{water}} = -mc\Delta T$. Measure the water's temperature change to find the reaction's heat.

■ Heat of reaction per mole

Divide the total heat by the moles reacted to get ΔH **per mole**: $\Delta H = \frac{q}{n}$ (with the right sign — negative if the water warmed).

2 Practice

Now apply the methods above.

2.1 Write the equation $q = mc\Delta T$ and name each symbol. [2]

2.2 Find the heat to warm 100 g of water ($c = 4.18$) by 5.0°C . [2]

2.3 In a calorimeter the water warms. Was the reaction exo- or endothermic? [1]

3 Exam-style questions

3.1 In $q = mc\Delta T$, ΔT is [1]

- **A** $T_{\text{initial}} - T_{\text{final}}$
- **B** $T_{\text{final}} - T_{\text{initial}}$
- **C** the average temperature
- **D** always positive

3.2 A reaction in a calorimeter warms 200 g of water ($c = 4.18$) by 6.0°C .

(a) Find the heat absorbed by the water. [2]

(b) State q for the reaction (sign and value). [2]

3.3 Burning 0.50 g of a fuel raises 100 g of water ($c = 4.18$) by 10.0°C . Find the heat released per gram of fuel. [4]

Solutions

2.1 q heat, m mass, c specific heat, ΔT temperature change.

2.2 $q = (100)(4.18)(5.0) = 2090 \text{ J}$.

2.3 Exothermic (it released heat to the water).

3.1 **B** — $T_{\text{final}} - T_{\text{initial}}$.

3.2 (a) $q = (200)(4.18)(6.0) = 5016 \text{ J} \approx 5.0 \text{ kJ}$. (b) $q_{\text{reaction}} = -5.0 \text{ kJ}$ (exothermic).

3.3 $q_{\text{water}} = (100)(4.18)(10.0) = 4180 \text{ J}$; heat released = 4180 J for 0.50 g; per gram = $4180/0.50 = 8360 \text{ J/g}$.

Name: _____

AP Chemistry: 2026

Question 1

1. A student performs a calorimetry experiment with KCl.

Part A

Consider the K^+ ion in KCl.

- Write** the complete ground-state electron configuration for the potassium ion, K^+ .
- Which has the larger radius, the K^+ ion or the K atom? **Explain** your reasoning using principles of atomic structure.

The following information applies to parts B, C, D, and E.

A student performs an experiment to determine the enthalpy of solution, ΔH_{soln} , of KCl. The student places water in a calorimeter; measures the initial temperature, adds $\text{KCl}(s)$, and stirs until the KCl dissolves completely. The temperature is continuously monitored during the experiment. Data from the experiment are given in the following table.

Mass of water	97.5 g
Mass of $\text{KCl}(s)$	6.80 g
Initial temperature of water	24.5°C
Final temperature of solution	21.1°C

Part B

Describe how the student can use the temperature readings during the experiment to determine when the dissolution is complete.

Part C

Use the data in the table to do the following.

- Calculate** the magnitude of the thermal energy, q , in joules, transferred during the dissolution. Show the work that leads to your answer. (Assume that the solution has a specific heat capacity of $3.95 \text{ J/(g}\cdot^\circ\text{C)}$.)
- Calculate** the value of the molar enthalpy of solution, ΔH_{soln} , in kJ/mol , for KCl given that 0.0912 mol of KCl dissolved. Show the work that leads to your answer. Include the sign with your answer.

Part D

The calorimeter is not perfectly insulated. Would this cause the magnitude of ΔH_{soln} calculated in part C (ii) to be greater than, less than, or equal to the accepted value? **Justify** your answer.

Part E

The student performs a second experiment using the same mass of water but 6.80 g of RbCl(s) instead of 6.80 g of KCl(s). The magnitude of the molar enthalpy of solution, ΔH_{soln} , of RbCl is approximately equal to that of KCl.

Is the magnitude of ΔT in the RbCl experiment greater than, less than, or equal to that in the KCl experiment? **Justify** your answer. (Assume that the specific heat capacities of the solutions are equal.)

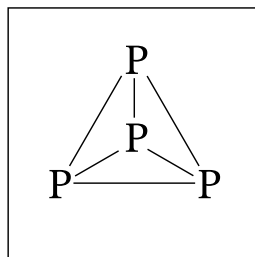
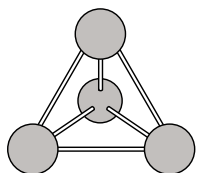
Part F

RbCl has a K_{sp} of 57 at 20°C.

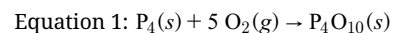
- Write** the net ionic equation for the dissolution of RbCl in pure water.
- Calculate** the molar solubility of RbCl in a saturated solution at 20°C. Show the work that leads to your answer.
- A second saturated solution is prepared by dissolving RbCl(s) in 1.0 M KCl(aq) at 20°C instead of in pure water. Will the molar solubility of RbCl in 1.0 M KCl(aq) be greater than, less than, or equal to the molar solubility calculated in part F (ii)? **Justify** your answer.

AP Chemistry: 2025

3. White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

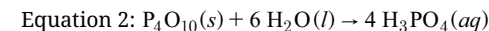


- In the box in part A, complete the Lewis diagram for P_4 by drawing the nonbonding electrons.
- The reaction of white phosphorus with oxygen to form $P_4O_{10}(s)$ is thermodynamically favorable at 298 K. The reaction is represented by equation 1.

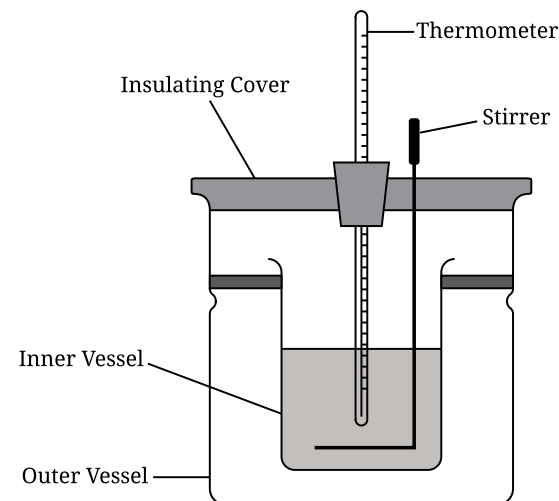


- The entropy change of the reaction, ΔS° , is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.
- The enthalpy change of the reaction, ΔH° , is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** by entropy. Is the student's claim correct? Justify your answer by using the relationship between ΔG° , ΔH° , and ΔS° .

$P_4O_{10}(s)$ reacts exothermically with water to form phosphoric acid, as represented by equation 2.



A chemist uses a calorimetry experiment to determine the enthalpy change for the reaction, as represented by the following diagram.



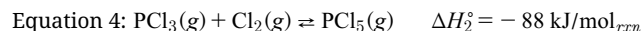
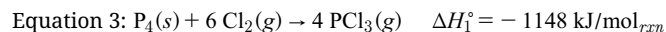
- C. The chemist carries out the calorimetry experiment and records the following information.

Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	22.00° C
Final temperature	22.38° C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g·°C)

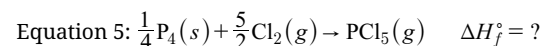
- Calculate the amount of heat, q , released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.
- Calculate the value of ΔH_{rxn}° for equation 2 in kJ/mol_{rxn}. Include the sign in your answer.

D. The chemist weighed out 0.100 g P_4O_{10} of and 100.0 g of H_2O to perform a second trial. In the second trial, some of the solid P_4O_{10} stuck to the weighing paper and was not transferred to the calorimeter. Given that P_4O_{10} is the limiting reactant, would ΔT for the second trial be greater than, less than, or equal to the value in the first trial? Justify your answer.

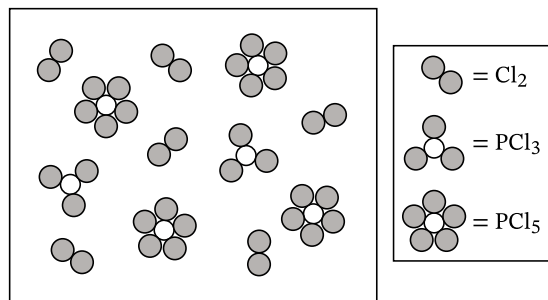
$\text{P}_4(\text{s})$ also reacts readily with $\text{Cl}_2(\text{g})$ to produce phosphorus trichloride, $\text{PCl}_3(\text{g})$, which in turn reacts with $\text{Cl}_2(\text{g})$ in an equilibrium process to produce $\text{PCl}_5(\text{g})$. The reactions are represented by equations 3 and 4.



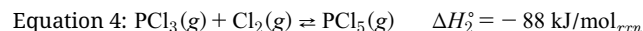
E. Calculate the standard enthalpy of formation of $\text{PCl}_5(\text{g})$ represented by equation 5.



The following particle-level diagram represents the contents of the vessel in an equilibrium mixture at 546 K involving equation 4.



F. Equation 4 for the reaction that occurs is shown.



- If each particle in the diagram represents a partial pressure of 1.00 atm, what is the value of K_p for the equilibrium mixture at 546 K?
- Does the value of K_p increase, decrease, or remain the same when the temperature is increased to 596 K? Justify your answer based on ΔH_2° .

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

CHEMISTRY

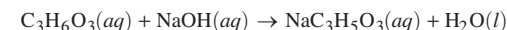
SECTION II

Time—1 hour and 45 minutes

7 Questions

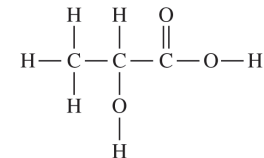
Directions: Questions 1–3 are long free-response questions that require about 23 minutes each to answer and are worth 10 points each. Questions 4–7 are short free-response questions that require about 9 minutes each to answer and are worth 4 points each.

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.



1. A student is studying the reaction between lactic acid, $\text{C}_3\text{H}_6\text{O}_3$, 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.

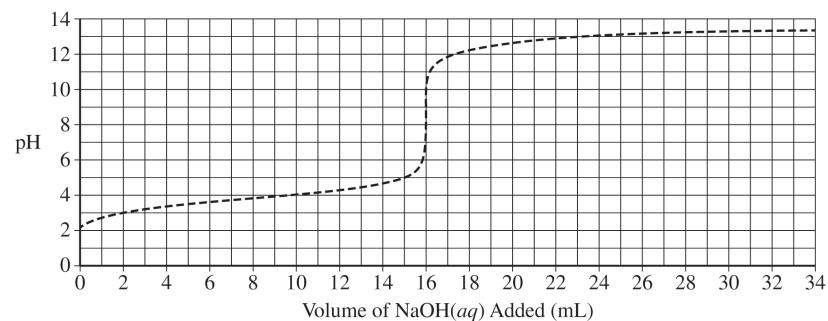


- (b) The student begins the experiment by dissolving 10.22 g of sodium hydroxide (molar mass 40.00 g/mol) in enough water to produce 500. mL of solution. Calculate the molarity of the sodium hydroxide solution.

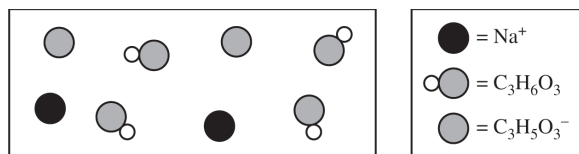
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Continue your response to **QUESTION 1** on this page.

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. _____



(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.)

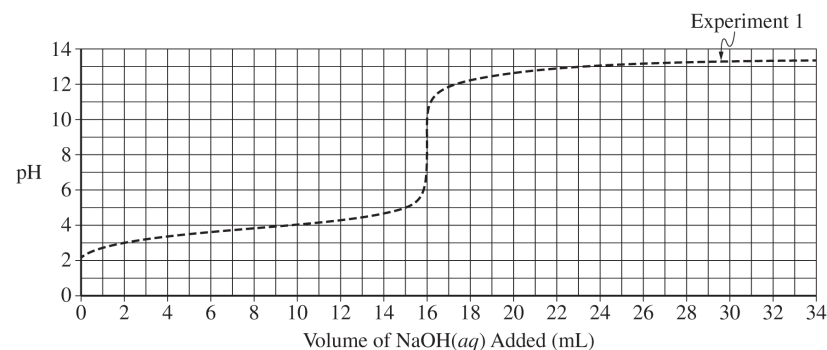
- Draw an X on the preceding titration curve at a point in the titration where the reaction mixture would be represented by this diagram.
- Justify your answer.

GO ON TO THE NEXT PAGE.

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

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

- The student repeats the experiment but uses a solution of $\text{NaOH}(aq)$ 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.



- 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).

- Calculate the quantity of heat produced in the reaction, in J.

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

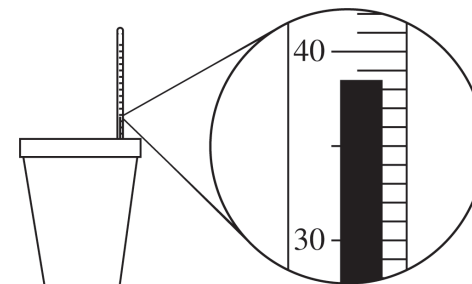
(ii) Calculate the molar enthalpy of reaction, in $\text{kJ/mol}_{\text{rxn}}$. Include the sign in your answer.

(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.

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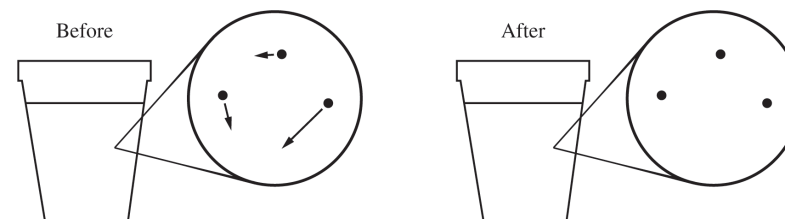
4. A student performs an experiment to determine the specific heat capacity of a metal. The student places a cube of the metal in boiling water so its temperature will be 100.0°C . The student then places the metal cube into a calorimeter that contains water and records the highest temperature of the water. A data table and a diagram of the thermometer at the highest temperature are shown.

Mass of metal cube	98.1 g
Mass of water	52.0 g
Initial temperature of metal cube	100.0°C
Initial temperature of water	25.0°C
Highest temperature of water	?



(a) What should the student report as the highest temperature of the water? _____

- (b) A particle-level representation of water molecules in the calorimeter before and after the metal cube was added is shown. The length of the arrows in the Before diagram represents the speed of the water molecules in the system. In the After diagram, draw an arrow for each molecule to indicate how the speed of each of the molecules changes after the metal cube is added.



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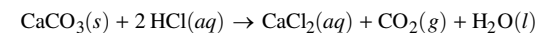
Continue your response to **QUESTION 4** on this page.

(c) Assuming the metal transfers 2940 J of thermal energy to the water, calculate the specific heat of the metal in J/(g·°C).

(d) In a second experiment, 2940 J of thermal energy is transferred from 98.1 g of aluminum, which has a specific heat capacity of 0.897 J / (g·°C). Explain how the magnitude of the temperature change of the aluminum, ΔT_{Al} , compares with the magnitude of the temperature change of the metal in the original experiment.

GO ON TO THE NEXT PAGE.

Answer the following questions about an experiment in which $\text{CaCO}_3(s)$ is combined with $\text{HCl}(aq)$, represented by the following balanced equation.



(a) Write the balanced net ionic equation for the reaction.

A student performs an investigation to study factors that affect the rate of the reaction. In each trial the student combines 50.0 mL of $\text{HCl}(aq)$ at 21.2°C with 1.00 g of $\text{CaCO}_3(s)$ and measures the time required for the reaction to go to completion. The data are given in the following table.

Trial	Concentration of $\text{HCl}(aq)$ (M)	Particle Size of $\text{CaCO}_3(s)$	Time of Reaction (s)
1	1.00	Fine powder	67
2	1.00	Small chunks	112
3	1.00	Large chunk	342
4	3.00	Fine powder	22
5	3.00	Small chunks	227
6	3.00	Large chunk	114

(b) The student correctly identifies that trial 5 is inconsistent with the other trials. Explain why the student's claim is correct using the data in the table.

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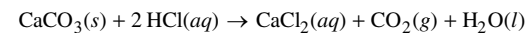
Continue your response to **QUESTION 3** on this page.

- (c) Based on the reaction conditions and the collisions that occur between particles, explain the reason for the difference in the reaction times for trial 2 and trial 3.

- (d) The student claims that the reaction is zero order with respect to $\text{HCl}(aq)$. Do you agree or disagree with the student's claim? Justify your answer using the student's data.

- (e) The $\text{HCl}(aq)$ was present in excess in all trials of the experiment. Determine the molarity of the $\text{HCl}(aq)$ in the beaker after the reaction is complete in trial 2. Assume that the volume of the mixture remains constant at 50.0 mL throughout the trial. (The molar mass of CaCO_3 is 100.09 g/mol.)

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

In order to measure the enthalpy of the reaction shown, the student repeats trial 1 by mixing 50.0 mL of $\text{HCl}(aq)$ with 1.00 g of $\text{CaCO}_3(s)$ using a coffee cup calorimeter. The student records the temperature of the system every 20 seconds. The data are given in the following table.

Time (s)	Measured Temperature of Solution ($^{\circ}\text{C}$)
0	21.20
20	21.51
40	21.70
60	21.85
80	21.90
100	21.90

- (f) Is the reaction endothermic or exothermic? Justify your answer using the information in the table.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

(g) Based on the experimental data, the mass of the system is 51.0 g, and the specific heat of the reaction mixture is $4.0 \text{ J} / (\text{g} \cdot ^\circ\text{C})$.

(i) Calculate the magnitude of heat transfer, q , in joules.

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

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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.

4. A student reacts 0.300 g of methyl salicylate ($\text{C}_8\text{H}_8\text{O}_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($\text{HC}_7\text{H}_5\text{O}_3$).

(a) For every 1 mole of $\text{C}_8\text{H}_8\text{O}_3$ (molar mass 152.15 g/mol) reactant used, 1 mole of salicylic acid crystals ($\text{HC}_7\text{H}_5\text{O}_3$, molar mass 138.12 g/mol) is produced. Calculate the maximum mass, in grams, of $\text{HC}_7\text{H}_5\text{O}_3$ that could be produced in this reaction.

GO ON TO THE NEXT PAGE.

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

As part of the experimental procedure to purify the $\text{HC}_7\text{H}_5\text{O}_3$ crystals after the reaction is complete, the crystals are filtered from the reaction mixture, rinsed with distilled water, and dried. Some physical properties of $\text{HC}_7\text{H}_5\text{O}_3$ are given in the following table.

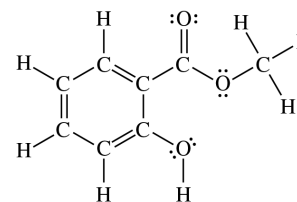
Properties of Salicylic Acid ($\text{HC}_7\text{H}_5\text{O}_3$)	
Melting point	159°C
Solubility in H_2O at 25°C	2.2 g/L
Specific heat capacity	1.17 J/(g·°C)
Heat of fusion	27.1 kJ/mol

- (b) The student's experiment results in an 87% yield of dry $\text{HC}_7\text{H}_5\text{O}_3$. The student suggests that some of the $\text{HC}_7\text{H}_5\text{O}_3$ 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.

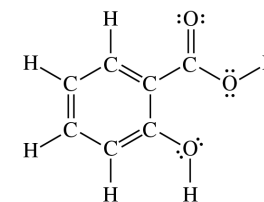
- (c) Given the physical properties in the table, calculate the quantity of heat that must be absorbed to increase the temperature of a 0.105 g sample of dry $\text{HC}_7\text{H}_5\text{O}_3$ (molar mass 138.12 g/mol) crystals from 25°C to the melting point of 159°C and melt the crystals completely.

GO ON TO THE NEXT PAGE.Continue your response to **QUESTION 1** on this page.

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



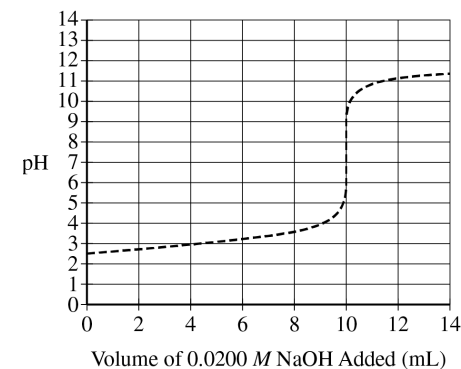
Methyl Salicylate
Melting Point: -9°C



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 student titrates 20.0 mL of 0.0100 M $\text{HC}_7\text{H}_5\text{O}_3(aq)$ with 0.0200 M NaOH, using a probe to monitor the pH of the solution. The data are plotted producing the following titration curve.

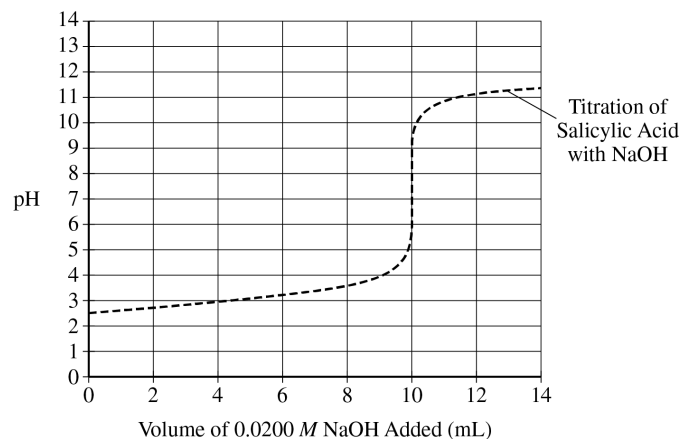
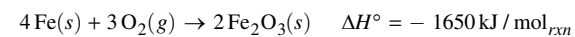
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Continue your response to **QUESTION 1** on this page.

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

- (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.

- (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.

**GO ON TO THE NEXT PAGE.**

4. A student investigates a reaction used in hand warmers, represented above. The student mixes $Fe(s)$ with a catalyst and sand in a small open container. The student measures the temperature of the mixture as the reaction proceeds. The data are given in the following table.

Time (min)	Temperature of Mixture ($^\circ\text{C}$)
0	22.0
1	25.1
2	34.6
3	37.3
4	39.7
5	39.4

- (a) The mixture ($Fe(s)$, catalyst, and sand) has a total mass of 15.0 g and a specific heat capacity of 0.72 J/(g $\cdot$ $^\circ\text{C}$). Calculate the amount of heat absorbed by the mixture from 0 minutes to 4 minutes.

- (b) Calculate the mass of $Fe(s)$, in grams, that reacted to generate the amount of heat calculated in part (a).

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

Continue your response to **QUESTION 4** on this page.

(c) In a second experiment, the student uses twice the mass of iron as that calculated in part (b) but the same mass of sand as in the first experiment. Would the maximum temperature reached in the second experiment be greater than, less than, or equal to the maximum temperature in the first experiment? Justify your answer.

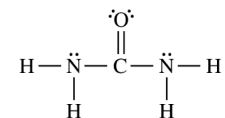
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Use a pencil or pen with black or dark blue ink only. Do NOT write your name. Do NOT write outside the box.

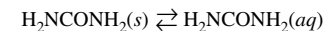
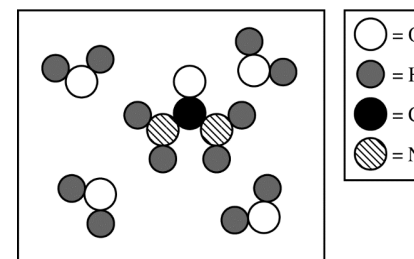
CHEMISTRY**Section II****Time—1 hour and 45 minutes****7 Questions****YOU MAY USE YOUR CALCULATOR FOR THIS SECTION.**

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.

Write your response in the space provided following each question. 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.



- 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.
 - Identify the hybridization of the valence orbitals of the carbon atom in the urea molecule.
 - 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.



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.

- (c) Calculate the concentration of urea, in mol/L, in the saturated solution at 20.°C.
- (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.



Polystyrene Cup



Thermometer



Stirring Rod



Bottle of Urea



Balance



Distilled Water

- (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.

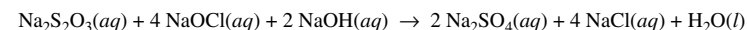
	S° (J/(mol·K))
$\text{H}_2\text{NCONH}_2(s)$	104.6
$\text{H}_2\text{NCONH}_2(aq)$	?

- (f) The entropy change for the dissolution of urea, $\Delta S^\circ_{\text{soln}}$, 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.
- (g) Using particle-level reasoning, explain why $\Delta S^\circ_{\text{soln}}$ is positive for the dissolution of urea in water.
- (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.

CHEMISTRY**Section II****Time—1 hour and 45 minutes****7 Questions****YOU MAY USE YOUR CALCULATOR FOR THIS SECTION.**

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Write your response in the space provided following each question. 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 performs an experiment to determine the value of the enthalpy change, $\Delta H^\circ_{\text{rxn}}$, for the oxidation-reduction reaction represented by the balanced equation above.

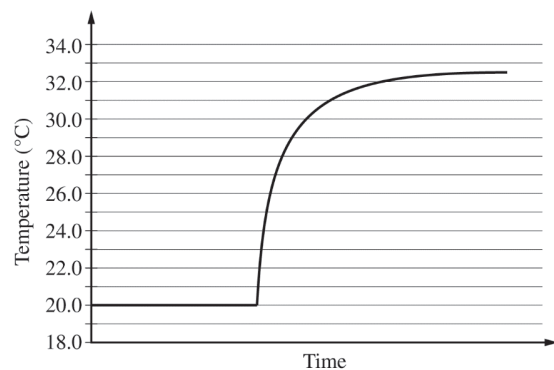
- (a) Determine the oxidation number of Cl in NaOCl.
- (b) Calculate the number of grams of $\text{Na}_2\text{S}_2\text{O}_3$ needed to prepare 100.00 mL of 0.500 *M* $\text{Na}_2\text{S}_2\text{O}_3(aq)$.

In the experiment, the student uses the solutions shown in the table below.

Solution	Concentration (<i>M</i>)	Volume (mL)
$\text{Na}_2\text{S}_2\text{O}_3(aq)$	0.500	5.00
$\text{NaOCl}(aq)$	0.500	5.00
$\text{NaOH}(aq)$	0.500	5.00

- (c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

The solutions, all originally at 20.0°C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.

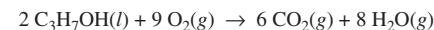


- (d) According to the graph, what is the temperature change of the reaction mixture?
- (e) The mass of the reaction mixture inside the calorimeter is 15.21 g.
- Calculate the magnitude of the heat energy, in joules, that is released during the reaction. Assume that the specific heat of the reaction mixture is 3.94 J/(g·°C) and that the heat absorbed by the calorimeter is negligible.
 - Using the balanced equation for the oxidation-reduction reaction and your answer to part (c), calculate the value of the enthalpy change of the reaction, ΔH_{rxn}° , in kJ/mol_{rxn}. Include the appropriate algebraic sign with your answer.

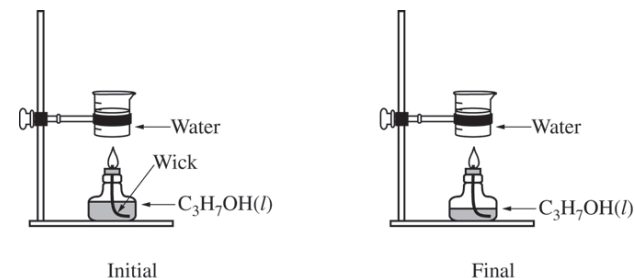
The student repeats the experiment, but this time doubling the volume of each of the reactants, as shown in the table below.

Solution	Concentration (M)	Volume (mL)
Na ₂ S ₂ O ₃ (aq)	0.500	10.0
NaOCl(aq)	0.500	10.0
NaOH(aq)	0.500	10.0

- (f) The magnitude of the enthalpy change, ΔH_{rxn}° , in kJ/mol_{rxn}, calculated from the results of the second experiment is the same as the result calculated in part (e)(ii). Explain this result.
- (g) Write the balanced net ionic equation for the given reaction.



5. A student performs an experiment to determine the enthalpy of combustion of 2-propanol, C₃H₇OH(l), which combusts in oxygen according to the equation above. The student heats a sample of water by burning some of the C₃H₇OH(l) that is in an alcohol burner, as represented below. The alcohol burner uses a wick to draw liquid up into the flame. The mass of C₃H₇OH(l) combusted is determined by weighing the alcohol burner before and after combustion.



Data from the experiment are given in the table below.

Mass of C ₃ H ₇ OH(l) combusted	0.55 g
Mass of water heated	125.00 g
Initial temperature of water	22.0°C
Final temperature of water	51.1°C
Specific heat of water	4.18 J/(g·°C)

- Calculate the magnitude of the heat energy, in kJ, absorbed by the water. (Assume that the energy released from the combustion is completely transferred to the water.)
- Based on the experimental data, if one mole of C₃H₇OH(l) is combusted, how much heat, in kJ, is released? Report your answer with the correct number of significant figures.
- A second student performs the experiment using the same mass of water at the same initial temperature. However, the student uses an alcohol burner containing C₃H₇OH(l) that is contaminated with water, which is miscible with C₃H₇OH(l). The difference in mass of the alcohol burner before and after the combustion in this experiment is also 0.55 g. Would the final temperature of the water in the beaker heated by the alcohol burner in this experiment be greater than, less than, or equal to the final temperature of the water in the beaker in the first student's experiment? Justify your answer.

CHEMISTRY**Section II****7 Questions****Time—1 hour and 45 minutes****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.

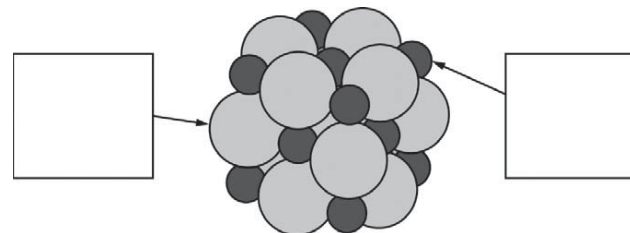
Write your response in the space provided following each question. Examples and equations may be included in your responses where appropriate. For calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer.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

1. A student investigates the enthalpy of solution, ΔH_{soln} , for two alkali metal halides, LiCl and NaCl. In addition to the salts, the student has access to a calorimeter, a balance with a precision of ± 0.1 g, and a thermometer with a precision of $\pm 0.1^\circ\text{C}$.
- (a) To measure ΔH_{soln} for LiCl, the student adds 100.0 g of water initially at 15.0°C to a calorimeter and adds 10.0 g of LiCl(s), stirring to dissolve. After the LiCl dissolves completely, the maximum temperature reached by the solution is 35.6°C .
- (i) Calculate the magnitude of the heat absorbed by the solution during the dissolution process, assuming that the specific heat capacity of the solution is $4.18 \text{ J/(g}\cdot^\circ\text{C)}$. Include units with your answer.
- (ii) Determine the value of ΔH_{soln} for LiCl in kJ/mol_{rxn} .

To explain why ΔH_{soln} for NaCl is different than that for LiCl, the student investigates factors that affect ΔH_{soln} and finds that ionic radius and lattice enthalpy (which can be defined as the ΔH associated with the separation of a solid crystal into gaseous ions) contribute to the process. The student consults references and collects the data shown in the table below.

Ion	Ionic Radius (pm)
Li^+	76
Na^+	102

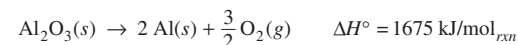
- (b) Write the complete electron configuration for the Na^+ ion in the ground state.
- (c) Using principles of atomic structure, explain why the Na^+ ion is larger than the Li^+ ion.
- (d) Which salt, LiCl or NaCl, has the greater lattice enthalpy? Justify your answer.
- (e) Below is a representation of a portion of a crystal of LiCl. Identify the ions in the representation by writing the appropriate formulas (Li^+ or Cl^-) in the boxes below.



- (f) The lattice enthalpy of LiCl is positive, indicating that it takes energy to break the ions apart in LiCl. However, the dissolution of LiCl in water is an exothermic process. Identify all particle-particle interactions that contribute significantly to the dissolution process being exothermic. For each interaction, include the particles that interact and the specific type of intermolecular force between those particles.

AP Chemistry: 2015

7. Aluminum metal can be recycled from scrap metal by melting the metal to evaporate impurities.
- (a) Calculate the amount of heat needed to purify 1.00 mole of Al originally at 298 K by melting it. The melting point of Al is 933 K. The molar heat capacity of Al is $24 \text{ J/(mol}\cdot\text{K)}$, and the heat of fusion of Al is 10.7 kJ/mol .
- (b) The equation for the overall process of extracting Al from Al_2O_3 is shown below. Which requires less energy, recycling existing Al or extracting Al from Al_2O_3 ? Justify your answer with a calculation.

**STOP****END OF EXAM**

6.5 Energy of Phase Changes

Name: _____ Class: _____ Date: _____

Total: 9 marks

KEY WORDS heat of fusion 熔化热 • phase change 相变 • heat of vaporization 汽化热
• heat 热量

Objective

Build the skills to answer exam questions on the **energy of phase changes**.

You must be able to:

- use the **heat of fusion** 熔化热 and **heat of vaporization** 汽化热
- explain the flat plateaus on a heating curve
- combine heating and phase-change steps

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Phase-change energy

Melting and boiling require energy to overcome intermolecular forces, at **constant temperature**:

$$q = n \Delta H_{\text{fus}} \quad (\text{melting}), \quad q = n \Delta H_{\text{vap}} \quad (\text{boiling}).$$

■ Why the temperature is flat

During a phase change the added energy goes into **separating particles**, not raising their kinetic energy — so the temperature holds steady (the plateau on a heating curve).

■ Combining steps

To take ice below 0°C to steam, add up: warm ice ($mc\Delta T$) + melt ($n\Delta H_{\text{fus}}$) + warm water ($mc\Delta T$) + boil ($n\Delta H_{\text{vap}}$) + warm steam.

■ A worked plateau

Boiling always needs **more** energy than melting for the same substance ($\Delta H_{\text{vap}} > \Delta H_{\text{fus}}$), because boiling fully separates the particles.

2 Practice

Now apply the methods above.

2.1 During melting, what happens to the temperature? [1]

2.2 Write the equation for the heat to melt n moles of a solid. [1]

2.3 Which needs more energy per mole: melting or boiling (same substance)? [1]

3 Exam-style questions

3.1 During a phase change, added energy goes into [1]

- **A** raising the temperature
- **B** overcoming intermolecular forces
- **C** breaking covalent bonds
- **D** speeding up the particles

3.2 2.0 mol of ice melts. $\Delta H_{\text{fus}} = 6.0 \text{ kJ/mol}$.

(a) Find the heat needed. [2]

(b) State what happens to the temperature during melting. [1]

3.3 Explain why the boiling plateau on a heating curve is longer than the melting plateau for the same substance and heating rate. [2]

Solutions

2.1 It stays constant.

2.2 $q = n \Delta H_{\text{fus}}$.

2.3 Boiling.

3.1 **B** — overcoming intermolecular forces.

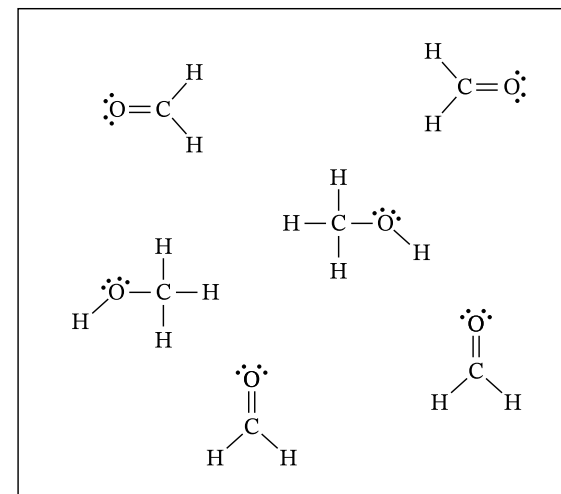
3.2 (a) $q = (2.0)(6.0) = 12 \text{ kJ}$. (b) The temperature stays constant (at the melting point).

3.3 Boiling requires more energy ($\Delta H_{\text{vap}} > \Delta H_{\text{fus}}$) because it fully separates the particles, so at the same heating rate it takes longer, giving a longer plateau.

Name: _____

AP Chemistry: 2025

4. A scientist is investigating the properties of a mixture of CH_3OH and H_2CO . The scientist generates the following diagram to represent the mixture.



- Identify the hybridization of the valence orbitals of the C atom in the H_2CO molecule.
- In the diagram provided, draw a SINGLE dashed line (---) to represent a strong hydrogen-bonding attraction between one CH_3OH molecule and one H_2CO molecule in the mixture.
- The scientist plans to cool a gaseous mixture of CH_3OH and H_2CO to form a liquid mixture and finds data on the two compounds. The data are summarized in the table.

Substance	Melting Point (K)	Boiling Point (K)	Enthalpy of Vaporization (kJ/mol)
CH_3OH	176	338	37.6
H_2CO	181	254	24.2

- Propose a temperature to which the mixture should be cooled such that CH_3OH and H_2CO will both be liquids.
- The scientist analyzes the mixture after it is cooled and determines that 8.59 g of $\text{CH}_3\text{OH}(l)$ is present. Calculate the amount of thermal energy, in kJ, that was removed to condense the 8.59 g of CH_3OH (molar mass 32.04 g/mol) at its boiling point.

. Answer the following questions related to $\text{HBr}(l)$ and $\text{HF}(l)$.

- (a) In the following table, list all of the types of intermolecular forces present in pure samples of $\text{HBr}(l)$ and $\text{HF}(l)$.

Liquid	$\text{HBr}(l)$	$\text{HF}(l)$
Intermolecular forces present		

- (b) The enthalpy of vaporization, $\Delta H_{\text{vap}}^\circ$, for each liquid is provided in the following table.

Liquid	$\text{HBr}(l)$	$\text{HF}(l)$
$\Delta H_{\text{vap}}^\circ$	17.3 kJ / mol	25.2 kJ / mol

- (i) Based on the types and relative strengths of intermolecular forces, explain why $\Delta H_{\text{vap}}^\circ$ of $\text{HF}(l)$ is greater than that of $\text{HBr}(l)$.

- (ii) Calculate the amount of thermal energy, in kJ, required to vaporize 6.85 g of $\text{HF}(l)$.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 6** on this page.

- (c) Based on the arrangement of electrons in the Br and F atoms, explain why the bond length in an HBr molecule is greater than that in an HF molecule.

GO ON TO THE NEXT 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 ($\text{C}_8\text{H}_8\text{O}_3$) with a stoichiometric amount of a strong base. This product is then acidified to produce salicylic acid crystals ($\text{HC}_7\text{H}_5\text{O}_3$).

- (a) For every 1 mole of $\text{C}_8\text{H}_8\text{O}_3$ (molar mass 152.15 g/mol) reactant used, 1 mole of salicylic acid crystals ($\text{HC}_7\text{H}_5\text{O}_3$, molar mass 138.12 g/mol) is produced. Calculate the maximum mass, in grams, of $\text{HC}_7\text{H}_5\text{O}_3$ that could be produced in this reaction.

GO ON TO THE NEXT PAGE.

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

As part of the experimental procedure to purify the $\text{HC}_7\text{H}_5\text{O}_3$ crystals after the reaction is complete, the crystals are filtered from the reaction mixture, rinsed with distilled water, and dried. Some physical properties of $\text{HC}_7\text{H}_5\text{O}_3$ are given in the following table.

Properties of Salicylic Acid ($\text{HC}_7\text{H}_5\text{O}_3$)	
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 $\text{HC}_7\text{H}_5\text{O}_3$. The student suggests that some of the $\text{HC}_7\text{H}_5\text{O}_3$ 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.

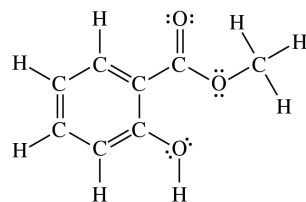
- (c) Given the physical properties in the table, calculate the quantity of heat that must be absorbed to increase the temperature of a 0.105 g sample of dry $\text{HC}_7\text{H}_5\text{O}_3$ (molar mass 138.12 g/mol) crystals from 25°C to the melting point of 159°C and melt the crystals completely.

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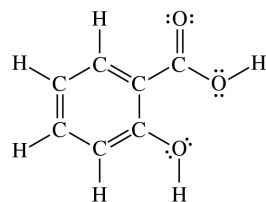


Continue your response to **QUESTION 1** on this page.

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



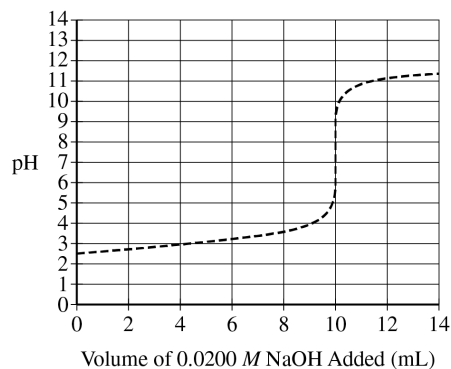
Methyl Salicylate
Melting Point: -9°C



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 student titrates 20.0 mL of 0.0100 M $\text{HC}_7\text{H}_5\text{O}_3(aq)$ with 0.0200 M NaOH, using a probe to monitor the pH of the solution. The data are plotted producing the following titration curve.



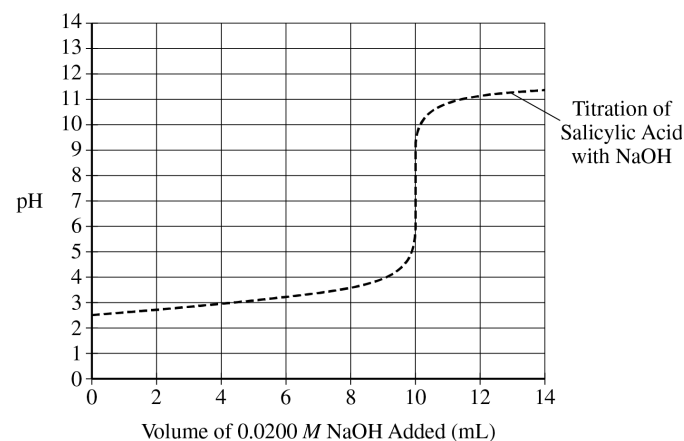
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Continue your response to **QUESTION 1** on this page.

- (e) Using the information in the graph, estimate the $\text{p}K_a$ of $\text{HC}_7\text{H}_5\text{O}_3$. _____
- (f) When the pH of the titration mixture is 4.00, is there a higher concentration of the weak acid, $\text{HC}_7\text{H}_5\text{O}_3$, or its conjugate base, $\text{C}_7\text{H}_5\text{O}_3^-$, in the flask? Justify your answer.

- (g) The student researches benzoic acid ($\text{HC}_7\text{H}_5\text{O}_2$) and finds that it has similar properties to salicylic acid ($\text{HC}_7\text{H}_5\text{O}_3$). The K_a for benzoic acid is 6.3×10^{-5} . Calculate the value of $\text{p}K_a$ for benzoic acid.

- (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.



GO ON TO THE NEXT PAGE.

Name:

AP Chemistry: 2022

Answer the following questions about the compounds NH_2Cl and NCl_3 . The Lewis electron-dot diagrams of the two compounds are shown.



(a) Calculate the number of moles of NH_2Cl (molar mass 51.48 g/mol) present in 1.0 L of a solution in which the concentration of NH_2Cl is 0.0016 g/L.

(b) NH_2Cl is highly soluble in water, whereas NCl_3 is nearly insoluble. Explain this observation in terms of the types and relative strengths of the intermolecular forces between each of the solutes and water.

GO ON TO THE NEXT PAGE.



Name:

AP Chemistry: 2022

Continue your response to **QUESTION 4** on this page.

(c) The value of $\Delta H_{\text{vaporization}}^\circ$ for $\text{NCl}_3(l)$ is 32.9 kJ/mol. Calculate the amount of energy required to vaporize a 15.0 g sample of NCl_3 (molar mass 120.36 g/mol).

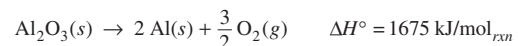
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7. Aluminum metal can be recycled from scrap metal by melting the metal to evaporate impurities.

(a) Calculate the amount of heat needed to purify 1.00 mole of Al originally at 298 K by melting it. The melting point of Al is 933 K. The molar heat capacity of Al is 24 J/(mol·K), and the heat of fusion of Al is 10.7 kJ/mol.

(b) The equation for the overall process of extracting Al from Al_2O_3 is shown below. Which requires less energy, recycling existing Al or extracting Al from Al_2O_3 ? Justify your answer with a calculation.



STOP

END OF EXAM



AP CHEMISTRY • EXERCISE SHEET

6.6 Introduction to Enthalpy of Reaction

Name: _____ Class: _____ Date: _____

Total: 10 marks

KEY WORDS enthalpy of reaction 反应焓 • heat 热量 • exothermic 放热 • endothermic 吸热

Objective

Build the skills to answer exam questions on the **enthalpy of reaction**.

You must be able to:

- interpret ΔH_{rxn} (heat at constant pressure)
- scale ΔH with the amount reacted
- use the sign to classify a reaction

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Enthalpy of reaction

ΔH_{rxn} is the heat exchanged at constant pressure for the amounts in the balanced equation. A **negative** value is exothermic, **positive** is endothermic.

■ Scaling with amount

ΔH is proportional to the moles reacted. If a reaction releases 200 kJ per mole, then 2 mol releases 400 kJ; 0.5 mol releases 100 kJ.

■ Per the equation as written

The value belongs to the equation as written. Doubling all coefficients doubles ΔH ; reversing the equation flips the sign.

■ A worked scaling

If $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$ has $\Delta H = -890$ kJ, burning 0.25 mol CH_4 releases $0.25 \times 890 = 222.5$ kJ.

2 Practice

Now apply the methods above.

2.1 What does a negative ΔH_{rxn} mean? [1]

2.2 A reaction releases 150 kJ/mol. How much for 3 mol? [1]

2.3 How does reversing a reaction change ΔH ? [1]

3 Exam-style questions

3.1 If a reaction as written has $\Delta H = -100$ kJ, then doubling all coefficients gives [1]

- **A** -50 kJ
- **B** -100 kJ
- **C** -200 kJ
- **D** $+100$ kJ

3.2 The reaction $\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3$ has $\Delta H = -92$ kJ.

(a) State whether it is exo- or endothermic. [1]

(b) Find the heat released when 1.0 mol NH_3 forms. [2]

3.3 Combustion of methane releases 890 kJ/mol. Find the heat released by burning 8.0 g of methane ($M = 16$ g/mol). [3]

Solutions

2.1 The reaction is exothermic (releases heat).

2.2 450 kJ.

2.3 It flips the sign.

3.1 **C** — ΔH scales with the coefficients, so it doubles to -200 kJ.

3.2 (a) Exothermic. (b) ΔH is -92 kJ per 2 mol NH_3 , so per 1 mol it is -46 kJ.

3.3 $8.0 \text{ g} \div 16 = 0.50$ mol; heat = $0.50 \times 890 = 445$ kJ.

Question 1

1. A student performs a calorimetry experiment with KCl.

Part A

Consider the K^+ ion in KCl.

- Write** the complete ground-state electron configuration for the potassium ion, K^+ .
- Which has the larger radius, the K^+ ion or the K atom? **Explain** your reasoning using principles of atomic structure.

The following information applies to parts B, C, D, and E.

A student performs an experiment to determine the enthalpy of solution, ΔH_{soln} , of KCl. The student places water in a calorimeter, measures the initial temperature, adds KCl(s), and stirs until the KCl dissolves completely. The temperature is continuously monitored during the experiment. Data from the experiment are given in the following table.

Mass of water	97.5 g
Mass of KCl(s)	6.80 g
Initial temperature of water	24.5°C
Final temperature of solution	21.1°C

Part B

Describe how the student can use the temperature readings during the experiment to determine when the dissolution is complete.

Part C

Use the data in the table to do the following.

- Calculate** the magnitude of the thermal energy, q , in joules, transferred during the dissolution. Show the work that leads to your answer. (Assume that the solution has a specific heat capacity of $3.95 \text{ J/(g}\cdot^\circ\text{C)}$.)
- Calculate** the value of the molar enthalpy of solution, ΔH_{soln} , in kJ/mol, for KCl given that 0.0912 mol of KCl dissolved. Show the work that leads to your answer. Include the sign with your answer.

Part D

The calorimeter is not perfectly insulated. Would this cause the magnitude of ΔH_{soln} calculated in part C (ii) to be greater than, less than, or equal to the accepted value? **Justify** your answer.

**Part E**

The student performs a second experiment using the same mass of water but 6.80 g of RbCl(s) instead of 6.80 g of KCl(s). The magnitude of the molar enthalpy of solution, ΔH_{soln} , of RbCl is approximately equal to that of KCl.

Is the magnitude of ΔT in the RbCl experiment greater than, less than, or equal to that in the KCl experiment? **Justify** your answer. (Assume that the specific heat capacities of the solutions are equal.)

Part F

RbCl has a K_{sp} of 57 at 20°C.

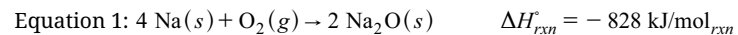
- Write** the net ionic equation for the dissolution of RbCl in pure water.
- Calculate** the molar solubility of RbCl in a saturated solution at 20°C. Show the work that leads to your answer.
- A second saturated solution is prepared by dissolving RbCl(s) in 1.0 M KCl(aq) at 20°C instead of in pure water. Will the molar solubility of RbCl in 1.0 M KCl(aq) be greater than, less than, or equal to the molar solubility calculated in part F (ii)? **Justify** your answer.



Question 7

The following information applies to parts A and B.

7. Sodium metal reacts with oxygen gas according to Equation 1.



Standard enthalpies of formation are provided in Table 1.

Table 1

Substance	ΔH_f° (kJ/mol)
Na(s)	0
O ₂ (g)	0
Na ₂ O(s)	?

Part A

Based on the information given, **calculate** the value of ΔH_f° for Na₂O(s). Show the work that leads to your answer.

Part B

An 18.4 g sample of Na(s) reacts with 12.8 g of O₂(g) according to Equation 1. **Calculate** the total amount of heat, in kilojoules, released during this process. Show the work that leads to your answer.

Part C

Lattice enthalpy can be defined as the energy required to separate an ionic crystal into gaseous ions. Rb₂O(s) and Na₂O(s) have similar crystal structures, and their lattice enthalpies are given in Table 2.

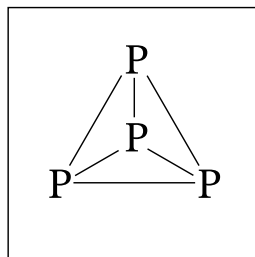
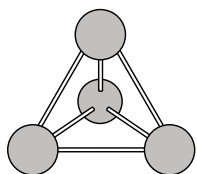
Table 2

Compound	Lattice Enthalpy (kJ/mol)
Na ₂ O(s)	2481
Rb ₂ O(s)	2163

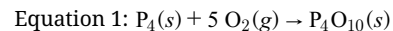
Using Coulomb's law, **explain** why the lattice enthalpy of Rb₂O(s) is smaller than that of Na₂O(s).

STOP
END OF EXAM

3. White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

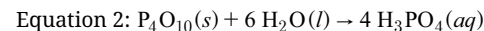


- A. In the box in part A, complete the Lewis diagram for P_4 by drawing the nonbonding electrons.
- B. The reaction of white phosphorus with oxygen to form $P_4O_{10}(s)$ is thermodynamically favorable at 298 K. The reaction is represented by equation 1.

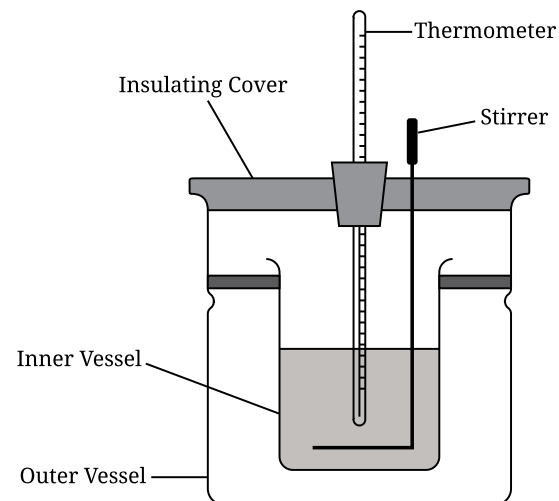


- The entropy change of the reaction, ΔS° , is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.
- The enthalpy change of the reaction, ΔH° , is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** by entropy. Is the student's claim correct? Justify your answer by using the relationship between ΔG° , ΔH° , and ΔS° .

$P_4O_{10}(s)$ reacts exothermically with water to form phosphoric acid, as represented by equation 2.



A chemist uses a calorimetry experiment to determine the enthalpy change for the reaction, as represented by the following diagram.



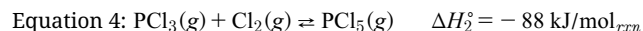
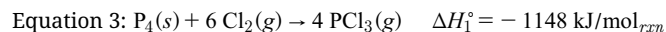
- C. The chemist carries out the calorimetry experiment and records the following information.

Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	22.00° C
Final temperature	22.38° C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g·°C)

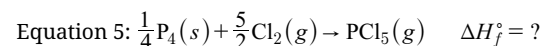
- Calculate the amount of heat, q , released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.
- Calculate the value of ΔH°_{rxn} for equation 2 in kJ/mol_{rxn}. Include the sign in your answer.

D. The chemist weighed out 0.100 g P_4O_{10} of and 100.0 g of H_2O to perform a second trial. In the second trial, some of the solid P_4O_{10} stuck to the weighing paper and was not transferred to the calorimeter. Given that P_4O_{10} is the limiting reactant, would ΔT for the second trial be greater than, less than, or equal to the value in the first trial? Justify your answer.

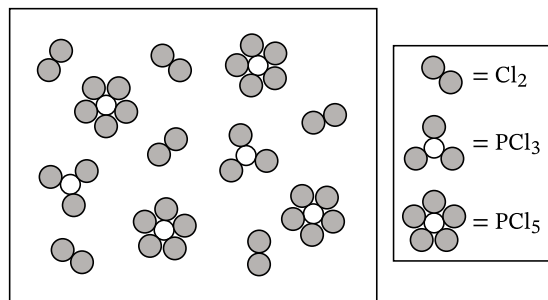
$\text{P}_4(\text{s})$ also reacts readily with $\text{Cl}_2(\text{g})$ to produce phosphorus trichloride, $\text{PCl}_3(\text{g})$, which in turn reacts with $\text{Cl}_2(\text{g})$ in an equilibrium process to produce $\text{PCl}_5(\text{g})$. The reactions are represented by equations 3 and 4.



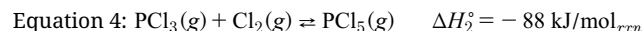
E. Calculate the standard enthalpy of formation of $\text{PCl}_5(\text{g})$ represented by equation 5.



The following particle-level diagram represents the contents of the vessel in an equilibrium mixture at 546 K involving equation 4.



F. Equation 4 for the reaction that occurs is shown.



- If each particle in the diagram represents a partial pressure of 1.00 atm, what is the value of K_p for the equilibrium mixture at 546 K?
- Does the value of K_p increase, decrease, or remain the same when the temperature is increased to 596 K? Justify your answer based on ΔH_2° .

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

CHEMISTRY

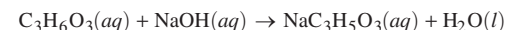
SECTION II

Time—1 hour and 45 minutes

7 Questions

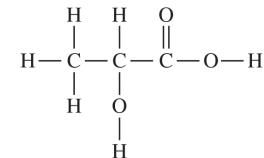
Directions: Questions 1–3 are long free-response questions that require about 23 minutes each to answer and are worth 10 points each. Questions 4–7 are short free-response questions that require about 9 minutes each to answer and are worth 4 points each.

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.



1. A student is studying the reaction between lactic acid, $\text{C}_3\text{H}_6\text{O}_3$, 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.

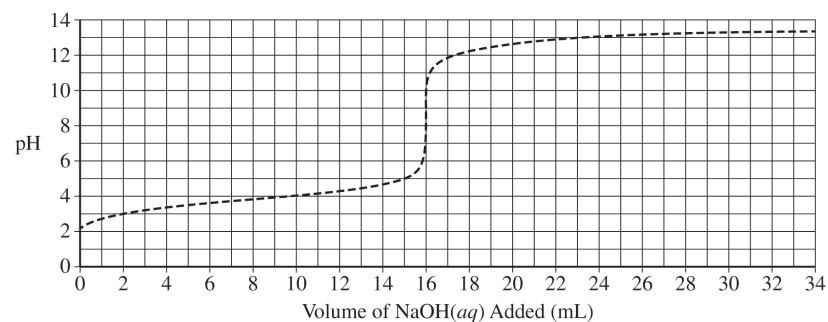


- (b) The student begins the experiment by dissolving 10.22 g of sodium hydroxide (molar mass 40.00 g/mol) in enough water to produce 500. mL of solution. Calculate the molarity of the sodium hydroxide solution.

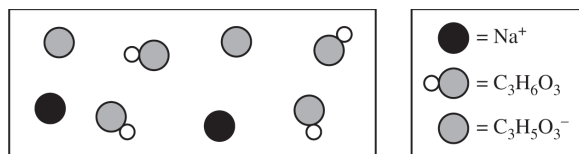
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Continue your response to **QUESTION 1** on this page.

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. _____



(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.)

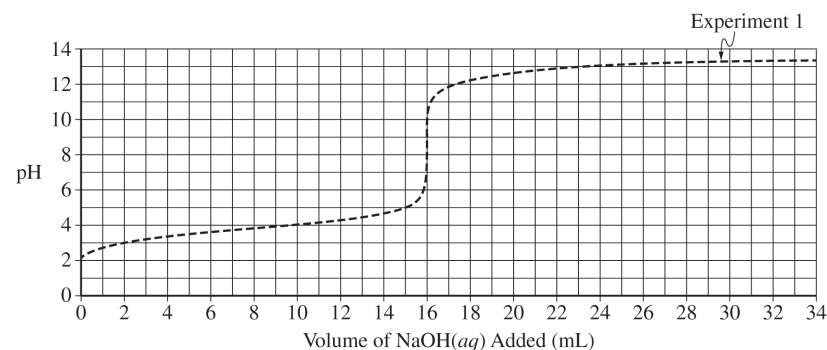
- Draw an X on the preceding titration curve at a point in the titration where the reaction mixture would be represented by this diagram.
- Justify your answer.

GO ON TO THE NEXT PAGE.

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

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

- The student repeats the experiment but uses a solution of $\text{NaOH}(aq)$ 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.



- 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).

- Calculate the quantity of heat produced in the reaction, in J.

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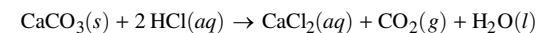
Continue your response to **QUESTION 1** on this page.

(ii) Calculate the molar enthalpy of reaction, in $\text{kJ} / \text{mol}_{\text{rxn}}$. Include the sign in your answer.

(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.

GO ON TO THE NEXT PAGE.

Answer the following questions about an experiment in which $\text{CaCO}_3(s)$ is combined with $\text{HCl}(aq)$, represented by the following balanced equation.



(a) Write the balanced net ionic equation for the reaction.

A student performs an investigation to study factors that affect the rate of the reaction. In each trial the student combines 50.0 mL of $\text{HCl}(aq)$ at 21.2°C with 1.00 g of $\text{CaCO}_3(s)$ and measures the time required for the reaction to go to completion. The data are given in the following table.

Trial	Concentration of $\text{HCl}(aq)$ (M)	Particle Size of $\text{CaCO}_3(s)$	Time of Reaction (s)
1	1.00	Fine powder	67
2	1.00	Small chunks	112
3	1.00	Large chunk	342
4	3.00	Fine powder	22
5	3.00	Small chunks	227
6	3.00	Large chunk	114

(b) The student correctly identifies that trial 5 is inconsistent with the other trials. Explain why the student's claim is correct using the data in the table.

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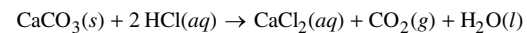
Continue your response to **QUESTION 3** on this page.

- (c) Based on the reaction conditions and the collisions that occur between particles, explain the reason for the difference in the reaction times for trial 2 and trial 3.

- (d) The student claims that the reaction is zero order with respect to $\text{HCl}(aq)$. Do you agree or disagree with the student's claim? Justify your answer using the student's data.

- (e) The $\text{HCl}(aq)$ was present in excess in all trials of the experiment. Determine the molarity of the $\text{HCl}(aq)$ in the beaker after the reaction is complete in trial 2. Assume that the volume of the mixture remains constant at 50.0 mL throughout the trial. (The molar mass of CaCO_3 is 100.09 g/mol.)

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

In order to measure the enthalpy of the reaction shown, the student repeats trial 1 by mixing 50.0 mL of $\text{HCl}(aq)$ with 1.00 g of $\text{CaCO}_3(s)$ using a coffee cup calorimeter. The student records the temperature of the system every 20 seconds. The data are given in the following table.

Time (s)	Measured Temperature of Solution ($^{\circ}\text{C}$)
0	21.20
20	21.51
40	21.70
60	21.85
80	21.90
100	21.90

- (f) Is the reaction endothermic or exothermic? Justify your answer using the information in the table.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 3** on this page.

(g) Based on the experimental data, the mass of the system is 51.0 g, and the specific heat of the reaction mixture is $4.0 \text{ J} / (\text{g} \cdot ^\circ\text{C})$.

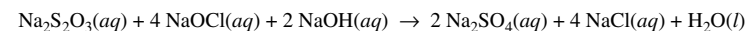
(i) Calculate the magnitude of heat transfer, q , in joules.

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

GO ON TO THE NEXT 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.

Write your response in the space provided following each question. 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 performs an experiment to determine the value of the enthalpy change, ΔH_{rxn}° , for the oxidation-reduction reaction represented by the balanced equation above.

(a) Determine the oxidation number of Cl in NaOCl.

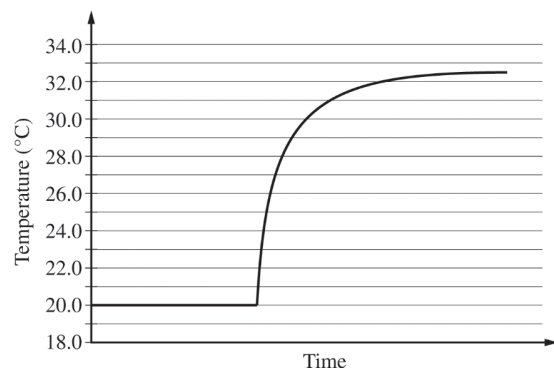
(b) Calculate the number of grams of $\text{Na}_2\text{S}_2\text{O}_3$ needed to prepare 100.00 mL of 0.500 M $\text{Na}_2\text{S}_2\text{O}_3(aq)$.

In the experiment, the student uses the solutions shown in the table below.

Solution	Concentration (M)	Volume (mL)
$\text{Na}_2\text{S}_2\text{O}_3(aq)$	0.500	5.00
$\text{NaOCl}(aq)$	0.500	5.00
$\text{NaOH}(aq)$	0.500	5.00

(c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

The solutions, all originally at 20.0°C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.



- (d) According to the graph, what is the temperature change of the reaction mixture?
- (e) The mass of the reaction mixture inside the calorimeter is 15.21 g.
- Calculate the magnitude of the heat energy, in joules, that is released during the reaction. Assume that the specific heat of the reaction mixture is 3.94 J/(g·°C) and that the heat absorbed by the calorimeter is negligible.
 - Using the balanced equation for the oxidation-reduction reaction and your answer to part (c), calculate the value of the enthalpy change of the reaction, ΔH_{rxn}° , in kJ/mol_{rxn}. Include the appropriate algebraic sign with your answer.

The student repeats the experiment, but this time doubling the volume of each of the reactants, as shown in the table below.

Solution	Concentration (M)	Volume (mL)
Na ₂ S ₂ O ₃ (aq)	0.500	10.0
NaOCl(aq)	0.500	10.0
NaOH(aq)	0.500	10.0

- (f) The magnitude of the enthalpy change, ΔH_{rxn}° , in kJ/mol_{rxn}, calculated from the results of the second experiment is the same as the result calculated in part (e)(ii). Explain this result.
- (g) Write the balanced net ionic equation for the given reaction.

AP CHEMISTRY • EXERCISE SHEET

6.7 Bond Enthalpies

Name: _____ Class: _____ Date: _____

Total: 11 marks

KEY WORDS exothermic 放热 • endothermic 吸热

Objective

Build the skills to answer exam questions on **bond enthalpies**.

You must be able to:

- use $\Delta H \approx \Sigma(\text{bonds broken}) - \Sigma(\text{bonds formed})$
- calculate a reaction enthalpy from bond energies
- explain the sign from bond breaking vs forming

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ The bond-enthalpy method

$$\Delta H \approx \sum(\text{bond enthalpies of bonds broken}) - \sum(\text{bond enthalpies of bonds formed}).$$

Breaking bonds costs energy (+); forming bonds releases energy (−).

■ A worked calculation

For $\text{H}_2 + \text{Cl}_2 \rightarrow 2\text{HCl}$: bonds broken = H–H (436) + Cl–Cl (242) = 678; bonds formed = 2 × H–Cl (2 × 431 = 862). So $\Delta H = 678 - 862 = -184$ kJ (exothermic).

■ The sign logic

If the bonds **formed** are stronger (release more) than those **broken**, ΔH is negative (exothermic). If breaking costs more than forming releases, it is endothermic.

■ An estimate, not exact

Bond enthalpies are **averages**, so this method gives an approximate ΔH — good for gases where all species have well-defined bonds.

2 Practice

Now apply the methods above.

2.1 Write the bond-enthalpy formula for ΔH . [1]

2.2 Breaking bonds — does it absorb or release energy? [1]

2.3 If bonds formed release 900 kJ and bonds broken cost 700 kJ, find ΔH . [2]

3 Exam-style questions

3.1 A reaction is exothermic when the bonds formed are [1]

- A weaker than the bonds broken
- B stronger than the bonds broken
- C equal to the bonds broken
- D all single bonds

3.2 For $\text{H}_2 + \text{Br}_2 \rightarrow 2\text{HBr}$: $\text{H-H} = 436$, $\text{Br-Br} = 193$, $\text{H-Br} = 366$ kJ/mol.

(a) Find the total energy to break the reactant bonds. [1]

(b) Find the total energy released forming the product bonds. [1]

(c) Find ΔH and classify it. [2]

3.3 Explain why bond-enthalpy calculations give only an approximate ΔH . [2]

Solutions

2.1 $\Delta H \approx \Sigma(\text{bonds broken}) - \Sigma(\text{bonds formed})$.

2.2 Absorbs energy.

2.3 $\Delta H = 700 - 900 = -200 \text{ kJ}$.

3.1 B — stronger bonds formed release more energy, giving a negative ΔH .

3.2 (a) $436 + 193 = 629 \text{ kJ}$. (b) $2 \times 366 = 732 \text{ kJ}$. (c) $\Delta H = 629 - 732 = -103 \text{ kJ}$, exothermic.

3.3 Bond enthalpies are **average** values over many molecules, so the actual bond strengths differ slightly, making the result approximate.

Name:

AP Chemistry: 2019

2. Answer the following questions relating to the chemistry of the halogens.

- (a) The molecular formulas of diatomic bromine, chlorine, fluorine, and iodine are written below. Circle the formula of the molecule that has the longest bond length. Justify your choice in terms of atomic structure.



A chemistry teacher wants to prepare Br_2 . The teacher has access to the following three reagents: $\text{NaBr}(aq)$, $\text{Cl}_2(g)$, and $\text{I}_2(s)$.

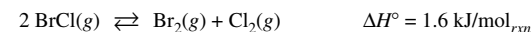
Half-Reaction	E° at 25°C (V)
$\text{Br}_2 + 2 e^- \rightarrow 2 \text{Br}^-$	1.07
$\text{Cl}_2 + 2 e^- \rightarrow 2 \text{Cl}^-$	1.36
$\text{I}_2 + 2 e^- \rightarrow 2 \text{I}^-$	0.53

- (b) Using the data in the table above, write the balanced equation for the thermodynamically favorable reaction that will produce Br_2 when the teacher combines two of the reagents. Justify that the reaction is thermodynamically favorable by calculating the value of E° for the reaction.

Br_2 and Cl_2 can react to form the compound BrCl .

- (c) The boiling point of Br_2 is 332 K, whereas the boiling point of BrCl is 278 K. Explain this difference in boiling point in terms of all the intermolecular forces present between molecules of each substance.

The compound BrCl can decompose into Br_2 and Cl_2 , as represented by the balanced chemical equation below.



A 0.100 mole sample of pure $\text{BrCl}(g)$ is placed in a previously evacuated, rigid 2.00 L container at 298 K. Eventually the system reaches equilibrium according to the equation above.

- (d) Calculate the pressure in the container before equilibrium is established.
 (e) Write the expression for the equilibrium constant, K_{eq} , for the decomposition of BrCl .

After the system has reached equilibrium, 42 percent of the original BrCl sample has decomposed.

- (f) Determine the value of K_{eq} for the decomposition reaction of BrCl at 298 K.
 (g) Calculate the bond energy of the Br-Cl bond, in kJ/mol, using ΔH° for the reaction (1.6 kJ/mol_{rxn}) and the information in the following table.

Bond	Bond Energy (kJ/mol)
Br – Br	193
Cl – Cl	243
Br – Cl	?

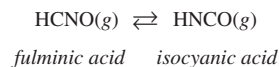
2. Answer the following questions about the isomers fulminic acid and isocyanic acid.

Two possible Lewis electron-dot diagrams for fulminic acid, HCNO, are shown below.



- (a) Explain why the diagram on the left is the better representation for the bonding in fulminic acid. Justify your choice based on formal charges.

Fulminic acid can convert to isocyanic acid according to the equation below.



Fulminic Acid	Isocyanic Acid
$\text{H}-\text{C}\equiv\text{N}-\ddot{\text{O}}:$	$\text{H}-\ddot{\text{N}}=\text{C}=\ddot{\text{O}}:$

- (b) Using the Lewis electron-dot diagrams of fulminic acid and isocyanic acid shown in the boxes above and the table of average bond enthalpies below, determine the value of ΔH° for the reaction of $\text{HCNO}(g)$ to form $\text{HNCO}(g)$.

Bond	Enthalpy (kJ/mol)	Bond	Enthalpy (kJ/mol)	Bond	Enthalpy (kJ/mol)
N–O	201	C=N	615	H–C	413
C=O	745	C≡N	891	H–N	391

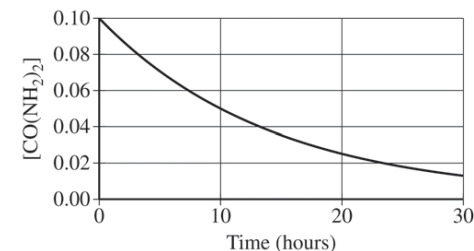
- (c) A student claims that ΔS° for the reaction is close to zero. Explain why the student's claim is accurate.
- (d) Which species, fulminic acid (HCNO) or isocyanic acid (HNCO), is present in higher concentration at equilibrium at 298 K? Justify your answer in terms of thermodynamic favorability and the equilibrium constant.

The ammonium salt of isocyanic acid is a product of the decomposition of urea, $\text{CO}(\text{NH}_2)_2$, represented below.



A student studying the decomposition reaction runs the reaction at 90°C . The student collects data on the concentration of urea as a function of time, as shown by the data table and the graph below.

Time (hours)	$[\text{CO}(\text{NH}_2)_2]$
0	0.1000
5	0.0707
10	0.0500
15	0.0354
20	0.0250
25	0.0177
30	0.0125



- (e) The student proposes that the rate law is $\text{rate} = k[\text{CO}(\text{NH}_2)_2]$.
- (i) Explain how the data support the student's proposed rate law.
- (ii) Using the proposed rate law and the student's results, determine the value of the rate constant, k . Include units with your answer.
- (f) The student learns that the decomposition reaction was run in a solution with a pH of 13. Briefly describe an experiment, including the initial conditions that you would change and the data you would gather, to determine whether the rate of the reaction depends on the concentration of $\text{OH}^-(aq)$.

6.8 Enthalpy of Formation

Name: _____ Class: _____ Date: _____

Total: 13 marks

KEY WORDS standard enthalpy of formation 生成焓

Objective

Build the skills to answer exam questions on **enthalpy of formation**.

You must be able to:

- use standard enthalpies of formation ΔH_f°
- apply $\Delta H_{\text{rxn}} = \Sigma \Delta H_f^\circ(\text{products}) - \Sigma \Delta H_f^\circ(\text{reactants})$
- know that ΔH_f° of an element is zero

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Standard enthalpy of formation

 ΔH_f° is the enthalpy change to make **1 mole** of a compound from its elements in their standard states. For an **element** in its standard state, $\Delta H_f^\circ = 0$.

■ The formula

$$\Delta H_{\text{rxn}}^\circ = \sum \Delta H_f^\circ(\text{products}) - \sum \Delta H_f^\circ(\text{reactants}),$$

weighting each by its coefficient.

■ A worked calculation

For $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$, with ΔH_f° : $\text{CH}_4 = -75$, $\text{CO}_2 = -394$, $\text{H}_2\text{O} = -286$, $\text{O}_2 = 0$:

$$\Delta H = [(-394) + 2(-286)] - [(-75) + 0] = -966 + 75 = -891 \text{ kJ}.$$

■ Don't forget coefficients

Multiply each ΔH_f° by the species' coefficient before summing — a common lost mark.

2 Practice

Now apply the methods above.

2.1 What is ΔH_f° of an element in its standard state? [1]2.2 Write the formula for ΔH_{rxn} from formation enthalpies. [1]2.3 For products summing to -500 and reactants to -200 kJ, find ΔH_{rxn} . [2]

3 Exam-style questions

3.1 The standard enthalpy of formation of $\text{O}_2(g)$ is [1]

- A -286 kJ/mol
- B 0
- C $+286$ kJ/mol
- D unknown

3.2 For $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$, $\Delta H_f^\circ(\text{H}_2\text{O}) = -286$ kJ/mol.(a) State ΔH_f° of H_2 and O_2 . [1](b) Find ΔH_{rxn} . [3]

3.3 For $\text{C}_2\text{H}_4 + 3\text{O}_2 \rightarrow 2\text{CO}_2 + 2\text{H}_2\text{O}$, with ΔH_f° : $\text{C}_2\text{H}_4 = +52$, $\text{CO}_2 = -394$, $\text{H}_2\text{O} = -286$, find ΔH_{rxn} . [4]

Solutions

2.1 Zero.

2.2 $\Delta H_{\text{rxn}} = \Sigma \Delta H_f^\circ(\text{products}) - \Sigma \Delta H_f^\circ(\text{reactants})$.

2.3 $-500 - (-200) = -300$ kJ.

3.1 B — an element in its standard state has $\Delta H_f^\circ = 0$.

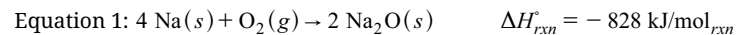
3.2 (a) Both 0 (elements). (b) $\Delta H = 2(-286) - [2(0) + 0] = -572$ kJ.

3.3 products = $2(-394) + 2(-286) = -1360$; reactants = $52 + 3(0) = 52$; $\Delta H = -1360 - 52 = -1412$ kJ.

Question 7

The following information applies to parts A and B.

7. Sodium metal reacts with oxygen gas according to Equation 1.



Standard enthalpies of formation are provided in Table 1.

Table 1

Substance	ΔH_f° (kJ/mol)
Na(s)	0
O ₂ (g)	0
Na ₂ O(s)	?

Part A

Based on the information given, **calculate** the value of ΔH_f° for Na₂O(s). Show the work that leads to your answer.

Part B

An 18.4 g sample of Na(s) reacts with 12.8 g of O₂(g) according to Equation 1. **Calculate** the total amount of heat, in kilojoules, released during this process. Show the work that leads to your answer.

Part C

Lattice enthalpy can be defined as the energy required to separate an ionic crystal into gaseous ions. Rb₂O(s) and Na₂O(s) have similar crystal structures, and their lattice enthalpies are given in Table 2.

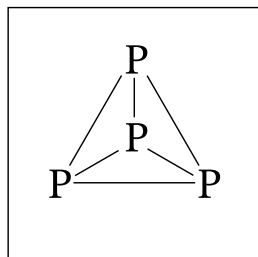
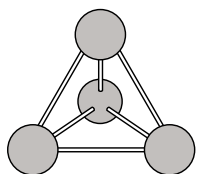
Table 2

Compound	Lattice Enthalpy (kJ/mol)
Na ₂ O(s)	2481
Rb ₂ O(s)	2163

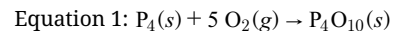
Using Coulomb's law, **explain** why the lattice enthalpy of Rb₂O(s) is smaller than that of Na₂O(s).

STOP
END OF EXAM

3. White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

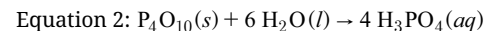


- A. In the box in part A, complete the Lewis diagram for P_4 by drawing the nonbonding electrons.
- B. The reaction of white phosphorus with oxygen to form $P_4O_{10}(s)$ is thermodynamically favorable at 298 K. The reaction is represented by equation 1.

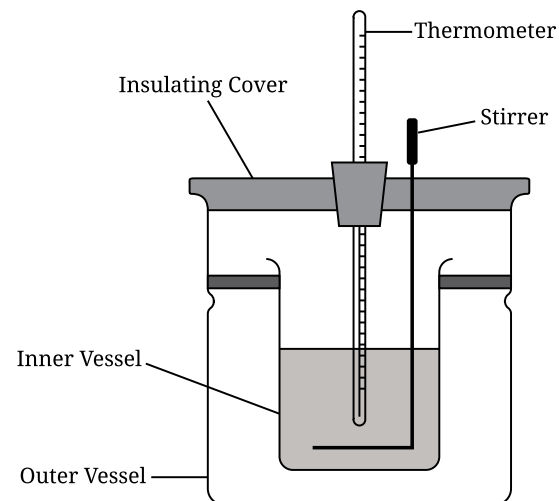


- The entropy change of the reaction, ΔS° , is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.
- The enthalpy change of the reaction, ΔH° , is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** by entropy. Is the student's claim correct? Justify your answer by using the relationship between ΔG° , ΔH° , and ΔS° .

$P_4O_{10}(s)$ reacts exothermically with water to form phosphoric acid, as represented by equation 2.



A chemist uses a calorimetry experiment to determine the enthalpy change for the reaction, as represented by the following diagram.



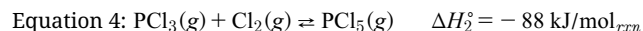
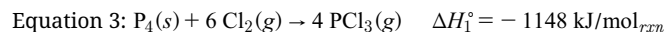
- C. The chemist carries out the calorimetry experiment and records the following information.

Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	22.00° C
Final temperature	22.38° C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g·°C)

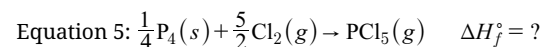
- Calculate the amount of heat, q , released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.
- Calculate the value of ΔH°_{rxn} for equation 2 in kJ/mol_{rxn}. Include the sign in your answer.

D. The chemist weighed out 0.100 g P_4O_{10} of and 100.0 g of H_2O to perform a second trial. In the second trial, some of the solid P_4O_{10} stuck to the weighing paper and was not transferred to the calorimeter. Given that P_4O_{10} is the limiting reactant, would ΔT for the second trial be greater than, less than, or equal to the value in the first trial? Justify your answer.

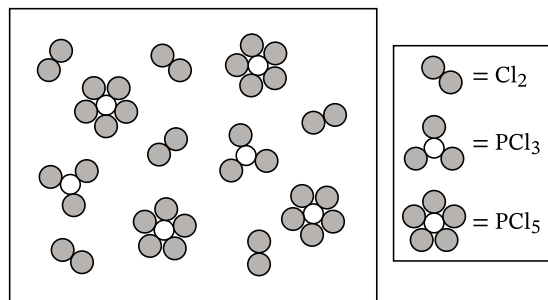
$\text{P}_4(\text{s})$ also reacts readily with $\text{Cl}_2(\text{g})$ to produce phosphorus trichloride, $\text{PCl}_3(\text{g})$, which in turn reacts with $\text{Cl}_2(\text{g})$ in an equilibrium process to produce $\text{PCl}_5(\text{g})$. The reactions are represented by equations 3 and 4.



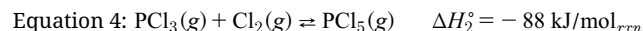
E. Calculate the standard enthalpy of formation of $\text{PCl}_5(\text{g})$ represented by equation 5.



The following particle-level diagram represents the contents of the vessel in an equilibrium mixture at 546 K involving equation 4.

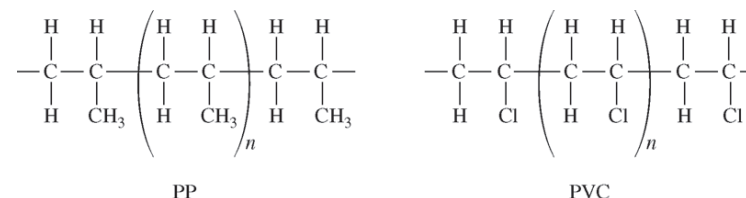


F. Equation 4 for the reaction that occurs is shown.



- If each particle in the diagram represents a partial pressure of 1.00 atm, what is the value of K_p for the equilibrium mixture at 546 K?
- Does the value of K_p increase, decrease, or remain the same when the temperature is increased to 596 K? Justify your answer based on ΔH_2° .

6. A student places a mixture of plastic beads consisting of polypropylene (PP) and polyvinyl chloride (PVC) in a 1.0 L beaker containing distilled water. After stirring the contents of the beaker vigorously, the student observes that the beads of one type of plastic sink to the bottom of the beaker and the beads of the other type of plastic float on the water. The chemical structures of PP and PVC are represented by the diagrams below, which show segments of each polymer.



- (a) Given that the spacing between polymer chains in PP and PVC is similar, the beads that sink are made of which polymer? Explain.

PP is synthesized from propene, C_3H_6 , and PVC is synthesized from vinyl chloride, $\text{C}_2\text{H}_3\text{Cl}$. The structures of the molecules are shown below.



- (b) The boiling point of liquid propene (226 K) is lower than the boiling point of liquid vinyl chloride (260 K). Account for this difference in terms of the types and strengths of intermolecular forces present in each liquid.

In a separate experiment, the student measures the enthalpies of combustion of propene and vinyl chloride. The student determines that the combustion of 2.00 mol of vinyl chloride releases 2300 kJ of energy, according to the equation below.



- (c) Using the table of standard enthalpies of formation below, determine whether the combustion of 2.00 mol of propene releases more, less, or the same amount of energy that 2.00 mol of vinyl chloride releases. Justify your answer with a calculation. The balanced equation for the combustion of 2.00 mol of propene is $2 \text{C}_3\text{H}_6(\text{g}) + 9 \text{O}_2(\text{g}) \rightarrow 6 \text{CO}_2(\text{g}) + 6 \text{H}_2\text{O}(\text{g})$.

Substance	$\text{C}_2\text{H}_3\text{Cl}(\text{g})$	$\text{C}_3\text{H}_6(\text{g})$	$\text{CO}_2(\text{g})$	$\text{H}_2\text{O}(\text{g})$	$\text{HCl}(\text{g})$	$\text{O}_2(\text{g})$
Standard Enthalpy of Formation (kJ/mol)	37	21	-394	-242	-92	0

6.9 Hess's Law

Name: _____ Class: _____ Date: _____

Total: 11 marks**KEY WORDS** hess's law 盖斯定律 • state function 状态函数

Objective

Build the skills to answer exam questions on **Hess's law**.**You must be able to:**

- combine known reactions to find an unknown ΔH (**Hess's law** 盖斯定律)
- **reverse** a reaction (flip ΔH sign) and **scale** it (multiply ΔH)
- add the steps so intermediates cancel

1 Worked examples

Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Hess's law

 ΔH depends only on the **start and end** states, not the path. So you can add known reactions to reach the target reaction, and add their ΔH values.

■ Two allowed moves

- **Reverse** a reaction $\rightarrow$ change the sign of its ΔH .
- **Multiply** a reaction by a factor $\rightarrow$ multiply its ΔH by the same factor.

■ A worked combination

Target: $\text{C} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}$. Given (1) $\text{C} + \text{O}_2 \rightarrow \text{CO}_2$, $\Delta H = -394$; (2) $\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2$, $\Delta H = -283$. Reverse (2): $\Delta H = +283$. Add (1) + reversed (2): CO_2 cancels, giving $\Delta H = -394 + 283 = -111$ kJ.

■ Cancel the intermediates

Arrange the steps so the species not in the target reaction cancel between the two sides. What remains must be the target equation.

2 Practice

Now apply the methods above.

2.1 State Hess's law in one sentence.

[1]

2.2 If reversing a reaction, what happens to ΔH ?

[1]

2.3 A reaction has $\Delta H = -100$ kJ. What is ΔH if you multiply the reaction by 2? [1]

3 Exam-style questions

3.1 Hess's law works because ΔH is a

[1]

- **A** state function (path-independent)
- **B** rate
- **C** catalyst
- **D** temperature

3.2 Find ΔH for $\text{N}_2 + 2\text{O}_2 \rightarrow 2\text{NO}_2$ using: (1) $\text{N}_2 + \text{O}_2 \rightarrow 2\text{NO}$, $\Delta H = +180$ kJ; (2) $2\text{NO} + \text{O}_2 \rightarrow 2\text{NO}_2$, $\Delta H = -112$ kJ.

(a) State how to combine (1) and (2).

[1]

(b) Find the target ΔH .

[2]

3.3 Find ΔH for $\text{C} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}$ using $\text{C} + \text{O}_2 \rightarrow \text{CO}_2$ (-394 kJ) and $\text{CO} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}_2$ (-283 kJ). Show your reasoning. ^[4]

Solutions

2.1 The enthalpy change of a reaction is the same regardless of the path taken.

2.2 Its sign changes.

2.3 -200 kJ .

3.1 A — ΔH is a state function.

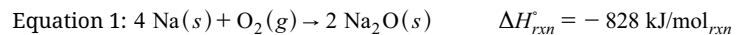
3.2 (a) Add (1) and (2) directly — the 2NO cancels. (b) $\Delta H = 180 + (-112) = +68 \text{ kJ}$.

3.3 Keep reaction 1 as is (-394); reverse reaction 2 ($\text{CO}_2 \rightarrow \text{CO} + \frac{1}{2}\text{O}_2$, $+283$); add — CO_2 cancels, leaving $\text{C} + \frac{1}{2}\text{O}_2 \rightarrow \text{CO}$; $\Delta H = -394 + 283 = -111 \text{ kJ}$.

Question 7

The following information applies to parts A and B.

7. Sodium metal reacts with oxygen gas according to Equation 1.



Standard enthalpies of formation are provided in Table 1.

Table 1

Substance	ΔH_f° (kJ/mol)
Na(s)	0
O ₂ (g)	0
Na ₂ O(s)	?

Part A

Based on the information given, **calculate** the value of ΔH_f° for Na₂O(s). Show the work that leads to your answer.

Part B

An 18.4 g sample of Na(s) reacts with 12.8 g of O₂(g) according to Equation 1. **Calculate** the total amount of heat, in kilojoules, released during this process. Show the work that leads to your answer.

Part C

Lattice enthalpy can be defined as the energy required to separate an ionic crystal into gaseous ions. Rb₂O(s) and Na₂O(s) have similar crystal structures, and their lattice enthalpies are given in Table 2.

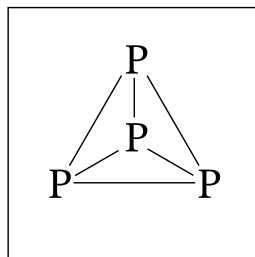
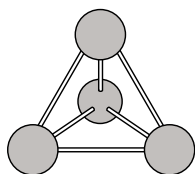
Table 2

Compound	Lattice Enthalpy (kJ/mol)
Na ₂ O(s)	2481
Rb ₂ O(s)	2163

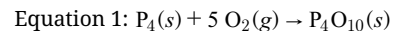
Using Coulomb's law, **explain** why the lattice enthalpy of Rb₂O(s) is smaller than that of Na₂O(s).

STOP
END OF EXAM

3. White phosphorus is composed of P_4 molecules with a tetrahedral structure, as shown in the diagram on the left. Each P atom is bonded to the other three P atoms by single bonds, as shown in the incomplete Lewis diagram on the right.

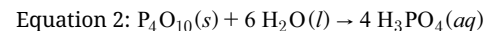


- A. In the box in part A, complete the Lewis diagram for P_4 by drawing the nonbonding electrons.
- B. The reaction of white phosphorus with oxygen to form $P_4O_{10}(s)$ is thermodynamically favorable at 298 K. The reaction is represented by equation 1.

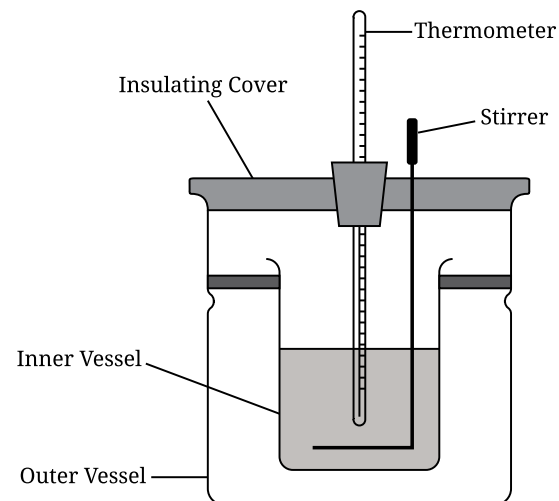


- The entropy change of the reaction, ΔS° , is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.
- The enthalpy change of the reaction, ΔH° , is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** by entropy. Is the student's claim correct? Justify your answer by using the relationship between ΔG° , ΔH° , and ΔS° .

$P_4O_{10}(s)$ reacts exothermically with water to form phosphoric acid, as represented by equation 2.



A chemist uses a calorimetry experiment to determine the enthalpy change for the reaction, as represented by the following diagram.



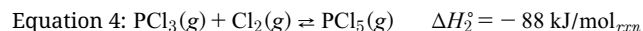
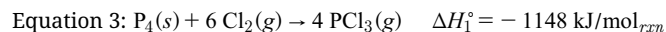
- C. The chemist carries out the calorimetry experiment and records the following information.

Mass of P_4O_{10}	0.100 g
Mass of H_2O	100.0 g
Initial temperature	22.00° C
Final temperature	22.38° C
Molar mass of P_4O_{10}	283.9 g/mol
Specific heat of H_2O	4.18 J/(g·°C)

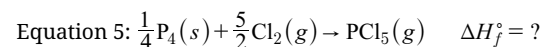
- Calculate the amount of heat, q , released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.
- Calculate the value of ΔH°_{rxn} for equation 2 in kJ/mol_{rxn}. Include the sign in your answer.

D. The chemist weighed out 0.100 g P_4O_{10} of and 100.0 g of H_2O to perform a second trial. In the second trial, some of the solid P_4O_{10} stuck to the weighing paper and was not transferred to the calorimeter. Given that P_4O_{10} is the limiting reactant, would ΔT for the second trial be greater than, less than, or equal to the value in the first trial? Justify your answer.

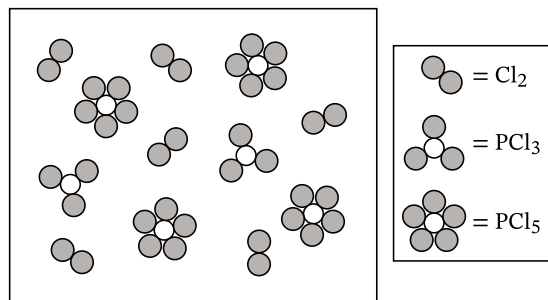
$\text{P}_4(\text{s})$ also reacts readily with $\text{Cl}_2(\text{g})$ to produce phosphorus trichloride, $\text{PCl}_3(\text{g})$, which in turn reacts with $\text{Cl}_2(\text{g})$ in an equilibrium process to produce $\text{PCl}_5(\text{g})$. The reactions are represented by equations 3 and 4.



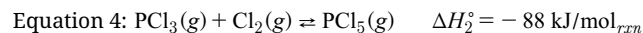
E. Calculate the standard enthalpy of formation of $\text{PCl}_5(\text{g})$ represented by equation 5.



The following particle-level diagram represents the contents of the vessel in an equilibrium mixture at 546 K involving equation 4.

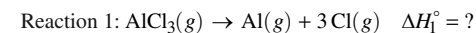


F. Equation 4 for the reaction that occurs is shown.



- If each particle in the diagram represents a partial pressure of 1.00 atm, what is the value of K_p for the equilibrium mixture at 546 K?
- Does the value of K_p increase, decrease, or remain the same when the temperature is increased to 596 K? Justify your answer based on ΔH_2° .

2. In the gas phase, AlCl_3 is a molecular substance. A reaction of gaseous AlCl_3 at high temperature is represented by the following balanced equation.



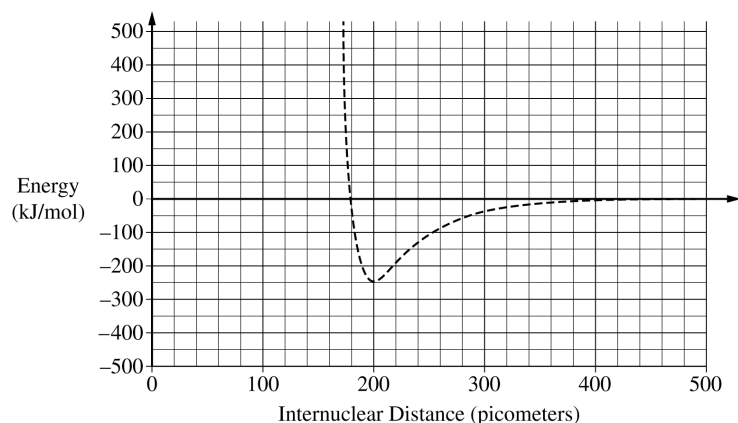
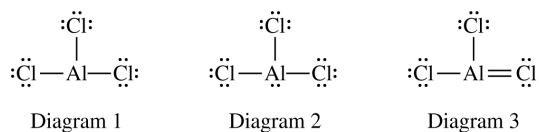
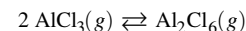
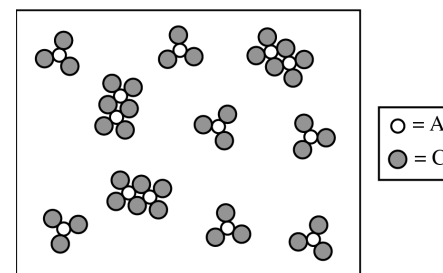
(a) How many grams of $\text{Cl}(\text{g})$ can be formed from 1.25 mol of $\text{AlCl}_3(\text{g})$?

Additional reactions that involve Al or Cl are shown in the following table.

Reaction Number	Equation	$\Delta H_{\text{rxn}}^\circ$ (kJ/mol _{rxn})
2	$\text{Al}(\text{s}) + \frac{3}{2} \text{Cl}_2(\text{g}) \rightarrow \text{AlCl}_3(\text{g})$	-583
3	$\text{Al}(\text{s}) \rightarrow \text{Al}(\text{g})$	+326
4	$\text{Cl}_2(\text{g}) \rightarrow 2 \text{Cl}(\text{g})$	+243

(b) Calculate the value of ΔH_1° , in kJ/mol_{rxn}, for reaction 1 above using reactions 2, 3, and 4.

GO ON TO THE NEXT PAGE.

Continue your response to **QUESTION 2** on this page.(c) A potential energy diagram for Cl_2 is shown in the following graph.(i) Based on the graph, what is the bond length, in picometers, for Cl_2 ? _____(ii) A student finds that the average $\text{Al} - \text{Cl}$ bond length is 220 picometers and the average bond energy is 425 kJ/mol. Draw the potential energy curve for the average $\text{Al} - \text{Cl}$ bond on the preceding graph.(d) Three proposed Lewis diagrams for the $\text{AlCl}_3(g)$ molecule are shown.(i) The $\text{AlCl}_3(g)$ molecule has a trigonal planar geometry. Which diagram (1, 2, or 3) can be eliminated based on geometry? Justify your choice based on VSEPR theory.**GO ON TO THE NEXT PAGE.**Continue your response to **QUESTION 2** on this page.(ii) Which of the three diagrams is the best representation for the bonding in AlCl_3 ? Justify your choice based on formal charges. AlCl_3 is known to dimerize reversibly in the gas phase. The dimerization equilibrium is represented by the following equation.(e) Write the expression for the equilibrium constant, K_p , for this reaction.A particle-level diagram of an equilibrium mixture of $\text{AlCl}_3(g)$ and $\text{Al}_2\text{Cl}_6(g)$ at 400°C in a 25 L closed container is shown.(f) Using the particle-level diagram, calculate the value of K_p for the reaction if the total pressure in the container is 22.1 atm.**GO ON TO THE NEXT PAGE.**

2. Answer the following questions relating to the chemistry of the halogens.

- (a) The molecular formulas of diatomic bromine, chlorine, fluorine, and iodine are written below. Circle the formula of the molecule that has the longest bond length. Justify your choice in terms of atomic structure.



A chemistry teacher wants to prepare Br₂. The teacher has access to the following three reagents: NaBr(aq), Cl₂(g), and I₂(s).

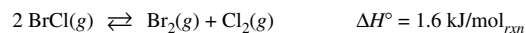
Half-Reaction	E° at 25°C (V)
$\text{Br}_2 + 2 e^- \rightarrow 2 \text{Br}^-$	1.07
$\text{Cl}_2 + 2 e^- \rightarrow 2 \text{Cl}^-$	1.36
$\text{I}_2 + 2 e^- \rightarrow 2 \text{I}^-$	0.53

- (b) Using the data in the table above, write the balanced equation for the thermodynamically favorable reaction that will produce Br₂ when the teacher combines two of the reagents. Justify that the reaction is thermodynamically favorable by calculating the value of E° for the reaction.

Br₂ and Cl₂ can react to form the compound BrCl.

- (c) The boiling point of Br₂ is 332 K, whereas the boiling point of BrCl is 278 K. Explain this difference in boiling point in terms of all the intermolecular forces present between molecules of each substance.

The compound BrCl can decompose into Br₂ and Cl₂, as represented by the balanced chemical equation below.



A 0.100 mole sample of pure BrCl(g) is placed in a previously evacuated, rigid 2.00 L container at 298 K. Eventually the system reaches equilibrium according to the equation above.

- (d) Calculate the pressure in the container before equilibrium is established.
 (e) Write the expression for the equilibrium constant, K_{eq} , for the decomposition of BrCl.

After the system has reached equilibrium, 42 percent of the original BrCl sample has decomposed.

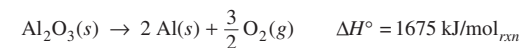
- (f) Determine the value of K_{eq} for the decomposition reaction of BrCl at 298 K.
 (g) Calculate the bond energy of the Br-Cl bond, in kJ/mol, using ΔH° for the reaction (1.6 kJ/mol_{rxn}) and the information in the following table.

Bond	Bond Energy (kJ/mol)
Br – Br	193
Cl – Cl	243
Br – Cl	?

7. Aluminum metal can be recycled from scrap metal by melting the metal to evaporate impurities.

- (a) Calculate the amount of heat needed to purify 1.00 mole of Al originally at 298 K by melting it. The melting point of Al is 933 K. The molar heat capacity of Al is 24 J/(mol·K), and the heat of fusion of Al is 10.7 kJ/mol.

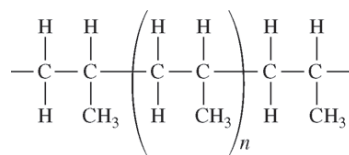
- (b) The equation for the overall process of extracting Al from Al₂O₃ is shown below. Which requires less energy, recycling existing Al or extracting Al from Al₂O₃? Justify your answer with a calculation.



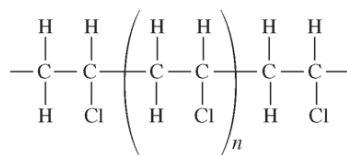
STOP

END OF EXAM

6. A student places a mixture of plastic beads consisting of polypropylene (PP) and polyvinyl chloride (PVC) in a 1.0 L beaker containing distilled water. After stirring the contents of the beaker vigorously, the student observes that the beads of one type of plastic sink to the bottom of the beaker and the beads of the other type of plastic float on the water. The chemical structures of PP and PVC are represented by the diagrams below, which show segments of each polymer.



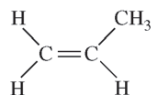
PP



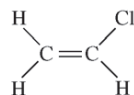
PVC

- (a) Given that the spacing between polymer chains in PP and PVC is similar, the beads that sink are made of which polymer? Explain.

PP is synthesized from propene, C_3H_6 , and PVC is synthesized from vinyl chloride, $\text{C}_2\text{H}_3\text{Cl}$. The structures of the molecules are shown below.



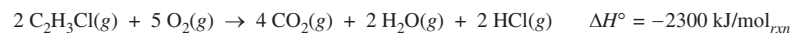
Propene



Vinyl Chloride (chloroethene)

- (b) The boiling point of liquid propene (226 K) is lower than the boiling point of liquid vinyl chloride (260 K). Account for this difference in terms of the types and strengths of intermolecular forces present in each liquid.

In a separate experiment, the student measures the enthalpies of combustion of propene and vinyl chloride. The student determines that the combustion of 2.00 mol of vinyl chloride releases 2300 kJ of energy, according to the equation below.



- (c) Using the table of standard enthalpies of formation below, determine whether the combustion of 2.00 mol of propene releases more, less, or the same amount of energy that 2.00 mol of vinyl chloride releases. Justify your answer with a calculation. The balanced equation for the combustion of 2.00 mol of propene is $2 \text{C}_3\text{H}_6(g) + 9 \text{O}_2(g) \rightarrow 6 \text{CO}_2(g) + 6 \text{H}_2\text{O}(g)$.

Substance	$\text{C}_2\text{H}_3\text{Cl}(g)$	$\text{C}_3\text{H}_6(g)$	$\text{CO}_2(g)$	$\text{H}_2\text{O}(g)$	$\text{HCl}(g)$	$\text{O}_2(g)$
Standard Enthalpy of Formation (kJ/mol)	37	21	-394	-242	-92	0