

Week 11

AP Chemistry

Homework bundle for this week

本周作业合集

exercises.lol

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4. Chemical Reactions

Starter Quiz · 课前小测

AP Chemistry

Name: _____ Score: _____

1. Select **all** signs that suggest a chemical reaction.

- ☐ a colour change
- ☐ a gas bubbling out
- ☐ a precipitate forming

Tick every correct option.

2. A spectator ion is one that...

- ☐ appears unchanged on both sides
- ☐ forms the precipitate
- ☐ is created in the reaction

3. Observing bubbles and a temperature rise is which level?

- ☐ macroscopic
- ☐ particulate
- ☐ symbolic

4. Burning wood into ash and smoke is a...

- ☐ chemical change
- ☐ physical change
- ☐ no change

5. In $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$, how many moles of water form from 3 mol of O_2 (excess H_2)?

_____ mol

6. 30 mL of acid is neutralized by 15 mL of 0.2 M base (1 to 1). The acid's molarity (in M)?

_____ M

7. $A + B \rightarrow AB$ is which type of reaction?

- ☐ synthesis
- ☐ decomposition
- ☐ combustion

8. In the Bronsted-Lowry model, an acid is a substance that...

- ☐ donates a proton (H^+)

☐ accepts a proton

☐ donates an electron

9. In a chemical reaction, the total mass of reactants equals the total mass of products.

☐ True ☐ False

10. You must balance the equation before reading off the mole ratio.

☐ True ☐ False

4. Chemical Reactions

Answers · 答案

AP Chemistry

1. a colour change; a gas bubbling out; a precipitate forming

Colour change, gas, and a precipitate all hint at new substances.

2. appears unchanged on both sides

Spectators do not change, so they cancel out.

3. macroscopic

What you directly see and measure is the macroscopic level.

4. chemical change

New substances (ash, gases) form, so it is chemical.

5. 6 mol

The ratio is 1 O₂ to 2 H₂O, so $3 \times 2 = 6$ mol.

6. 0.1 M

$M_a(30) = (0.2)(15) = 3$, so $M_a = 0.1$ M.

7. synthesis

Two things combining into one is a synthesis.

8. donates a proton (H⁺)

An acid is a proton donor; a base is a proton acceptor.

9. True

Atoms are conserved, so mass is conserved.

10. True

The coefficients only give the correct ratio when balanced.

AP CHEMISTRY · EXERCISE SHEET

4.1 Recognizing a Chemical Reaction

Name: _____ Class: _____ Date: _____ **Total: 12 marks**

KEY WORDS chemical reaction 化学反应 • precipitate 沉淀 • chemical change 化学变化
• acid 酸

Objective

Build the skills to answer exam questions on **recognizing a chemical reaction**.

You must be able to:

- spot evidence of a **chemical change** 化学变化 (gas, precipitate, color, temperature, light)
- distinguish a chemical change from a physical one
- link the evidence to new substances 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.

■ Signs of a chemical reaction

A chemical reaction makes **new substances**. Common evidence:

- a **gas** is produced (bubbles);
- an insoluble **precipitate** 沉淀 forms;
- a **color change**;
- a **temperature change** (heat released or absorbed);
- light or a flame.

■ One sign is a clue, not proof

A single sign (like bubbles) suggests a reaction, but could be physical (boiling makes bubbles too). Look for new substances with different properties.

■ A worked judgement

Mixing two clear solutions that turn cloudy → a **precipitate** formed → a chemical reaction. Ice melting to water → same substance, only a **physical** change.

■ Energy as evidence

A reaction that gets hot (or cold) is exchanging energy as bonds break and form — evidence of a chemical change.

2 Practice

Now apply the methods above.

2.1 List two signs that a chemical reaction has occurred. [2]

2.2 Cloudiness forms when two solutions mix. What has formed? [1]

2.3 Is dissolving sugar in water a chemical change? Give a reason. [2]

3 Exam-style questions

3.1 Which is the best evidence of a **chemical** reaction? [1]

- A water evaporating
- B a precipitate forming from two clear solutions
- C ice melting
- D sugar dissolving

3.2 A student adds a metal to acid and observes bubbling and warming.

(a) State the two signs of a chemical reaction. [2]

(b) Explain why bubbling alone is not conclusive. [1]

3.3 Classify each as physical or chemical: (a) iron rusting, (b) crushing a can, (c) a firework exploding. [3]

Solutions

2.1 Any two: gas produced, precipitate, color change, temperature change, light.

2.2 A precipitate (an insoluble solid).

2.3 No — it is physical; the sugar keeps its identity and can be recovered by evaporation.

3.1 B — a precipitate forming is a new substance, evidence of a chemical reaction.

3.2 (a) Bubbling (gas produced) and warming (temperature change). (b) Bubbling can also be physical (e.g. boiling), so it is not conclusive on its own.

3.3 (a) chemical; (b) physical; (c) chemical.

AP CHEMISTRY • EXERCISE SHEET

4.2 Net Ionic Equations

Name: _____ Class: _____ Date: _____

Total: 11 marks

KEY WORDS net ionic equation 净离子方程 • spectator ions 旁观离子
• complete ionic equation 完整离子方程 • precipitate 沉淀

Objective

Build the skills to answer exam questions on **net ionic equations**.

You must be able to:

- write a **complete ionic equation** 完整离子方程 by separating soluble strong electrolytes into ions
- cancel **spectator ions** 旁观离子
- write the **net ionic equation** 净离子方程

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.

■ Three forms of an equation

- **Molecular:** $\text{AgNO}_3 + \text{NaCl} \rightarrow \text{AgCl} + \text{NaNO}_3$.
- **Complete ionic:** separate all **soluble** ionic compounds into ions.
- **Net ionic:** cancel the ions that appear on both sides.

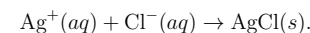
■ Splitting into ions

Soluble strong electrolytes are written as **separate ions**; solids, gases, and molecular substances stay together. So $\text{AgNO}_3 \rightarrow \text{Ag}^+ + \text{NO}_3^-$, but the precipitate $\text{AgCl}(s)$ stays whole.

■ Spectator ions

Ions that appear **unchanged** on both sides (here Na^+ and NO_3^-) are **spectators** — cancel them.

■ The net ionic equation



Only the species that actually react remain — the real chemistry.

2 Practice

Now apply the methods above.

2.1 Write Na^+ and Cl^- as they appear when NaCl dissolves. [1]

2.2 In a reaction, K^+ appears on both sides unchanged. What is it called? [1]

2.3 Which species are NOT split into ions in an ionic equation? [1]

3 Exam-style questions

3.1 A spectator ion is one that [1]

- **A** forms the precipitate
- **B** appears unchanged on both sides
- **C** is a gas
- **D** is the solvent

3.2 Consider $\text{Pb}(\text{NO}_3)_2(aq) + 2\text{KI}(aq) \rightarrow \text{PbI}_2(s) + 2\text{KNO}_3(aq)$.

(a) Identify the spectator ions. [2]

(b) Write the net ionic equation. [2]

3.3 For the reaction of $\text{HCl}(aq)$ with $\text{NaOH}(aq)$ to form water and $\text{NaCl}(aq)$, write the net ionic equation. [3]

Solutions

2.1 $\text{Na}^+(aq) + \text{Cl}^-(aq)$ (separate ions).

2.2 A spectator ion.

2.3 Solids, gases, molecular substances (and weak electrolytes).

3.1 B — unchanged on both sides.

3.2 (a) K^+ and NO_3^- . (b) $\text{Pb}^{2+}(aq) + 2\text{I}^-(aq) \rightarrow \text{PbI}_2(s)$.

3.3 Complete ionic cancels Na^+ and Cl^- ; net ionic: $\text{H}^+(aq) + \text{OH}^-(aq) \rightarrow \text{H}_2\text{O}(l)$.

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 $3.95 \text{ J}/(\text{g}\cdot^\circ\text{C})$.)
- 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.

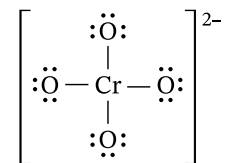
- Write** the net ionic equation for the dissolution of RbCl in pure water.
- Calculate** the molar solubility of RbCl in a saturated solution at 20°C. Show the work that leads to your answer.
- A second saturated solution is prepared by dissolving RbCl(s) in 1.0 M KCl(aq) at 20°C instead of in pure 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 2: Version J

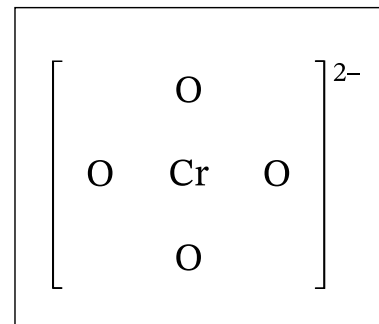
2. Answer the following questions about the chromate ion, CrO_4^{2-} , and the dichromate ion, $\text{Cr}_2\text{O}_7^{2-}$.

Part A

The bonds between chromium and oxygen in CrO_4^{2-} can be represented as covalent bonds. One possible Lewis diagram for the CrO_4^{2-} ion is shown in Figure 1.

Figure 1

- Based on VSEPR theory, **predict** the molecular geometry of the CrO_4^{2-} ion.
- On Figure 2, **draw** a complete Lewis diagram for a resonance structure of CrO_4^{2-} that results in a formal charge of zero on two of the O atoms and a formal charge of -1 on the other two O atoms. Your diagram should contain the same number of valence electrons as in Figure 1.

Figure 2

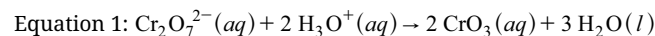
Part B

When reacted with a strong acid like $\text{HNO}_3(aq)$, $\text{CrO}_4^{2-}(aq)$ can be converted to $\text{Cr}_2\text{O}_7^{2-}(aq)$ and $\text{H}_2\text{O}(l)$ in a reversible reaction.

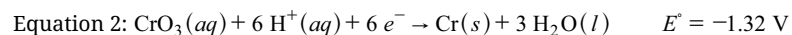
- Write** a balanced net ionic equation for the reaction between $\text{CrO}_4^{2-}(aq)$ and a strong acid.
- Is the reaction a redox reaction? **Justify** your answer based on the oxidation number of Cr.

The following information applies to parts C and D.

In acidic solutions, $\text{Cr}_2\text{O}_7^{2-}(aq)$ reacts to form $\text{CrO}_3(aq)$ according to Equation 1.



$\text{CrO}_3(aq)$ can be electrolyzed to plate objects with a thin layer of chromium metal according to Equation 2.

**Part C**

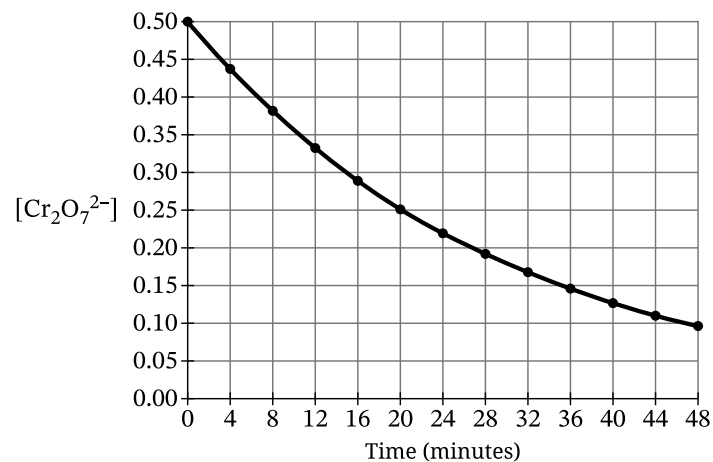
Is the reaction represented by Equation 2 thermodynamically favorable or unfavorable under standard conditions? **Justify** your answer with a calculation of ΔG° . Show the work that leads to your answer.

Part D

Calculate the number of grams of $\text{Cr}(s)$ that could be plated onto the surface of a steel rod when 15.0 A of current is applied for 3250 seconds. Show the work that leads to your answer.

Part E

In a separate experiment, an iron wire is placed directly in a solution of 0.50 M $\text{Cr}_2\text{O}_7^{2-}(aq)$ with $\text{pH} = 1.99$. The concentration of $\text{Cr}_2\text{O}_7^{2-}(aq)$ remaining is recorded over time, and the results are presented in Figure 3.

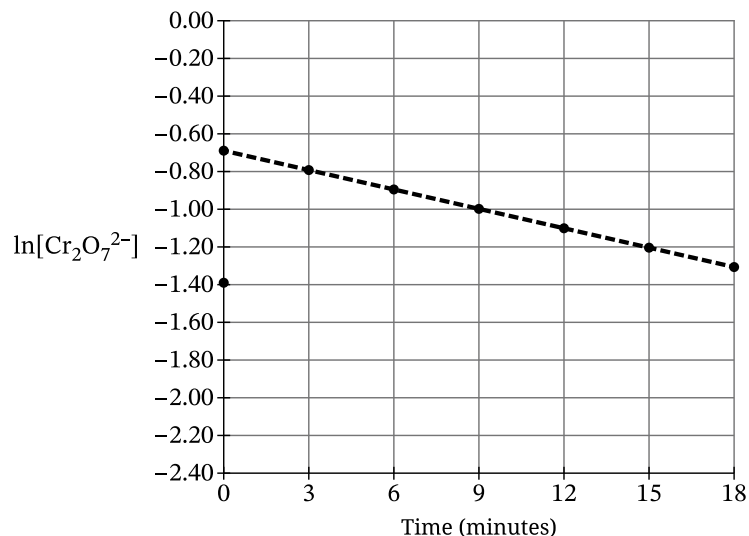
Figure 3

Explain how the data in Figure 3 support the conclusion that the reaction is first order with respect to $\text{Cr}_2\text{O}_7^{2-}$.

The following information applies to parts F and G.

The student creates a plot of $\ln[\text{Cr}_2\text{O}_7^{2-}]$ versus time for a trial with an initial concentration of $0.50\text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$, as shown in Figure 4.

Figure 4



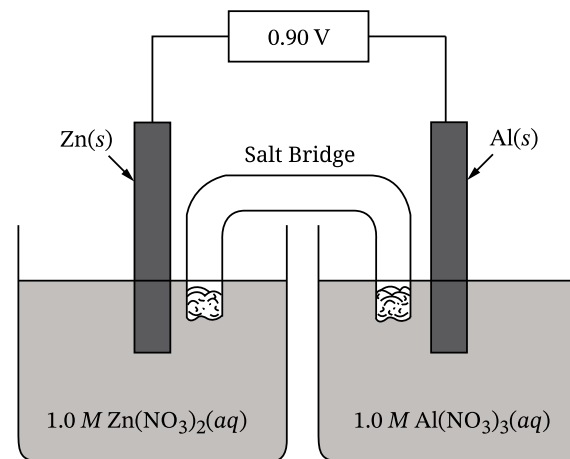
Part F

Calculate the value of the rate constant, k , for the reaction. Report your answer in units of min^{-1} . Show the work that leads to your answer.

Part G

The student then runs a second trial of the experiment under identical conditions but uses an initial concentration of $0.25\text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$ instead of $0.50\text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$. On Figure 4, carefully **draw** the plot of $\ln[\text{Cr}_2\text{O}_7^{2-}]$ versus time that would be expected for the second experiment. The point at time zero has already been plotted.

6. A scientist constructs a galvanic cell as shown in the diagram. As the cell operates, the $\text{Zn}(\text{s})$ electrode increases in mass and the $\text{Al}(\text{s})$ electrode decreases in mass. A data table with the standard reduction potentials for the substances follows the diagram.



Half-Reaction	E° (V)
$\text{Zn}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Zn}(\text{s})$	-0.76
$\text{Al}^{3+}(\text{aq}) + 3\text{e}^- \rightarrow \text{Al}(\text{s})$	-1.66

- Write the half-reaction for the oxidation that occurs at the anode.
- Write the balanced net ionic equation for the overall reaction that occurs in the galvanic cell.
- Initially, each electrode has a mass of 50.0 g. The cell is allowed to run for a period of time and is then stopped. Which electrode's mass changed the most? Justify your answer with a calculation.

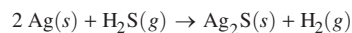
AP CHEMISTRY 2025 FREE-RESPONSE QUESTIONS

Reduction Half-Reaction	E° (V)
$\text{Au}^{3+}(\text{aq}) + 3\text{e}^- \rightarrow \text{Au}(\text{s})$	+1.50
$\text{Zn}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Zn}(\text{s})$	-0.76
$\text{Mn}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Mn}(\text{s})$	-1.19
$\text{Al}^{3+}(\text{aq}) + 3\text{e}^- \rightarrow \text{Al}(\text{s})$	-1.66
$\text{Be}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Be}(\text{s})$	-1.85

- The standard Zn/Al cell has a value of E°_{cell} equal to 0.90 V. The scientist needs a galvanic cell that produces a greater voltage. The scientist has access to the chemical systems in the table. If the scientist uses the Zn half-cell and one of the other options from the table, what is the MAXIMUM voltage that could be generated at standard conditions?

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

3. Sterling silver is an alloy that is commonly used to make jewelry and consists of 92.5% silver and 7.5% other metals, such as copper, by mass. Over time, the alloy can form a tarnish of $\text{Ag}_2\text{S}(s)$ when it reacts with hydrogen sulfide, as represented by the following equation.



- (a) What are the oxidation numbers of silver in $\text{Ag}(s)$ and $\text{Ag}_2\text{S}(s)$?

$\text{Ag}(s)$ _____ $\text{Ag}_2\text{S}(s)$ _____

- (b) The following table contains the atomic radii for silver and copper.

Element	Silver (Ag)	Copper (Cu)
Atomic radius (pm)	165	145

- (i) Explain why sterling silver is better classified as a substitutional alloy than as an interstitial alloy.

- (ii) Using principles of atomic structure and Coulomb's law, explain why silver has a larger atomic radius than copper does.

GO ON TO THE NEXT PAGE.

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

The Ag_2S tarnish on sterling silver can be removed until only sterling silver remains. A student weighs a tarnished sterling silver sample both before and after removing the $\text{Ag}_2\text{S}(s)$ (molar mass 247.80 g / mol) and records the data in the following table.

	Before Tarnish Removal	After Tarnish Removal
Mass	409.21 g	398.94 g

- (c) Assuming that only $\text{Ag}_2\text{S}(s)$ is removed, calculate the number of moles of silver atoms removed.

Rhodium plating is a process used to protect sterling silver from tarnishing. This involves electroplating (depositing) solid rhodium, $\text{Rh}(s)$, onto the surface of the metal from an acidified solution of $\text{Rh}_2(\text{SO}_4)_3(aq)$. Oxygen gas is produced during this process.

- (d) A table of half-reactions related to the overall reaction is provided.

Half-Reaction	E° (V)
$\text{Rh}^{3+}(aq) + 3 e^- \rightarrow \text{Rh}(s)$	+0.80
$\text{O}_2(g) + 4 \text{H}^+(aq) + 4 e^- \rightarrow 2 \text{H}_2\text{O}(l)$	+1.23

- (i) Write the balanced net ionic equation for plating $\text{Rh}(s)$ from the acidified $\text{Rh}_2(\text{SO}_4)_3(aq)$ solution.

- (ii) Calculate the value of E°_{cell} for the reaction in part (d)(i).

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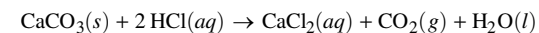
Continue your response to **QUESTION 3** on this page.

(iii) Based on your answer to part (d)(ii), explain why this process requires the use of an external power source.

(e) Calculate the length of time, in seconds, required to plate 2.8 g of Rh(s) onto a piece of sterling silver if 2.0 C / s of current is applied.

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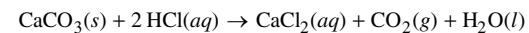
Continue your response to **QUESTION 3** on this page.

- (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.

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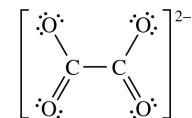
Continue your response to **QUESTION 3** on this page.

(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.



A Lewis electron-dot diagram of the oxalate ion, $\text{C}_2\text{O}_4^{2-}$, is shown.

(a) Identify the hybridization of the valence orbitals of either carbon atom in the oxalate ion.

(b) Silver oxalate, $\text{Ag}_2\text{C}_2\text{O}_4(s)$, is slightly soluble in water. The value of K_{sp} for $\text{Ag}_2\text{C}_2\text{O}_4$ is 5.40×10^{-12} .

(i) Write the expression for the solubility-product constant, K_{sp} , for $\text{Ag}_2\text{C}_2\text{O}_4$.

(ii) Calculate the molar solubility of $\text{Ag}_2\text{C}_2\text{O}_4$ in neutral distilled water.

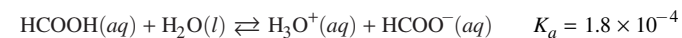
(iii) The molar solubility of $\text{Ag}_2\text{C}_2\text{O}_4$ increases when it is dissolved in $0.5 \text{ M HClO}_4(aq)$ instead of neutral distilled water. Write a balanced, net-ionic equation for the process that occurs between species in solution that contributes to the increased solubility of $\text{Ag}_2\text{C}_2\text{O}_4(aq)$ in $\text{HClO}_4(aq)$.

GO ON TO THE NEXT PAGE.

STOP**END OF EXAM****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. Methanoic acid, HCOOH, ionizes according to the equation above.

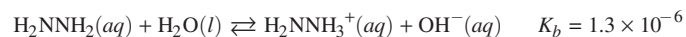
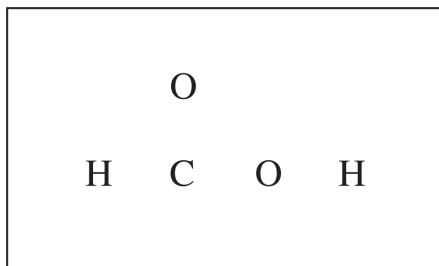
(a) Write the expression for the equilibrium constant, K_a , for the reaction.

(b) Calculate the pH of a 0.25 M solution of HCOOH.

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(c) In the box below, complete the Lewis electron-dot diagram for HCOOH . Show all bonding and nonbonding valence electrons.



(d) In aqueous solution, the compound H_2NNH_2 reacts according to the equation above. A 50.0 mL sample of 0.25 M $\text{H}_2\text{NNH}_2(aq)$ is combined with a 50.0 mL sample of 0.25 M $\text{HCOOH}(aq)$.

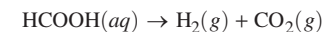
(i) Write the balanced net ionic equation for the reaction that occurs when H_2NNH_2 is combined with HCOOH .

(ii) Is the resulting solution acidic, basic, or neutral? Justify your answer.

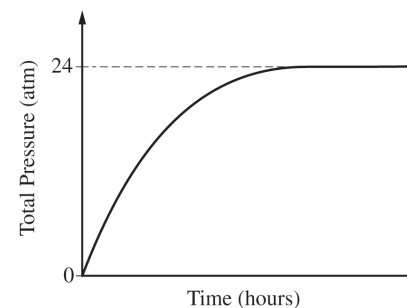
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When a catalyst is added to a solution of $\text{HCOOH}(aq)$, the reaction represented by the following equation occurs.



(e) Is the reaction a redox reaction? Justify your answer.



(f) The reaction occurs in a rigid 4.3 L vessel at 25°C , and the total pressure is monitored, as shown in the graph above. The vessel originally did not contain any gas. Calculate the number of moles of $\text{CO}_2(g)$ produced in the reaction. (Assume that the amount of $\text{CO}_2(g)$ dissolved in the solution is negligible.)

(g) After the reaction has proceeded for several minutes, does the amount of catalyst increase, decrease, or remain the same? Justify your answer.

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3. A student is given the task of determining the molar concentration of a CuSO_4 solution using two different procedures, precipitation and spectrophotometry.

For the precipitation experiment, the student adds 20.0 mL of 0.200 M $\text{Ba}(\text{NO}_3)_2$ to 50.0 mL of the $\text{CuSO}_4(aq)$. The reaction goes to completion, and a white precipitate forms. The student filters the precipitate and dries it overnight. The data are given in the following table.

Mass of dry filter paper	0.764 g
Volume of $\text{CuSO}_4(aq)$	50.0 mL
Volume of 0.200 M $\text{Ba}(\text{NO}_3)_2$	20.0 mL
Mass of filter paper and dried precipitate	1.136 g

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

(b) Calculate the number of moles of precipitate formed.

(c) Calculate the molarity of the original CuSO_4 solution.

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For the spectrophotometry experiment, the student first makes a standard curve. The student uses a 0.1000 M solution of $\text{CuSO}_4(aq)$ to make three more solutions of known concentration (0.0500 M , 0.0300 M , and 0.0100 M) in 50.00 mL volumetric flasks.

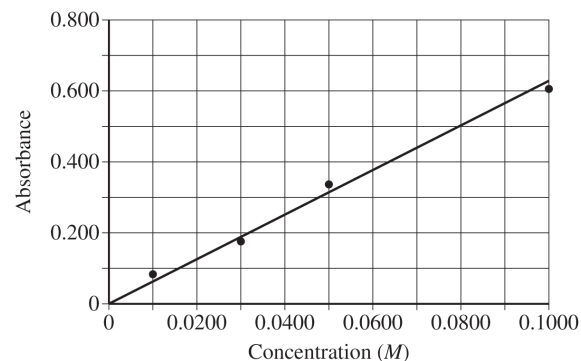
(d) Calculate the volume of 0.1000 M $\text{CuSO}_4(aq)$ needed to make 50.00 mL of 0.0500 M $\text{CuSO}_4(aq)$.

(e) Briefly describe the procedure the student should follow to make 50.00 mL of 0.0500 M $\text{CuSO}_4(aq)$ using 0.1000 M $\text{CuSO}_4(aq)$, a 50.00 mL volumetric flask, and other standard laboratory equipment. Assume that all appropriate safety precautions will be taken.

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The standard curve is given below.



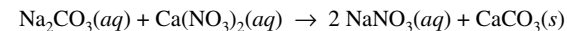
(f) The absorbance of the CuSO_4 solution of unknown concentration is 0.219. Determine the molarity of the solution.

(g) A second student performs the same experiment. There are a few drops of water in the cuvette before the second student adds the $\text{CuSO}_4(aq)$ solution of unknown concentration. Will this result in a $\text{CuSO}_4(aq)$ concentration for the unknown that is greater than, less than, or equal to the concentration determined in part (f)? Justify your answer.

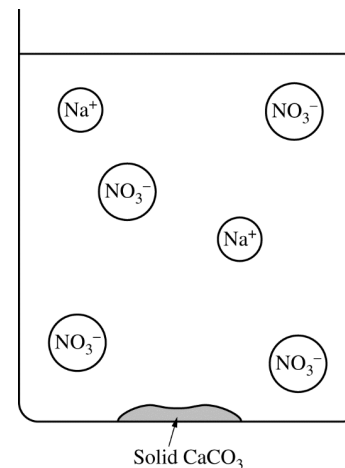
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3. A student is given 50.0 mL of a solution of Na_2CO_3 of unknown concentration. To determine the concentration of the solution, the student mixes the solution with excess 1.0 M $\text{Ca}(\text{NO}_3)_2(aq)$, causing a precipitate to form. The balanced equation for the reaction is shown below.



- (a) Write the net ionic equation for the reaction that occurs when the solutions of Na_2CO_3 and $\text{Ca}(\text{NO}_3)_2$ are mixed.
- (b) The diagram below is incomplete. Draw in the species needed to accurately represent the major ionic species remaining in the solution after the reaction has been completed.

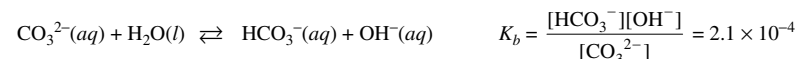


The student filters and dries the precipitate of CaCO_3 (molar mass 100.1 g/mol) and records the data in the table below.

Volume of Na_2CO_3 solution	50.0 mL
Volume of 1.0 M $\text{Ca}(\text{NO}_3)_2$ added	100.0 mL
Mass of CaCO_3 precipitate collected	0.93 g

- (c) Determine the number of moles of Na_2CO_3 in the original 50.0 mL of solution.
- (d) The student realizes that the precipitate was not completely dried and claims that as a result, the calculated Na_2CO_3 molarity is too low. Do you agree with the student's claim? Justify your answer.
- (e) After the precipitate forms and is filtered, the liquid that passed through the filter is tested to see if it can conduct electricity. What would be observed? Justify your answer.

The student decides to determine the molarity of the same Na_2CO_3 solution using a second method. When Na_2CO_3 is dissolved in water, $\text{CO}_3^{2-}(aq)$ hydrolyzes to form $\text{HCO}_3^-(aq)$, as shown by the following equation.

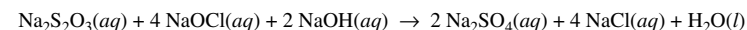


- (f) The student decides to first determine $[\text{OH}^-]$ in the solution, then use that result to calculate the initial concentration of $\text{CO}_3^{2-}(aq)$.
- (i) Identify a laboratory method (not titration) that the student could use to collect data to determine $[\text{OH}^-]$ in the solution.
- (ii) Explain how the student could use the measured value in part (f)(i) to calculate the initial concentration of $\text{CO}_3^{2-}(aq)$. (Do not do any numerical calculations.)
- (g) In the original Na_2CO_3 solution at equilibrium, is the concentration of $\text{HCO}_3^-(aq)$ greater than, less than, or equal to the concentration of $\text{CO}_3^{2-}(aq)$? Justify your answer.
- (h) The student needs to make a $\text{CO}_3^{2-}/\text{HCO}_3^-$ buffer. Is the Na_2CO_3 solution suitable for making a buffer with a pH of 6? Explain why or why not.

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.



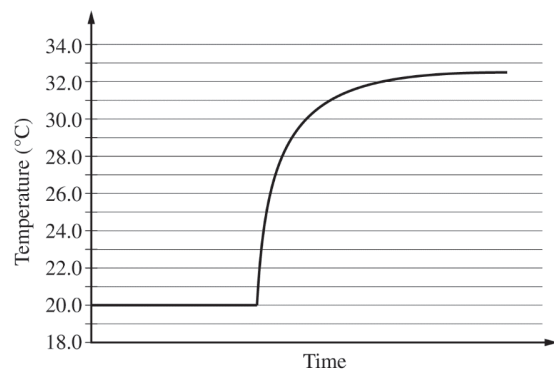
1. A student performs an experiment to determine the value of the enthalpy change, ΔH_{rxn}° , for the oxidation-reduction reaction represented by the balanced equation above.
- (a) Determine the oxidation number of Cl in NaOCl .
- (b) Calculate the number of grams of $\text{Na}_2\text{S}_2\text{O}_3$ 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

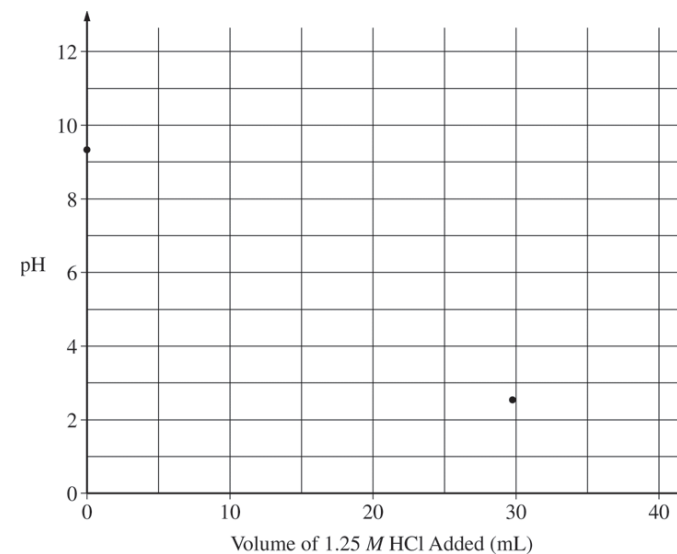
- (f) The magnitude of the enthalpy change, ΔH_{rxn}° , in kJ/mol_{rxn}, calculated from the results of the second experiment is the same as the result calculated in part (e)(ii). Explain this result.
- (g) Write the balanced net ionic equation for the given reaction.

3. Potassium sorbate, KC₆H₇O₂ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of KC₆H₇O₂(aq) of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 M HCl(aq) using both an indicator and a pH meter. The value of K_a for sorbic acid, HC₆H₇O₂, is 1.7×10^{-5} .

- (a) Write the net-ionic equation for the reaction between KC₆H₇O₂(aq) and HCl(aq).
- (b) A total of 29.95 mL of 1.25 M HCl(aq) is required to reach the equivalence point. Calculate [KC₆H₇O₂] in the stock solution.
- (c) The pH at the equivalence point of the titration is measured to be 2.54. Which of the following indicators would be the best choice for determining the end point of the titration? Justify your answer.

Indicator	pK _a
Phenolphthalein	9.3
Bromothymol blue	7.0
Methyl red	5.0
Thymol blue	2.0
Methyl violet	0.80

- (d) Calculate the pH at the half-equivalence point.
- (e) The initial pH and the equivalence point are plotted on the graph below. Accurately sketch the titration curve on the graph below. Mark the position of the half-equivalence point on the curve with an X.



- (f) The pH of the soft drink is 3.37 after the addition of the KC₆H₇O₂(aq). Which species, HC₆H₇O₂ or C₆H₇O₂⁻, has a higher concentration in the soft drink? Justify your answer.

Compound	Melting Point (°C)
LiI	449
KI	686
LiF	845
NaF	993

6. A student learns that ionic compounds have significant covalent character when a cation has a polarizing effect on a large anion. As a result, the student hypothesizes that salts composed of small cations and large anions should have relatively low melting points.
- (a) Select two compounds from the table and explain how the data support the student's hypothesis.
- (b) Identify a compound from the table that can be dissolved in water to produce a basic solution. Write the net ionic equation for the reaction that occurs to cause the solution to be basic.

4.3 Three Ways to Represent a Reaction

Name: _____ Class: _____ Date: _____ **Total: 12 marks**

Objective

Build the skills to answer exam questions on the **three ways to represent a reaction** — symbolic, particulate, and macroscopic.

You must be able to:

- connect the **symbolic** (equation), **particulate** (particle diagram), and **macroscopic** (observations) levels
- draw or read a particle diagram of a reaction
- match a balanced equation to a particle picture

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 three levels

Chemists describe a reaction three ways:

- Macroscopic** — what you see (a gas, a color change);
- Symbolic** — the balanced equation, e.g. $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$;
- Particulate** — a diagram of the atoms/molecules before and after.

■ Particle diagrams conserve atoms

A correct particle diagram has the **same number of each atom** before and after (mass is conserved). If you start with 4 H and 2 O atoms, they must all appear in the products.

■ Reading coefficients as ratios

The coefficients give the **ratio** of particles: $2\text{H}_2 + \text{O}_2$ means two H_2 molecules react with one O_2 . A particle diagram should show that ratio.

■ Matching levels

Given a balanced equation, a valid particle diagram shows the right numbers and types; given a diagram, you can write the balanced equation by counting.

2 Practice

Now apply the methods above.

2.1 Name the three levels chemists use to represent a reaction. [3]

2.2 In $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$, how many H_2 molecules react per O_2 ? [1]

2.3 What must be equal on both sides of a particle diagram? [1]

3 Exam-style questions

3.1 A particle diagram of a reaction must show, before and after, the same number of each [1]

- **A** molecule
- **B** atom
- **C** color
- **D** container

3.2 A particle diagram shows 3 molecules of N_2 and 9 of H_2 fully reacting.

(a) Write the balanced equation for $\text{N}_2 + \text{H}_2 \rightarrow \text{NH}_3$. [2]

(b) How many NH_3 molecules form from 3 N_2 and 9 H_2 ? [2]

3.3 Explain why a particle diagram cannot show 4 H atoms before and only 2 H atoms after a reaction. [2]

Solutions

2.1 Macroscopic, symbolic, particulate.

2.2 Two.

2.3 The number of each type of atom.

3.1 B — the same number of each atom (conservation of mass).

3.2 (a) $\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3$. (b) 3 N_2 with 9 H_2 (a 1:3 ratio) makes 6 NH_3 .

3.3 Atoms are conserved in a reaction; they are rearranged, not created or destroyed, so the count of each element must match on both sides.

Name:

AP Chemistry: 2022

3. Answer the following questions relating to the element aluminum, Al.

(a) Write the complete ground-state electron configuration of an Al atom.

(b) Based on principles of atomic structure, explain why the radius of the Al atom is larger than the radius of the Al^{3+} ion.

A student plans to combine solid aluminum with an aqueous solution of silver ions. The student determines the mass of solid AgNO_3 needed to prepare the solution with a specific concentration.

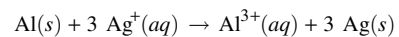
(c) In the following table, briefly list the steps necessary to prepare 200.0 mL of an aqueous solution of AgNO_3 using only equipment selected from the choices given. Assume that all appropriate safety measures are already in place. Not all equipment or lines in the table may be needed.

- | | | |
|-------------------------|------------------------------|------------------|
| · Solid AgNO_3 | · Weighing paper and scoop | · 250 mL beakers |
| · Distilled water | · 200.00 mL volumetric flask | · Pipet |
| · Balance | · 50.0 mL graduated cylinder | |

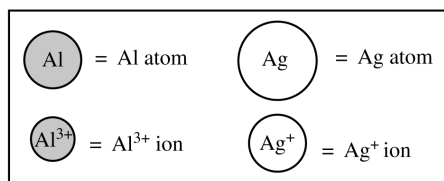
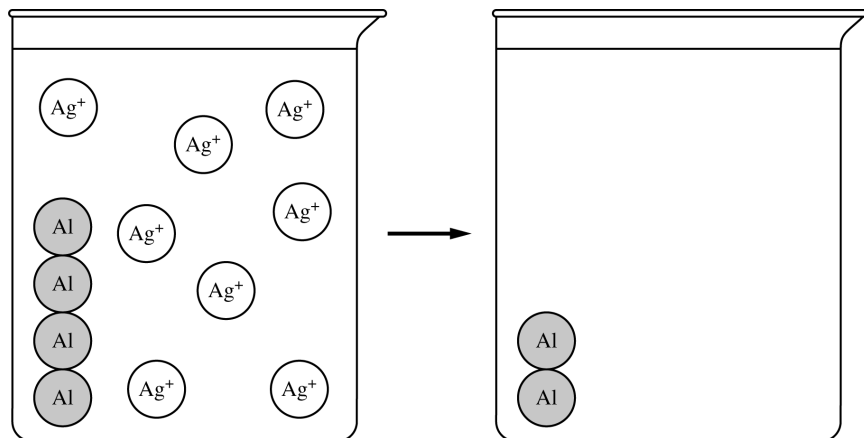
Step	Step Description
1.	Use weighing paper to measure the determined mass of solid AgNO_3 on a balance.
2.	

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After preparing the solution, the student places some of the solution into a beaker and adds a sample of aluminum. The reaction represented by the following equation occurs.



- (d) The following diagram gives an incomplete particulate representation of the reaction. The beaker on the left represents the system before the mixture reacts. Complete the drawing on the right to represent the system after the reaction has occurred. Be sure to include 1) the correct type and number of particles based on the number shown on the left and 2) the relative spacing to depict the appropriate phases.



The student finds the standard reduction potentials given in the table, which are related to the reaction that occurs.

Half-Reaction	E°
$\text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s)$	0.80 V
$\text{Al}^{3+}(aq) + 3 e^- \rightarrow \text{Al}(s)$	-1.66 V

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- (e) Using the standard reduction potentials, calculate the value of E° for the reaction.

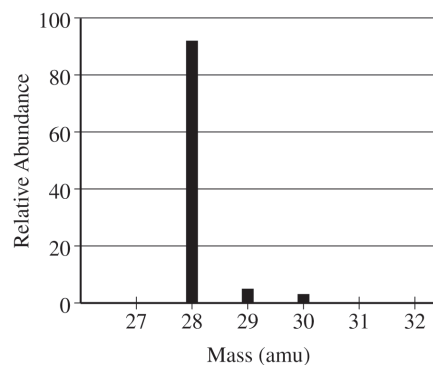
- (f) Based on the value of E° , would the standard free energy change of the reaction under standard conditions, ΔG° , be positive, negative, or zero? Justify your answer.

- (g) Once the reaction appears to stop progressing, would the change in free energy, ΔG , be positive, negative, or zero? Justify your answer.

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1. Answer the following questions about the element Si and some of its compounds.

(a) The mass spectrum of a pure sample of Si is shown below.



(i) How many protons and how many neutrons are in the nucleus of an atom of the most abundant isotope of Si?

(ii) Write the ground-state electron configuration of Si.

Two compounds that contain Si are SiO_2 and SiH_4 .

(b) At 161 K, SiH_4 boils but SiO_2 remains as a solid. Using principles of interparticle forces, explain the difference in boiling points.

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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.



At high temperatures, SiH_4 decomposes to form solid silicon and hydrogen gas.

(c) Write a balanced equation for the reaction.

A table of absolute entropies of some substances is given below.

Substance	S° (J/(mol · K))
$\text{H}_2(g)$	131
$\text{Si}(s)$	18
$\text{SiH}_4(g)$	205

(d) Explain why the absolute molar entropy of $\text{Si}(s)$ is less than that of $\text{H}_2(g)$.

(e) Calculate the value, in J/(mol · K), of ΔS° for the reaction.

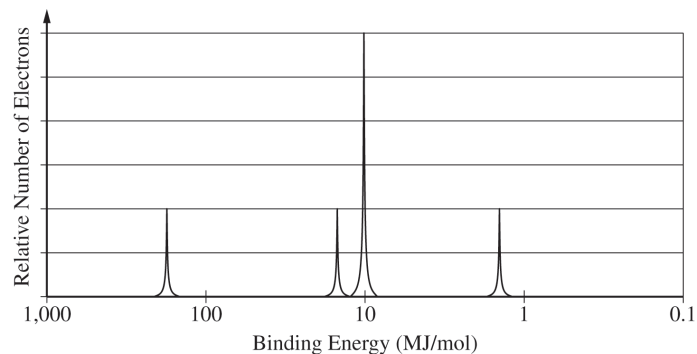
(f) The reaction is thermodynamically favorable at all temperatures. Explain why the reaction occurs only at high temperatures.

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(g) A partial photoelectron spectrum of pure Si is shown below. On the spectrum, draw the missing peak that corresponds to the electrons in the $3p$ sublevel.

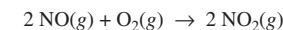


(h) Using principles of atomic structure, explain why the first ionization energy of Ge is lower than that of Si.

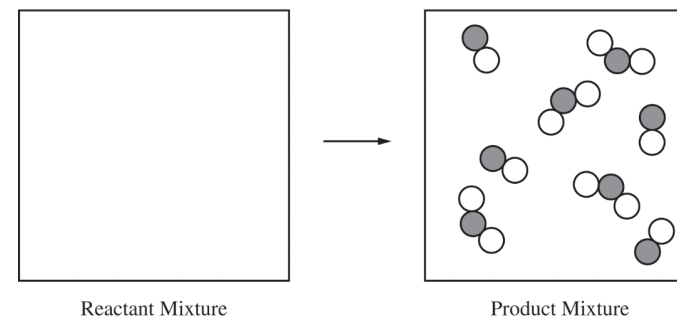
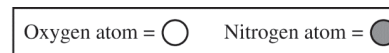
(i) A single photon with a wavelength of $4.00 \times 10^{-7} \text{ m}$ is absorbed by the Si sample. Calculate the energy of the photon in joules.

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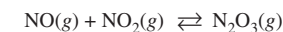
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2. A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.
- (a) The particle-level representation of the equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ in the flask at the completion of the reaction between $\text{NO}(g)$ and $\text{O}_2(g)$ is shown below in the box on the right. In the box below on the left, draw the particle-level representation of the reactant mixture of $\text{NO}(g)$ and $\text{O}_2(g)$ that would yield the product mixture shown in the box on the right. In your drawing, represent oxygen atoms and nitrogen atoms as indicated below.



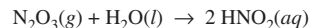
The student reads in a reference text that $\text{NO}(g)$ and $\text{NO}_2(g)$ will react as represented by the equation below. Thermodynamic data for the reaction are given in the table below the equation.



ΔH_{298}°	ΔS_{298}°	ΔG_{298}°
$-40.4 \text{ kJ/mol}_{\text{rxn}}$	$-138.5 \text{ J/(K} \cdot \text{mol}_{\text{rxn}})$	$0.87 \text{ kJ/mol}_{\text{rxn}}$

- (b) The student begins with an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.
- (i) Calculate the value of the equilibrium constant, K , for the reaction at 298 K.
- (ii) If both P_{NO} and P_{NO_2} in the vessel are initially 1.0 atm, will $P_{\text{N}_2\text{O}_3}$ at equilibrium be equal to 1.0 atm? Justify your answer.
- (c) The student hypothesizes that increasing the temperature will increase the amount of $\text{N}_2\text{O}_3(g)$ in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.

$\text{N}_2\text{O}_3(g)$ reacts with water to form nitrous acid, $\text{HNO}_2(aq)$, a compound involved in the production of acid rain. The reaction is represented below.



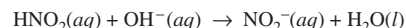
(d) The skeletal structure of the HNO_2 molecule is shown in the box below.

- (i) Complete the Lewis electron-dot diagram of the HNO_2 molecule in the box below, including any lone pairs of electrons.

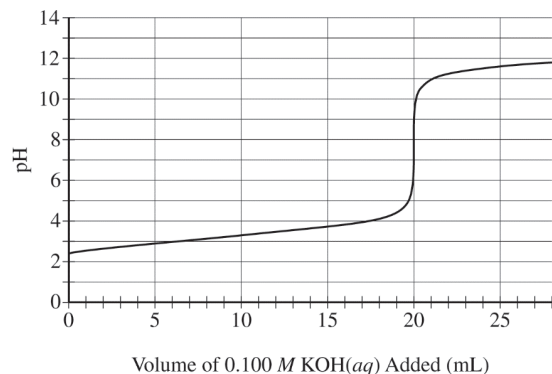


- (ii) Based on your completed diagram above, identify the hybridization of the nitrogen atom in the HNO_2 molecule.

To produce an aqueous solution of HNO_2 , the student bubbles $\text{N}_2\text{O}_3(g)$ into distilled water. Assume that the reaction goes to completion and that HNO_2 is the only species produced. To determine the concentration of $\text{HNO}_2(aq)$ in the resulting solution, the student titrates a 100. mL sample of the solution with 0.100 M $\text{KOH}(aq)$. The neutralization reaction is represented below.



The following titration curve shows the change in pH of the solution during the titration.



- (e) Use the titration curve and the information above to
- determine the initial concentration of the $\text{HNO}_2(aq)$ solution
 - estimate the value of $\text{p}K_a$ for $\text{HNO}_2(aq)$
- (f) During the titration, after a volume of 15 mL of 0.100 M $\text{KOH}(aq)$ has been added, which species, $\text{HNO}_2(aq)$ or $\text{NO}_2^-(aq)$, is present at a higher concentration in the solution? Justify your answer.

AP CHEMISTRY • EXERCISE SHEET

4.4 Physical Changes versus Chemical Changes

Name: _____ Class: _____ Date: _____

Total: 11 marks

KEY WORDS chemical 化学变化 • physical 物理变化 • precipitate 沉淀

Objective

Build the skills to answer exam questions on **physical versus chemical changes**.

You must be able to:

- classify a change as **physical** 物理变化 or **chemical** 化学变化
- justify with whether **new substances** form
- recognise state changes as physical

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 key test

A **chemical change** makes **new substances** with new properties (and is usually hard to reverse). A **physical change** keeps the same substance, only its form or state changing.

■ Physical changes

Melting, boiling, dissolving, crushing, and mixing (without reacting) are physical — the substance's identity is unchanged and often easily reversed.

■ Chemical changes

Burning, rusting, digestion, and reactions producing a gas or precipitate are chemical — new substances form and bonds are rearranged.

■ A worked judgement

Boiling water: liquid $\rightarrow$ gas, still $\text{H}_2\text{O} \rightarrow$ **physical**. Burning wood: makes CO_2 , ash, water $\rightarrow$ new substances $\rightarrow$ **chemical**.

2 Practice

Now apply the methods above.

2.1 Classify melting ice as physical or chemical. [1]

2.2 Classify iron rusting, with a reason. [2]

2.3 What is the single best test for a chemical change? [1]

3 Exam-style questions

3.1 Which is a **chemical** change? [1]

- A boiling water
- B dissolving salt
- C burning paper
- D breaking glass

3.2 A student heats sugar until it turns black and gives off a smell.

(a) State whether this is physical or chemical. [1]

(b) Justify your answer. [2]

3.3 Classify each and give a one-word reason: (a) evaporating alcohol, (b) a battery discharging, (c) tearing paper. [3]

Solutions

2.1 Physical.

2.2 Chemical — a new substance (iron oxide) forms.

2.3 Whether new substances (with new properties) form.

3.1 C — burning paper forms new substances.

3.2 (a) Chemical. (b) New substances form (the black solid and the smell are different materials), so it is a chemical change.

3.3 (a) physical (state change); (b) chemical (reaction); (c) physical (shape).

AP CHEMISTRY • EXERCISE SHEET

4.5 Stoichiometry

Name: _____ Class: _____ Date: _____

Total: 14 marks

KEY WORDS limiting reactant 限制反应物 • mole ratio 摩尔比 • stoichiometry 化学计量

Objective

Build the skills to answer exam questions on **stoichiometry** — mole ratios in a balanced equation.

You must be able to:

- convert mass to **moles** using molar mass
- use the **mole ratio** 摩尔比 from a balanced equation
- find the mass of a product and identify the **limiting reactant** 限制反应物

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 mole map

Mass $\rightarrow$ moles ($\div$ molar mass) $\rightarrow$ moles of other species ($\times$ **mole ratio**) $\rightarrow$ mass ($\times$ molar mass). The balanced equation supplies the ratio.

■ A worked mass-to-mass

For $2\text{H}_2 + \text{O}_2 \rightarrow 2\text{H}_2\text{O}$, find the mass of water from 4.0 g H_2 : $4.0 \text{ g} \div 2.0 = 2.0 \text{ mol H}_2$; ratio $\text{H}_2 : \text{H}_2\text{O} = 2 : 2$, so $2.0 \text{ mol H}_2\text{O}$; mass = $2.0 \times 18 = 36 \text{ g}$.

■ Limiting reactant

The **limiting reactant** runs out first and sets the amount of product. Compare the moles of each reactant divided by its coefficient; the **smallest** value limits.

■ A worked limiting-reactant check

For $\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3$ with 1 mol N_2 and 2 mol H_2 : H_2 needs 3 mol per N_2 but only 2 are present, so H_2 is limiting.

2 Practice

Now apply the methods above.

2.1 How many moles are in 8.0 g of CH_4 ($M = 16 \text{ g/mol}$)? [2]

2.2 For $\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3$, how many moles of NH_3 form from 2 mol N_2 (excess H_2)? [2]

2.3 State what “limiting reactant” means. [1]

3 Exam-style questions

3.1 The mole ratio in a reaction comes from [1]

- **A** the molar masses
- **B** the balanced-equation coefficients
- **C** the masses given
- **D** Avogadro’s number

3.2 For $2\text{Al} + 3\text{Cl}_2 \rightarrow 2\text{AlCl}_3$, start with 4.0 mol Al and excess Cl_2 .

(a) Find the moles of AlCl_3 produced. [2]

(b) Find the moles of Cl_2 consumed. [2]

3.3 For $\text{N}_2 + 3\text{H}_2 \rightarrow 2\text{NH}_3$, you have 3.0 mol N_2 and 6.0 mol H_2 .

(a) Identify the limiting reactant. [2]

(b) Find the moles of NH_3 produced. [2]

Solutions

2.1 $8.0 \div 16 = 0.50$ mol.

2.2 ratio $\text{N}_2 : \text{NH}_3 = 1 : 2$, so $2 \times 2 = 4$ mol NH_3 .

2.3 The reactant that runs out first, limiting how much product forms.

3.1 **B** — the balanced-equation coefficients.

3.2 (a) ratio $\text{Al} : \text{AlCl}_3 = 2 : 2$, so 4.0 mol AlCl_3 . (b) ratio $\text{Al} : \text{Cl}_2 = 2 : 3$, so $4.0 \times \frac{3}{2} = 6.0$ mol Cl_2 .

3.3 (a) H_2 needs $3 \times 3.0 = 9.0$ mol but only 6.0 present, so H_2 is limiting. (b) $6.0 \text{ mol } \text{H}_2 \times \frac{2}{3} = 4.0$ mol NH_3 .

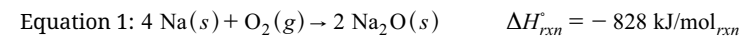
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AP Chemistry: 2026

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)
$\text{Na}(s)$	0
$\text{O}_2(g)$	0
$\text{Na}_2\text{O}(s)$	?

Part A

Based on the information given, **calculate** the value of ΔH_f° for $\text{Na}_2\text{O}(s)$. Show the work that leads to your answer.

Part B

An 18.4 g sample of $\text{Na}(s)$ reacts with 12.8 g of $\text{O}_2(g)$ 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. $\text{Rb}_2\text{O}(s)$ and $\text{Na}_2\text{O}(s)$ have similar crystal structures, and their lattice enthalpies are given in Table 2.

Table 2

Compound	Lattice Enthalpy (kJ/mol)
$\text{Na}_2\text{O}(s)$	2481
$\text{Rb}_2\text{O}(s)$	2163

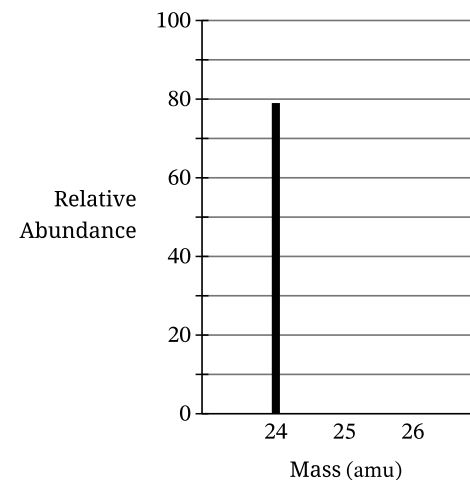
Using Coulomb's law, **explain** why the lattice enthalpy of $\text{Rb}_2\text{O}(s)$ is smaller than that of $\text{Na}_2\text{O}(s)$.

STOP
END OF EXAM



1. Answer the following questions about magnesium.

A. An incomplete mass spectrum for magnesium is shown in the diagram.

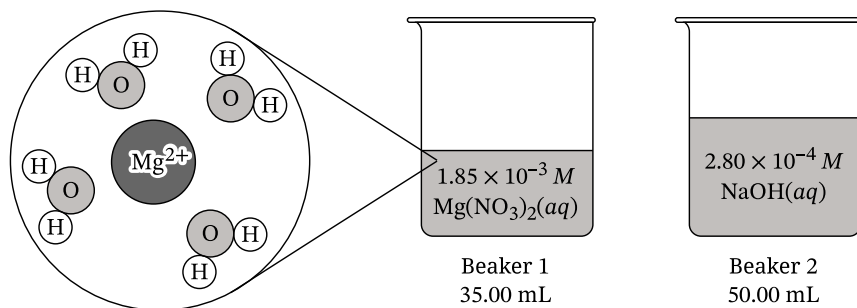


The percent abundance of magnesium-24 is 79%. The percent abundances of the other two natural isotopes of magnesium, magnesium-25 and magnesium-26, are approximately equal.

- Complete the mass spectrum in part A by drawing thick lines in the appropriate locations to represent the percent abundance of magnesium-25 and magnesium-26.
- Describe the difference in atomic structure that accounts for the difference in mass between magnesium-25 and magnesium-26.



A student prepares a $1.85 \times 10^{-3} M$ solution of $\text{Mg}(\text{NO}_3)_2(aq)$ in beaker 1 and a $2.80 \times 10^{-4} M$ solution of $\text{NaOH}(aq)$ in beaker 2, as shown.

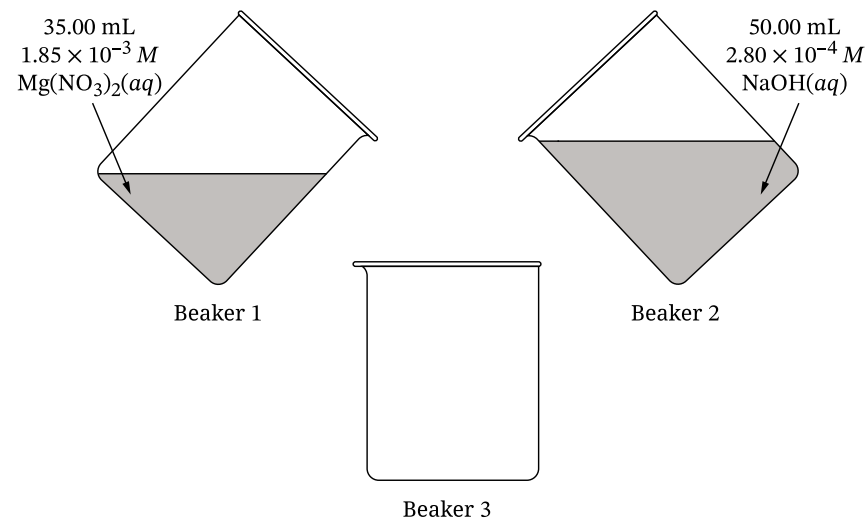


B. The particle diagram shown represents a magnesium ion, Mg^{2+} , in beaker 1. A sodium ion, Na^+ , in beaker 2 has a weaker attraction to water than the Mg^{2+} does. Explain this phenomenon using Coulomb's law and each of the following.

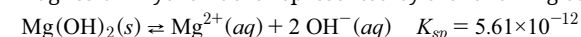
- The relative charge of the ions
- The relative radii of the ions

C. Calculate the pH of the solution in beaker 2.

D. A student combines 35.00 mL of $1.85 \times 10^{-3} M$ $\text{Mg}(\text{NO}_3)_2(aq)$ with 50.00 mL of $2.80 \times 10^{-4} M$ $\text{NaOH}(aq)$, as shown in the diagram. Calculate $[\text{Mg}^{2+}]$ after the two solutions are combined but before any reaction takes place. (Assume that volumes are additive.)



E. The dissolution of magnesium hydroxide is represented by the following equation.



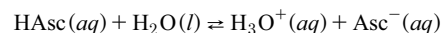
- Write the expression for the solubility product constant, K_{sp} .
 - After the two solutions are combined in beaker 3 as described in part D, but before any reaction takes place, $[\text{OH}^-] = 1.65 \times 10^{-4} M$. Using your answer to part D, calculate the value of the reaction quotient, Q .
 - Using the reaction quotient, Q , predict whether a precipitate should form as the mixture in beaker 3 approaches equilibrium. Justify your answer.
- F. In a separate experiment, the student adds $\text{HNO}_3(aq)$ to decrease the pH of a saturated solution containing undissolved $\text{Mg}(\text{OH})_2(s)$. Does the amount of undissolved $\text{Mg}(\text{OH})_2(s)$ increase, decrease, or remain the same as the $\text{HNO}_3(aq)$ is added? Justify your answer.

2. Answer the following questions about ascorbic acid (vitamin C).

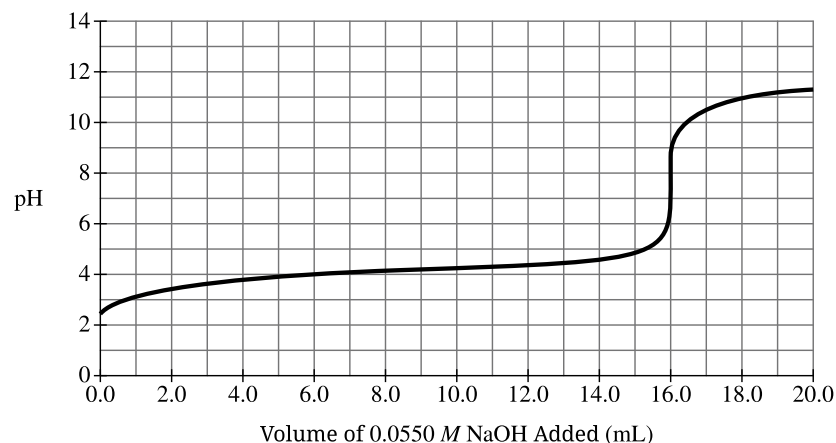
A. A student combusts a sample of ascorbic acid, $C_xH_yO_z$, to determine its chemical composition. The only products of the reaction are 0.2400 mol of CO_2 and 2.883 g of H_2O .

- Calculate the number of moles of H_2O produced.
- The mole ratio of carbon (C) to oxygen (O) is 1:1 in ascorbic acid. Based on this information and your answer to part A (i), determine the empirical formula of ascorbic acid.

B. Ascorbic acid, $HAsc(aq)$, acts as a weak acid, as shown in the equation.



The following titration curve was produced when a 10.0 mL sample of $HAsc(aq)$ was titrated using 0.0550 M $NaOH(aq)$.



- Calculate the molar concentration of the ascorbic acid solution.
- From the titration curve, determine the approximate pK_a of ascorbic acid.
- What is the value of the ratio $\frac{[Asc^-]}{[HAsc]}$ when the pH of the solution is 4.7?

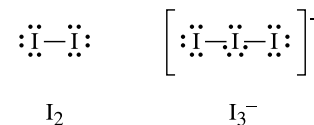
C. Dehydroascorbic acid (DHAsc) can be produced by reacting ascorbic acid with the triiodide ion, I_3^- , as represented by the following equation.



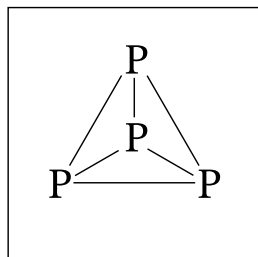
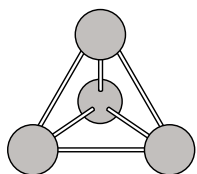
The student runs three trials of the reaction with different initial concentrations of $HAsc$ and I_3^- , producing the following data.

Trial	$[HAsc] (M)$	$[I_3^-] (M)$	Initial Rate of DHAsc Formation (M/s)
1	0.450	1.200	2.457×10^{-4}
2	0.450	0.600	1.229×10^{-4}
3	0.900	1.200	4.914×10^{-4}

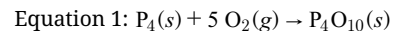
- The rate law for the reaction is $rate = k[HAsc][I_3^-]$. Explain how the data in the table support the conclusion that the reaction is first order with respect to $[HAsc]$.
 - Calculate the value of the rate constant, k , for the reaction. Include units with your answer.
- D. The triiodide ion, I_3^- , is significantly more soluble in water than elemental iodine, I_2 , is. Identify an intermolecular force between I_3^- and water that is **not** present between I_2 and water, which could explain the difference in solubility. Lewis diagrams for I_2 and I_3^- are provided.



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.

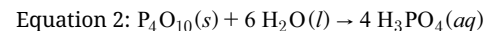


- A. In the box in part A, complete the Lewis diagram for P_4 by drawing the nonbonding electrons.
- B. The reaction of white phosphorus with oxygen to form $P_4O_{10}(s)$ is thermodynamically favorable at 298 K. The reaction is represented by equation 1.

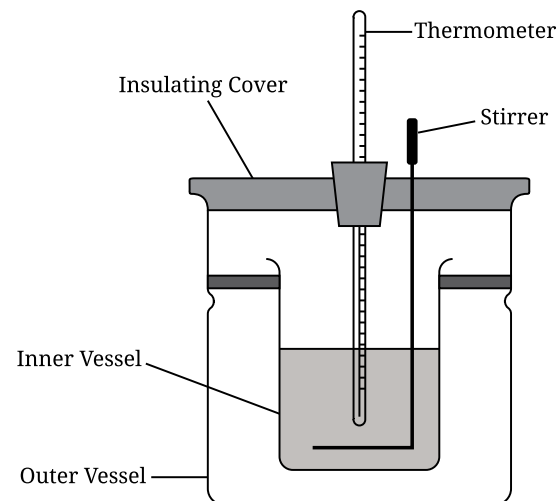


- The entropy change of the reaction, ΔS° , is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.
- The enthalpy change of the reaction, ΔH° , is also negative. A student claims that the favorability of the reaction is driven by enthalpy and **not** 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.



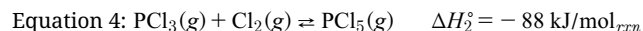
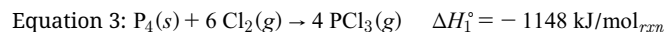
- C. The chemist carries out the calorimetry experiment and records the following information.

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)

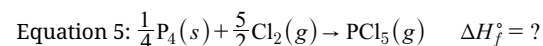
- Calculate the amount of heat, q , released during the experiment, in kJ. Assume that the specific heat of the solution is the same as that of water.
- Calculate the value of ΔH°_{rxn} for equation 2 in kJ/mol_{rxn}. Include the sign in your answer.

- 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.

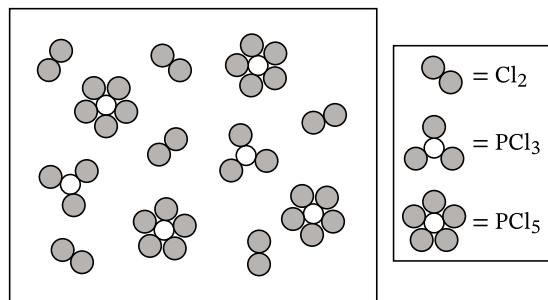
$\text{P}_4(\text{s})$ also reacts readily with $\text{Cl}_2(\text{g})$ to produce phosphorus trichloride, $\text{PCl}_3(\text{g})$, which in turn reacts with $\text{Cl}_2(\text{g})$ in an equilibrium process to produce $\text{PCl}_5(\text{g})$. The reactions are represented by equations 3 and 4.



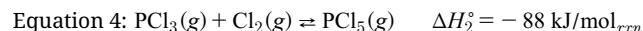
- E. Calculate the standard enthalpy of formation of $\text{PCl}_5(\text{g})$ represented by equation 5.



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

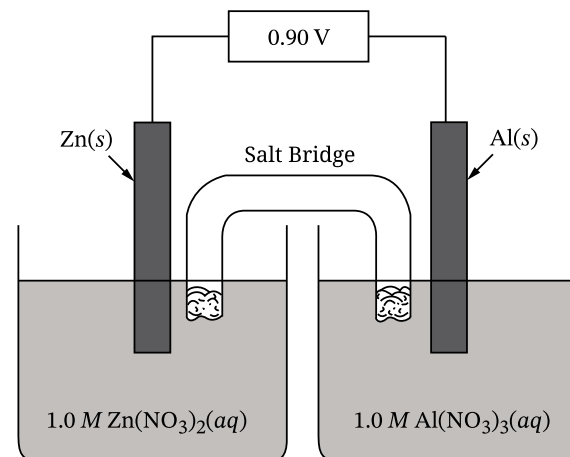


- F. Equation 4 for the reaction that occurs is shown.



- 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 scientist constructs a galvanic cell as shown in the diagram. As the cell operates, the $\text{Zn}(\text{s})$ electrode increases in mass and the $\text{Al}(\text{s})$ electrode decreases in mass. A data table with the standard reduction potentials for the substances follows the diagram.



Half-Reaction	E° (V)
$\text{Zn}^{2+}(\text{aq}) + 2 e^- \rightarrow \text{Zn}(\text{s})$	-0.76
$\text{Al}^{3+}(\text{aq}) + 3 e^- \rightarrow \text{Al}(\text{s})$	-1.66

- Write the half-reaction for the oxidation that occurs at the anode.
- Write the balanced net ionic equation for the overall reaction that occurs in the galvanic cell.
- Initially, each electrode has a mass of 50.0 g. The cell is allowed to run for a period of time and is then stopped. Which electrode's mass changed the most? Justify your answer with a calculation.

AP CHEMISTRY 2025 FREE-RESPONSE QUESTIONS

Reduction Half-Reaction	E° (V)
$\text{Au}^{3+}(\text{aq}) + 3 e^- \rightarrow \text{Au}(\text{s})$	+1.50
$\text{Zn}^{2+}(\text{aq}) + 2 e^- \rightarrow \text{Zn}(\text{s})$	-0.76
$\text{Mn}^{2+}(\text{aq}) + 2 e^- \rightarrow \text{Mn}(\text{s})$	-1.19
$\text{Al}^{3+}(\text{aq}) + 3 e^- \rightarrow \text{Al}(\text{s})$	-1.66
$\text{Be}^{2+}(\text{aq}) + 2 e^- \rightarrow \text{Be}(\text{s})$	-1.85

- D. The standard Zn/Al cell has a value of E_{cell}° equal to 0.90 V. The scientist needs a galvanic cell that produces a greater voltage. The scientist has access to the chemical systems in the table. If the scientist uses the Zn half-cell and one of the other options from the table, what is the MAXIMUM voltage that could be generated at standard conditions?

2. A chemical reaction between maleic acid ($\text{H}_2\text{C}_4\text{H}_2\text{O}_4$) and sodium bicarbonate (NaHCO_3) occurs in the presence of water to produce carbon dioxide and sodium maleate ($\text{Na}_2\text{C}_4\text{H}_2\text{O}_4$), as represented by the following equation.



- (a) A student combines equal masses of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$ chunks and $\text{NaHCO}_3(s)$ chunks with sufficient water at 20.0°C . The student determines that 0.0114 mol of $\text{CO}_2(g)$ is produced after the reaction goes to completion.

(i) Calculate the number of grams of $\text{CO}_2(g)$ produced.

(ii) The $\text{CO}_2(g)$ produced from the reaction at 20.0°C was collected and found to have a pressure of 1.25 atm . Calculate the volume of $\text{CO}_2(g)$, in liters.

- (b) The student performs a second experiment that is identical to the first except that the student grinds the chunks of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4(s)$ and $\text{NaHCO}_3(s)$ into powder before combining the powder with water.

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

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

GO ON TO THE NEXT PAGE.

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

- (iii) When the reaction is complete, will the volume of $\text{CO}_2(g)$ at the end of the second experiment be greater than, less than, or equal to the volume at the end of the first experiment? Justify your answer.

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

Trial	Mass of $\text{H}_2\text{C}_4\text{H}_2\text{O}_4$ (grams)	Mass of NaHCO_3 (grams)	Moles of CO_2 Produced (mol)
3	1.543	1.251	0.01489
4	1.543	1.686	0.02007

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

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

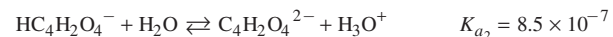
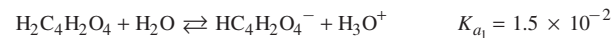
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Continue your response to **QUESTION 2** on this page.

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

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

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



- (f) Calculate the $\text{p}K_{a2}$ value for the $\text{HC}_4\text{H}_2\text{O}_4^-$ ion.

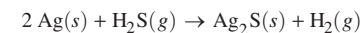
- (g) A buffer solution with a pH of 7.00 is prepared using $\text{C}_4\text{H}_2\text{O}_4^{2-}$ and $\text{HC}_4\text{H}_2\text{O}_4^-$. Calculate the ratio

$$\frac{[\text{C}_4\text{H}_2\text{O}_4^{2-}]}{[\text{HC}_4\text{H}_2\text{O}_4^-]} \text{ in this solution.}$$

GO ON TO THE NEXT PAGE.

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

3. Sterling silver is an alloy that is commonly used to make jewelry and consists of 92.5% silver and 7.5% other metals, such as copper, by mass. Over time, the alloy can form a tarnish of $\text{Ag}_2\text{S}(s)$ when it reacts with hydrogen sulfide, as represented by the following equation.



- (a) What are the oxidation numbers of silver in $\text{Ag}(s)$ and $\text{Ag}_2\text{S}(s)$?



- (b) The following table contains the atomic radii for silver and copper.

Element	Silver (Ag)	Copper (Cu)
Atomic radius (pm)	165	145

- (i) Explain why sterling silver is better classified as a substitutional alloy than as an interstitial alloy.

- (ii) Using principles of atomic structure and Coulomb's law, explain why silver has a larger atomic radius than copper does.

GO ON TO THE NEXT PAGE.

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

The Ag_2S tarnish on sterling silver can be removed until only sterling silver remains. A student weighs a tarnished sterling silver sample both before and after removing the $\text{Ag}_2\text{S}(s)$ (molar mass 247.80 g/mol) and records the data in the following table.

	Before Tarnish Removal	After Tarnish Removal
Mass	409.21 g	398.94 g

(c) Assuming that only $\text{Ag}_2\text{S}(s)$ is removed, calculate the number of moles of silver atoms removed.

Rhodium plating is a process used to protect sterling silver from tarnishing. This involves electroplating (depositing) solid rhodium, $\text{Rh}(s)$, onto the surface of the metal from an acidified solution of $\text{Rh}_2(\text{SO}_4)_3(aq)$. Oxygen gas is produced during this process.

(d) A table of half-reactions related to the overall reaction is provided.

Half-Reaction	E° (V)
$\text{Rh}^{3+}(aq) + 3 e^- \rightarrow \text{Rh}(s)$	+0.80
$\text{O}_2(g) + 4 \text{H}^+(aq) + 4 e^- \rightarrow 2 \text{H}_2\text{O}(l)$	+1.23

(i) Write the balanced net ionic equation for plating $\text{Rh}(s)$ from the acidified $\text{Rh}_2(\text{SO}_4)_3(aq)$ solution.

(ii) Calculate the value of E°_{cell} for the reaction in part (d)(i).

GO ON TO THE NEXT PAGE.Continue your response to **QUESTION 3** on this page.

(iii) Based on your answer to part (d)(ii), explain why this process requires the use of an external power source.

(e) Calculate the length of time, in seconds, required to plate 2.8 g of $\text{Rh}(s)$ onto a piece of sterling silver if 2.0 C/s of current is applied.

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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.

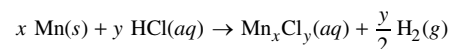
1. Answer the following questions related to manganese compounds.

(a) Manganese has several common oxidation states.

(i) Write the complete electron configuration for an Mn atom in the ground state.

(ii) When manganese forms cations, electrons are lost from which subshell first? Identify both the number and letter associated with the subshell.

A student performs an experiment to produce a manganese salt of unknown composition, $\text{Mn}_x\text{Cl}_y(\text{aq})$, and determine its empirical formula. The student places a sample of $\text{Mn}(\text{s})$ in a beaker containing excess $\text{HCl}(\text{aq})$, as represented by the following equation.



GO ON TO THE NEXT PAGE.

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

The student heats the resulting mixture until only $\text{Mn}_x\text{Cl}_y(\text{s})$ remains in the beaker. The data are given in the following table.

Mass of empty beaker	60.169 g
Mass of beaker and $\text{Mn}(\text{s})$	61.262 g
Mass of beaker and Mn_xCl_y after heating to constant mass	62.673 g

(b) Calculate the mass of Cl in the sample of $\text{Mn}_x\text{Cl}_y(\text{s})$ remaining in the beaker.

(c) Calculate the number of moles of Cl in the sample of $\text{Mn}_x\text{Cl}_y(\text{s})$ remaining in the beaker.

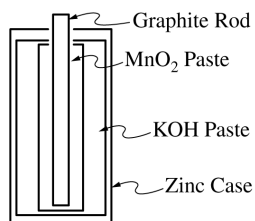
(d) The student determines that 0.0199 mol of Mn was used in the experiment. Use the data to determine the empirical formula of the $\text{Mn}_x\text{Cl}_y(\text{s})$.

(e) The student repeats the experiment using the same amounts of Mn and HCl and notices that some of the Mn_xCl_y splatters out of the beaker as it is heated to dryness. Will the number of moles of Cl calculated for this trial be greater than, less than, or equal to the number calculated in part (c)? Justify your answer.

GO ON TO THE NEXT PAGE.

Continue your response to QUESTION 1 on this page.

- (f) Another compound of manganese, MnO_2 , is used in alkaline batteries, represented by the following diagram. Some half-reactions are given in the table.



Reduction Half-Reaction	E° (V)
$\text{Zn}^{2+}(aq) + 2 e^- \rightarrow \text{Zn}(s)$	-0.76
$\text{ZnO}(s) + \text{H}_2\text{O}(l) + 2 e^- \rightarrow \text{Zn}(s) + 2 \text{OH}^-(aq)$	-1.28
$2 \text{MnO}_2(s) + \text{H}_2\text{O}(l) + 2 e^- \rightarrow \text{Mn}_2\text{O}_3(s) + 2 \text{OH}^-(aq)$	0.15

- (i) Based on the half-reactions given in the table, write the balanced net ionic equation for the reaction that has the greatest thermodynamic favorability.

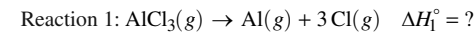
- (ii) Calculate the value of E°_{cell} for the overall reaction.

- (iii) Calculate the value of ΔG° in $\text{kJ/mol}_{\text{rxn}}$.

- (iv) A student claims that the total mass of an alkaline battery decreases as the battery operates because the anode loses mass. Do you agree with the student's claim? Justify your answer.

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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.



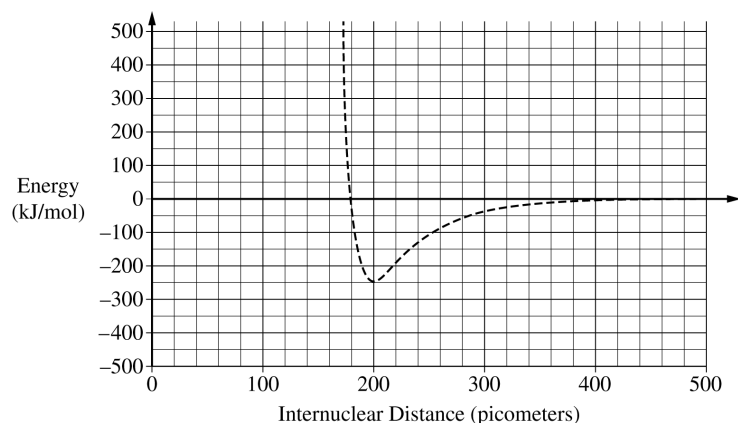
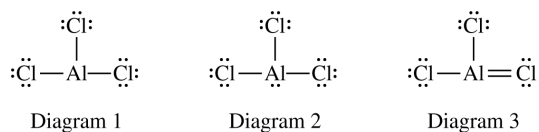
- (a) How many grams of $\text{Cl}(g)$ can be formed from 1.25 mol of $\text{AlCl}_3(g)$?

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

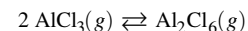
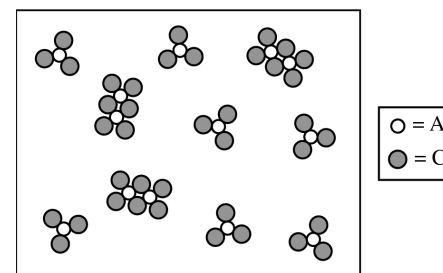
Reaction Number	Equation	$\Delta H^\circ_{\text{rxn}}$ ($\text{kJ/mol}_{\text{rxn}}$)
2	$\text{Al}(s) + \frac{3}{2} \text{Cl}_2(g) \rightarrow \text{AlCl}_3(g)$	-583
3	$\text{Al}(s) \rightarrow \text{Al}(g)$	+326
4	$\text{Cl}_2(g) \rightarrow 2 \text{Cl}(g)$	+243

- (b) Calculate the value of ΔH°_1 , in $\text{kJ/mol}_{\text{rxn}}$, for reaction 1 above using reactions 2, 3, and 4.

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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.

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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.

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.)

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Continue your response to **QUESTION 2** 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.

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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.

A student is asked to prepare a buffer solution made with equimolar amounts of $\text{CH}_3\text{NH}_2(aq)$ and $\text{CH}_3\text{NH}_3\text{Cl}(s)$. The student uses 25.00 mL of 0.100 M $\text{CH}_3\text{NH}_2(aq)$, which contains 0.00250 mol of CH_3NH_2 , to make the buffer.

(a) Calculate the mass of $\text{CH}_3\text{NH}_3\text{Cl}(s)$ that contains 0.00250 mol of $\text{CH}_3\text{NH}_3\text{Cl}$.

The student has the following materials and equipment available.

- Distilled water
- Electronic balance
- 50 mL beaker
- Pipets
- 0.100 M $\text{CH}_3\text{NH}_2(aq)$
- Weighing paper
- 10.0 mL graduated cylinder
- pH meter
- Solid $\text{CH}_3\text{NH}_3\text{Cl}$
- 50.00 mL buret
- Small spatula

(b) The following table contains a partial procedure for making the buffer solution. Fill in steps 1 and 4 to complete the procedure using only materials and equipment selected from the choices given. (Not all materials listed will be used. Assume that all appropriate safety measures are already in place.)

Step	Procedure
1	
2	Place the solid in the 50 mL beaker.
3	Clean the buret and rinse with distilled water.
4	
5	Use the buret to add 25.00 mL of 0.100 M $\text{CH}_3\text{NH}_2(aq)$ to the beaker.
6	Mix well.
7	Check the pH with the pH meter.

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

The value of K_b for $\text{CH}_3\text{NH}_2(aq)$ is 4.4×10^{-4} , and the pH of the buffer the student prepared is 10.64.

(c) The student prepares a second buffer solution. The student uses 25.00 mL of 0.050 M $\text{CH}_3\text{NH}_2(aq)$ instead of 25.00 mL of 0.100 M $\text{CH}_3\text{NH}_2(aq)$, and half the mass of $\text{CH}_3\text{NH}_3\text{Cl}(s)$ that was used in the first buffer. Is the pH of the second buffer greater than, less than, or equal to the pH of the first buffer? Justify your answer.

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

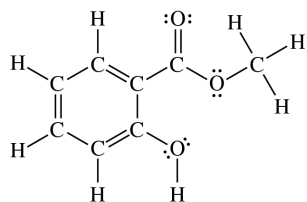
- (b) The student's experiment results in an 87% yield of dry $\text{HC}_7\text{H}_5\text{O}_3$. The student suggests that some of the $\text{HC}_7\text{H}_5\text{O}_3$ crystals dissolved in the distilled water during the rinsing step. Is the student's claim consistent with the calculated percent yield 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.

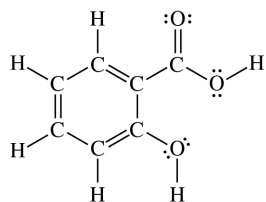
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Continue your response to **QUESTION 1** on this page.

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



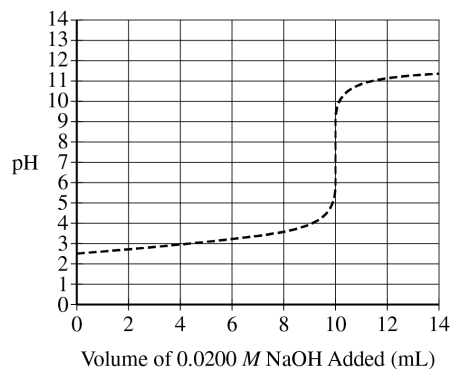
Methyl Salicylate
Melting Point: -9°C



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.



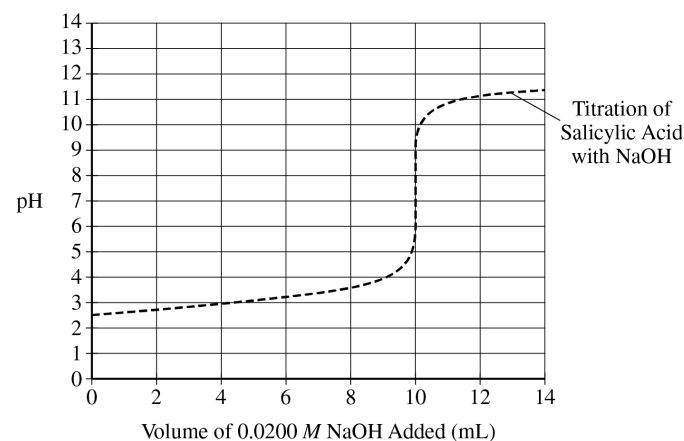
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Continue your response to **QUESTION 1** on this page.

- (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.



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4.6 Introduction to Titration

Name: _____ Class: _____ Date: _____

Total: 14 marks**KEY WORDS** acid 酸 • titration 滴定 • base 碱 • equivalence point 等当点

Objective

Build the skills to answer exam questions on **titration** — finding an unknown concentration.

You must be able to:

- use $\text{mol} = M \times V$ and the reaction's mole ratio
- find an unknown concentration from titration data
- identify the **equivalence point** 等当点

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 titration idea

A solution of known concentration (the **titrant**) is added until it exactly reacts with the unknown — the **equivalence point**, often shown by an indicator's color change (**endpoint**).

■ The calculation route

1. moles of titrant = $M \times V$;
2. moles of unknown = (moles of titrant) $\times$ mole ratio;
3. concentration of unknown = moles $\div$ its volume.

■ A worked 1:1 titration

25.0 mL of HCl is neutralized by 20.0 mL of 0.100 M NaOH (1:1). Moles NaOH = $0.100 \times 0.0200 = 0.00200$; so moles HCl = 0.00200; $[\text{HCl}] = \frac{0.00200}{0.0250} = 0.0800 \text{ M}$.

■ Watch the mole ratio

For $\text{H}_2\text{SO}_4 + 2\text{NaOH}$, one acid needs **two** base — include the 1 : 2 ratio, or the answer is off by a factor of two.

2 Practice

Now apply the methods above.

2.1 Find the moles in 30.0 mL of 0.200 M NaOH. [2]

2.2 In a 1:1 titration, 0.0030 mol of base neutralizes how many moles of acid? [1]

2.3 What is the equivalence point? [1]

3 Exam-style questions

3.1 At the equivalence point of an acid-base titration, [1]

- **A** the acid is in excess
- **B** the moles of acid and base have exactly reacted (per the ratio)
- **C** the base is in excess
- **D** nothing has reacted

3.2 25.0 mL of an unknown HCl solution is neutralized by 18.0 mL of 0.150 M NaOH (1:1).

(a) Find the moles of NaOH used. [2]

(b) Find the concentration of the HCl. [3]

3.3 20.0 mL of H_2SO_4 is neutralized by 25.0 mL of 0.200 M NaOH. Using $\text{H}_2\text{SO}_4 + 2\text{NaOH} \rightarrow \text{products}$, find the concentration of the acid. ^[4]

Solutions

2.1 $0.200 \times 0.0300 = 0.00600$ mol.

2.2 0.0030 mol.

2.3 The point where the titrant has exactly reacted with the unknown (per the mole ratio).

3.1 B — the acid and base have exactly reacted in the stoichiometric ratio.

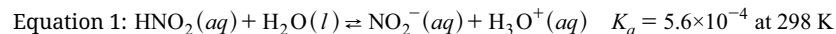
3.2 (a) $0.150 \times 0.0180 = 0.00270$ mol. (b) moles HCl = 0.00270; $[\text{HCl}] = \frac{0.00270}{0.0250} = 0.108$ M.

3.3 moles NaOH = $0.200 \times 0.0250 = 0.00500$; moles $\text{H}_2\text{SO}_4 = 0.00500 \div 2 = 0.00250$;
 $[\text{H}_2\text{SO}_4] = \frac{0.00250}{0.0200} = 0.125$ M.

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 .

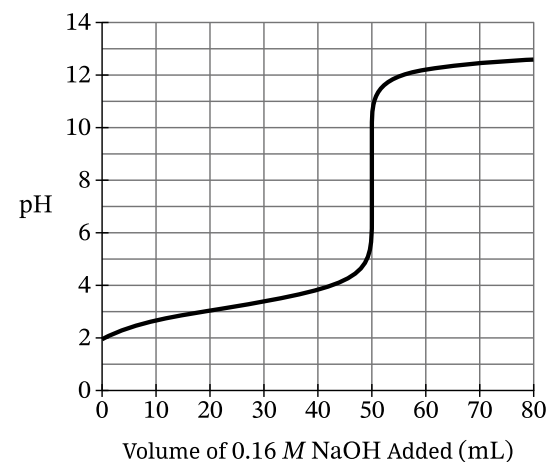
The following information applies to parts D, E, and F.

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

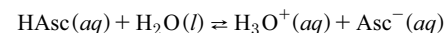
The student conducts a second titration by adding two drops of methyl orange indicator to 35.0 mL of the $\text{HNO}_2(aq)$ solution and titrating the solution with 0.16 M $\text{NaOH}(aq)$ until a color change from red to yellow occurs.

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

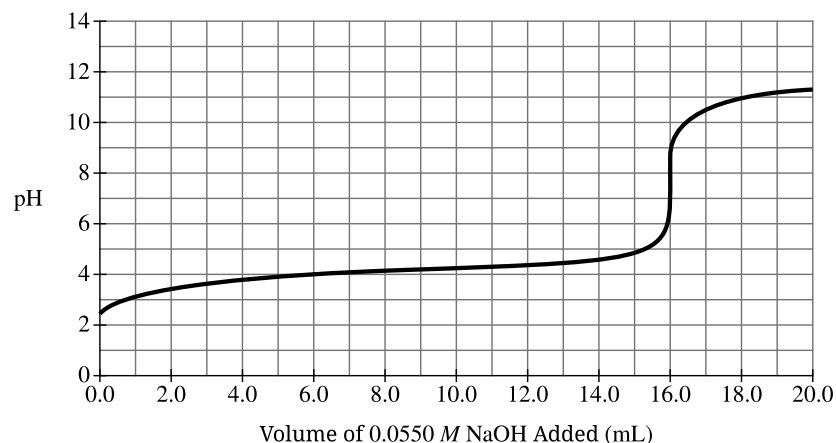
2. Answer the following questions about ascorbic acid (vitamin C).

- A. A student combusts a sample of ascorbic acid, $\text{C}_x\text{H}_y\text{O}_z$, to determine its chemical composition. The only products of the reaction are 0.2400 mol of CO_2 and 2.883 g of H_2O .
- Calculate the number of moles of H_2O produced.
 - The mole ratio of carbon (C) to oxygen (O) is 1:1 in ascorbic acid. Based on this information and your answer to part A (i), determine the empirical formula of ascorbic acid.

B. Ascorbic acid, $\text{HAsc}(aq)$, acts as a weak acid, as shown in the equation.



The following titration curve was produced when a 10.0 mL sample of $\text{HAsc}(aq)$ was titrated using 0.0550 M $\text{NaOH}(aq)$.



- Calculate the molar concentration of the ascorbic acid solution.
- From the titration curve, determine the approximate $\text{p}K_a$ of ascorbic acid.
- What is the value of the ratio $\frac{[\text{Asc}^-]}{[\text{HAsc}]}$ when the pH of the solution is 4.7?

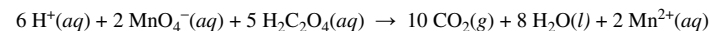
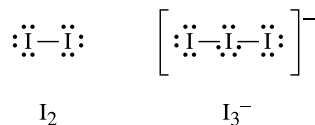
C. Dehydroascorbic acid (DHAsc) can be produced by reacting ascorbic acid with the triiodide ion, I_3^- , as represented by the following equation.



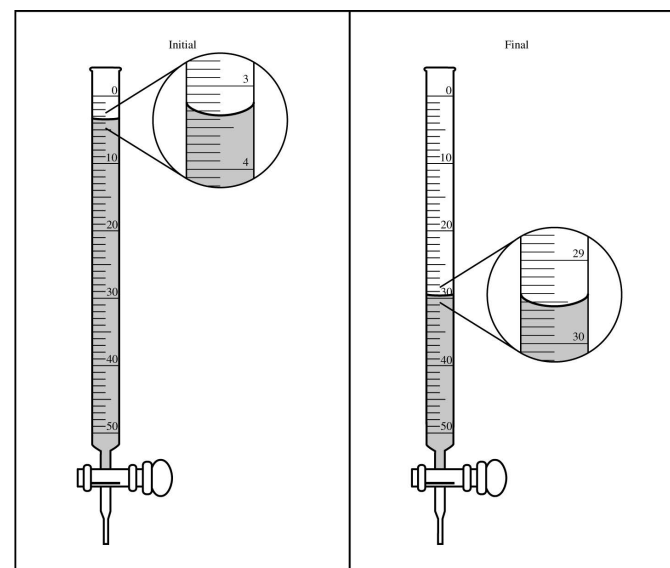
The student runs three trials of the reaction with different initial concentrations of HAsc and I_3^- , producing the following data.

Trial	[HAsc] (M)	$[\text{I}_3^-]$ (M)	Initial Rate of DHAsc Formation (M/s)
1	0.450	1.200	2.457×10^{-4}
2	0.450	0.600	1.229×10^{-4}
3	0.900	1.200	4.914×10^{-4}

- The rate law for the reaction is $\text{rate} = k[\text{HAsc}][\text{I}_3^-]$. Explain how the data in the table support the conclusion that the reaction is first order with respect to $[\text{HAsc}]$.
 - Calculate the value of the rate constant, k , for the reaction. Include units with your answer.
- D. The triiodide ion, I_3^- , is significantly more soluble in water than elemental iodine, I_2 , is. Identify an intermolecular force between I_3^- and water that is **not** present between I_2 and water, which could explain the difference in solubility. Lewis diagrams for I_2 and I_3^- are provided.



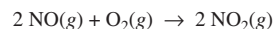
7. A student dissolved a 0.139 g sample of oxalic acid, $\text{H}_2\text{C}_2\text{O}_4$, in water in an Erlenmeyer flask. Then the student titrated the $\text{H}_2\text{C}_2\text{O}_4$ solution in the flask with a solution of KMnO_4 , which has a dark purple color. The balanced chemical equation for the reaction that occurred during the titration is shown above.
- Identify the species that was reduced in the titration reaction. Justify your answer in terms of oxidation numbers.
 - The student used a 50.0 mL buret to add the $\text{KMnO}_4(aq)$ to the $\text{H}_2\text{C}_2\text{O}_4(aq)$ until a faint lavender color was observed in the flask, an indication that the end point of the titration had been reached. The initial and final volume readings of the solution in the buret are shown below. Write down the initial reading and the final reading and use them to determine the volume of $\text{KMnO}_4(aq)$ that was added during the titration.



- Given that the concentration of $\text{KMnO}_4(aq)$ was 0.0235 M, calculate the number of moles of MnO_4^- ions that completely reacted with the $\text{H}_2\text{C}_2\text{O}_4$.
- The student proposes to perform another titration using a 0.139 g sample of $\text{H}_2\text{C}_2\text{O}_4$, but this time using 0.00143 M $\text{KMnO}_4(aq)$ in the buret. Would this titrant concentration be a reasonable choice to use if the student followed the same procedure and used the same equipment as before? Justify your response.

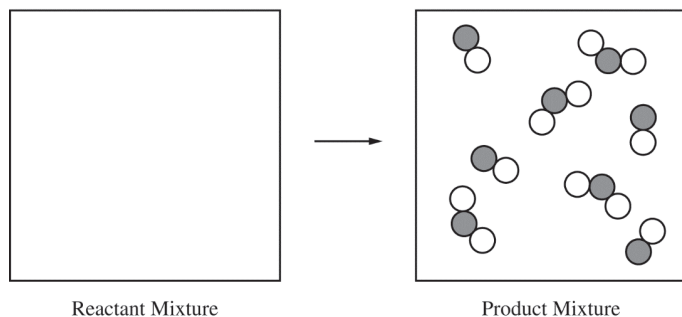
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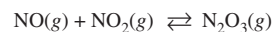


2. A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$, which the student produces by using the reaction represented above.

- (a) The particle-level representation of the equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ in the flask at the completion of the reaction between $\text{NO}(g)$ and $\text{O}_2(g)$ is shown below in the box on the right. In the box below on the left, draw the particle-level representation of the reactant mixture of $\text{NO}(g)$ and $\text{O}_2(g)$ that would yield the product mixture shown in the box on the right. In your drawing, represent oxygen atoms and nitrogen atoms as indicated below.



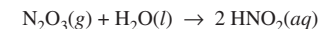
The student reads in a reference text that $\text{NO}(g)$ and $\text{NO}_2(g)$ will react as represented by the equation below. Thermodynamic data for the reaction are given in the table below the equation.



ΔH_{298}°	ΔS_{298}°	ΔG_{298}°
$-40.4 \text{ kJ/mol}_{\text{rxn}}$	$-138.5 \text{ J/(K} \cdot \text{mol}_{\text{rxn}})$	$0.87 \text{ kJ/mol}_{\text{rxn}}$

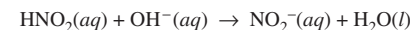
- (b) The student begins with an equimolar mixture of $\text{NO}(g)$ and $\text{NO}_2(g)$ in a rigid reaction vessel and the mixture reaches equilibrium at 298 K.
- Calculate the value of the equilibrium constant, K , for the reaction at 298 K.
 - If both P_{NO} and P_{NO_2} in the vessel are initially 1.0 atm, will $P_{\text{N}_2\text{O}_3}$ at equilibrium be equal to 1.0 atm? Justify your answer.
- (c) The student hypothesizes that increasing the temperature will increase the amount of $\text{N}_2\text{O}_3(g)$ in the equilibrium mixture. Indicate whether you agree or disagree with the hypothesis. Justify your answer.

$\text{N}_2\text{O}_3(g)$ reacts with water to form nitrous acid, $\text{HNO}_2(aq)$, a compound involved in the production of acid rain. The reaction is represented below.

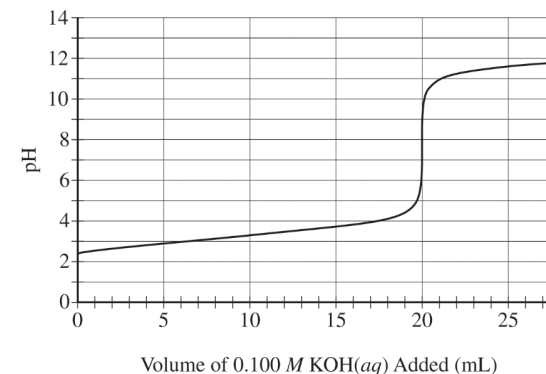


- (d) The skeletal structure of the HNO_2 molecule is shown in the box below.
- Complete the Lewis electron-dot diagram of the HNO_2 molecule in the box below, including any lone pairs of electrons.
- H O N O
- Based on your completed diagram above, identify the hybridization of the nitrogen atom in the HNO_2 molecule.

To produce an aqueous solution of HNO_2 , the student bubbles $\text{N}_2\text{O}_3(g)$ into distilled water. Assume that the reaction goes to completion and that HNO_2 is the only species produced. To determine the concentration of $\text{HNO}_2(aq)$ in the resulting solution, the student titrates a 100. mL sample of the solution with 0.100 M $\text{KOH}(aq)$. The neutralization reaction is represented below.



The following titration curve shows the change in pH of the solution during the titration.



- (e) Use the titration curve and the information above to
- determine the initial concentration of the $\text{HNO}_2(aq)$ solution
 - estimate the value of $\text{p}K_a$ for $\text{HNO}_2(aq)$
- (f) During the titration, after a volume of 15 mL of 0.100 M $\text{KOH}(aq)$ has been added, which species, $\text{HNO}_2(aq)$ or $\text{NO}_2^-(aq)$, is present at a higher concentration in the solution? Justify your answer.

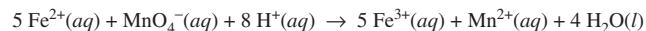
3. Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+} .

- (a) Write the ground-state electron configuration of the Fe^{2+} ion.

Ion	Ionic Radius (pm)
Fe^{2+}	92
Fe^{3+}	79

- (b) The radii of the ions are given in the table above. Using principles of atomic structure, explain why the radius of the Fe^{2+} ion is larger than the radius of the Fe^{3+} ion.
- (c) Fe^{3+} ions interact more strongly with water molecules in aqueous solution than Fe^{2+} ions do. Give one reason for this stronger interaction, and justify your answer using Coulomb's law.

A student obtains a solution that contains an unknown concentration of $\text{Fe}^{2+}(\text{aq})$. To determine the concentration of $\text{Fe}^{2+}(\text{aq})$ in the solution, the student titrates a sample of the solution with $\text{MnO}_4^-(\text{aq})$, which converts $\text{Fe}^{2+}(\text{aq})$ to $\text{Fe}^{3+}(\text{aq})$, as represented by the following equation.



- (d) Write the balanced equation for the half-reaction for the oxidation of $\text{Fe}^{2+}(\text{aq})$ to $\text{Fe}^{3+}(\text{aq})$.
- (e) The student titrates a 10.0 mL sample of the $\text{Fe}^{2+}(\text{aq})$ solution. Calculate the value of $[\text{Fe}^{2+}]$ in the solution if it takes 17.48 mL of added 0.0350 M $\text{KMnO}_4(\text{aq})$ to reach the equivalence point of the titration.

To deliver the 10.0 mL sample of the $\text{Fe}^{2+}(\text{aq})$ solution in part (e), the student has the choice of using one of the pieces of glassware listed below.

- 25 mL buret
- 25 mL beaker
- 25 mL graduated cylinder
- 25 mL volumetric flask

- (f) Explain why the 25 mL volumetric flask would be a poor choice to use for delivering the required volume of the $\text{Fe}^{2+}(\text{aq})$ solution.

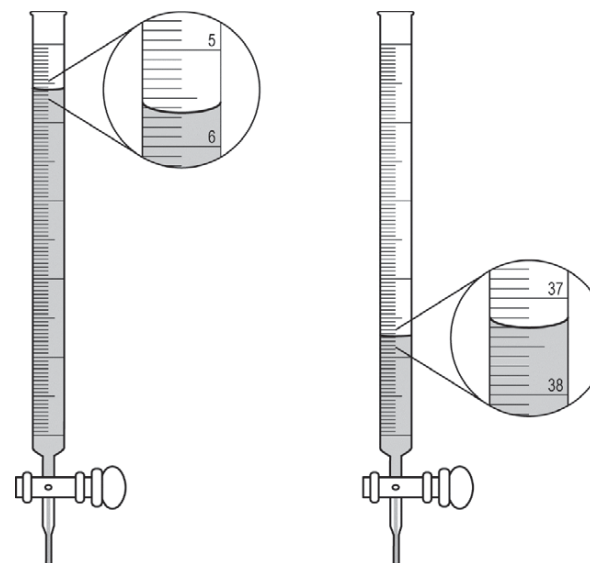
In a separate experiment, the student is given a sample of powdered $\text{Fe}(\text{s})$ that contains an inert impurity. The student uses a procedure to oxidize the $\text{Fe}(\text{s})$ in the sample to $\text{Fe}_2\text{O}_3(\text{s})$. The student collects the following data during the experiment.

Mass of $\text{Fe}(\text{s})$ with inert impurity	6.724 g
Mass of $\text{Fe}_2\text{O}_3(\text{s})$ produced	7.531 g

- (g) Calculate the number of moles of Fe in the $\text{Fe}_2\text{O}_3(\text{s})$ produced.
- (h) Calculate the percent by mass of Fe in the original sample of powdered $\text{Fe}(\text{s})$ with the inert impurity.
- (i) If the oxidation of the $\text{Fe}(\text{s})$ in the original sample was incomplete so that some of the 7.531 g of product was $\text{FeO}(\text{s})$ instead of $\text{Fe}_2\text{O}_3(\text{s})$, would the calculated mass percent of $\text{Fe}(\text{s})$ in the original sample be higher, lower, or the same as the actual mass percent of $\text{Fe}(\text{s})$? Justify your answer.

7. A student is given a 25.0 mL sample of a solution of an unknown monoprotic acid and asked to determine the concentration of the acid by titration. The student uses a standardized solution of 0.110 M $\text{NaOH}(\text{aq})$, a buret, a flask, an appropriate indicator, and other laboratory equipment necessary for the titration.

- (a) The images below show the buret before the titration begins (below left) and at the end point (below right). What should the student record as the volume of $\text{NaOH}(\text{aq})$ delivered to the flask?



- (b) Based on the given information and your answer to part (a), determine the value of the concentration of the acid that should be recorded in the student's lab report.
- (c) In a second trial, the student accidentally added more $\text{NaOH}(\text{aq})$ to the flask than was needed to reach the end point, and then recorded the final volume. Would this error increase, decrease, or have no effect on the calculated acid concentration for the second trial? Justify your answer.

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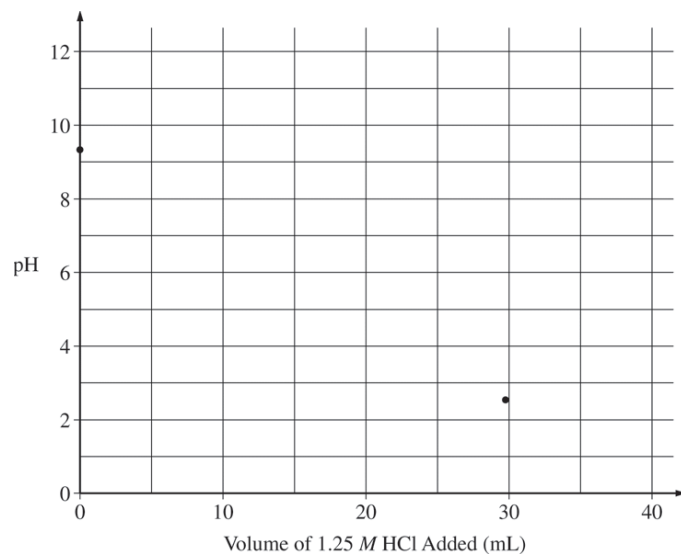
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3. Potassium sorbate, $\text{KC}_6\text{H}_7\text{O}_2$ (molar mass 150. g/mol) is commonly added to diet soft drinks as a preservative. A stock solution of $\text{KC}_6\text{H}_7\text{O}_2(aq)$ of known concentration must be prepared. A student titrates 45.00 mL of the stock solution with 1.25 M $\text{HCl}(aq)$ using both an indicator and a pH meter. The value of K_a for sorbic acid, $\text{HC}_6\text{H}_7\text{O}_2$, is 1.7×10^{-5} .

- (a) Write the net-ionic equation for the reaction between $\text{KC}_6\text{H}_7\text{O}_2(aq)$ and $\text{HCl}(aq)$.
- (b) A total of 29.95 mL of 1.25 M $\text{HCl}(aq)$ is required to reach the equivalence point. Calculate $[\text{KC}_6\text{H}_7\text{O}_2]$ in the stock solution.
- (c) The pH at the equivalence point of the titration is measured to be 2.54. Which of the following indicators would be the best choice for determining the end point of the titration? Justify your answer.

Indicator	$\text{p}K_a$
Phenolphthalein	9.3
Bromothymol blue	7.0
Methyl red	5.0
Thymol blue	2.0
Methyl violet	0.80

- (d) Calculate the pH at the half-equivalence point.
- (e) The initial pH and the equivalence point are plotted on the graph below. Accurately sketch the titration curve on the graph below. Mark the position of the half-equivalence point on the curve with an X.



- (f) The pH of the soft drink is 3.37 after the addition of the $\text{KC}_6\text{H}_7\text{O}_2(aq)$. Which species, $\text{HC}_6\text{H}_7\text{O}_2$ or $\text{C}_6\text{H}_7\text{O}_2^-$, has a higher concentration in the soft drink? Justify your answer.



2. Propanoic acid, $\text{CH}_3\text{CH}_2\text{COOH}$, is a carboxylic acid that reacts with water according to the equation above. At 25°C the pH of a 50.0 mL sample of 0.20 M $\text{CH}_3\text{CH}_2\text{COOH}$ is 2.79.
- (a) Identify a Brønsted-Lowry conjugate acid-base pair in the reaction. Clearly label which is the acid and which is the base.
- (b) Determine the value of K_a for propanoic acid at 25°C.
- (c) For each of the following statements, determine whether the statement is true or false. In each case, explain the reasoning that supports your answer.
- The pH of a solution prepared by mixing the 50.0 mL sample of 0.20 M $\text{CH}_3\text{CH}_2\text{COOH}$ with a 50.0 mL sample of 0.20 M NaOH is 7.00.
 - If the pH of a hydrochloric acid solution is the same as the pH of a propanoic acid solution, then the molar concentration of the hydrochloric acid solution must be less than the molar concentration of the propanoic acid solution.

A student is given the task of determining the concentration of a propanoic acid solution of unknown concentration. A 0.173 M NaOH solution is available to use as the titrant. The student uses a 25.00 mL volumetric pipet to deliver the propanoic acid solution to a clean, dry flask. After adding an appropriate indicator to the flask, the student titrates the solution with the 0.173 M NaOH, reaching the end point after 20.52 mL of the base solution has been added.

- (d) Calculate the molarity of the propanoic acid solution.
- (e) The student is asked to redesign the experiment to determine the concentration of a butanoic acid solution instead of a propanoic acid solution. For butanoic acid the value of $\text{p}K_a$ is 4.83. The student claims that a different indicator will be required to determine the equivalence point of the titration accurately. Based on your response to part (b), do you agree with the student's claim? Justify your answer.

4.7 Types of Chemical Reactions

Name: _____ Class: _____ Date: _____ **Total: 11 marks****KEY WORDS** combustion 燃烧 • decomposition 分解 • synthesis 化合 • acid 酸 • base 碱

Objective

Build the skills to answer exam questions on the **types of chemical reactions**.**You must be able to:**

- recognise **synthesis** 化合, **decomposition** 分解, **combustion** 燃烧, **precipitation**, and **acid-base** reactions
- predict products for simple cases
- classify a given equation

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 main reaction types

- **Synthesis (combination):** $A + B \rightarrow AB$.
- **Decomposition:** $AB \rightarrow A + B$.
- **Combustion:** a fuel + $O_2 \rightarrow CO_2 + H_2O$.
- **Precipitation:** two solutions form an insoluble solid.
- **Acid-base (neutralization):** acid + base $\rightarrow$ salt + water.

■ Recognising by pattern

Count reactants and products: one product = synthesis; one reactant = decomposition; O_2 + a hydrocarbon = combustion; two solutions $\rightarrow$ a solid = precipitation.

■ A worked classification

 $2Mg + O_2 \rightarrow 2MgO$: two reactants, one product $\rightarrow$ **synthesis** (also a combustion of a metal).

■ Combustion products

Complete combustion of a hydrocarbon always gives CO_2 and H_2O . $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$.

2 Practice

Now apply the methods above.

2.1 Classify $CaCO_3 \rightarrow CaO + CO_2$. [1]**2.2** Classify $HCl + NaOH \rightarrow NaCl + H_2O$. [1]**2.3** What are the products of complete combustion of a hydrocarbon? [2]

3 Exam-style questions

3.1 A reaction $A + B \rightarrow AB$ is a [1]

- **A** decomposition
- **B** synthesis
- **C** combustion
- **D** precipitation

3.2 Classify each reaction:(a) $2H_2O \rightarrow 2H_2 + O_2$ [1](b) $C_3H_8 + 5O_2 \rightarrow 3CO_2 + 4H_2O$ [1](c) $AgNO_3 + NaCl \rightarrow AgCl + NaNO_3$ [1]

3.3 Write the balanced equation for the complete combustion of ethane, C_2H_6 . [3]

Solutions

2.1 Decomposition.

2.2 Acid-base (neutralization).

2.3 Carbon dioxide and water.

3.1 B — synthesis (combination).

3.2 (a) decomposition; (b) combustion; (c) precipitation.

3.3 $2\text{C}_2\text{H}_6 + 7\text{O}_2 \rightarrow 4\text{CO}_2 + 6\text{H}_2\text{O}$.

4.8 Acid-Base Reactions

Name: _____ Class: _____ Date: _____

Total: 12 marks

KEY WORDS brønsted-lowry 布朗斯特 • neutralization 中和
 • conjugate acid-base pairs 共轭酸碱对 • acid 酸 • base 碱

Objective

Build the skills to answer exam questions on **acid-base reactions**.

You must be able to:

- identify **Brønsted-Lowry** 布朗斯特-劳里 acids (proton donors) and bases (proton acceptors)
- write **neutralization** 中和 as acid + base $\rightarrow$ salt + water
- identify **conjugate acid-base pairs** 共轭酸碱对

1 Worked examples

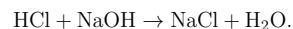
Study these first. Each one shows the method for a question type used later — follow the steps and you can do the Practice and Exam-style questions yourself.

■ Brønsted-Lowry definition

An **acid** donates a proton (H^+); a **base** accepts one. In $\text{HCl} + \text{H}_2\text{O} \rightarrow \text{H}_3\text{O}^+ + \text{Cl}^-$, HCl donates ($\rightarrow$ acid), water accepts ($\rightarrow$ base).

■ Neutralization

Acid + base $\rightarrow$ **salt** + **water**:



The net ionic form is $\text{H}^+ + \text{OH}^- \rightarrow \text{H}_2\text{O}$.

■ Conjugate pairs

When an acid donates its proton, what remains is its **conjugate base**. HCl (acid) $\rightarrow \text{Cl}^-$ (conjugate base). H_2O (base) $\rightarrow \text{H}_3\text{O}^+$ (conjugate acid). A pair differs by **one H^+** .

■ Identifying pairs

Look for two species that differ by a single proton on each side of the equation.

2 Practice

Now apply the methods above.

2.1 Define a Brønsted-Lowry acid. [1]

2.2 Write the products of $\text{HNO}_3 + \text{KOH}$. [2]

2.3 What is the conjugate base of HF? [1]

3 Exam-style questions

3.1 A Brønsted-Lowry base is a [1]

- **A** proton donor
- **B** proton acceptor
- **C** electron donor
- **D** hydroxide only

3.2 Consider $\text{NH}_3 + \text{H}_2\text{O} \rightleftharpoons \text{NH}_4^+ + \text{OH}^-$.

(a) Identify the acid and base on the left. [2]

(b) Identify the conjugate acid-base pairs. [2]

3.3 Write the balanced molecular equation for the neutralization of sulfuric acid H_2SO_4 with sodium hydroxide. [3]

Solutions

2.1 A proton (H^+) donor.

2.2 $\text{KNO}_3 + \text{H}_2\text{O}$ (salt + water).

2.3 F^- .

3.1 B — a proton acceptor.

3.2 (a) H_2O is the acid (donates H^+); NH_3 is the base (accepts). (b) $\text{NH}_3/\text{NH}_4^+$ and $\text{H}_2\text{O}/\text{OH}^-$.

3.3 $\text{H}_2\text{SO}_4 + 2\text{NaOH} \rightarrow \text{Na}_2\text{SO}_4 + 2\text{H}_2\text{O}$.



2. A student designs an experiment to study the reaction between NaHCO_3 and $\text{HC}_2\text{H}_3\text{O}_2$. The reaction is represented by the equation above. The student places 2.24 g of NaHCO_3 in a flask and adds 60.0 mL of 0.875 M $\text{HC}_2\text{H}_3\text{O}_2$. The student observes the formation of bubbles and that the flask gets cooler as the reaction proceeds.

- (a) Identify the reaction represented above as an acid-base reaction, precipitation reaction, or redox reaction. Justify your answer.
- (b) Based on the information above, identify the limiting reactant. Justify your answer with calculations.
- (c) The student observes that the bubbling is rapid at the beginning of the reaction and gradually slows as the reaction continues. Explain this change in the reaction rate in terms of the collisions between reactant particles.

- (d) In thermodynamic terms, a reaction can be driven by enthalpy, entropy, or both.

- (i) Considering that the flask gets cooler as the reaction proceeds, what drives the chemical reaction between $\text{NaHCO}_3(s)$ and $\text{HC}_2\text{H}_3\text{O}_2(aq)$? Answer by drawing a circle around one of the choices below.

Enthalpy only

Entropy only

Both enthalpy and entropy

- (ii) Justify your selection in part (d)(i) in terms of ΔG° .

- (e) The HCO_3^- ion has three carbon-to-oxygen bonds. Two of the carbon-to-oxygen bonds have the same length and the third carbon-to-oxygen bond is longer than the other two. The hydrogen atom is bonded to one of the oxygen atoms. In the box below, draw a Lewis electron-dot diagram (or diagrams) for the HCO_3^- ion that is (are) consistent with the given information.

- (f) A student prepares a solution containing equimolar amounts of $\text{HC}_2\text{H}_3\text{O}_2$ and $\text{NaC}_2\text{H}_3\text{O}_2$. The pH of the solution is measured to be 4.7. The student adds two drops of 3.0 M $\text{HNO}_3(aq)$ and stirs the sample, observing that the pH remains at 4.7. Write a balanced, net-ionic equation for the reaction between $\text{HNO}_3(aq)$ and the chemical species in the sample that is responsible for the pH remaining at 4.7.

AP CHEMISTRY • EXERCISE SHEET

4.9 Oxidation-Reduction (Redox) Reactions

Name: _____ Class: _____ Date: _____ **Total: 12 marks****KEY WORDS** oxidation 氧化 • oxidation numbers 氧化数 • reduction 还原 • redox 氧化还原

Objective

Build the skills to answer exam questions on **oxidation-reduction (redox) reactions**.**You must be able to:**

- assign **oxidation numbers** 氧化数
- identify what is **oxidized** (loses electrons) and **reduced** (gains electrons)
- name the **oxidizing** and **reducing agents**

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.

■ Oxidation numbers

Assign each atom an oxidation number: free element = 0; a monatomic ion = its charge; O usually -2; H usually +1; the sum equals the overall charge.

■ OIL RIG

Oxidation Is Loss of electrons; **Reduction Is Gain**. Oxidation raises the oxidation number; reduction lowers it.

■ A worked redox

 $\text{Zn} + \text{Cu}^{2+} \rightarrow \text{Zn}^{2+} + \text{Cu}$: Zn goes 0 $\rightarrow$ +2 (**oxidized**, loses e^-); Cu goes +2 $\rightarrow$ 0 (**reduced**, gains e^-).

■ Agents

The **reducing agent** is the species that is oxidized (it gives electrons away); the **oxidizing agent** is the species that is reduced (it takes electrons). Here Zn is the reducing agent, Cu^{2+} the oxidizing agent.

2 Practice

Now apply the methods above.

2.1 State the oxidation number of an element in its free (uncombined) form. [1]

2.2 Find the oxidation number of S in SO_4^{2-} (O is -2). [2]

2.3 In $\text{Mg} \rightarrow \text{Mg}^{2+} + 2e^-$, is Mg oxidized or reduced? [1]

3 Exam-style questions

3.1 Oxidation is defined as the [1]

- **A** gain of electrons
- **B** loss of electrons
- **C** gain of protons
- **D** loss of protons

3.2 Consider $\text{Fe} + \text{Cu}^{2+} \rightarrow \text{Fe}^{2+} + \text{Cu}$.

(a) State the oxidation number change for Fe and for Cu. [2]

(b) Identify which is oxidized and which is reduced. [2]

3.3 For $\text{Zn} + 2\text{HCl} \rightarrow \text{ZnCl}_2 + \text{H}_2$, identify the oxidizing agent and the reducing agent.[3]

Solutions

2.1 0.

2.2 $S + 4(-2) = -2 \Rightarrow S = +6$.

2.3 Oxidized (loses electrons).

3.1 B — loss of electrons.

3.2 (a) Fe: $0 \rightarrow +2$; Cu: $+2 \rightarrow 0$. (b) Fe is oxidized; Cu^{2+} is reduced.

3.3 Zn is oxidized ($0 \rightarrow +2$), so Zn is the reducing agent; H^+ is reduced ($+1 \rightarrow 0$), so HCl is the oxidizing agent.

Name: _____

AP Chemistry: 2026

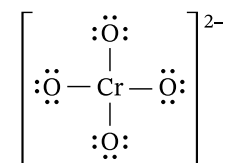
Question 2: Version J

2. Answer the following questions about the chromate ion, CrO_4^{2-} , and the dichromate ion, $\text{Cr}_2\text{O}_7^{2-}$.

Part A

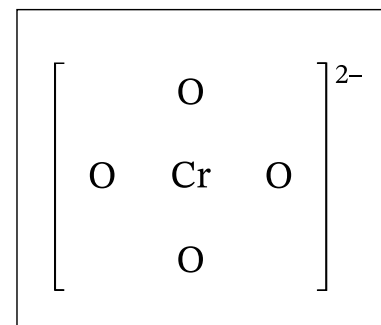
The bonds between chromium and oxygen in CrO_4^{2-} can be represented as covalent bonds. One possible Lewis diagram for the CrO_4^{2-} ion is shown in Figure 1.

Figure 1



- Based on VSEPR theory, **predict** the molecular geometry of the CrO_4^{2-} ion.
- On Figure 2, **draw** a complete Lewis diagram for a resonance structure of CrO_4^{2-} that results in a formal charge of zero on two of the O atoms and a formal charge of -1 on the other two O atoms. Your diagram should contain the same number of valence electrons as in Figure 1.

Figure 2



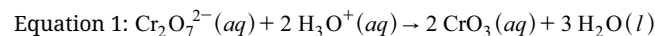
Part B

When reacted with a strong acid like $\text{HNO}_3(aq)$, $\text{CrO}_4^{2-}(aq)$ can be converted to $\text{Cr}_2\text{O}_7^{2-}(aq)$ and $\text{H}_2\text{O}(l)$ in a reversible reaction.

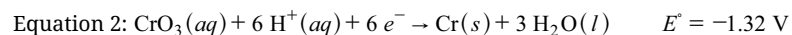
- Write** a balanced net ionic equation for the reaction between $\text{CrO}_4^{2-}(aq)$ and a strong acid.
- Is the reaction a redox reaction? **Justify** your answer based on the oxidation number of Cr.

The following information applies to parts C and D.

In acidic solutions, $\text{Cr}_2\text{O}_7^{2-}(aq)$ reacts to form $\text{CrO}_3(aq)$ according to Equation 1.



$\text{CrO}_3(aq)$ can be electrolyzed to plate objects with a thin layer of chromium metal according to Equation 2.

**Part C**

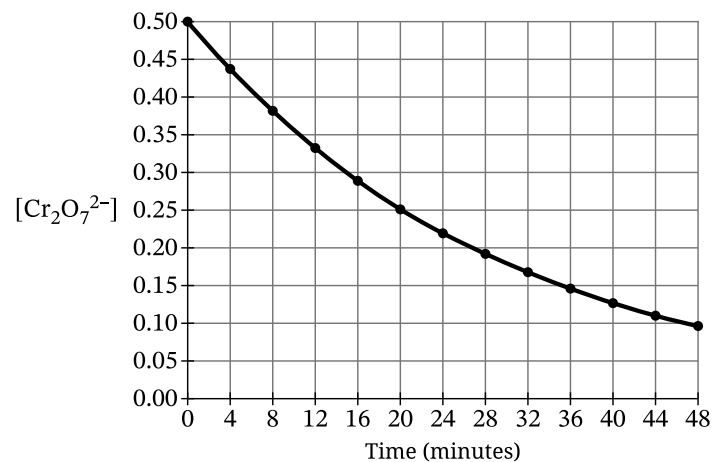
Is the reaction represented by Equation 2 thermodynamically favorable or unfavorable under standard conditions? **Justify** your answer with a calculation of ΔG° . Show the work that leads to your answer.

Part D

Calculate the number of grams of $\text{Cr}(s)$ that could be plated onto the surface of a steel rod when 15.0 A of current is applied for 3250 seconds. Show the work that leads to your answer.

Part E

In a separate experiment, an iron wire is placed directly in a solution of $0.50 \text{ M } \text{Cr}_2\text{O}_7^{2-}(aq)$ with $\text{pH} = 1.99$. The concentration of $\text{Cr}_2\text{O}_7^{2-}(aq)$ remaining is recorded over time, and the results are presented in Figure 3.

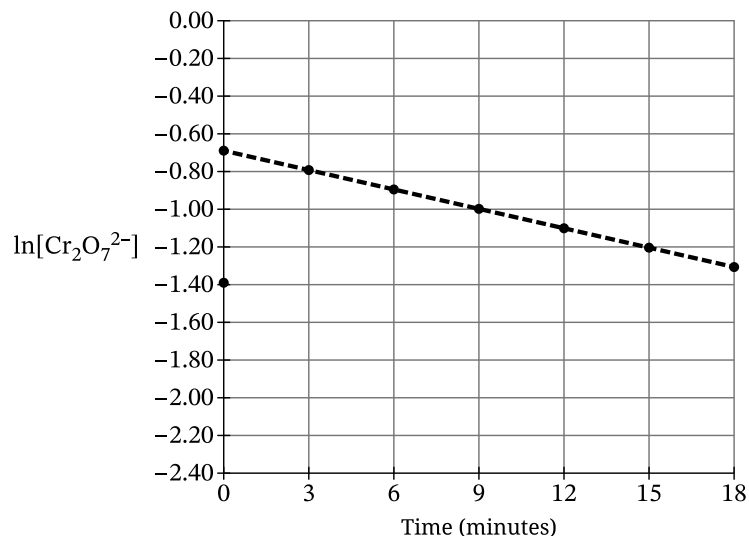
Figure 3

Explain how the data in Figure 3 support the conclusion that the reaction is first order with respect to $\text{Cr}_2\text{O}_7^{2-}$.

The following information applies to parts F and G.

The student creates a plot of $\ln[\text{Cr}_2\text{O}_7^{2-}]$ versus time for a trial with an initial concentration of $0.50\text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$, as shown in Figure 4.

Figure 4



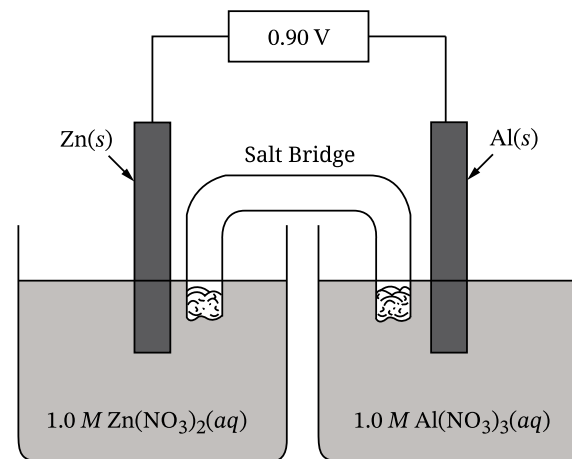
Part F

Calculate the value of the rate constant, k , for the reaction. Report your answer in units of min^{-1} . Show the work that leads to your answer.

Part G

The student then runs a second trial of the experiment under identical conditions but uses an initial concentration of $0.25\text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$ instead of $0.50\text{ M Cr}_2\text{O}_7^{2-}(\text{aq})$. On Figure 4, carefully **draw** the plot of $\ln[\text{Cr}_2\text{O}_7^{2-}]$ versus time that would be expected for the second experiment. The point at time zero has already been plotted.

6. A scientist constructs a galvanic cell as shown in the diagram. As the cell operates, the $\text{Zn}(\text{s})$ electrode increases in mass and the $\text{Al}(\text{s})$ electrode decreases in mass. A data table with the standard reduction potentials for the substances follows the diagram.



Half-Reaction	E° (V)
$\text{Zn}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Zn}(\text{s})$	-0.76
$\text{Al}^{3+}(\text{aq}) + 3\text{e}^- \rightarrow \text{Al}(\text{s})$	-1.66

- Write the half-reaction for the oxidation that occurs at the anode.
- Write the balanced net ionic equation for the overall reaction that occurs in the galvanic cell.
- Initially, each electrode has a mass of 50.0 g. The cell is allowed to run for a period of time and is then stopped. Which electrode's mass changed the most? Justify your answer with a calculation.

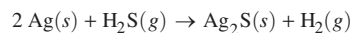
AP CHEMISTRY 2025 FREE-RESPONSE QUESTIONS

Reduction Half-Reaction	E° (V)
$\text{Au}^{3+}(\text{aq}) + 3\text{e}^- \rightarrow \text{Au}(\text{s})$	+1.50
$\text{Zn}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Zn}(\text{s})$	-0.76
$\text{Mn}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Mn}(\text{s})$	-1.19
$\text{Al}^{3+}(\text{aq}) + 3\text{e}^- \rightarrow \text{Al}(\text{s})$	-1.66
$\text{Be}^{2+}(\text{aq}) + 2\text{e}^- \rightarrow \text{Be}(\text{s})$	-1.85

- The standard Zn/Al cell has a value of E°_{cell} equal to 0.90 V. The scientist needs a galvanic cell that produces a greater voltage. The scientist has access to the chemical systems in the table. If the scientist uses the Zn half-cell and one of the other options from the table, what is the MAXIMUM voltage that could be generated at standard conditions?

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

3. Sterling silver is an alloy that is commonly used to make jewelry and consists of 92.5% silver and 7.5% other metals, such as copper, by mass. Over time, the alloy can form a tarnish of $\text{Ag}_2\text{S}(s)$ when it reacts with hydrogen sulfide, as represented by the following equation.



- (a) What are the oxidation numbers of silver in $\text{Ag}(s)$ and $\text{Ag}_2\text{S}(s)$?

$\text{Ag}(s)$ _____ $\text{Ag}_2\text{S}(s)$ _____

- (b) The following table contains the atomic radii for silver and copper.

Element	Silver (Ag)	Copper (Cu)
Atomic radius (pm)	165	145

- (i) Explain why sterling silver is better classified as a substitutional alloy than as an interstitial alloy.

- (ii) Using principles of atomic structure and Coulomb's law, explain why silver has a larger atomic radius than copper does.

GO ON TO THE NEXT PAGE.

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

The Ag_2S tarnish on sterling silver can be removed until only sterling silver remains. A student weighs a tarnished sterling silver sample both before and after removing the $\text{Ag}_2\text{S}(s)$ (molar mass 247.80 g / mol) and records the data in the following table.

	Before Tarnish Removal	After Tarnish Removal
Mass	409.21 g	398.94 g

- (c) Assuming that only $\text{Ag}_2\text{S}(s)$ is removed, calculate the number of moles of silver atoms removed.

Rhodium plating is a process used to protect sterling silver from tarnishing. This involves electroplating (depositing) solid rhodium, $\text{Rh}(s)$, onto the surface of the metal from an acidified solution of $\text{Rh}_2(\text{SO}_4)_3(aq)$. Oxygen gas is produced during this process.

- (d) A table of half-reactions related to the overall reaction is provided.

Half-Reaction	E° (V)
$\text{Rh}^{3+}(aq) + 3 e^- \rightarrow \text{Rh}(s)$	+0.80
$\text{O}_2(g) + 4 \text{H}^+(aq) + 4 e^- \rightarrow 2 \text{H}_2\text{O}(l)$	+1.23

- (i) Write the balanced net ionic equation for plating $\text{Rh}(s)$ from the acidified $\text{Rh}_2(\text{SO}_4)_3(aq)$ solution.

- (ii) Calculate the value of E°_{cell} for the reaction in part (d)(i).

GO ON TO THE NEXT PAGE.

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

(iii) Based on your answer to part (d)(ii), explain why this process requires the use of an external power source.

(e) Calculate the length of time, in seconds, required to plate 2.8 g of Rh(s) onto a piece of sterling silver if 2.0 C / s of current is applied.

GO ON TO THE NEXT 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.

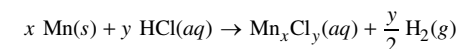
Answer the following questions related to manganese compounds.

(a) Manganese has several common oxidation states.

(i) Write the complete electron configuration for an Mn atom in the ground state.

(ii) When manganese forms cations, electrons are lost from which subshell first? Identify both the number and letter associated with the subshell.

A student performs an experiment to produce a manganese salt of unknown composition, $\text{Mn}_x\text{Cl}_y(aq)$, and determine its empirical formula. The student places a sample of Mn(s) in a beaker containing excess $\text{HCl}(aq)$, as represented by the following equation.



GO ON TO THE NEXT PAGE.

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

The student heats the resulting mixture until only $\text{Mn}_x\text{Cl}_y(s)$ remains in the beaker. The data are given in the following table.

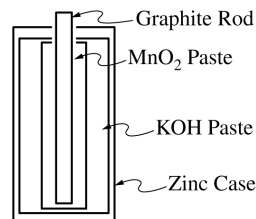
Mass of empty beaker	60.169 g
Mass of beaker and $\text{Mn}(s)$	61.262 g
Mass of beaker and Mn_xCl_y after heating to constant mass	62.673 g

- (b) Calculate the mass of Cl in the sample of $\text{Mn}_x\text{Cl}_y(s)$ remaining in the beaker.
- (c) Calculate the number of moles of Cl in the sample of $\text{Mn}_x\text{Cl}_y(s)$ remaining in the beaker.
- (d) The student determines that 0.0199 mol of Mn was used in the experiment. Use the data to determine the empirical formula of the $\text{Mn}_x\text{Cl}_y(s)$.
- (e) The student repeats the experiment using the same amounts of Mn and HCl and notices that some of the Mn_xCl_y splatters out of the beaker as it is heated to dryness. Will the number of moles of Cl calculated for this trial be greater than, less than, or equal to the number calculated in part (c)? Justify your answer.

GO ON TO THE NEXT PAGE.

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

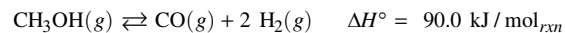
- (f) Another compound of manganese, MnO_2 , is used in alkaline batteries, represented by the following diagram. Some half-reactions are given in the table.



Reduction Half-Reaction	E° (V)
$\text{Zn}^{2+}(aq) + 2 e^- \rightarrow \text{Zn}(s)$	-0.76
$\text{ZnO}(s) + \text{H}_2\text{O}(l) + 2 e^- \rightarrow \text{Zn}(s) + 2 \text{OH}^-(aq)$	-1.28
$2 \text{MnO}_2(s) + \text{H}_2\text{O}(l) + 2 e^- \rightarrow \text{Mn}_2\text{O}_3(s) + 2 \text{OH}^-(aq)$	0.15

- (i) Based on the half-reactions given in the table, write the balanced net ionic equation for the reaction that has the greatest thermodynamic favorability.
- (ii) Calculate the value of E_{cell}° for the overall reaction.
- (iii) Calculate the value of ΔG° in kJ/mol_{rxn} .
- (iv) A student claims that the total mass of an alkaline battery decreases as the battery operates because the anode loses mass. Do you agree with the student's claim? Justify your answer.

GO ON TO THE NEXT PAGE.



Methanol vapor decomposes to form carbon monoxide gas and hydrogen gas at high temperatures in the presence of a platinum catalyst, as represented by the balanced chemical equation given.

(a) Are the hydrogen atoms oxidized or are they reduced in the forward reaction? Justify your answer in terms of oxidation numbers.

(b) In the following box, draw the complete Lewis electron-dot diagram for the carbon monoxide molecule in which every atom obeys the octet rule. Show all bonding and nonbonding valence electrons.



(c) The values of the standard molar entropies of the compounds involved in the reaction are given in the following table.

Substance	S° (J/(K·mol))
$\text{CH}_3\text{OH}(g)$	240.
$\text{CO}(g)$	198
$\text{H}_2(g)$	131

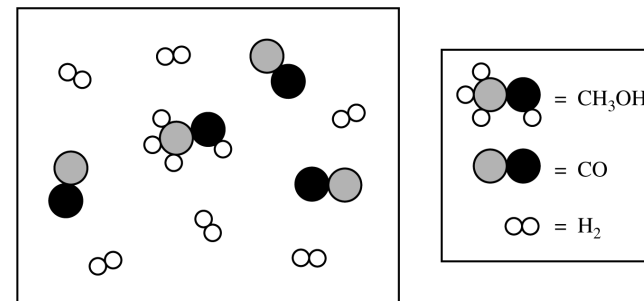
(i) Use the data in the table to calculate the value of the standard entropy change, ΔS° , in J/(K·mol_{rxn}), for the reaction.

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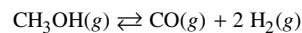
Continue your response to **QUESTION 2** on this page.

(ii) Calculate the value of ΔG° , in kJ/mol_{rxn}, for the reaction at 375 K. Assume that ΔH° and ΔS° are independent of temperature.

The following particle-level diagram shows a representative sample of the equilibrium mixture represented by the equation given.



Continue your response to SECTION II on this page.



The reaction system represented by the equation is allowed to achieve equilibrium at a different temperature. The following table gives the partial pressure of each species in the equilibrium mixture.

Substance	Partial Pressure at Different Temperature
$\text{CH}_3\text{OH}(g)$	2.7 atm
$\text{CO}(g)$	4.2 atm
$\text{H}_2(g)$	8.4 atm

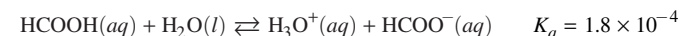
(f) Use the information in the table to calculate the value of the equilibrium constant, K_p , at the new temperature.

(g) The volume of the container is rapidly doubled with no change in temperature. As equilibrium is re-established, does the number of moles of $\text{CH}_3\text{OH}(g)$ increase, decrease, or remain the same? Justify your answer by comparing the value of the reaction quotient, Q , with the value of the equilibrium constant, K_p .

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. Methanoic acid, HCOOH , ionizes according to the equation above.

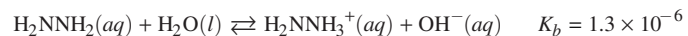
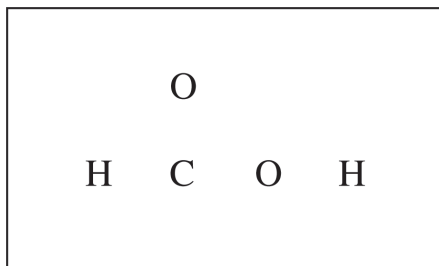
(a) Write the expression for the equilibrium constant, K_a , for the reaction.

(b) Calculate the pH of a 0.25 M solution of HCOOH .

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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.

(c) In the box below, complete the Lewis electron-dot diagram for HCOOH . Show all bonding and nonbonding valence electrons.



(d) In aqueous solution, the compound H_2NNH_2 reacts according to the equation above. A 50.0 mL sample of 0.25 M $\text{H}_2\text{NNH}_2(aq)$ is combined with a 50.0 mL sample of 0.25 M $\text{HCOOH}(aq)$.

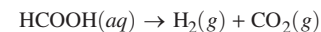
(i) Write the balanced net ionic equation for the reaction that occurs when H_2NNH_2 is combined with HCOOH .

(ii) Is the resulting solution acidic, basic, or neutral? Justify your answer.

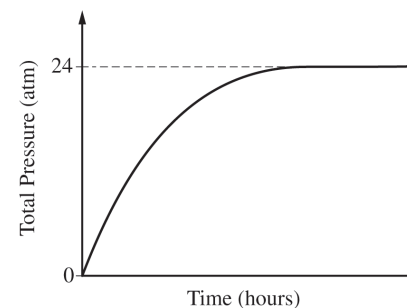
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Use a pencil or pen with black or dark blue ink only. Do NOT write your name. Do NOT write outside the box.

When a catalyst is added to a solution of $\text{HCOOH}(aq)$, the reaction represented by the following equation occurs.



(e) Is the reaction a redox reaction? Justify your answer.



(f) The reaction occurs in a rigid 4.3 L vessel at 25°C , and the total pressure is monitored, as shown in the graph above. The vessel originally did not contain any gas. Calculate the number of moles of $\text{CO}_2(g)$ produced in the reaction. (Assume that the amount of $\text{CO}_2(g)$ dissolved in the solution is negligible.)

(g) After the reaction has proceeded for several minutes, does the amount of catalyst increase, decrease, or remain the same? Justify your answer.

GO ON TO THE NEXT PAGE.

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

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).

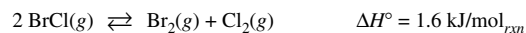
Half-Reaction	E° at 25°C (V)
$\text{Br}_2 + 2 e^- \rightarrow 2 \text{Br}^-$	1.07
$\text{Cl}_2 + 2 e^- \rightarrow 2 \text{Cl}^-$	1.36
$\text{I}_2 + 2 e^- \rightarrow 2 \text{I}^-$	0.53

- (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.



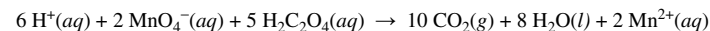
A 0.100 mole sample of pure BrCl(g) is placed in a previously evacuated, rigid 2.00 L container at 298 K. Eventually the system reaches equilibrium according to the equation above.

- (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.

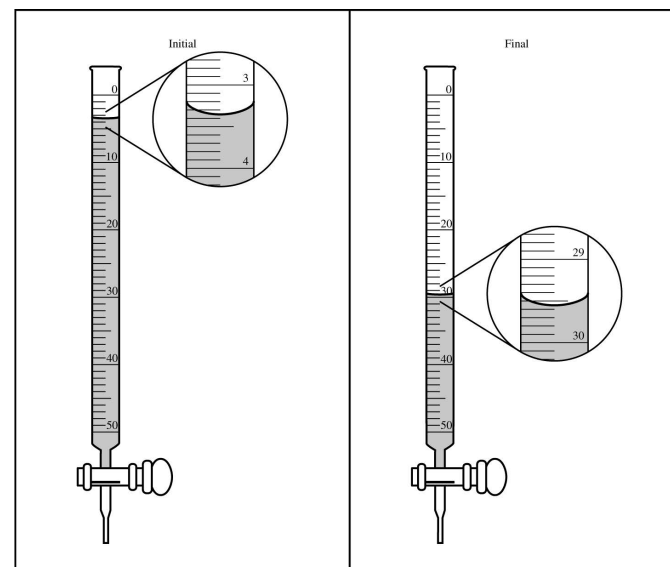
- (f) Determine the value of K_{eq} for the decomposition reaction of BrCl at 298 K.
 (g) Calculate the bond energy of the Br-Cl bond, in kJ/mol, using ΔH° for the reaction (1.6 kJ/mol_{rxn}) and the information in the following table.

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



7. A student dissolved a 0.139 g sample of oxalic acid, H₂C₂O₄, in water in an Erlenmeyer flask. Then the student titrated the H₂C₂O₄ solution in the flask with a solution of KMnO₄, which has a dark purple color. The balanced chemical equation for the reaction that occurred during the titration is shown above.

- (a) Identify the species that was reduced in the titration reaction. Justify your answer in terms of oxidation numbers.
 (b) The student used a 50.0 mL buret to add the KMnO₄(aq) to the H₂C₂O₄(aq) until a faint lavender color was observed in the flask, an indication that the end point of the titration had been reached. The initial and final volume readings of the solution in the buret are shown below. Write down the initial reading and the final reading and use them to determine the volume of KMnO₄(aq) that was added during the titration.



- (c) Given that the concentration of KMnO₄(aq) was 0.0235 M, calculate the number of moles of MnO₄⁻ ions that completely reacted with the H₂C₂O₄.
 (d) The student proposes to perform another titration using a 0.139 g sample of H₂C₂O₄, but this time using 0.00143 M KMnO₄(aq) in the buret. Would this titrant concentration be a reasonable choice to use if the student followed the same procedure and used the same equipment as before? Justify your response.

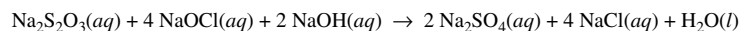
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END OF EXAM

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.

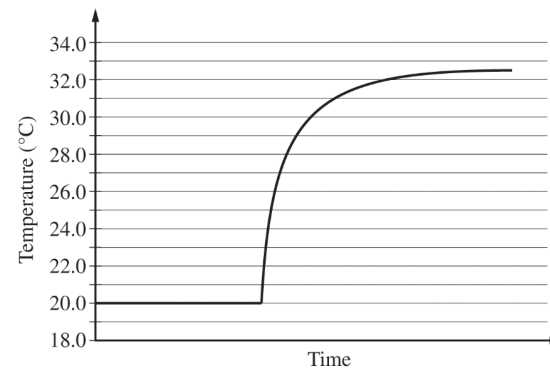
- (a) Determine the oxidation number of Cl in NaOCl.
 (b) Calculate the number of grams of $\text{Na}_2\text{S}_2\text{O}_3$ needed to prepare 100.00 mL of 0.500 M $\text{Na}_2\text{S}_2\text{O}_3(aq)$.

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.
 (i) 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.
 (ii) 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)
$\text{Na}_2\text{S}_2\text{O}_3(aq)$	0.500	10.0
$\text{NaOCl}(aq)$	0.500	10.0
$\text{NaOH}(aq)$	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.

3. Answer the following questions relating to Fe and its ions, Fe^{2+} and Fe^{3+} .

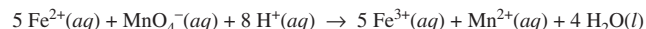
(a) Write the ground-state electron configuration of the Fe^{2+} ion.

Ion	Ionic Radius (pm)
Fe^{2+}	92
Fe^{3+}	79

(b) The radii of the ions are given in the table above. Using principles of atomic structure, explain why the radius of the Fe^{2+} ion is larger than the radius of the Fe^{3+} ion.

(c) Fe^{3+} ions interact more strongly with water molecules in aqueous solution than Fe^{2+} ions do. Give one reason for this stronger interaction, and justify your answer using Coulomb's law.

A student obtains a solution that contains an unknown concentration of $\text{Fe}^{2+}(aq)$. To determine the concentration of $\text{Fe}^{2+}(aq)$ in the solution, the student titrates a sample of the solution with $\text{MnO}_4^-(aq)$, which converts $\text{Fe}^{2+}(aq)$ to $\text{Fe}^{3+}(aq)$, as represented by the following equation.



(d) Write the balanced equation for the half-reaction for the oxidation of $\text{Fe}^{2+}(aq)$ to $\text{Fe}^{3+}(aq)$.

(e) The student titrates a 10.0 mL sample of the $\text{Fe}^{2+}(aq)$ solution. Calculate the value of $[\text{Fe}^{2+}]$ in the solution if it takes 17.48 mL of added 0.0350 M $\text{KMnO}_4(aq)$ to reach the equivalence point of the titration.

To deliver the 10.0 mL sample of the $\text{Fe}^{2+}(aq)$ solution in part (e), the student has the choice of using one of the pieces of glassware listed below.

- 25 mL buret
- 25 mL beaker
- 25 mL graduated cylinder
- 25 mL volumetric flask

(f) Explain why the 25 mL volumetric flask would be a poor choice to use for delivering the required volume of the $\text{Fe}^{2+}(aq)$ solution.

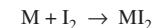
In a separate experiment, the student is given a sample of powdered $\text{Fe}(s)$ that contains an inert impurity. The student uses a procedure to oxidize the $\text{Fe}(s)$ in the sample to $\text{Fe}_2\text{O}_3(s)$. The student collects the following data during the experiment.

Mass of $\text{Fe}(s)$ with inert impurity	6.724 g
Mass of $\text{Fe}_2\text{O}_3(s)$ produced	7.531 g

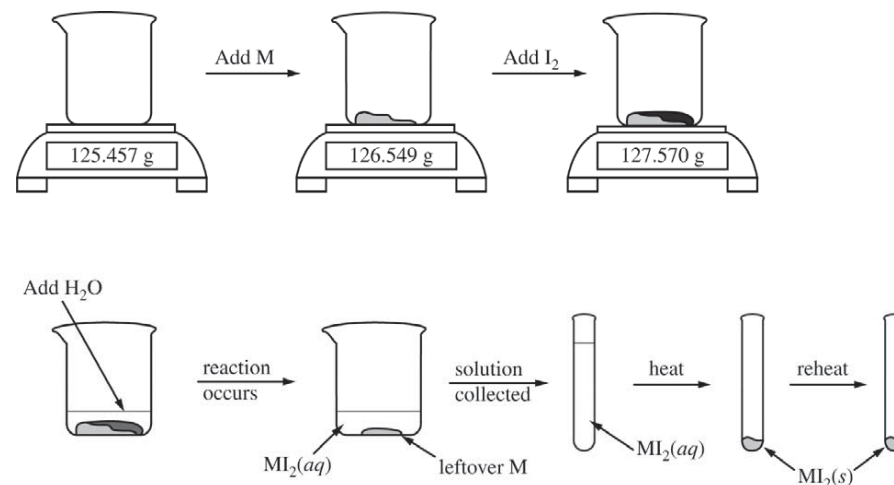
(g) Calculate the number of moles of Fe in the $\text{Fe}_2\text{O}_3(s)$ produced.

(h) Calculate the percent by mass of Fe in the original sample of powdered $\text{Fe}(s)$ with the inert impurity.

(i) If the oxidation of the $\text{Fe}(s)$ in the original sample was incomplete so that some of the 7.531 g of product was $\text{FeO}(s)$ instead of $\text{Fe}_2\text{O}_3(s)$, would the calculated mass percent of $\text{Fe}(s)$ in the original sample be higher, lower, or the same as the actual mass percent of $\text{Fe}(s)$? Justify your answer.



3. To determine the molar mass of an unknown metal, M, a student reacts iodine with an excess of the metal to form the water-soluble compound MI_2 , as represented by the equation above. The reaction proceeds until all of the I_2 is consumed. The $\text{MI}_2(aq)$ solution is quantitatively collected and heated to remove the water, and the product is dried and weighed to constant mass. The experimental steps are represented below, followed by a data table.



Data for Unknown Metal Lab	
Mass of beaker	125.457 g
Mass of beaker + metal M	126.549 g
Mass of beaker + metal M + I_2	127.570 g
Mass of MI_2 , first weighing	1.284 g
Mass of MI_2 , second weighing	1.284 g

(a) Given that the metal M is in excess, calculate the number of moles of I_2 that reacted.

(b) Calculate the molar mass of the unknown metal M.

The student hypothesizes that the compound formed in the synthesis reaction is ionic.

(c) Propose an experimental test the student could perform that could be used to support the hypothesis. Explain how the results of the test would support the hypothesis if the substance was ionic.

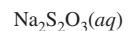
The student hypothesizes that Br_2 will react with metal M more vigorously than I_2 did because Br_2 is a liquid at room temperature.

- (d) Explain why I_2 is a solid at room temperature whereas Br_2 is a liquid. Your explanation should clearly reference the types and relative strengths of the intermolecular forces present in each substance.

While cleaning up after the experiment, the student wishes to dispose of the unused solid I_2 in a responsible manner. The student decides to convert the solid I_2 to $\text{I}^-(aq)$ anion. The student has access to three solutions, $\text{H}_2\text{O}_2(aq)$, $\text{Na}_2\text{S}_2\text{O}_3(aq)$, and $\text{Na}_2\text{S}_4\text{O}_6(aq)$, and the standard reduction table shown below.

Half reaction	E° (V)
$\text{S}_4\text{O}_6^{2-}(aq) + 2 e^- \rightarrow 2 \text{S}_2\text{O}_3^{2-}(aq)$	0.08
$\text{I}_2(s) + 2 e^- \rightarrow 2 \text{I}^-(aq)$	0.54
$\text{O}_2(g) + 2 \text{H}^+(aq) + 2 e^- \rightarrow \text{H}_2\text{O}_2(aq)$	0.68

- (e) Which solution should the student add to $\text{I}_2(s)$ to reduce it to $\text{I}^-(aq)$? Circle your answer below. Justify your answer, including a calculation of E° for the overall reaction.



- (f) Write the balanced net-ionic equation for the reaction between I_2 and the solution you selected in part (e).