2025

AP® Chemistry

Free-Response Questions

by Dr. Chen

CHEMISTRY

SECTION II

TIME – 1 HOUR AND 45 MINUTES

Directions:

Section II has 7 questions and lasts 1 hour and 45 minutes.

You may use the available paper for scratch work and planning, but you must write your answers in the free-response booklet. Label parts (e.g., A, B, C) and sub-parts (e.g., i, ii, iii) as needed. Use a pencil or a pen with black or dark blue ink to write your responses.

For each question, show your work for each part in the space provided for that part in the free-response booklet. 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.

A calculator is allowed in this section. You may use a handheld four-function, scientific, or graphing calculator, or the calculator available in this application. Reference information, including a periodic table and lists of equations and constants, is available in this application and can be accessed throughout the exam.

You may pace yourself as you answer the questions in this section, or you may use these optional timing recommendations:

Questions 1–3 are long free-response questions. It is suggested that you spend about 23 minutes on each of those questions. Questions 4–7 are short free-response questions. It is suggested that you spend about 9 minutes on each of those questions.

You can go back and forth between questions in this section until time expires. The clock will turn red when 5 minutes remain—**the proctor will not give you any time updates or warnings.**

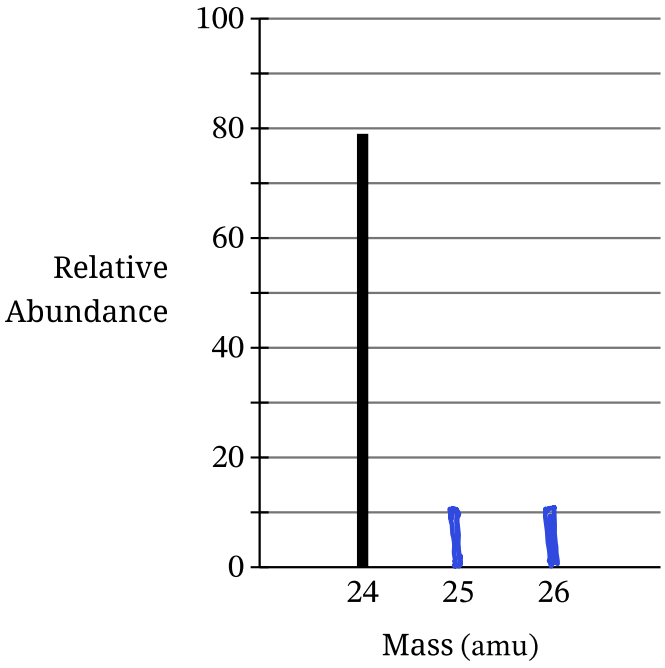
Note: This exam was originally administered digitally. It is presented here in a format optimized for teacher and student use in the classroom.

During the AP Exam administration, students have access to reference information. To see the reference information for this course, please visit AP Central: https://apcentral.collegeboard.org/courses/ap-chemistry/exam

Fundamental atomic structures/MS, Ion-Dipole, Ksp and Eq-

1. Answer the following questions about magnesium.

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



$\frac{100-79}{2} = 10.5$

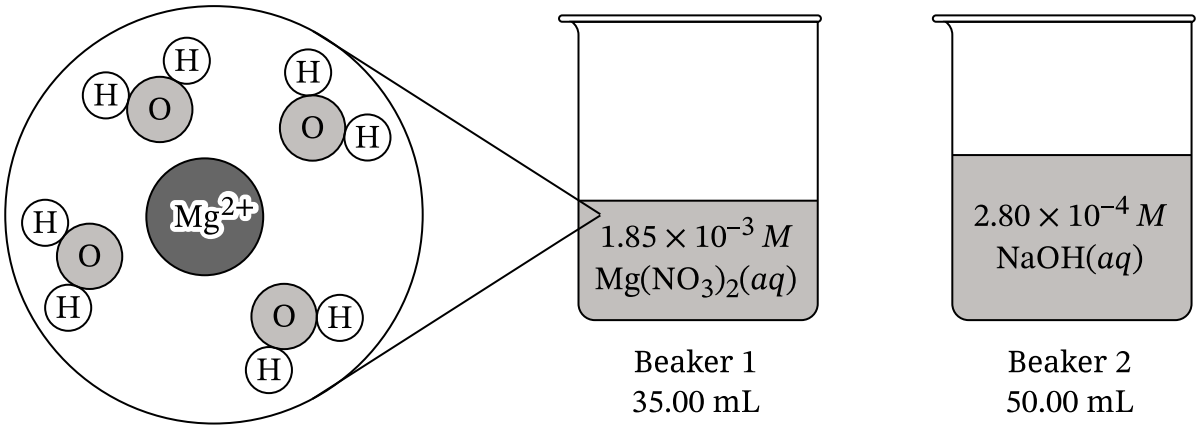
The percent abundance of magnesium-24 is 79%. The percent abundances of the other two natural isotopes of magnesium, magnesium-25 and magnesium-26, are approximately equal.

i. 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.

ii. Describe the difference in atomic structure that accounts for the difference in mass between magnesium-25 and magnesium-26.

^{26}Mg has one more neutron in the nucleus than ^{25}Mg.

A student prepares a $1.85\times10^{-3}\ M$ solution of $Mg(NO_3)_2(aq)$ in beaker 1 and a $2.80\times10^{-4}\ M$ solution of $NaOH(aq)$ 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.

i. The relative charge of the ions

ii. The relative radii of the ions

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

B: Mg^{2+} has a higher charge and a smaller size than Na^+, according to Coulomb's Law, there are stronger ion-dipole interactions between the positively charged cations (Mg^{2+} and Na^+) and the negatively charged O atoms of H_2O molecules.

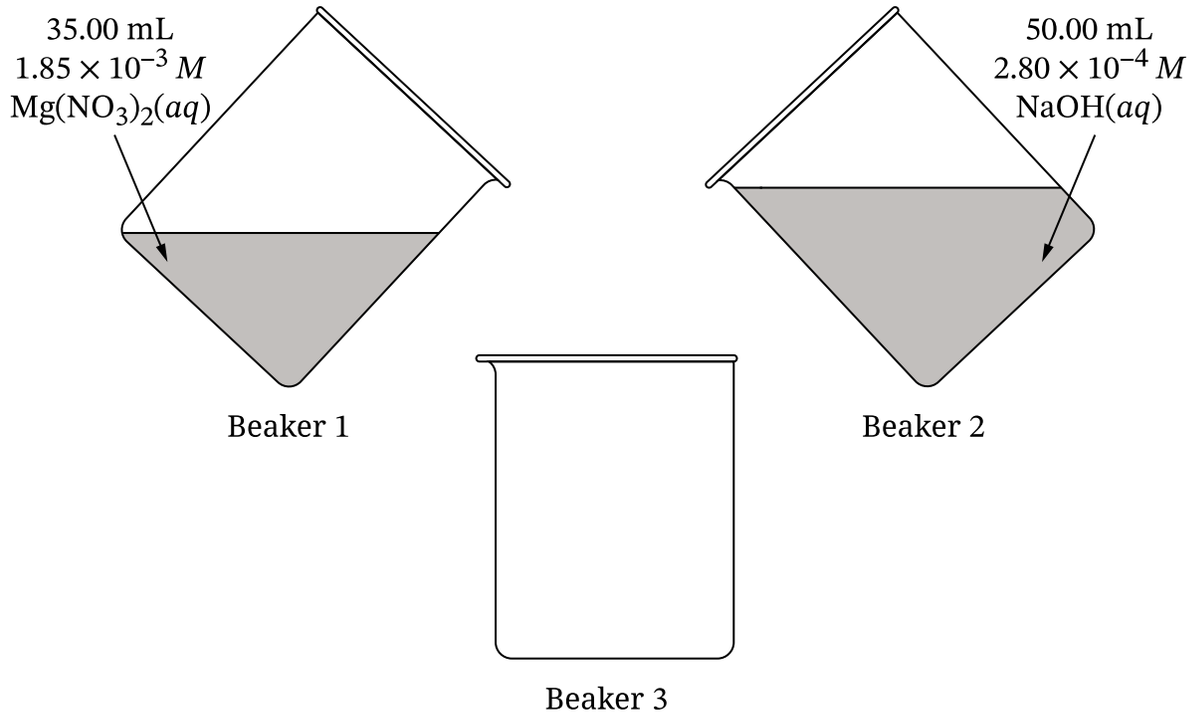
C: $[OH^-] = 2.80\times10^{-4}\ M$,

$pOH = 3.55$

$pH = 10.45$

F (continued): Thus, according to LCP, the dissolution equilibrium of $Mg(OH)_2$ shifts to the right side, causing $Mg(OH)_2(s)$ to dissolve!

D. A student combines 35.00 mL of $1.85\times10^{-3}\ M\ Mg(NO_3)_2(aq)$ with 50.00 mL of $2.80\times10^{-4}\ M\ NaOH(aq)$, as shown in the diagram. Calculate $[Mg^{2+}]$ 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.

$$Mg(OH)_2(s) \rightleftarrows Mg^{2+}(aq) + 2\ OH^-(aq) \quad K_{sp} = 5.61\times10^{-12}$$

i. Write the expression for the solubility product constant, K_{sp}.

ii. After the two solutions are combined in beaker 3 as described in part D, but before any reaction takes place, $[OH^-] = 1.65\times10^{-4}\ M$. Using your answer to part D, calculate the value of the reaction quotient, Q.

iii. 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 $HNO_3(aq)$ to decrease the pH of a saturated solution containing undissolved $Mg(OH)_2(s)$. Does the amount of undissolved $Mg(OH)_2(s)$ increase, decrease, or remain the same as the $HNO_3(aq)$ is added? Justify your answer.

D: $[Mg^{2+}]_b = \frac{35.00\ mL \times 1.85\times10^{-3}\ M}{35.00\ mL + 50.00\ mL} = 7.62\times10^{-4}\ M$

E: i) $K_{sp} = [Mg^{2+}]_{eq}[OH^-]_{eq}^2$

ii) $Q_{sp} = 7.62\times10^{-4} \times (1.65\times10^{-4})^2 = 2.07\times10^{-11}$

iii) $Q_{sp} > K_{sp}$ meaning there are more ions than the system can hold at equilibrium, thus, precipation is formed

F: Decrease, as H^+ is added, $[OH^-]$ decreases by forming H_2O

Empirical formula, A-B titration and curve, Buffer calcula-

2. Answer the following questions about ascorbic acid (vitamin C). Kinetics, Ion-dipole-

A. A student combusts a sample of ascorbic acid, $C_xH_yO_x$, 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.

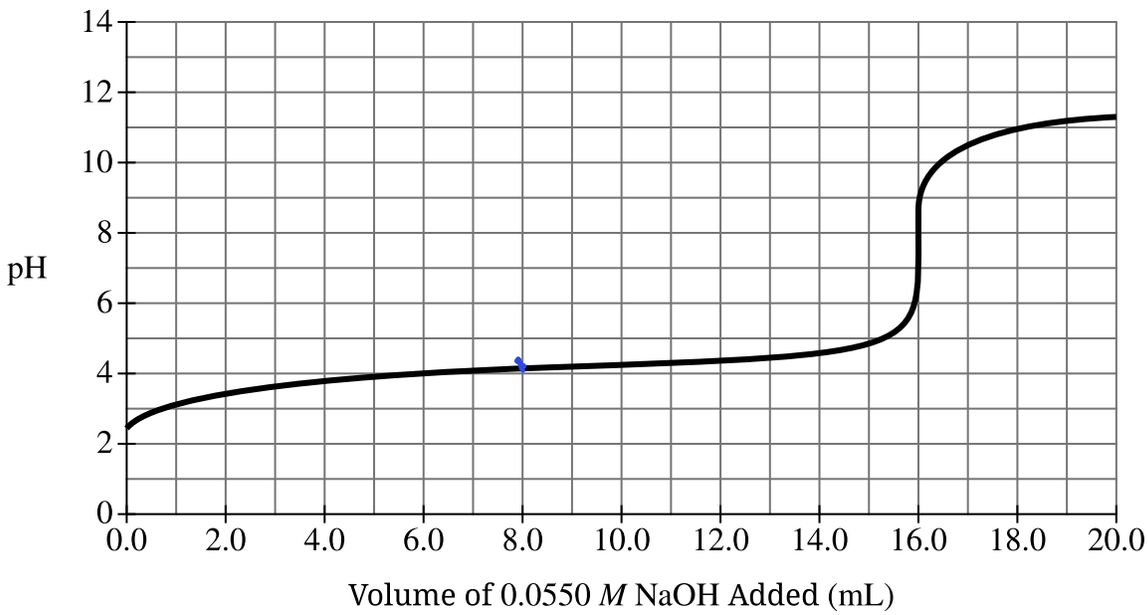
i. Calculate the number of moles of H_2O produced.

ii. 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.

$$HAsc(aq) + H_2O(l) \rightleftharpoons H_3O^+(aq) + Asc^-(aq)$$

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



i. Calculate the molar concentration of the ascorbic acid solution.

ii. From the titration curve, determine the approximate pK_a of ascorbic acid.

iii. What is the value of the ratio $\frac{[Asc^-]}{[HAsc]}$ when the pH of the solution is 4.7?

A: i) $n(H_2O) = \frac{2.883\,g}{18.02\,g/mol} = 0.1600\ mol$

ii) $n(C) = n(O) = 0.2400\ mol \Rightarrow C:H:O = 3:4:3 \Rightarrow C_3H_4O_3$ Empirical:

B: i) V_{NaOH} at endpoint $= 16.0\ mL \Rightarrow C(HAsc) = \frac{16.0 \times 0.0550}{10.0} = 0.0880\ M$

ii) pH = pKa at half-eq point ($V_{OH^-} = 8.0\ mL$)

pKa = 4.1

iii) H-H equation: $pH = pK_a + (?)\frac{[Asc^-]}{[HAsc]} \Rightarrow \frac{[Asc^-]}{[HAsc]} = 3.98$

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

$$HAsc + I_3^- \rightarrow DHAsc + 3\,I^- + 2\,H^+$$

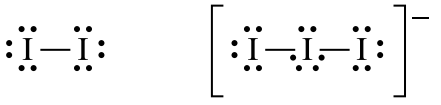
The student runs three trials of the reaction with different initial concentrations of HAsc and I_3^-, producing the following data.

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}

i. 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].

ii. 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.



I_2 $\qquad$ I_3^-

C: i) Comparing trial 1 and 3, $[I_3^-]$ is the same, but [HAsc] is doubled, and the initial rate of DHAsc formation is doubled, so the reaction is first order with respect to [HAsc].

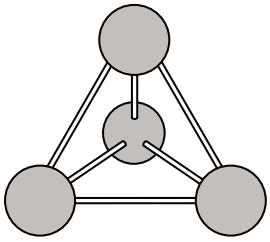
ii) Using data in trial 1: $2.457\times10^{-4} = k \times 0.450 \times 1.200$

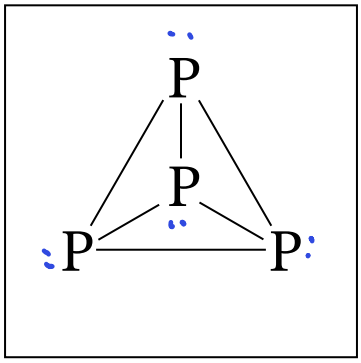
$\Rightarrow k = 4.55\times10^{-4}\ M^{-1}\cdot s^{-1}$ (or average of all 3 trials)

D: ion-dipole interaction

Lewis, Thermodynamics, Calorimetry, Hess's Law, K and LCP.

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.

Equation 1: $P_4(s) + 5\ O_2(g) \rightarrow P_4O_{10}(s)$

i. The entropy change of the reaction, ΔS°, is negative. Using particle-level reasoning, explain why the entropy decreases as the reaction progresses.

ii. 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°.

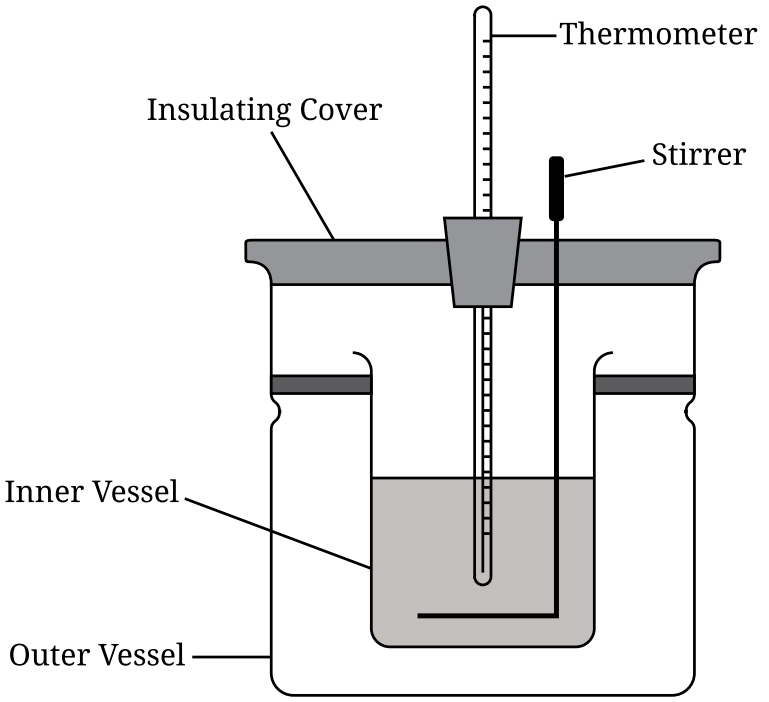
B: i) The reaction converts 1 mol of solid and 5 moles of gases into 1 mol of solid. Gas molecules moves faster and random, and have more freedom and larger disorder, thus a much larger entropy than solid, whose particles are fixed in their positions.

ii) Yes! $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$, as ΔS° is negative, that said the $-T\Delta S$ part makes the ΔG° positive, which unfavors the reaction! And ΔH° is negative, which favors the reaction! Thus ...

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

Equation 2: $P_4O_{10}(s) + 6\ H_2O(l) \rightarrow 4\ H_3PO_4(aq)$

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 $J/(g\cdot°C)$

i. 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.

ii. Calculate the value of ΔH°_{rxn} for equation 2 in kJ/mol_{rxn}. Include the sign in your answer.

i): $q = cm\Delta T = 4.18 \times (100.0 + 0.100) \times (22.38 - 22.00) = 159\ J = 0.16\ kJ$

ii) $n(P_4O_{10}) = 0.100 \div 283.9 = 3.52 \times 10^{-4}\ mol$;

$\Delta H^\circ_{rxn} = \frac{q}{n} = -0.16 \div 3.52 \times 10^{-4} = -455\ kJ/mol$

D: Smaller mass of P_4O_{10} is reacted with H_2O to release less heat, according to $q = cm\Delta T$, q is smaller, m is pretty much the same, c is the same, then ΔT ↓.

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.

$P_4(s)$ also reacts readily with $Cl_2(g)$ to produce phosphorus trichloride, $PCl_3(g)$, which in turn reacts with $Cl_2(g)$ in an equilibrium process to produce $PCl_5(g)$. The reactions are represented by equations 3 and 4.

Equation 3: $P_4(s) + 6\ Cl_2(g) \rightarrow 4\ PCl_3(g) \qquad \Delta H_1^\circ = -1148\ \text{kJ/mol}_{rxn}$

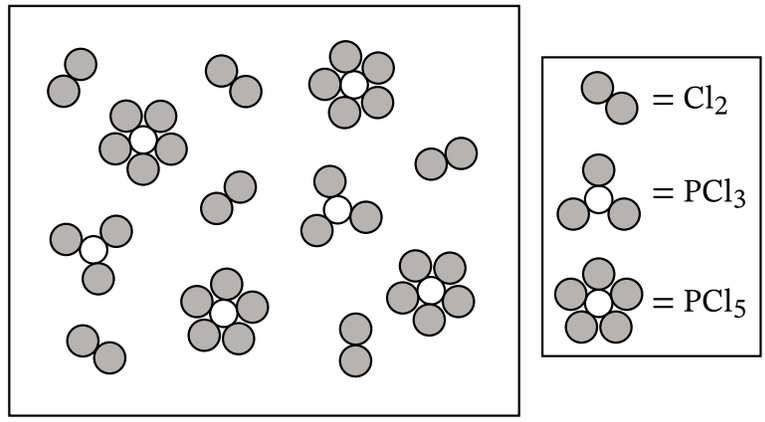
Equation 4: $PCl_3(g) + Cl_2(g) \rightleftarrows PCl_5(g) \qquad \Delta H_2^\circ = -88\ \text{kJ/mol}_{rxn}$

E: $\Delta H_f^\circ = (\Delta H_{f1}^\circ + 4 \times \Delta H_{f2}^\circ) \times \frac{1}{4} = -1148 \times \frac{1}{4} + (-88) = -375\ \text{kJ/mol}$

E. Calculate the standard enthalpy of formation of $PCl_5(g)$ represented by equation 5.

Equation 5: $\frac{1}{4}P_4(s) + \frac{5}{2}Cl_2(g) \rightarrow PCl_5(g) \qquad \Delta H_f^\circ = ?$

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.

Equation 4: $PCl_3(g) + Cl_2(g) \rightleftarrows PCl_5(g) \qquad \Delta H_2^\circ = -88\ \text{kJ/mol}_{rxn}$

i. 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?

ii. 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°.

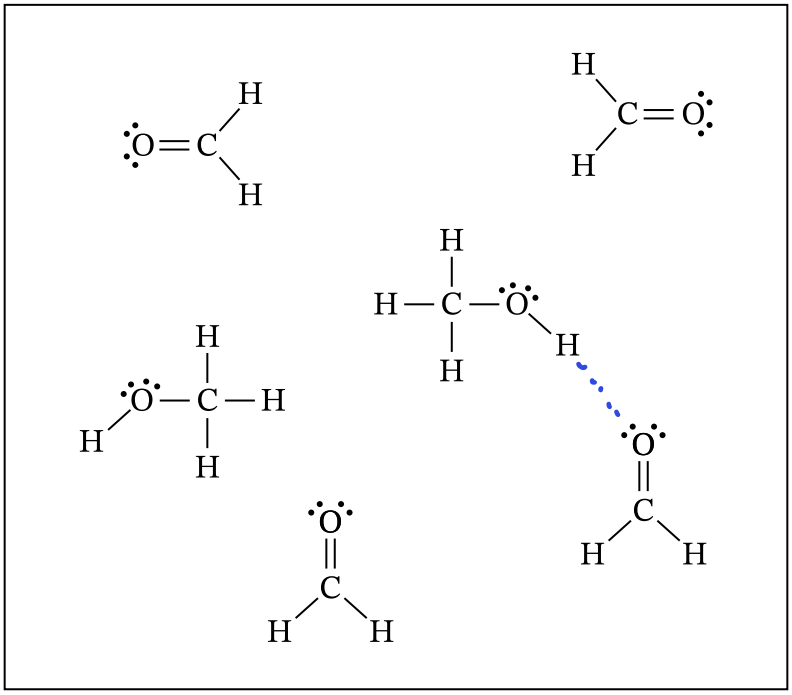
F: i) $P(PCl_5) = 4$ atm, $P(PCl_3) = 2$ atm; $P(Cl_2) = 6$ atm

$K_p = \frac{4}{2 \times 6} = \frac{1}{3} = 0.333$

ii) K_p ↓. The reaction is exothermic, according to Q, higher T shifts the reaction to the left side to reach re-equilibrium, thus, the K_c is getting smaller.

Hybrid, Hydrogen Bond, Phase Change,

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



A. Identify the hybridization of the valence orbitals of the C atom in the H_2CO molecule.

B. In the diagram provided, draw a SINGLE dashed line (----) to represent a strong hydrogen-bonding attraction between one CH_3OH molecule and one H_2CO molecule in the mixture.

C. The scientist plans to cool a gaseous mixture of CH_3OH and H_2CO to form a liquid mixture and finds data on the two compounds. The data are summarized in the table.

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

i. Propose a temperature to which the mixture should be cooled such that CH_3OH and H_2CO will both be liquids.

ii. The scientist analyzes the mixture after it is cooled and determines that 8.59 g of $CH_3OH(l)$ is present. Calculate the amount of thermal energy, in kJ, that was removed to condense the 8.59 g of CH_3OH (molar mass 32.04 g/mol) at its boiling point.

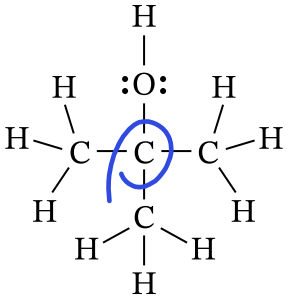
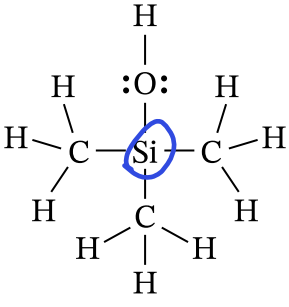
C: i) ~254 K (g)

ii) $E = 8.59 \div 32.04 \times 37.6 = 10.1$ kJ

VSEPR, IMFs and bp/vp, ideal gas law.

5. Complete Lewis diagrams and some physical properties for compounds X and Y are given.

D: $n = \frac{PV}{RT} = \frac{2.30 \times 12.5}{0.0821 \times (273+198)} = 0.7444$ mols

Compound	X	Y
Lewis diagram		
Molar mass	74.1 g/mol	90.2 g/mol
Boiling point	82°C	98°C

A. Based on VSEPR theory, predict the geometry around the Si atom in compound Y.

B. A student claims that compound Y has a higher boiling point than that of compound X because compound Y has stronger London dispersion forces. Do you agree or disagree? Justify your answer.

C. An equimolar mixture of the two compounds is heated. When the mixture reaches 82°C, which compound will have the higher vapor pressure? Justify your answer.

D. The mixture is heated to 198°C in a sealed, rigid 12.5 L container, at which point both substances are gases and the total pressure in the container is 2.30 atm. Calculate the number of moles of gas particles in the container.

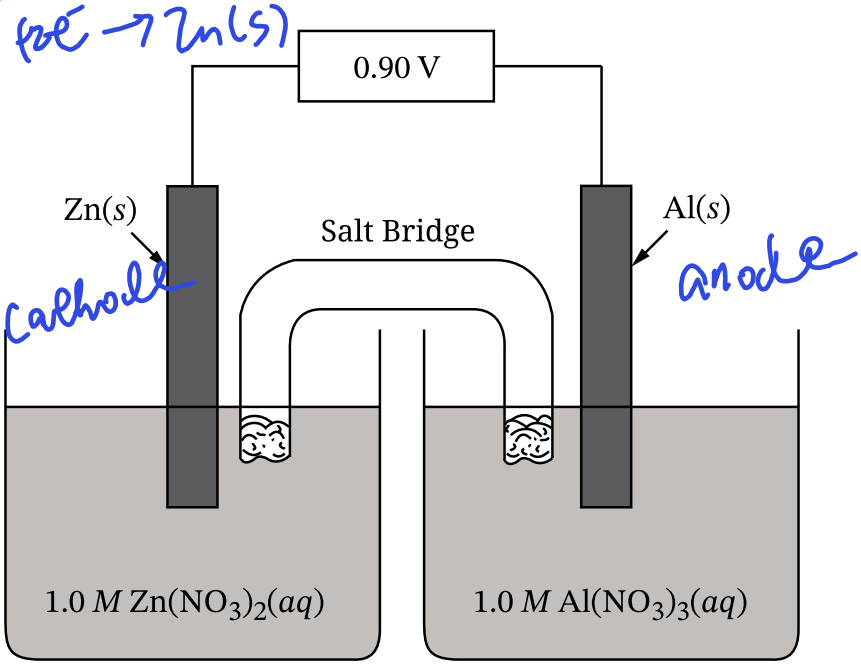
A: Si in Y has a geometry of tetrahedral.

B: Yes, Y has a higher bp than X, and they both have a -OH group with comparable hydrogen bond, so the higher bp of Y is mainly caused by Y's larger LDFs, as larger molar mass molecules generally are more polarizable with a larger LDFs.

C: X. At 82°C, X is at its boiling point, its vapor pressure is 1 atm, while Y's bp is 98°C, much higher than 82°C, so Y's vapor pressure is much smaller than 1 atm.

Fundamental Galvanic cell.

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



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

A. Write the half-reaction for the oxidation that occurs at the anode.

B. Write the balanced net ionic equation for the overall reaction that occurs in the galvanic cell.

C. 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.

A: anode: $Al(s) - 3e^- \rightarrow Al^{3+}(aq)$

B: $2Al(s) + 3Zn^{2+}(aq) \rightarrow 3Zn(s) + 2Al^{3+}(aq)$

C: $\Delta m(Zn) = \frac{n(e^-)}{2} \times 65.4 = 32.7\,n(e^-)$;

$\Delta m(Al) = \frac{n(e^-)}{3} \times 26.98 \approx 13.5\,n(e^-) < \Delta m(Zn)$

Al electrode has a smaller mass change than Zn.

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

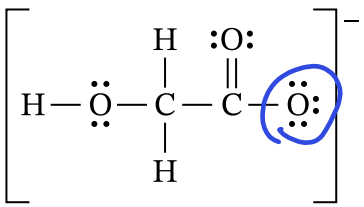
D. The standard Zn/Al cell has a value of E°_{cell} equal to 0.90 V. The scientist needs a galvanic cell that produces a greater voltage. The scientist has access to the chemical systems in the table. If the scientist uses the Zn half-cell and one of the other options from the table, what is the MAXIMUM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

D: $E^\circ_{max} = 1.50 - (-0.76) = 2.26$ V

$3Zn(s) + 2Au^{3+}(aq) \rightarrow 2Au(s) + 3Zn^{2+}(aq)$

A-B calculation, Catalyst.

7. Answer the following questions about the glycolate ion, $C_2H_3O_3^-$, which acts as a base in aqueous solution. A Lewis diagram for the ion is provided.



A. On the Lewis diagram in part A, circle the atom that accepts the proton when the glycolate ion reacts with water.

When the glycolate ion reacts with water, it forms glycolic acid, $HC_2H_3O_3$, according to the following equation. The K_b expression for the reaction is provided.

$$C_2H_3O_3^-(aq) + H_2O(l) \rightleftarrows HC_2H_3O_3(aq) + OH^-(aq) \qquad K_b = \frac{[HC_2H_3O_3][OH^-]}{[C_2H_3O_3^-]}$$

B. At 25°C, a 2.5 M solution of glycolate is found to have $[OH^-] = 1.3 \times 10^{-5}\ M$.

i. Calculate the value of K_b for the glycolate ion.

ii. Using your answer to part B (i), calculate the value of K_a for glycolic acid at 25°C.

Glycolic acid can be produced from the hydrolysis of methyl glycolate, $C_3H_6O_3$. A proposed mechanism for the reaction is given.

Step 1: $C_3H_6O_3 + H_3O^+ \rightleftarrows C_2H_5O_3^+ + CH_3OH$

Step 2: $C_2H_5O_3^+ + H_2O \rightleftarrows HC_2H_3O_3 + H_3O^+$

Overall: $C_3H_6O_3 + H_2O \rightleftarrows HC_2H_3O_3 + CH_3OH$

C. A student claims that H_3O^+ is a catalyst for the reaction. Do you agree or disagree? Justify your answer based on the mechanism given.

B: i) $[OH^-] \approx [HC_2H_3O_3] = 1.3\times10^{-5}\ M$, $[C_2H_3O_3^-] = 2.5 - 1.3\times10^{-5} = 2.5\ M$

$K_b = \frac{(1.3\times10^{-5})^2}{2.5} = 6.8\times10^{-11}$

STOP

END OF EXAM

ii) $K_a = \frac{K_w}{K_b} = \frac{10^{-14}}{6.8\times10^{-11}} = 1.5\times10^{-4}$

C: Agree, H_3O^+ is involved in the initial step, and then reproduced in the second step, which speeds up the overall reaction but doesn't appear in the overall reaction equation, so it is a catalyst!