

CHEMISTRY

SECTION I

Time—1 hour and 30 minutes

60 Questions

Note: For all questions, assume that the temperature is 298 K, the pressure is 1.0 atm, and solutions are aqueous unless otherwise specified.

Directions: Each of the questions or incomplete statements below is followed by four suggested answers or completions. Select the one that is best in each case and then fill in the corresponding circle on the answer sheet.

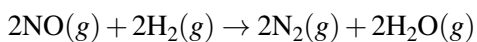
- An atom of chlorine and an atom of which of the following elements will form a bond with the most ionic character?
(A) Germanium
(B) Carbon
(C) Copper
(D) Potassium
- The single-step reaction represented above takes place in a sealed container. Which of the following will reduce the value of k , the rate constant for the reaction?
(A) Decreasing the temperature
(B) Increasing the temperature
(C) Decreasing the size of the sealed container
(D) Increasing the size of the sealed container
- The pH of a solution of 0.009 M KOH(aq) is closest to which of the following?
(A) 2
(B) 5
(C) 9
(D) 12
- Which of the following is the ground-state electron configuration for the Na⁺ ion?
(A) $1s^2 2s^2 2p^5$
(B) $1s^2 2s^2 2p^6$
(C) $1s^2 2s^2 2p^6 3s^1$
(D) $1s^2 2s^2 2p^6 3s^2$
- A 1.5 g sample of ice, H₂O(s), at is placed in a warm room. Which of the following best describes the energy transfer involved in melting the ice to create liquid water at 0.0°C? (The heat of fusion of H₂O(s) is 334 J/g.)
(A) 334 joules of energy is transferred from the ice to the room.
(B) 334 joules of energy is transferred from the room to the ice.
(C) 501 joules of energy is transferred from the ice to the room.
(D) 501 joules of energy is transferred from the room to the ice.
- A student dissolves a quantity of KNO₃(s) in water. What information must the student use to calculate the molarity of the aqueous solution?
(A) Grams of KNO₃ and the density of water
(B) Liters of KNO₃ and liters of solution
(C) Moles of KNO₃ and the density of water
(D) Moles of KNO₃ and liters of solution

7. A student titrates 25 mL of a 0.10 *M* solution of an unknown acid, HX, with a 0.10 *M* solution of sodium hydroxide, NaOH(*aq*), to the equivalence point. Which of the following pieces of experimental evidence would best help the student confirm that HX is a weak acid?
- (A) The initial pH of the acid solution is greater than 1.
(B) The initial pH of the acid solution is less than 1.
(C) Less than 25 mL of NaOH(*aq*) is required to reach the equivalence point.
(D) More than 25 mL of NaOH(*aq*) is required to reach the equivalence point.
8. Which of the following best explains how the bonding in a metal allows it to be ductile (i.e., allows it to be drawn into a wire)?
- (A) Metal atoms are spherical; therefore, the solid metal can be easily drawn into wires that have a round cross-section.
(B) Because of strongly directional bonding in the solid metal, the atoms both in front of and behind a given atom in a wire will bind together more strongly than the atoms not along the direction of the wire.
(C) Because the mobile electrons attract the metal cations equally in all directions, the metal cations can move easily past one another as the metal is drawn into a wire.
(D) Metal atoms tend to be much smaller than nonmetal atoms; therefore, they can move easily past one another as the metal is drawn into a wire.
9. A 100 g sample of a substance decomposes so that 25 g of the original substance remains after 40 seconds. If the decomposition is first order, which of the following is the rate constant, *k*, of the decomposition reaction?
- (A) 0.017 s⁻¹
(B) 0.035 s⁻¹
(C) 1.4 s⁻¹
(D) 20 s⁻¹
10. A student attempts to prepare a buffer solution with a pH of 10.0 by adding NaHCO₃ (*pK_a* = 10.3) and Na₂CO₃ to distilled water. Instead of the desired pH, the measured pH of the buffer solution is 9.5. Which of the following is the most likely reason that the pH is too low?
- (A) Too much NaHCO₃ was used.
(B) Too much Na₂CO₃ was used.
(C) There was water in the flask before NaHCO₃ and Na₂CO₃ were added.
(D) In order to prepare the buffer, a few drops of a strong base should have been added.
11. Which of the following best explains why H₂(*g*) behaves more ideally than most other gases?
- (A) The number of particles in a given volume of H₂(*g*) is smallest in comparison to other gases, because the molar mass of H₂ is smallest.
(B) Collisions between gas particles and the walls of a container are more frequent for smaller molecules, because the average velocity is very high.
(C) The average kinetic energy of H₂ molecules at a given temperature is large, because the average velocity of the H₂ molecules is very high.
(D) Intermolecular attractions between H₂ molecules are weak, because the electron clouds of H₂ molecules are small.
12. Which of the following best accounts for the decrease in the first-ionization energy of the alkaline earth metals going down the group?
- (A) The number of protons in the nucleus increases, resulting in increased attraction between the nucleus and the electron being removed.
(B) The number of protons in the nucleus increases, resulting in a greater effective nuclear charge attracting the electron being removed.
(C) The number of electron shells increases, resulting in a greater average distance between the nucleus and the electron being removed.
(D) The number of electron shells increases, resulting in less shielding between the nucleus and the electron being removed.

Substance	Specific Heat (J/g·°C)
Water	4.18
Ethanol	2.44
Fe(s)	0.449

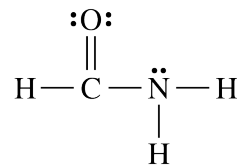
13. Two identical insulated containers hold equal masses of liquid at the same temperature; one contains water and the other contains ethanol. Two identical cubes of Fe(s) are heated to the same temperature, one cube is placed in each container, and both systems are allowed to reach thermal equilibrium. Based on the information in the table shown, which of the following best predicts what will be observed?

- (A) Both systems will have the same final temperature because the mass and initial temperature of the liquids are the same.
- (B) Both systems will have the same final temperature because the Fe(s) cubes will transfer the same amount of heat to both liquids.
- (C) The ethanol system will have the higher final temperature because the specific heat of ethanol is lower than that of water.
- (D) The ethanol system will have the lower final temperature because the specific heat of ethanol is lower than that of water.



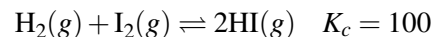
14. The rate law for the reaction shown is $\text{rate} = k[\text{NO}]^2[\text{H}_2]$. What is the overall order of the reaction?

- (A) First order
- (B) Second order
- (C) Third order
- (D) Fourth order



15. The complete Lewis electron-dot diagram for HCONH₂ is shown above. Identify the hybridization of the valence orbitals for the carbon atom and the approximate hydrogen-carbon-nitrogen bond angle according to VSEPR theory.

- (A) sp hybridized and 180°
- (B) sp^2 hybridized and 120°
- (C) sp^2 hybridized and 180°
- (D) sp^3 hybridized and 120°



16. Equimolar amounts of H₂(g) and I₂(g) are pumped into a previously evacuated, rigid 1.0 L container and allowed to attain the equilibrium shown above at a constant temperature. If 0.600 mol of HI(g) is present at equilibrium, how many moles of H₂(g) were initially added to the container?

- (A) 0.0036 mol
- (B) 0.060 mol
- (C) 0.36 mol
- (D) 0.60 mol

	Ionization Energy (kJ/mol)
First	786
Second	1,577
Third	3,232
Fourth	4,356
Fifth	16,091

17. Based on the successive ionization energies of element X shown in the table above, which of the following is most likely the formula of the compound produced when element X reacts with fluorine?

(A) XF
(B) XF₂
(C) XF₄
(D) XF₅

Lewis Dot Diagram	Boiling Point (°C)
H–C≡N:	26
:N≡N:	–196

18. Which of the following best helps to explain why the boiling point of HCN is so much higher than that of N₂, as shown by the data in the table above?

(A) HCN contains three atoms, whereas N₂ contains two atoms.
(B) HCN is polar, whereas N₂ is nonpolar.
(C) HCN has a molar entropy greater than that of N₂.
(D) The C≡N bond is stronger than the N≡N bond.

19. A reaction is known to have a negative value of ΔH° and a positive value of ΔS° . Which of the following statements correctly describes the equilibrium constant, K_{eq} , for this reaction?

(A) K_{eq} will be less than 1 only at high temperatures.
(B) K_{eq} will be less than 1 at all temperatures.
(C) K_{eq} will be greater than 1 only at low temperatures.
(D) K_{eq} will be greater than 1 at all temperatures.

	HX(aq)	HZ(aq)
Conductivity	low	high

20. A student tests the electrical conductivity of 0.10 M solutions of two different monoprotic acids, HX(aq) and HZ(aq). Results from the experiment are shown in the table. Which of the following is a question that could be answered based on the data in the table?

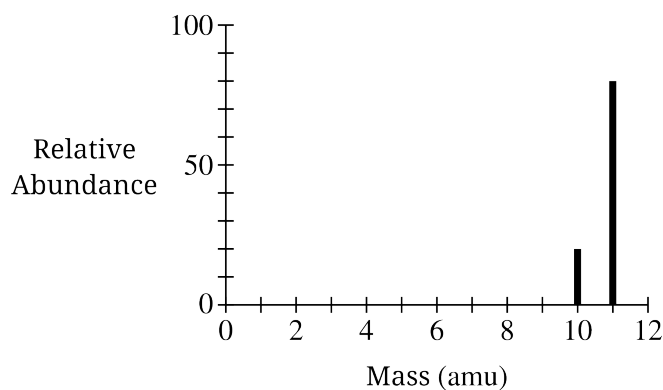
(A) Which acid has the larger K_a value?
(B) Which acid has the larger molar mass?
(C) Which acid solution has the larger density?
(D) Which acid solution has the larger standard molar entropy?

21. A compound made up of only carbon and hydrogen is completely combusted in excess O₂(g). Equimolar quantities of CO₂(g) and H₂O(g) are produced. Which of the following could be the molecular formula of the compound?

(A) CH₄
(B) C₂H₂
(C) C₂H₄
(D) C₂H₆

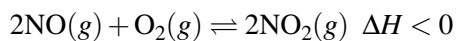
22. Which of the following processes will most likely have a negative $\Delta S^\circ_{\text{rxn}}$?

(A) $3\text{H}_2(\text{g}) + \text{N}_2(\text{g}) \rightarrow 2\text{NH}_3(\text{g})$
(B) $\text{H}_2(\text{g}) + \text{Cl}_2(\text{g}) \rightarrow 2\text{HCl}(\text{g})$
(C) $\text{H}_2\text{O}(\text{s}) \rightarrow \text{H}_2\text{O}(\text{l})$
(D) $2\text{O}_3(\text{g}) \rightarrow 3\text{O}_2(\text{g})$



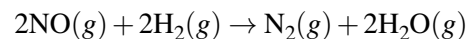
23. Based on the mass spectrum of a sample of boron shown above, how many neutrons are in the most common isotope of boron?

(A) 5
(B) 6
(C) 10
(D) 11



24. Which of the following changes will increase the amount of $\text{NO}_2(g)$ in the reaction system at equilibrium represented above?

(A) Adding a catalyst to the reaction system
(B) Increasing the pressure by adding $\text{Ne}(g)$ to the system at constant temperature
(C) Increasing the temperature at constant volume
(D) Decreasing the volume at constant temperature

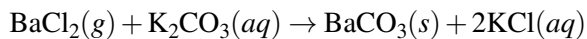


25. The rate law for the reaction represented is $\text{rate} = k[\text{NO}_2]^2[\text{H}_2]$. What happens to the rate of the reaction when the concentration of $\text{NO}(g)$ is doubled and the concentration of $\text{H}_2(g)$ is halved?

(A) The rate is halved.
(B) The rate is the same.
(C) The rate is doubled.
(D) The rate is quadrupled.

Questions 26-28

Students are asked to design an experiment to determine the molarity of a $\text{BaCl}_2(aq)$ solution. After examining the K_{sp} values of some barium-containing compounds, the students decide to use $0.100\text{ M K}_2\text{CO}_3(aq)$ to precipitate the barium ions. An excess of $\text{K}_2\text{CO}_3(aq)$ is added to a 50.0 mL sample of the $\text{BaCl}_2(aq)$ solution, and the reaction represented by the following equation occurs.



The $\text{BaCO}_3(s)$ is filtered, dried, and weighed. The data are recorded in the following table.

Volume of $\text{BaCl}_2(aq)$	Volume of $0.100\text{ M K}_2\text{CO}_3(aq)$	Mass of $\text{BaCO}_3(s)$
50.0 mL	150.0 mL	1.97 g

The molar masses of BaCl_2 and BaCO_3 are 208 g/mol and 197 g/mol , respectively.

26. Of the following species, which is present in the highest concentration in the filtrate?

(A) $\text{H}^+(aq)$
 (B) $\text{K}^+(aq)$
 (C) $\text{Cl}^-(aq)$
 (D) $\text{CO}_3^{2-}(aq)$

Substance	K_{sp}
$\text{Ba}(\text{NO}_3)_2$	3.33×10^{-1}
BaF_2	1.84×10^{-7}
BaSO_4	1.08×10^{-10}
BaCrO_4	1.17×10^{-10}

27. On the basis of the experimental data, what was $[\text{Ba}^{2+}]$ in the original 50.0 mL sample of the solution?

(A) 0.05 M
 (B) 0.10 M
 (C) 0.20 M
 (D) 0.40 M

28. Considering the K_{sp} values listed above, which of the following solutions, when used instead of $\text{K}_2\text{CO}_3(aq)$ in the precipitation procedure, would produce the least number of moles of precipitate?

(A) $0.200\text{ M NaNO}_3(aq)$
 (B) $0.200\text{ M NaF}(aq)$
 (C) $0.200\text{ M Na}_2\text{SO}_4(aq)$
 (D) $0.200\text{ M Na}_2\text{CrO}_4(aq)$

Questions 29-31

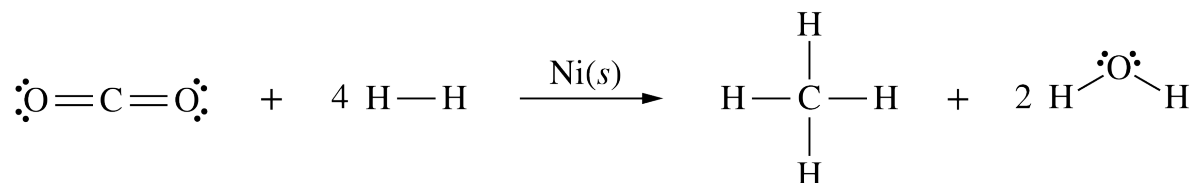
Three equimolar gas samples are at the conditions given in the following table. Assume that the gases behave ideally.

Gas	Volume (L)	Pressure (atm)	Temperature (K)
F ₂	10.0	2.0	200.0
N ₂	5.0	4.0	200.0
O ₂	4.0	5.0	200.0

29. Which gas, if any, has the greatest density?
- (A) F₂
(B) N₂
(C) O₂
(D) All three samples have the same density.
30. Which gas, if any, has molecules with the greatest average kinetic energy?
- (A) F₂
(B) N₂
(C) O₂
(D) The molecules in all three samples have the same average kinetic energy.
31. The number of moles of N₂(g) is closest to which of the following?
- (A) 0.10 mol
(B) 1.2 mol
(C) 22 mol
(D) 28 mol

Questions 32-36

In the gas-phase reaction represented by the following equation, methane (CH_4) and water (H_2O) are produced from carbon dioxide (CO_2) and hydrogen (H_2) at high temperature and pressure.



32. Which of the following is a correct statement about oxidation and reduction during the reaction?
- (A) Hydrogen is oxidized, and carbon is reduced.
 - (B) Carbon is oxidized, and oxygen is reduced.
 - (C) Oxygen is oxidized, and hydrogen is reduced.
 - (D) It is not an oxidation-reduction reaction.
33. The reaction is catalyzed by solid nickel. Which of the following describes the effect of the catalyst on the reaction?
- (A) The presence of the catalyst results in an overall reaction that releases less energy.
 - (B) The presence of the catalyst results in a reaction pathway that requires a lower activation energy.
 - (C) The presence of the catalyst results in an overall reaction that requires more energy.
 - (D) The presence of the catalyst results in a reaction pathway that requires a greater activation energy.

34. Based on the Lewis diagrams, which of the products is more soluble in ethanol ($\text{C}_2\text{H}_5\text{OH}$)?

- (A) Methane, because it has more hydrogen atoms than water does, so it can form more hydrogen bonds with ethanol.
- (B) Methane, because it is a larger molecule than water, so its electron cloud is more polarizable.
- (C) Water, because water has a greater molar mass than methane does.
- (D) Water, because water molecules can form hydrogen bonds with ethanol molecules, but methane molecules cannot.

35. Which of the following identifies the hybridization of the valence orbitals of the central atoms of the methane and water molecules?

CH_4 H_2O

- (A) sp^2 sp
- (B) sp^2 sp^2
- (C) sp^3 sp^2
- (D) sp^3 sp^3

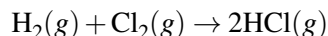
Substance	Standard Heat of Formation (kJ/mol)
$\text{CO}_2(g)$	-394
$\text{CH}_4(g)$	-75
$\text{H}_2(g)$	0
$\text{H}_2\text{O}(g)$	-242

36. Based on the information given, ΔH_{rxn} is closest to which of the following?

- (A) $-165 \text{ kJ/mol}_{\text{rxn}}$
- (B) $-77 \text{ kJ/mol}_{\text{rxn}}$
- (C) $+77 \text{ kJ/mol}_{\text{rxn}}$
- (D) $+165 \text{ kJ/mol}_{\text{rxn}}$

Questions 37-40

Gaseous hydrogen and gaseous chlorine can react to form hydrogen chloride gas, as represented by the following equation.



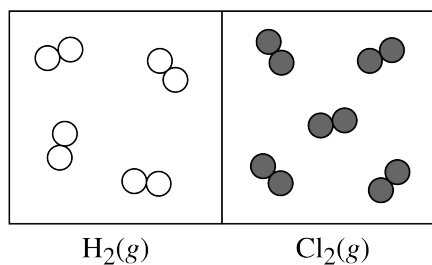
37. Equimolar amounts of H_2 and Cl_2 are placed in an evacuated reaction vessel at 500 K. Which of the following statements correctly predicts how the pressure will be affected as the reaction proceeds at a constant temperature and explains why?

- (A) The pressure will remain constant because the number of gas particles is constant.
- (B) The pressure will be halved because one substance is produced from two substances.
- (C) The pressure will increase because the coefficient of HCl in the balanced chemical equation is greater than that of the reactants.
- (D) The pressure will decrease because the average speed of the gaseous product molecules is less than the average speed of the gaseous reactant molecules.

Bond	Bond Energy (kJ/mol)
H—H	432
Cl—Cl	239
H—Cl	427

38. Based on the table of bond energies shown, the value of ΔH for the reaction $\text{H}_2 + \text{Cl}_2 \rightarrow 2\text{HCl}$ is closest to which of the following?

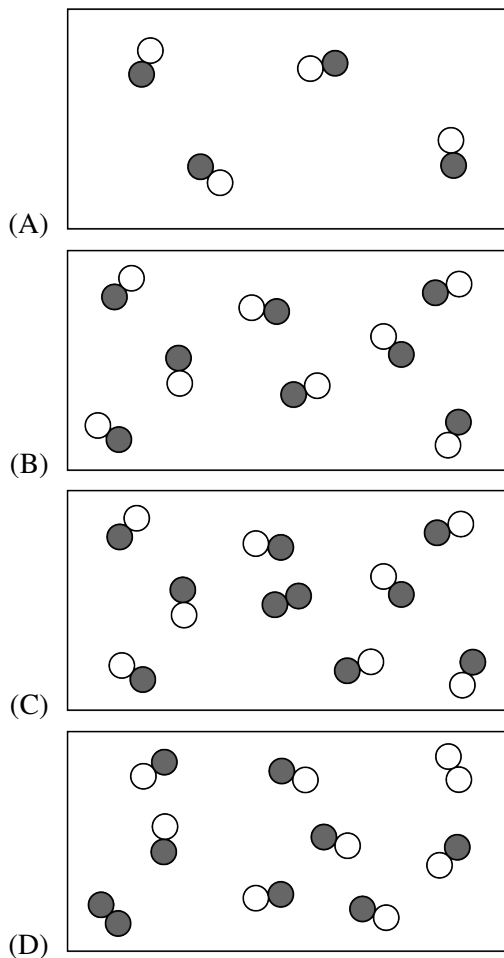
- (A) $-244 \text{ kJ/mol}_{\text{rxn}}$
- (B) $-183 \text{ kJ/mol}_{\text{rxn}}$
- (C) $+183 \text{ kJ/mol}_{\text{rxn}}$
- (D) $+244 \text{ kJ/mol}_{\text{rxn}}$

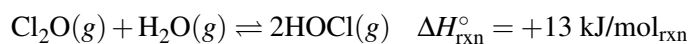


40. Which of the following correctly ranks the internuclear distances for the H_2 , Cl_2 , and HCl molecules from shortest to longest?

- (A) $\text{H}_2 < \text{Cl}_2 < \text{HCl}$
- (B) $\text{H}_2 < \text{HCl} < \text{Cl}_2$
- (C) $\text{Cl}_2 < \text{HCl} < \text{H}_2$
- (D) $\text{Cl}_2 < \text{H}_2 < \text{HCl}$

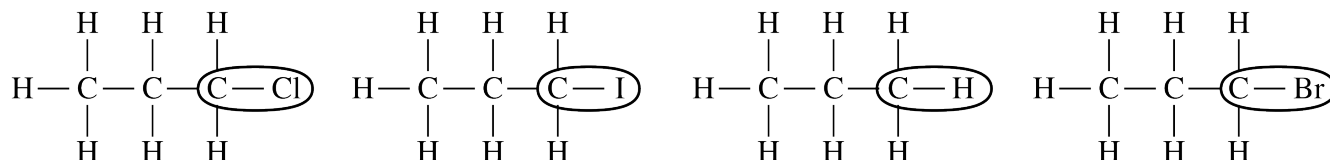
39. The diagrams show particulate representations for samples of gaseous H_2 and Cl_2 separated by a barrier. After the barrier is removed, the gases react. Which of the following diagrams best represents the mixture if the reaction goes to completion?





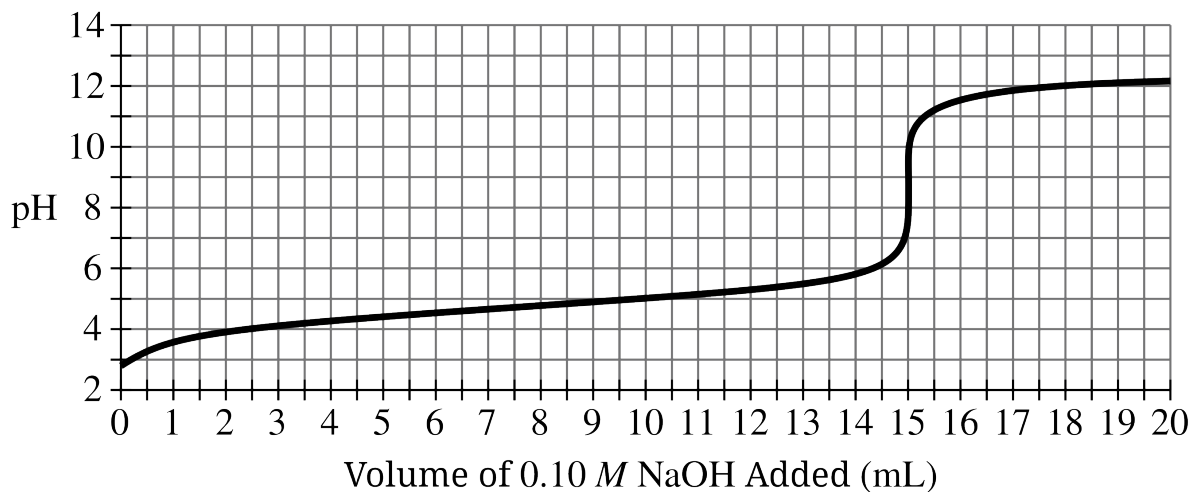
41. A chemical system at equilibrium is represented above. Which of the following changes will increase the number of moles of $\text{HOCl}(g)$ present in the system?

- (A) Increasing the temperature
- (B) Decreasing the volume of the reaction vessel
- (C) Adding a catalyst
- (D) Removing $\text{Cl}_2\text{O}(g)$



42. Which of the following bonds represented in the diagram above is the most polar?

- (A) C–Cl
- (B) C–I
- (C) C–H
- (D) C–Br



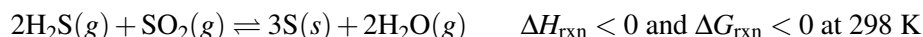
43. A sample of an acid is titrated with 0.10 M NaOH , and the results are shown in the graph. Based on the pH range of the color change given for each indicator, which of the following indicators would be the best choice for the titration?

- (A) Thymol blue; 1.2 – 2.8
- (B) Congo red; 3.0 – 5.0
- (C) Phenol red; 6.8 – 8.2
- (D) Indigo carmine; 11.6 – 14.0

Half-Reaction	E° (V)
$\text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s)$	0.80
$\text{Ni}^{2+}(aq) + 2e^- \rightarrow \text{Ni}(s)$	-0.25

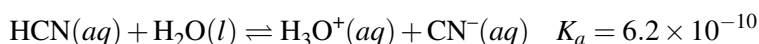
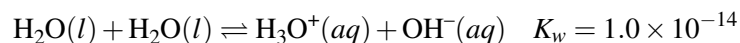
44. The standard reduction potentials of the half-reactions associated with a galvanic cell are listed in the table above. Which of the following statements identifies the electrode that increases in mass as the cell operates, and correctly explains why?

(A) The Ag electrode, because $\text{Ag}^+(aq)$ in the solution is reduced to form $\text{Ag}(s)$.
 (B) The Ag electrode, because Ag has a greater molar mass than Ni has.
 (C) The Ni electrode, because Ni is chemically more reactive than Ag is.
 (D) The Ni electrode, because $\text{Ni}^{2+}(aq)$ is reduced at a faster rate than $\text{Ag}^+(aq)$ is.



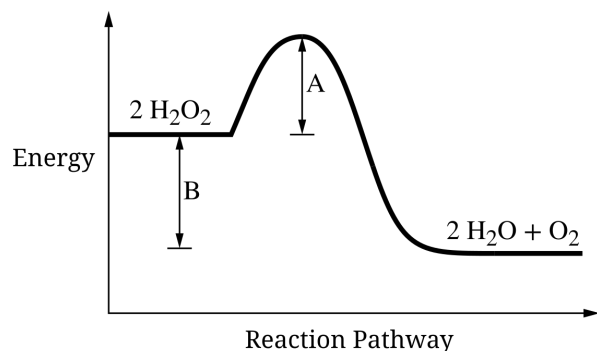
45. A 0.20 mol sample of $\text{H}_2\text{S}(g)$ and a 0.10 mol sample of $\text{SO}_2(g)$ are placed in a previously evacuated 10.0 L vessel at 298 K. Even though the reaction represented by the equation above is thermodynamically favorable, the formation of $\text{S}(s)$ was not observed. Which of the following best explains why $\text{S}(s)$ is not produced at 298 K?

(A) At 298 K, some $\text{S}(s)$ must first be present for the reaction to occur.
 (B) At 298 K, the value of the equilibrium constant is less than 1.
 (C) At 298 K, the energy of most molecular collisions is lower than the activation energy for the reaction.
 (D) At 298 K, the loss of entropy is too great to make molecular collisions likely to occur.



46. Based on the chemical equations given, which of the following statements is correct?

(A) HCN is a weaker acid than H_2O .
 (B) CN^- is a stronger acid than HCN .
 (C) CN^- is a stronger base than H_2O .
 (D) H_2O is a weaker base than HCN .



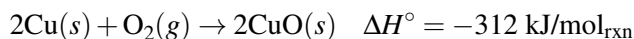
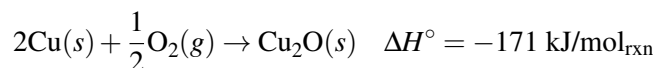
47. The potential energy diagram for the uncatalyzed decomposition of $\text{H}_2\text{O}_2(l)$ is shown above. The arrows labeled A and B represent different amounts of energy. When $\text{I}^-(aq)$ is used as a catalyst, how do the magnitudes of A and B in the new reaction energy diagram compare to the uncatalyzed diagram shown above?

	<u>Energy A</u>	<u>Energy B</u>
--	-----------------	-----------------

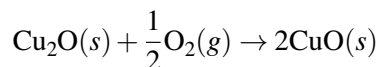
- | | | |
|-----|-----------|-----------|
| (A) | Larger | Larger |
| (B) | Smaller | Smaller |
| (C) | Smaller | Unchanged |
| (D) | Unchanged | Smaller |
48. Based on the information in the table, which of the following substances produces the most energy per gram of substance combusted?

Substance	Molar Mass (g/mol)	Heat Released from Combustion of One Mole of Substance (kJ)
$\text{H}_2(l)$	2	290
$\text{CH}_4(l)$	16	900
$\text{C}_2\text{H}_5\text{OH}(l)$	46	1,400
$\text{C}_{18}\text{H}_{38}(l)$	254	12,000

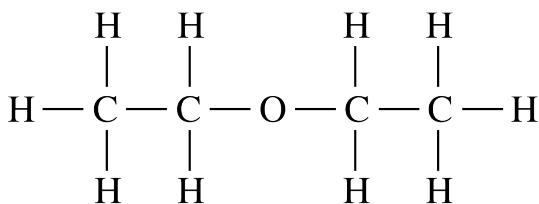
- (A) $\text{H}_2(l)$
 (B) $\text{CH}_4(l)$
 (C) $\text{C}_2\text{H}_5\text{OH}(l)$
 (D) $\text{C}_{18}\text{H}_{38}(l)$



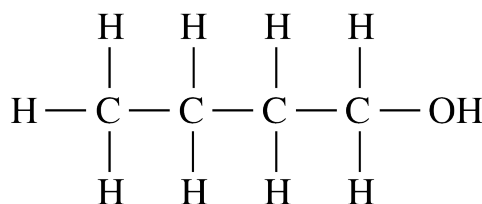
49. Based on the information above, what is the value of ΔH° for the following reaction?



- (A) $-483 \text{ kJ/mol}_{\text{rxn}}$
- (B) $-141 \text{ kJ/mol}_{\text{rxn}}$
- (C) $+141 \text{ kJ/mol}_{\text{rxn}}$
- (D) $+483 \text{ kJ/mol}_{\text{rxn}}$



Compound 1

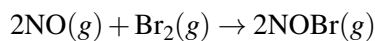


Compound 2

50. The structural formulas of two compounds that are liquids at room temperature are shown above. Which of the following statements best explains the observation that compound 1 boils at 35°C , whereas its structural isomer, compound 2, boils at 118°C ?
- (A) Molecules of compound 1 have a linear shape and no net dipole, whereas molecules of compound 2 have a bent shape and are polar.
 - (B) Molecules of compound 1 are bent less than molecules of compound 2; thus they have weaker dipole-dipole attractions.
 - (C) There are dipole-dipole attractions among molecules of compound 1, whereas there are only dispersion forces among molecules of compound 2.
 - (D) Although there are dipole-dipole attractions among molecules of both compound 1 and compound 2, the $-\text{OH}$ group in compound 2 allows strong hydrogen bonding to occur.

51. Which of the following is the best method for preparing 100.0 mL of 0.100 *M* KCl(*aq*)?

- (A) Place 74.6 g of KCl(*s*) in a 100 mL graduated cylinder and fill to the 100.0 mL mark with water.
- (B) Place 7.46 g of KCl(*s*) in a 100 mL Erlenmeyer flask, add 92.54 g of water, and invert several times.
- (C) Place 7.46 g of KCl(*s*) in a 100 mL volumetric flask, partially fill with water, swirl flask to dissolve solid, fill to the 100.0 mL mark with water, and invert several times.
- (D) Place 7.46 g of KCl(*s*) in a 100 mL volumetric flask, partially fill with water, swirl flask to dissolve solid, add 92.54 mL of water, and invert several times.

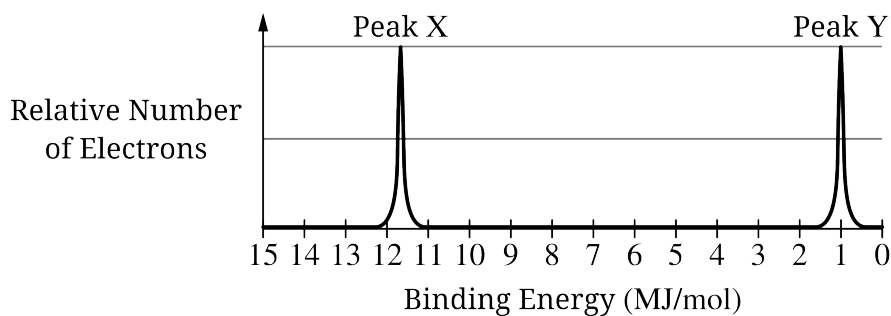


52. The two mechanisms in the table below have been proposed for the reaction represented above.

Mechanism 1	Mechanism 2
Step 1: $\text{NO}(g) + \text{NO}(g) \rightarrow \text{N}_2\text{O}_2(g)$ slow	Step 1: $\text{NO}(g) + \text{Br}_2(g) \rightarrow \text{NOBr}(g)$ slow
Step 2: $\text{N}_2\text{O}_2(g) + \text{Br}_2(g) \rightarrow \text{NOBr}_2(g)$ fast	Step 2: $\text{NOBr}_2(g) + \text{NO}(g) \rightarrow 2\text{NOBr}(g)$ fast

Which of the following observations would support mechanism 1 but not mechanism 2?

- (A) The reaction rate is independent of $[\text{NO}]$.
- (B) The reaction rate is independent of $[\text{Br}_2]$.
- (C) The reaction is exothermic.
- (D) The reaction is second order overall.

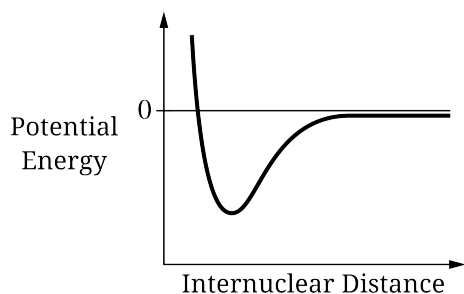


53. The complete photoelectron spectrum of a pure element is represented above. Which of the following correctly identifies both the element and the atomic orbitals represented by peak X and peak Y?

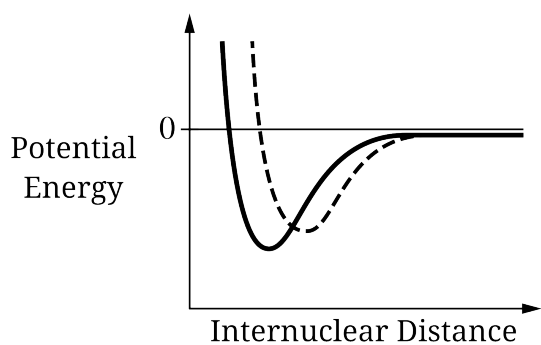
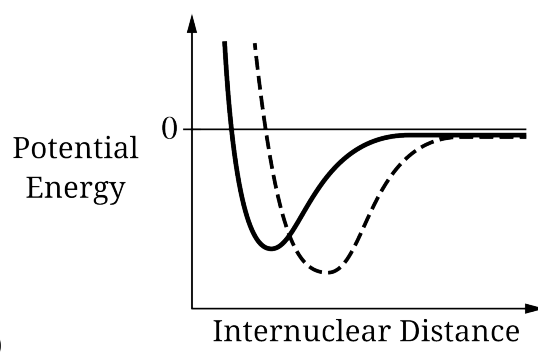
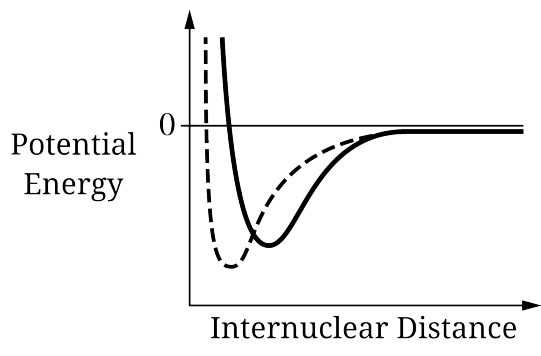
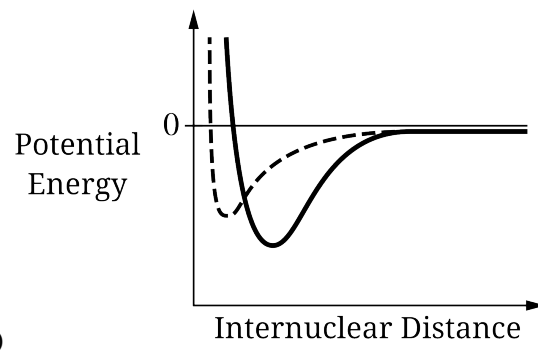
	Element	Peak X	Peak Y
(A)	Li	1s	2s
(B)	Li	2s	1s
(C)	Be	1s	2s
(D)	Be	2s	1s

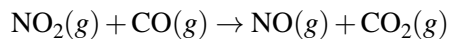
Acid	pK_a
$\text{HClO}_2(aq)$	1.92
$\text{HNO}_2(aq)$	3.25
$\text{HC}_3\text{H}_5\text{O}_2(aq)$	4.88
$\text{HOCl}(aq)$	7.42

54. Based on the information in the table, which of the following mixtures forms a buffer with a pH closest to 3?
- (A) 50.0 mL of 0.10 M $\text{HClO}_2(aq)$ and 25.0 mL of 0.10 M $\text{NaOH}(aq)$
- (B) 50.0 mL of 0.20 M $\text{HNO}_2(aq)$ and 50.0 mL of 0.10 M $\text{NaOH}(aq)$
- (C) 50.0 mL of 0.10 M $\text{HC}_3\text{H}_5\text{O}_2(aq)$ and 50.0 mL of 0.050 M $\text{NaOH}(aq)$
- (D) 50.0 mL of 0.10 M $\text{HOCl}(aq)$ and 25.0 mL of 0.10 M $\text{NaOH}(aq)$

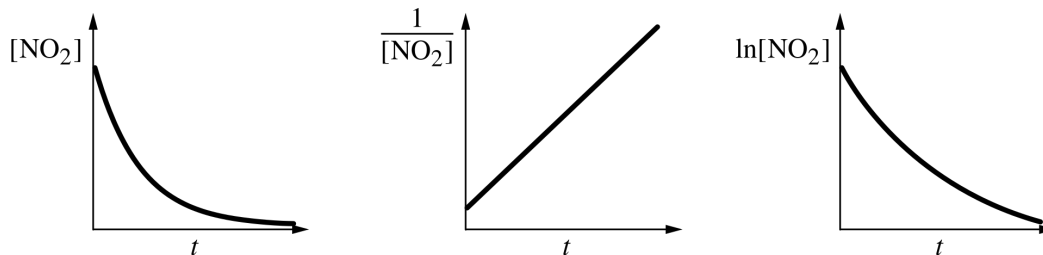


55. The graph of potential energy versus internuclear distance for the HCl molecule is shown. Which of the following graphs includes the plot for the HBr molecule, shown as a dashed line?





56. A group of students studied the rate of the reaction represented above at a fixed temperature. During the reaction, the concentration of CO was in large excess. The graphs shown below were created using the data collected by the students. Based on the graphs, which of the following is the rate law?

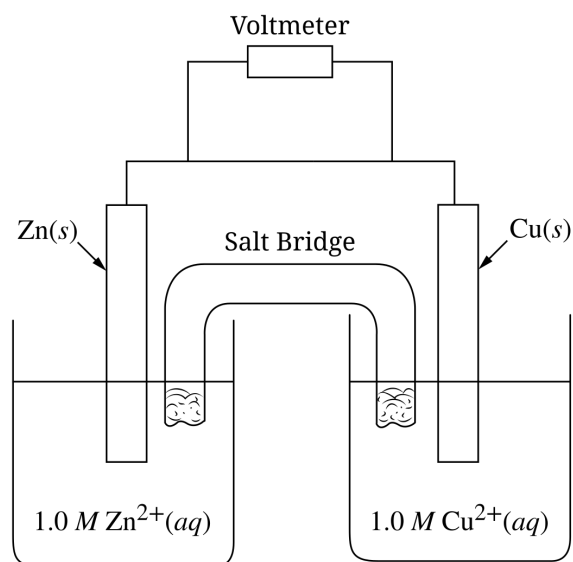


- (A) $\text{Rate} = k$
(B) $\text{Rate} = [\text{NO}_2]$
(C) $\text{Rate} = k[\text{NO}_2]$
(D) $\text{Rate} = k[\text{NO}_2]^2$



57. Equal volumes of 0.1 M solutions of $\text{Fe}^{3+}(aq)$ and $\text{SCN}^{-}(aq)$ are mixed and allowed to attain the equilibrium represented above at a temperature of 25°C . Which of the following statements is correct about the system at equilibrium?

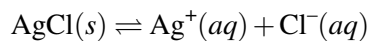
- (A) $[\text{SCN}^{-}] > [\text{FeSCN}^{2+}]$
(B) $[\text{SCN}^{-}] < [\text{FeSCN}^{2+}]$
(C) $[\text{Fe}^{3+}] > [\text{FeSCN}^{2+}]$
(D) $[\text{Fe}^{3+}] = [\text{FeSCN}^{2+}]$



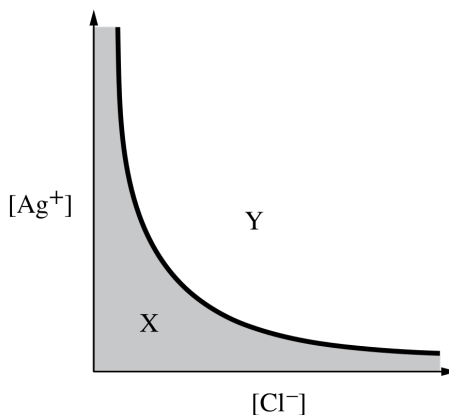
Half-Reaction	E° (V)
$\text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s)$	0.80
$\text{Cu}^{2+}(aq) + 2e^- \rightarrow \text{Cu}(s)$	0.34
$\text{Zn}^{2+}(aq) + 2e^- \rightarrow \text{Zn}(s)$	-0.76

58. A student sets up a standard galvanic cell, as shown in the diagram, and measures a voltage of 1.10 V. Based on the standard reduction potentials in the table, which of the following will occur if the student makes a new standard cell but uses a silver wire in place of the salt bridge?

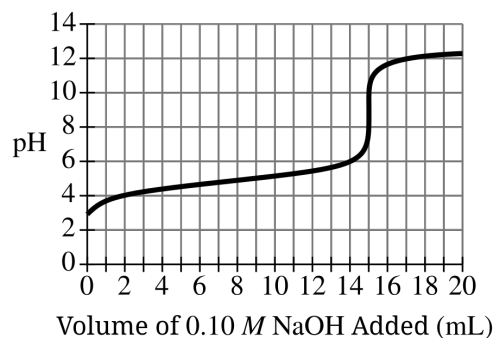
- (A) The voltage will be greater than 1.10 V.
- (B) The voltage will be 0.
- (C) The silver wire will become thinner.
- (D) $\text{Zn}(s)$ and $\text{Cu}(s)$ will form on the silver wire.



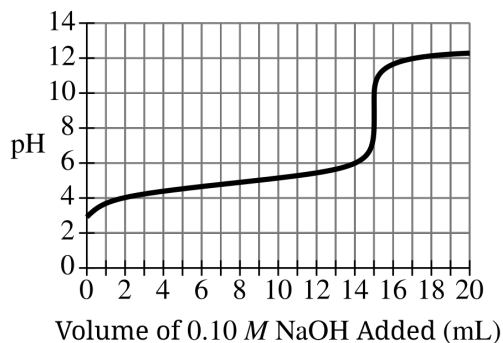
59. The preceding equation represents the equilibrium of a saturated solution of $\text{AgCl}(aq)$ in contact with $\text{AgCl}(s)$. All points on the curve in the following graph represent values of $[\text{Ag}^+]$ and $[\text{Cl}^-]$ for which the product $[\text{Ag}^+][\text{Cl}^-]$ is equal to the value of K_{sp} for AgCl . Which of the following provides the correct comparison of Q and K_{sp} describes the net process that occurs at any point in region Y (unshaded) of the graph?



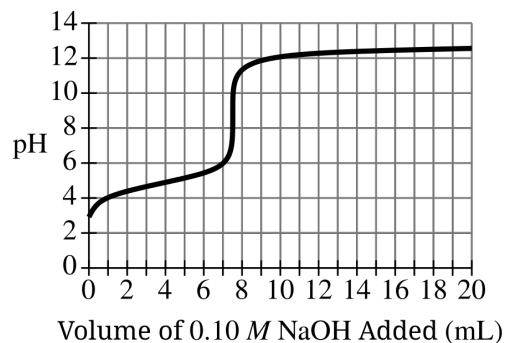
- (A) $Q > K_{sp}$ and dissolution of $\text{AgCl}(s)$ occurs.
(B) $Q < K_{sp}$ and dissolution of $\text{AgCl}(s)$ occurs.
(C) $Q > K_{sp}$ and precipitation of $\text{AgCl}(s)$ occurs.
(D) $Q < K_{sp}$ and precipitation of $\text{AgCl}(s)$ occurs.



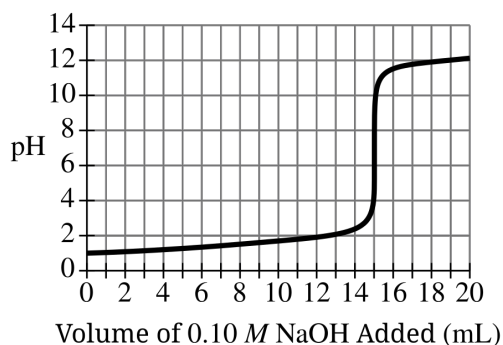
60. A 15.0 mL sample of 0.10 M $\text{HC}_2\text{H}_3\text{O}_2$ is titrated with 0.10 M NaOH, and the data are shown in the graph above. Which of the following graphs shows the change in pH when a 15.0 mL sample of 0.10 M HCl is titrated with 0.10 M NaOH?



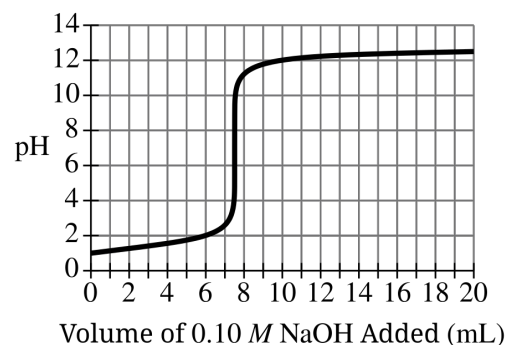
(A)



(B)



(C)



(D)

STOP
END OF SECTION I

CHEMISTRY

SECTION II

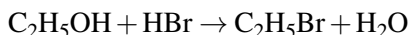
Time—1 hour and 45 minutes

7 Questions

Note: 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.

Directions: 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. Ethanol ($\text{C}_2\text{H}_5\text{OH}$) reacts with hydrobromic acid (HBr) to produce ethyl bromide ($\text{C}_2\text{H}_5\text{Br}$) and water according to the following balanced equation.



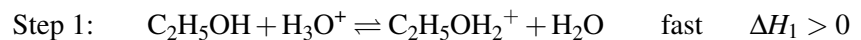
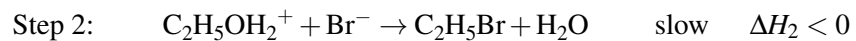
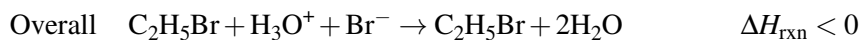
- (a) At the conclusion of the reaction, the product mixture includes $\text{C}_2\text{H}_5\text{Br}$, H_2O , and excess unreacted $\text{C}_2\text{H}_5\text{OH}$.
- Identify all of the types of intermolecular forces that can exist between one molecule of $\text{C}_2\text{H}_5\text{OH}$ and one molecule of $\text{C}_2\text{H}_5\text{Br}$ in the product mixture.
 - The aqueous solubility of $\text{C}_2\text{H}_5\text{OH}$ is greater than that of $\text{C}_2\text{H}_5\text{Br}$. Explain this observation based on the types and relative strengths of intermolecular forces between each solute and H_2O .

The reaction is found to be first order with respect to HBr when $\text{C}_2\text{H}_5\text{OH}$ is in excess. The following data were recorded showing how the concentration of HBr changes over time.

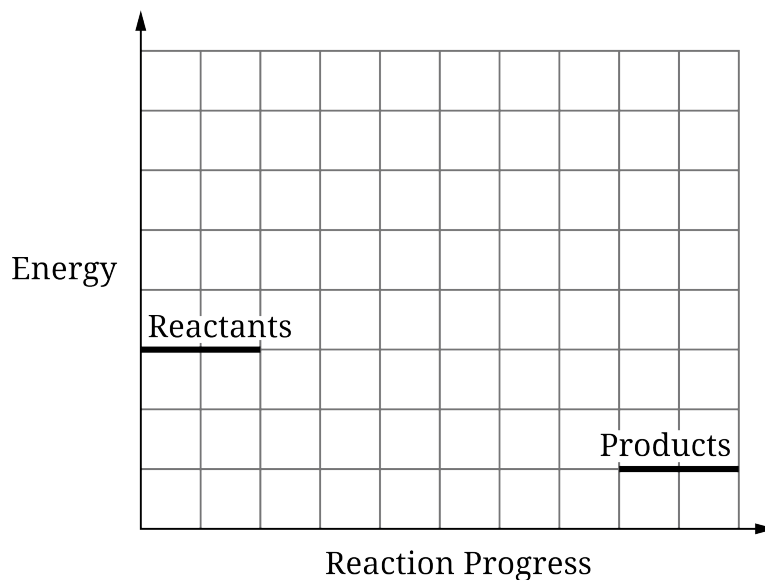
Time (min)	0	50.0	100.0	150.0	200.0
$[\text{HBr}]$ (M)	2.00	1.80	1.62	1.46	1.32

- (b) Using the data provided, calculate the value of the rate constant, k , in min^{-1} .
- (c) Using the data provided, determine the half-life of the reaction, in minutes.
- (d) The experiment is repeated at a higher temperature.
- Explain the effect, if any, that the higher temperature has on collisions between reactant particles.
 - Identify the effect, if any, that the higher temperature has on the rate constant. Explain your reasoning.

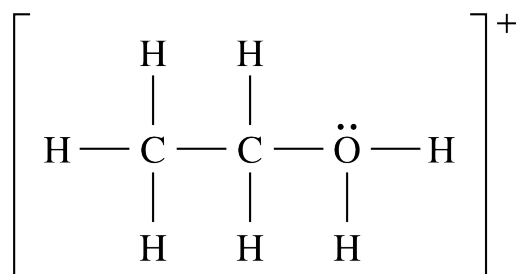
(e) The following reaction mechanism has been proposed for the reaction of $\text{C}_2\text{H}_5\text{OH}$ and HBr .



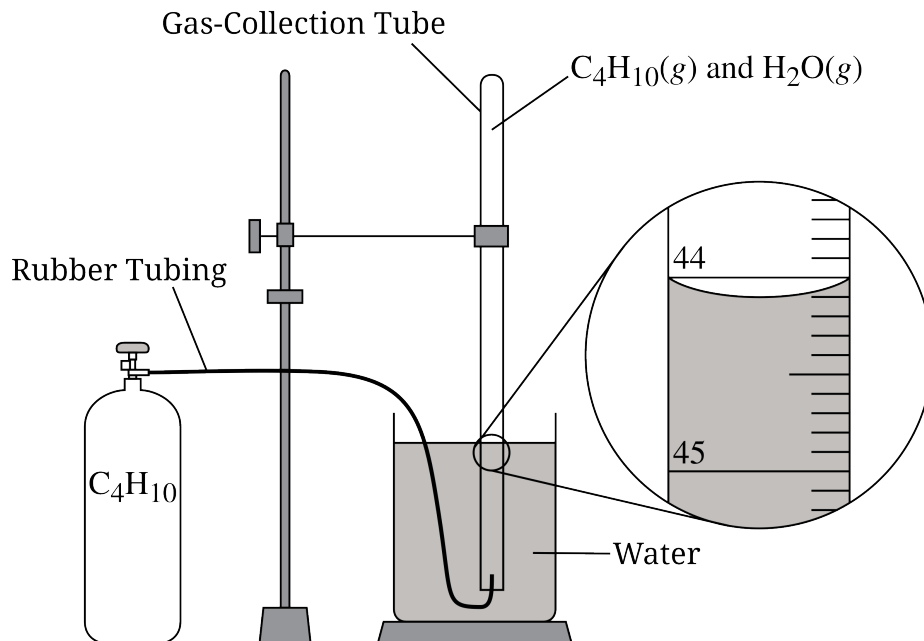
i. Sketch an energy diagram that represents this reaction mechanism on the axes given.



- ii. In step 2 of the mechanism, only the $\text{C}-\text{O}$ bond is broken and the $\text{C}-\text{Br}$ bond is formed. Given that $\Delta H_2 < 0$, a student claims that more energy is needed to break the $\text{C}-\text{O}$ bond than $\text{C}-\text{Br}$ is released when the bond forms. Do you agree or disagree? Justify your answer.
- iii. The following Lewis diagram is for the reaction intermediate, $\text{C}_2\text{H}_5\text{OH}_2^+$. On the Lewis diagram, circle an atom that has a formal charge of +1.



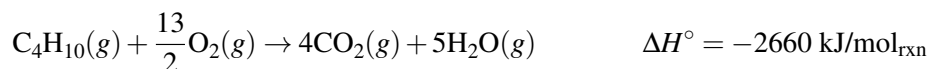
2. A student performs an experiment to determine the molar mass of butane, C_4H_{10} .



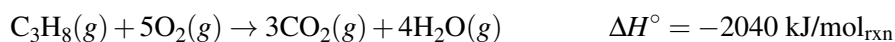
Initial mass of C_4H_{10} container	25.012 g
Final mass of C_4H_{10} container	24.911 g
Initial volume of gas	0.00 mL
Final volume of gas	?
Atmospheric pressure	0.970 atm
Temperature	21.0 °C

- (a) To determine the molar mass, the student collects a sample of butane gas over water in a 50.0 mL gas-collection tube, as shown in the following diagram. The student then adjusts the position of the tube so the water level is the same inside and outside the tube. A partial data table for the experiment is also shown.
- What should the student record for the volume of the gas collected, in mL?
 - Given that the vapor pressure of water at 25 °C is 0.0246 atm, calculate the partial pressure, in atmospheres, of butane collected. Assume that the total pressure in the gas-collection tube is equal to the atmospheric pressure in the laboratory.
 - Calculate the number of moles of butane gas in the gas-collection tube.
- (b) The student then incorrectly determines the molar mass of butane by dividing the initial mass of the container with butane (25.012 g) by the number of moles of butane calculated in part (a)(iii). Assuming that the number of moles calculated in part (a)(iii) is accurate, describe how to correct the student's calculation.

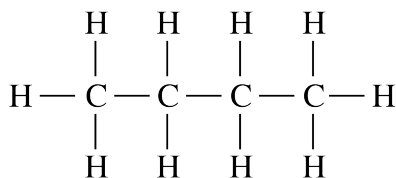
Butane undergoes combustion according to the following balanced equation.



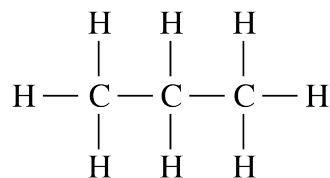
- (c) Which species undergoes reduction in the combustion reaction? Justify your answer with oxidation numbers.
- (d) Determine the sign of the entropy change for the reaction. Use particle reasoning to justify your answer.
- (e) A student combusts 9.29×10^{-4} mol of butane as shown in the preceding equation in a calorimeter containing 100.0 g of water.
- Calculate the heat, in J, released during the combustion of butane.
 - Calculate the temperature change of the water in the calorimeter. (Assume that the calorimeter is perfectly insulated and all the heat released by the combustion of butane is transferred to the 100.0 g sample of water.) The specific heat capacity of water is $4.18 \text{ J/(g}\cdot^\circ\text{C)}$.



- (f) Predict whether the change in temperature observed during the combustion would be greater than, less than, or equal to the change in part (e)(ii). Justify your answer.



Butane

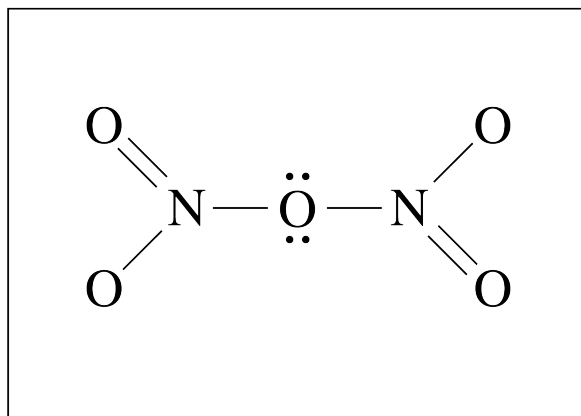


Propane

- (g) The Lewis diagrams for butane and propane are shown above. Both compounds exhibit London dispersion attractive forces. Explain why the London dispersion forces between molecules of butane are stronger than those between molecules of propane.

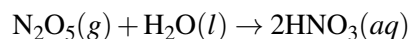
3. Answer the following questions related to N_2O_5 and H_2NO_3 .

(a) An incomplete Lewis diagram for N_2O_5 is shown. Draw all of the remaining nonbonding electrons on the diagram.



(b) Based on VSEPR theory and the molecular geometry around the central O atom, what is the predicted N—O—N bond angle?

When $\text{N}_2\text{O}_5(g)$ is added to water, $\text{HNO}_3(aq)$ is formed according to the following equation.

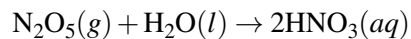


Thermodynamic data for the reaction at 298 K are given in the following table.

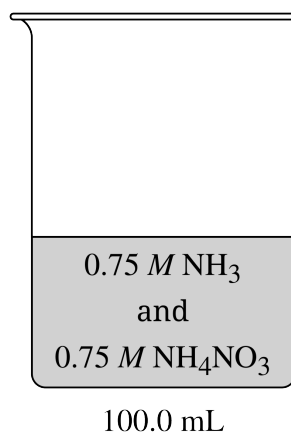
ΔH°	$-140 \text{ kJ/mol}_{\text{rxn}}$
ΔS°	$-124 \text{ J/(K}\cdot\text{mol}_{\text{rxn}})$

(c) Calculate the value of ΔG° , in $\text{kJ/mol}_{\text{rxn}}$, at 298 K.

(d) A student claims that lowering the temperature makes the value of ΔG° more negative. Do you agree or disagree? Justify your answer.



- (e) Enough $\text{N}_2\text{O}_5(g)$ is added to distilled water to make 350.0 mL of $\text{HNO}_3(aq)$, as shown in the preceding equation. The resulting solution has pH a of 1.62.
- Calculate the value of $[\text{H}_3\text{O}^+]$ in the solution.
 - Assuming the $\text{HNO}_3(aq)$ is produced with 100% yield, calculate the mass of $\text{N}_2\text{O}_5(g)$ (molar mass 108.02 g/mol) that was added in part (e).



- (f) A buffer solution is prepared in a beaker as shown. Calculate the pH of the solution in the beaker. The K_a of NH_4^+ is 5.6×10^{-10} .
- (g) Four students are each given a different beaker containing 100.0 mL of a solution that contains 0.75 M NH_3 and 0.75 M NH_4NO_3 . Each student adds a different amount of 1.0 M HNO_3 and then correctly measures the pH of their solution, as shown in the following table.

Student	Volume of Buffer (mL)	Amount of HNO_3 Added (mL)	pH after HNO_3 Addition
A	100.0	20	9.01
B	100.0	40	8.73
C	100.0	60	8.30
D	100.0	80	1.56

- Write a balanced net ionic equation for the reaction that occurs when a small amount of HNO_3 is added to Student A's buffer solution.
- What evidence in the data table indicates that the buffer capacity is exceeded only in the solution prepared by Student D?

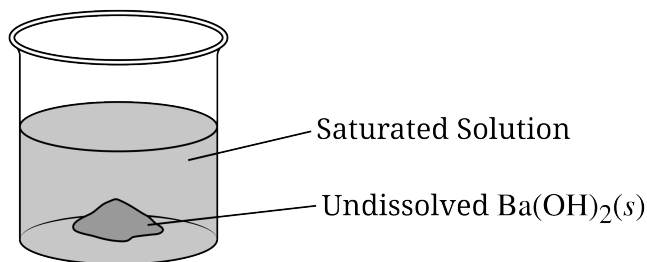
4. Answer the following questions about atomic structure and bonding.

- (a) Write the complete ground-state electron configuration of the Kr atom.
- (b) The Rb^+ ion has the same electron configuration as the neutral Kr atom. Which has the larger radius, the Rb^+ ion or the Kr atom? Justify your answer in terms of Coulomb's law.
- (c) The composition of a sample of solid Rb containing a high percentage of the radioactive isotope Rb-83 is given in the following table.

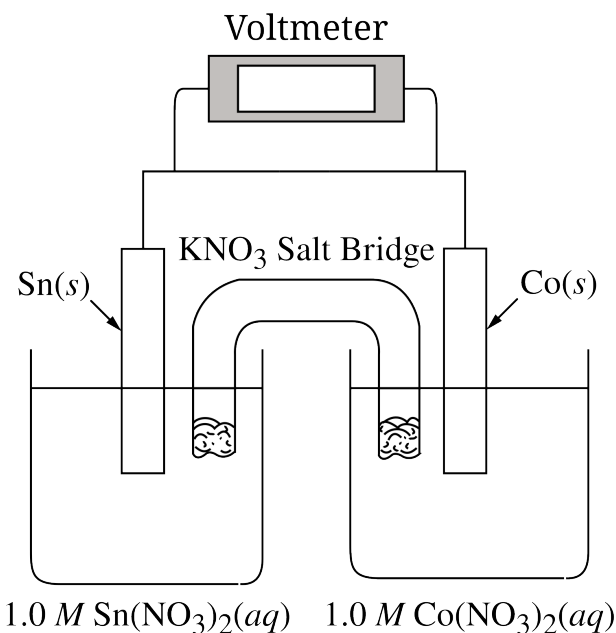
Isotope	Isotopic Mass (amu)	Percentage of Sample	Isotope Half-Life
Rb-83	82.92	32.5%	86 days
Rb-85	84.91	50.8%	stable
Rb-87	86.91	16.7%	stable

- i. Using the values in the table, calculate the average atomic mass, in amu, of Rb in the sample.
- ii. Rb-83 undergoes radioactive decay into gaseous Kr-83, which leaves the solid sample. Over time, how will the average atomic mass of the remaining sample compare to the value calculated in part (c)(i)?

5. To determine the value of the solubility product constant, K_{sp} , a student prepares a saturated solution by dissolving $\text{Ba(OH)}_2(s)$ in water. The K_{sp} expression is $K_{sp} = [\text{Ba}^{2+}][\text{OH}^-]^2$.
- (a) Write the balanced equation for the dissociation reaction that is consistent with the K_{sp} expression.
- (b) The student determines that the solubility of $\text{Ba(OH)}_2(s)$ is 18.5 g/L at 25 °C.
- Calculate the molar solubility of $\text{Ba(OH)}_2(s)$ in mol/L at 25 °C.
 - Calculate the value of K_{sp} for $\text{Ba(OH)}_2(s)$ at 25 °C.



- (c) The student creates a saturated solution of Ba(OH)_2 in water, as shown in the diagram. The student claims that the amount of undissolved $\text{Ba(OH)}_2(s)$ will decrease when $\text{HNO}_3(aq)$ is added. Do you agree or disagree with the student's claim? Justify your answer with a comparison of Q and K_{sp} .



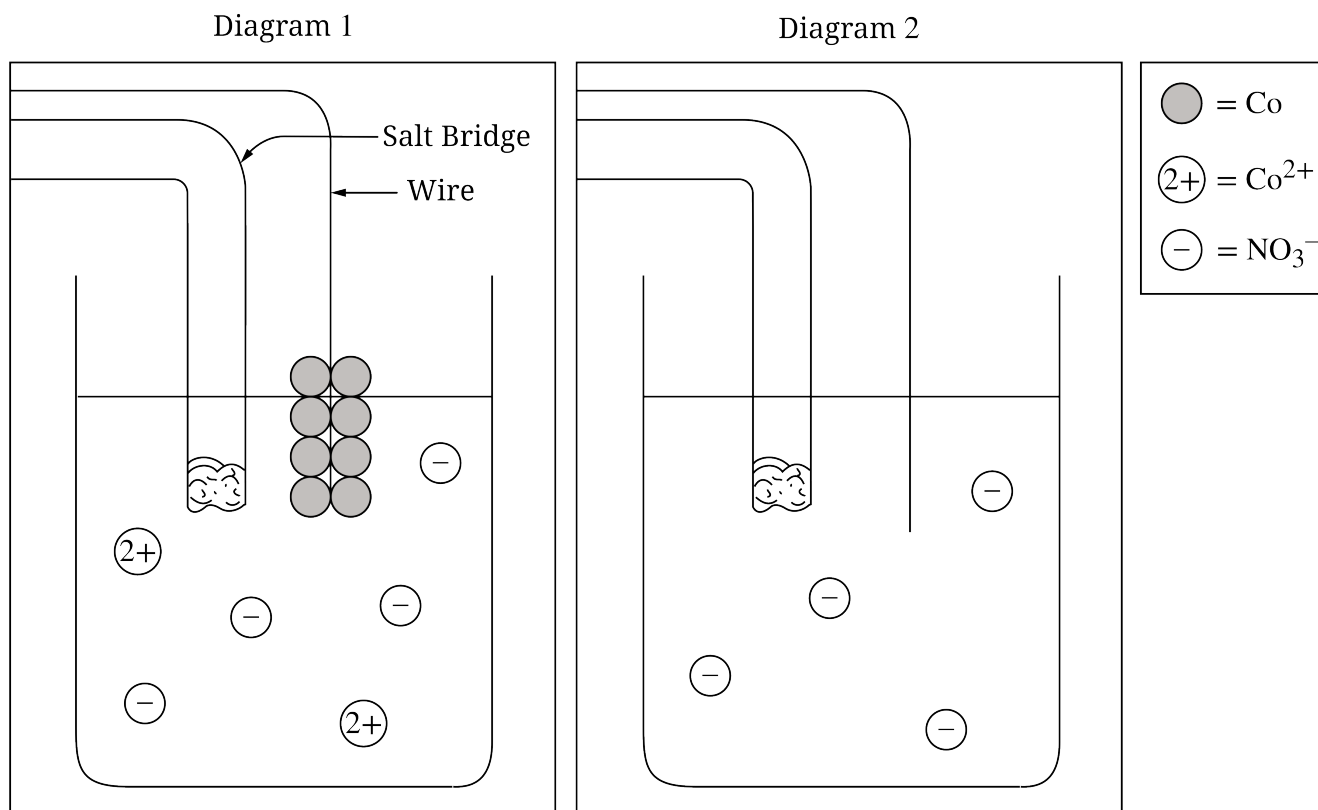
6. A student sets up a galvanic cell with one half-cell made with a tin electrode and a Sn^{2+} solution and the second half-cell made with a cobalt electrode and a Co^{2+} solution, as shown. The salt bridge contains $\text{KNO}_3(\text{aq})$.

(a) The following table provides standard reduction potentials.

Half-Reaction	E° (V)
$\text{Sn}^{2+}(\text{aq}) + 2e^- \rightarrow \text{Sn}(\text{s})$	-0.138
$\text{Co}^{2+}(\text{aq}) + 2e^- \rightarrow \text{Co}(\text{s})$	-0.277

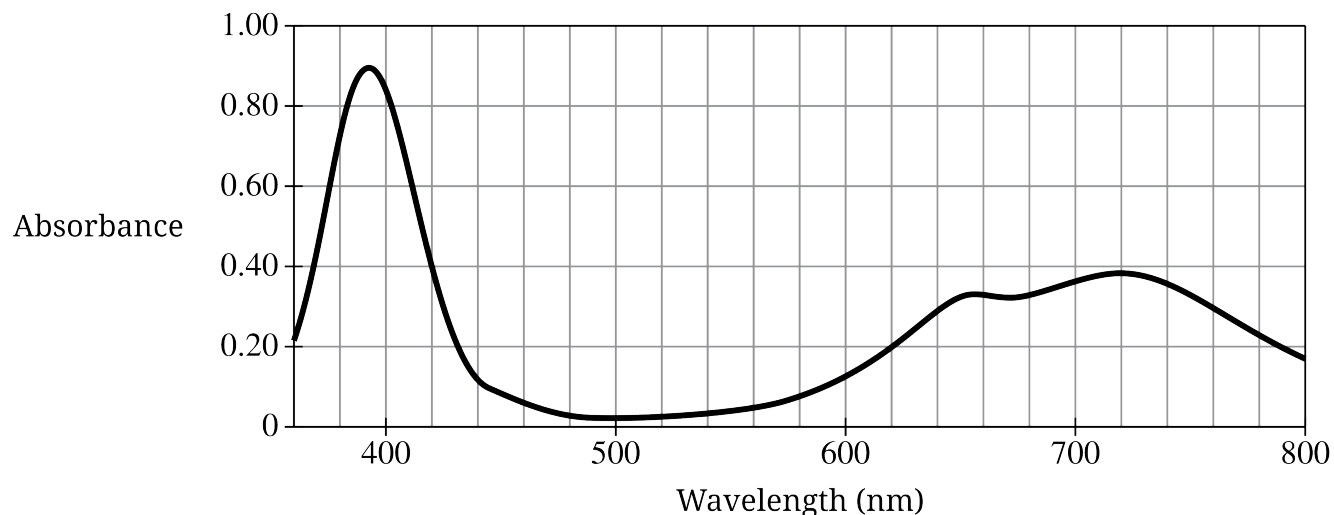
- i. Given the balanced equation $\text{Sn}^{2+} + \text{Co} \rightarrow \text{Sn} + \text{Co}^{2+}$, determine the standard cell potential, E°_{cell} .
- ii. Is the value of ΔG° for the overall electrochemical reaction greater than, less than, or equal to zero? Justify your answer based on the value of E°_{cell} .

- (b) A representation of the cobalt half-cell before the reaction starts is shown in diagram 1. The student observes that as the cell operates, the solution becomes a darker shade of pink. In diagram 2, complete the representation of the cobalt half-cell after the cell has operated for a short time. Be sure that mass is conserved. The balance of charge is not necessary, and all species may not need to be shown in the drawing.

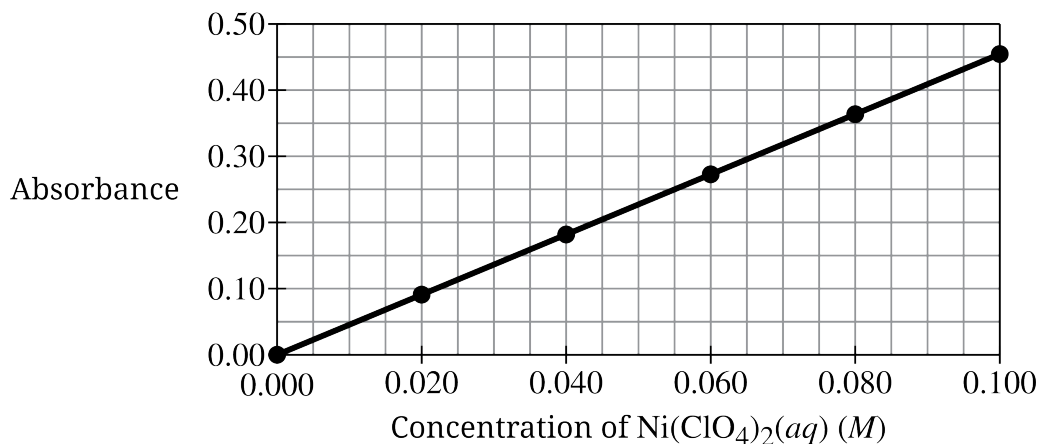


- (c) A second galvanic cell is constructed such that $[\text{Sn}^{2+}] = 1.0\text{ M}$ and $[\text{Co}^{2+}] = 0.20\text{ M}$. How does the cell potential of this second galvanic cell compare to the cell potential of the first cell?

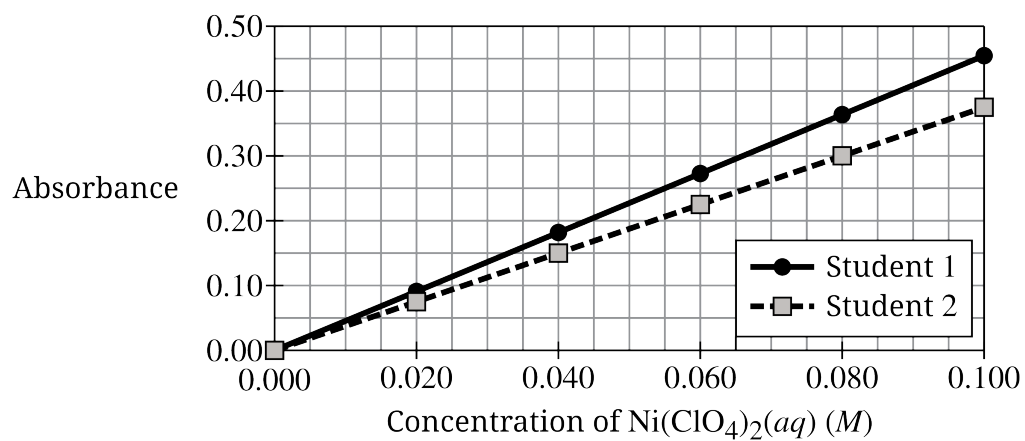
7. A student performs a spectrophotometry experiment using solutions of $\text{Ni}(\text{ClO}_4)_2(aq)$. The student needs to make a standard curve and determine the concentration of $\text{Ni}(\text{ClO}_4)_2(aq)$ in a sample with an unknown concentration.



- (a) Based on the absorbance spectrum of $\text{Ni}(\text{ClO}_4)_2(aq)$ shown in the preceding graph, what wavelength should the student use in the experiment to achieve the greatest precision?
- (b) To make the standard curve, the student must prepare $\text{Ni}(\text{ClO}_4)_2(aq)$ solutions with different concentrations. The student has a standard solution of $\text{Ni}(\text{ClO}_4)_2(aq)$ with a concentration of 0.198 M . Calculate the volume, in mL, of 0.198 M $\text{Ni}(\text{ClO}_4)_2(aq)$ that is needed to prepare 250.0 mL of 0.0400 M $\text{Ni}(\text{ClO}_4)_2(aq)$.



- (c) The standard curve generated by the student is provided above. The student measures an absorbance of 0.30 for the unknown solution. Using the standard curve provided, determine the molarity of $\text{Ni}(\text{ClO}_4)_2(aq)$ in the unknown solution.



- (d) A second student repeats the procedure using the same spectrophotometer but makes an error, which results in the dashed line shown in the graph above. Assuming that the first student's data (shown by the solid line) are correct, identify one error that could account for the second student's standard curve being less steep than that obtained by the first student.

STOP
END OF EXAM

APPENDIX - ANSWERS

AP CHEMISTRY 2023

Multiple-choice key transcribed from the matching supplied source.

Question	Answer	Question	Answer	Question	Answer
1	D	21	C	41	A
2	A	22	A	42	A
3	D	23	B	43	C
4	B	24	D	44	A
5	D	25	C	45	C
6	D	26	B	46	C
7	A	27	C	47	C
8	C	28	A	48	A
9	B	29	C	49	B
10	A	30	D	50	D
11	D	31	B	51	C
12	C	32	A	52	B
13	C	33	B	53	C
14	C	34	D	54	B
15	B	35	D	55	A
16	C	36	A	56	D
17	C	37	A	57	B
18	B	38	B	58	B
19	D	39	C	59	C
20	A	40	B	60	C

Scoring-extract items 61-67 correspond to FRQs 1-7.

2023 Form I

1. An atom of chlorine and an atom of which of the following elements will form a bond with the most ionic character?

(A) Germanium
(B) Carbon
(C) Copper

(D) Potassium



2. $\text{NO}_2\text{Cl}(g) + \text{Cl}(g) \rightarrow \text{NO}_2(g) + \text{Cl}_2(g)$

The single-step reaction represented above takes place in a sealed container. Which of the following will reduce the value of k , the rate constant for the reaction?

(A) Decreasing the temperature



(B) Increasing the temperature
(C) Decreasing the size of the sealed container
(D) Increasing the size of the sealed container

3. The pH of a 0.009 M solution of $\text{KOH}(aq)$ is closest to which of the following?

(A) 2
(B) 5
(C) 9

(D) 12



4. Which of the following is the ground-state electron configuration for the Na^+ ion?

(A) $1s^2 2s^2 2p^5$

(B) $1s^2 2s^2 2p^6$



(C) $1s^2 2s^2 2p^6 3s^1$
(D) $1s^2 2s^2 2p^6 3s^2$

5. A 1.5 g sample of ice, $\text{H}_2\text{O}(s)$, at 0.0°C is placed in a warm room. Which of the following best describes the energy transfer involved in melting the ice to create liquid water at 0.0°C ? (The heat of fusion of $\text{H}_2\text{O}(s)$ is 334 J/g .)

(A) 334 joules of energy is transferred from the ice to the room.
(B) 334 joules of energy is transferred from the room to the ice.
(C) 501 joules of energy is transferred from the ice to the room.

(D) 501 joules of energy is transferred from the room to the ice.



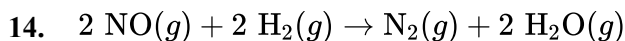
2023 Form I

6. A student dissolves a quantity of $\text{KNO}_3(s)$ in water. What information must the student use to calculate the molarity of the aqueous solution?
- (A) Grams of KNO_3 and the density of water
- (B) Liters of KNO_3 and liters of solution
- (C) Moles of KNO_3 and the density of water
- (D) Moles of KNO_3 and liters of solution ✓
7. A student titrates 25 mL of a 0.10 M solution of an unknown acid, HX , with a 0.10 M solution of sodium hydroxide, $\text{NaOH}(aq)$, to the equivalence point. Which of the following pieces of experimental evidence would best help the student confirm that HX is a weak acid?
- (A) The initial pH of the acid solution is greater than 1. ✓
- (B) The initial pH of the acid solution is less than 1.
- (C) Less than 25 mL of $\text{NaOH}(aq)$ is required to reach the equivalence point.
- (D) More than 25 mL of $\text{NaOH}(aq)$ is required to reach the equivalence point.
8. Which of the following best explains how the bonding in a metal allows it to be ductile (i.e., allows it to be drawn into a wire)?
- (A) Metal atoms are spherical; therefore, the solid metal can be easily drawn into wires that have a round cross-section.
- (B) Because of strongly directional bonding in the solid metal, the atoms both in front of and behind a given atom in a wire will bind together more strongly than the atoms not along the direction of the wire.
- (C) Because the mobile electrons attract the metal cations equally in all directions, the metal cations can move easily past one another as the metal is drawn into a wire. ✓
- (D) Metal atoms tend to be much smaller than nonmetal atoms; therefore, they can move easily past one another as the metal is drawn into a wire.
9. A 100. g sample of a substance decomposes so that 25 g of the original substance remains after 40. seconds. If the decomposition is first order, which of the following is the rate constant, k , of the decomposition reaction?
- (A) 0.017 s^{-1}
- (B) 0.035 s^{-1} ✓
- (C) 1.4 s^{-1}
- (D) $20. \text{ s}^{-1}$
10. A student attempts to prepare a buffer solution with a pH of 10.0 by adding NaHCO_3 ($\text{p}K_a = 10.3$) and Na_2CO_3 to distilled water. Instead of the desired pH , the measured pH of the buffer solution is 9.5. Which of the following is the most likely reason that the pH is too low?
- (A) Too much NaHCO_3 was used. ✓
- (B) Too much Na_2CO_3 was used.
- (C) There was water in the flask before NaHCO_3 and Na_2CO_3 were added.
- (D) In order to prepare the buffer, a few drops of a strong base should have been added.

2023 Form I

11. Which of the following best explains why $\text{H}_2(g)$ behaves more ideally than most other gases?
- (A) The number of particles in a given volume of $\text{H}_2(g)$ is smallest in comparison to other gases, because the molar mass of H_2 is smallest.
 - (B) Collisions between gas particles and the walls of a container are more frequent for smaller molecules, because the average velocity is very high.
 - (C) The average kinetic energy of H_2 molecules at a given temperature is large, because the average velocity of the H_2 molecules is very high.
 - (D) Intermolecular attractions between H_2 molecules are weak, because the electron clouds of H_2 molecules are small. ✓
12. Which of the following best accounts for the decrease in the first-ionization energy of the alkaline earth metals going down the group?
- (A) The number of protons in the nucleus increases, resulting in increased attraction between the nucleus and the electron being removed.
 - (B) The number of protons in the nucleus increases, resulting in a greater effective nuclear charge attracting the electron being removed.
 - (C) The number of electron shells increases, resulting in a greater average distance between the nucleus and the electron being removed. ✓
 - (D) The number of electron shells increases, resulting in less shielding between the nucleus and the electron being removed.
- 13.
- | Substance | Specific Heat
(J/(g · °C)) |
|-----------|-------------------------------|
| Water | 4.18 |
| Ethanol | 2.44 |
| Fe(s) | 0.449 |
- Two identical insulated containers hold equal masses of liquid at the same temperature; one contains water and the other contains ethanol. Two identical cubes of Fe(s) are heated to the same temperature, one cube is placed in each container, and both systems are allowed to reach thermal equilibrium. Based on the information in the table shown, which of the following best predicts what will be observed?
- (A) Both systems will have the same final temperature because the mass and initial temperature of the liquids are the same.
 - (B) Both systems will have the same final temperature because the Fe(s) cubes will transfer the same amount of heat to both liquids.
 - (C) The ethanol system will have the higher final temperature because the specific heat of ethanol is lower than that of water. ✓
 - (D) The ethanol system will have the lower final temperature because the specific heat of ethanol is lower than that of water.

2023 Form I

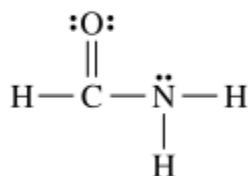


The rate law for the reaction shown is $\text{rate} = k[\text{NO}]^2[\text{H}_2]$. What is the overall order of the reaction?

- (A) First order
(B) Second order
(C) Third order
(D) Fourth order

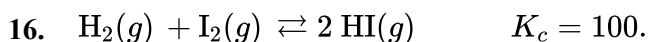


15.



The complete Lewis electron-dot diagram for HCONH_2 is shown above. Identify the hybridization of the valence orbitals for the carbon atom and the approximate hydrogen-carbon-nitrogen bond angle according to VSEPR theory.

- (A) sp hybridized and 180°
(B) sp^2 hybridized and 120°
(C) sp^2 hybridized and 180°
(D) sp^3 hybridized and 120°



Equimolar amounts of $\text{H}_2(g)$ and $\text{I}_2(g)$ are pumped into a previously evacuated, rigid 1.0 L container and allowed to attain the equilibrium shown above at a constant temperature. If 0.600 mol of $\text{HI}(g)$ is present at equilibrium, how many moles of $\text{H}_2(g)$ were initially added to the container?

- (A) 0.0036 mol
(B) 0.060 mol
(C) 0.36 mol
(D) 0.60 mol



2023 Form I

17.

	Ionization Energy (kJ / mol)
First	786
Second	1,577
Third	3,232
Fourth	4,356
Fifth	16,091

Based on the successive ionization energies of element X shown in the table above, which of the following is most likely the formula of the compound produced when element X reacts with fluorine?

- (A) XF
(B) XF_2
(C) XF_4
(D) XF_5



18.

Lewis Dot Diagram	Boiling Point ($^{\circ}\text{C}$)
$\text{H}-\text{C}\equiv\text{N:}$	26
$:\text{N}\equiv\text{N:}$	-196

Which of the following best helps to explain why the boiling point of HCN is so much higher than that of N_2 , as shown by the data in the table above?

- (A) HCN contains three atoms, whereas N_2 contains two atoms.
(B) HCN is polar, whereas N_2 is nonpolar.
(C) HCN has a molar entropy greater than that of N_2 .
(D) The $\text{C}\equiv\text{N}$ bond is stronger than the $\text{N}\equiv\text{N}$ bond.



19. A reaction is known to have a negative value of ΔH° and a positive value of ΔS° . Which of the following statements correctly describes the equilibrium constant, K_{eq} , for this reaction?

2023 Form I

- (A) K_{eq} will be less than 1 only at high temperatures.
- (B) K_{eq} will be less than 1 at all temperatures.
- (C) K_{eq} will be greater than 1 only at low temperatures.
- (D) K_{eq} will be greater than 1 at all temperatures. ✓

20.

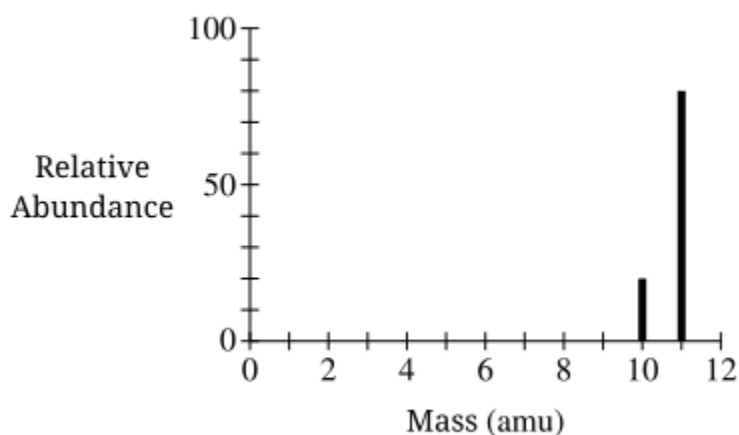
	HX(aq)	HZ(aq)
Conductivity	low	high

A student tests the electrical conductivity of 0.10 M solutions of two different monoprotic acids, HX(aq) and HZ(aq). Results from the experiment are shown in the table. Which of the following is a question that could be answered based on the data in the table?

- (A) Which acid has the larger K_a value? ✓
- (B) Which acid has the larger molar mass?
- (C) Which acid solution has the larger density?
- (D) Which acid solution has the larger standard molar entropy?
21. A compound made up of only carbon and hydrogen is completely combusted in excess $O_2(g)$. Equimolar quantities of $CO_2(g)$ and $H_2O(g)$ are produced. Which of the following could be the molecular formula of the compound?
- (A) CH_4
- (B) C_2H_2
- (C) C_2H_4 ✓
- (D) C_2H_6
22. Which of the following processes will most likely have a negative ΔS_{rxn}° ?
- (A) $3 H_2(g) + N_2(g) \rightarrow 2 NH_3(g)$ ✓
- (B) $H_2(g) + Cl_2(g) \rightarrow 2 HCl(g)$
- (C) $H_2O(s) \rightarrow H_2O(l)$
- (D) $2 O_3(g) \rightarrow 3 O_2(g)$

2023 Form I

23.



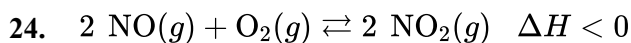
Based on the mass spectrum of a sample of boron shown above, how many neutrons are in the most common isotope of boron?

(A) 5

(B) 6

(C) 10

(D) 11



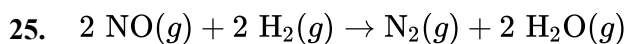
Which of the following changes will increase the amount of $\text{NO}_2(g)$ in the reaction system at equilibrium represented above?

(A) Adding a catalyst to the reaction system

(B) Increasing the pressure by adding $\text{Ne}(g)$ to the system at constant temperature

(C) Increasing the temperature at constant volume

(D) Decreasing the volume at constant temperature



The rate law for the reaction represented is $\text{rate} = k[\text{NO}]^2[\text{H}_2]$. What happens to the rate of the reaction when the concentration of $\text{NO}(g)$ is doubled and the concentration of $\text{H}_2(g)$ is halved?

(A) The rate is halved.

(B) The rate is the same.

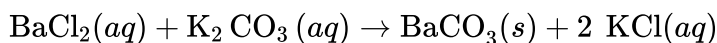
(C) The rate is doubled.

(D) The rate is quadrupled.



2023 Form I

Students are asked to design an experiment to determine the molarity of a $\text{BaCl}_2(aq)$ solution. After examining the K_{sp} values of some barium-containing compounds, the students decide to use $0.100\text{ M K}_2\text{CO}_3(aq)$ to precipitate the barium ions. An excess of $\text{K}_2\text{CO}_3(aq)$ is added to a 50.0 mL sample of the $\text{BaCl}_2(aq)$ solution, and the reaction represented by the following equation occurs.



The $\text{BaCO}_3(s)$ is filtered, dried, and weighed. The data are recorded in the following table.

Volume of $\text{BaCl}_2(aq)$	Volume of $0.100\text{ M K}_2\text{CO}_3(aq)$	Mass of $\text{BaCO}_3(s)$
50.0 mL	$150.\text{ mL}$	1.97 g

The molar masses of BaCl_2 and BaCO_3 are 208 g/mol and 197 g/mol , respectively.

26. Of the following species, which is present in the highest concentration in the filtrate?

(A) $\text{H}^+(aq)$

(B) $\text{K}^+(aq)$

(C) $\text{Cl}^-(aq)$

(D) $\text{CO}_3^{2-}(aq)$



27. On the basis of the experimental data, what was $[\text{Ba}^{2+}]$ in the original 50.0 mL sample of the solution?

(A) 0.05 M

(B) 0.10 M

(C) 0.20 M

(D) 0.40 M



28.

Substance	K_{sp}
$\text{Ba}(\text{NO}_3)_2$	3.33×10^{-1}
BaF_2	1.84×10^{-7}
BaSO_4	1.08×10^{-10}
BaCrO_4	1.17×10^{-10}

Considering the K_{sp} values listed above, which of the following solutions, when used instead of $\text{K}_2\text{CO}_3(aq)$ in the precipitation procedure, would produce the least number of moles of precipitate?

2023 Form I

(A) 0.200 M $\text{NaNO}_3(aq)$



(B) 0.200 M $\text{NaF}(aq)$

(C) 0.100 M $\text{Na}_2\text{SO}_4(aq)$

(D) 0.100 M $\text{Na}_2\text{CrO}_4(aq)$

Three equimolar gas samples are at the conditions given in the following table. Assume that the gases behave ideally.

Gas	Volume (L)	Pressure (atm)	Temperature (K)
F_2	10.	2.0	200.
N_2	5.0	4.0	200.
O_2	4.0	5.0	200.

29. Which gas, if any, has the greatest density?

(A) F_2

(B) N_2

(C) O_2



(D) All three samples have the same density.

30. Which gas, if any, has molecules with the greatest average kinetic energy?

(A) F_2

(B) N_2

(C) O_2

(D) The molecules in all three samples have the same average kinetic energy.



31. The number of moles of $\text{N}_2(g)$ is closest to which of the following?

(A) 0.10 mol

(B) 1.2 mol



(C) 22 mol

(D) 28 mol

2023 Form I

In the gas-phase reaction represented by the following equation, methane (CH_4) and water (H_2O) are produced from carbon dioxide (CO_2) and hydrogen (H_2) at high temperature and pressure.



32. Which of the following is a correct statement about oxidation and reduction during the reaction?
- (A) Hydrogen is oxidized, and carbon is reduced. ✓
- (B) Carbon is oxidized, and oxygen is reduced.
- (C) Oxygen is oxidized, and hydrogen is reduced.
- (D) It is not an oxidation-reduction reaction.
33. The reaction is catalyzed by solid nickel. Which of the following describes the effect of the catalyst on the reaction?
- (A) The presence of the catalyst results in an overall reaction that releases less energy.
- (B) The presence of the catalyst results in a reaction pathway that requires a lower activation energy. ✓
- (C) The presence of the catalyst results in an overall reaction that requires more energy.
- (D) The presence of the catalyst results in a reaction pathway that requires a greater activation energy.
34. Based on the Lewis diagrams, which of the products is more soluble in ethanol ($\text{C}_2\text{H}_5\text{OH}$) ?
- (A) Methane, because it has more hydrogen atoms than water does, so it can form more hydrogen bonds with ethanol.
- (B) Methane, because it is a larger molecule than water, so its electron cloud is more polarizable.
- (C) Water, because water has a greater molar mass than methane does.
- (D) Water, because water molecules can form hydrogen bonds with ethanol molecules, but methane molecules cannot. ✓

2023 Form I

35. Which of the following identifies the hybridization of the valence orbitals of the central atoms of the methane and water molecules?

	CH ₄	H ₂ O
A	sp^2	sp
B	sp^2	sp^2
C	sp^3	sp^2
D	sp^3	sp^3

- (A) A
(B) B
(C) C

(D) D



36.

Substance	Standard Heat of Formation (kJ/mol)
CO ₂ (g)	−394
CH ₄ (g)	−75
H ₂ (g)	0
H ₂ O(g)	−242

Based on the information given, ΔH_{rxn} is closest to which of the following?

(A) −165 kJ/mol_{rxn}

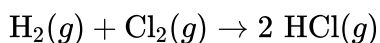
(B) −77 kJ/mol_{rxn}

(C) +77 kJ/mol_{rxn}

(D) +165 kJ/mol_{rxn}



Gaseous hydrogen and gaseous chlorine can react to form hydrogen chloride gas, as represented by the following equation.



37. Equimolar amounts of H₂ and Cl₂ are placed in an evacuated reaction vessel at 500 K. Which of the following statements correctly predicts how the pressure will be affected as the reaction proceeds at a constant temperature and explains why?

2023 Form I

- (A) The pressure will remain constant because the number of gas particles is constant. ✓
- (B) The pressure will be halved because one substance is produced from two substances.
- (C) The pressure will increase because the coefficient of HCl in the balanced chemical equation is greater than that of the reactants.
- (D) The pressure will decrease because the average speed of the gaseous product molecules is less than the average speed of the gaseous reactant molecules.

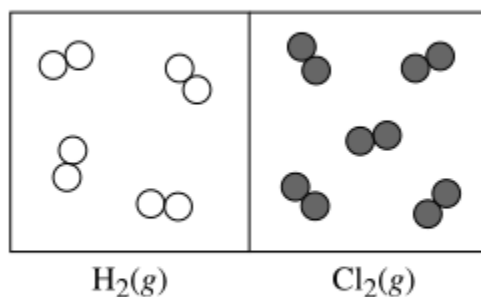
38.

Bond	Bond Energy (kJ/mol)
H–H	432
Cl–Cl	239
H–Cl	427

Based on the table of bond energies shown, the value of ΔH for the reaction $\text{H}_2 + \text{Cl}_2 \rightarrow 2 \text{HCl}$ is closest to which of the following?

- (A) $-244 \text{ kJ/mol}_{\text{rxn}}$
- (B) $-183 \text{ kJ/mol}_{\text{rxn}}$ ✓
- (C) $+183 \text{ kJ/mol}_{\text{rxn}}$
- (D) $+244 \text{ kJ/mol}_{\text{rxn}}$

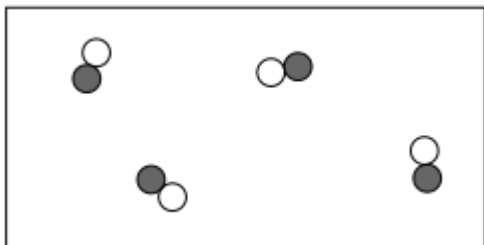
39.



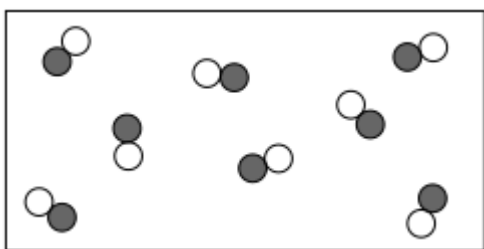
The diagrams show particulate representations for samples of gaseous H_2 and Cl_2 separated by a barrier. After the barrier is removed, the gases react. Which of the following diagrams best represents the mixture if the reaction goes to completion?

2023 Form I

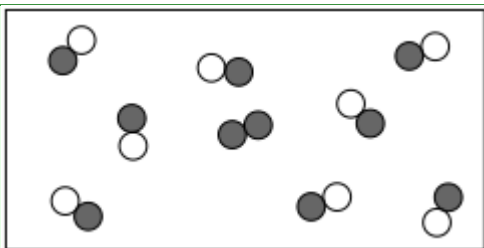
(A)



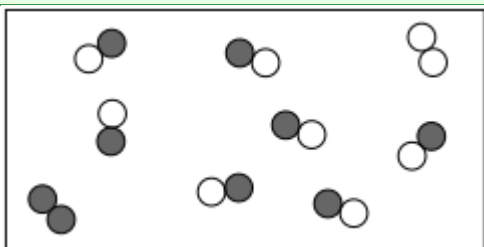
(B)



(C)



(D)



40. Which of the following correctly ranks the internuclear distances for the H_2 , Cl_2 , and HCl molecules from shortest to longest?

(A) $\text{H}_2 < \text{Cl}_2 < \text{HCl}$ (B) $\text{H}_2 < \text{HCl} < \text{Cl}_2$ (C) $\text{Cl}_2 < \text{HCl} < \text{H}_2$ (D) $\text{Cl}_2 < \text{H}_2 < \text{HCl}$ 

41. $\text{Cl}_2\text{O}(g) + \text{H}_2\text{O}(g) \rightleftharpoons 2 \text{HOCl}(g) \quad \Delta H^\circ = +13 \text{ kJ/mol}_{rxn}$

A chemical system at equilibrium is represented above. Which of the following changes will increase the number of moles of $\text{HOCl}(g)$ present in the system?

2023 Form I

(A) Increasing the temperature

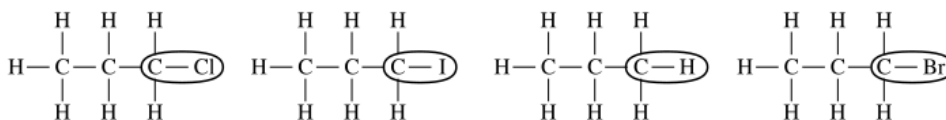


(B) Decreasing the volume of the reaction vessel

(C) Adding a catalyst

(D) Removing $\text{Cl}_2\text{O}(g)$

42.



Which of the following bonds represented in the diagram above is the most polar?

(A) C–Cl

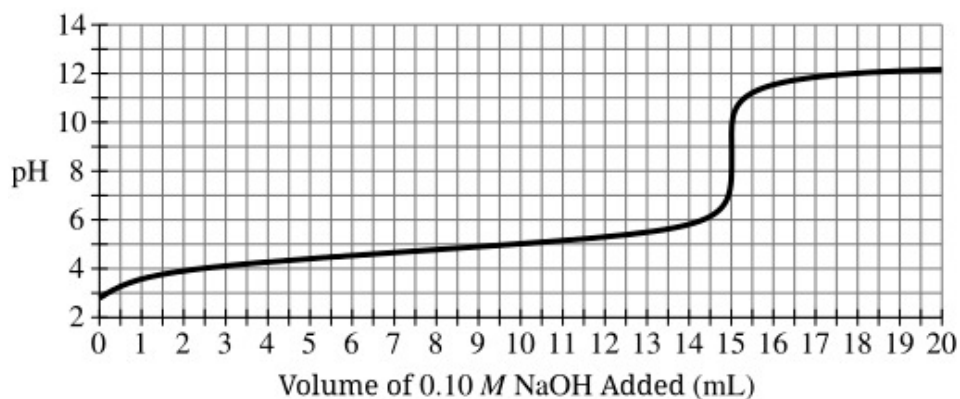


(B) C–I

(C) C–H

(D) C–Br

43.



A sample of an acid is titrated with 0.10 M NaOH , and the results are shown in the graph. Based on the pH range of the color change given for each indicator, which of the following indicators would be the best choice for the titration?

(A) Thymol blue; 1.2 – 2.8

(B) Congo red; 3.0 – 5.0

(C) Phenol red; 6.8 – 8.2



(D) Indigo carmine; 11.6 – 14.0

2023 Form I

44.

Half-Reaction	E° (V)
$\text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s)$	0.80
$\text{Ni}^{2+}(aq) + 2 e^- \rightarrow \text{Ni}(s)$	-0.25

The standard reduction potentials of the half-reactions associated with a galvanic cell are listed in the table above. Which of the following statements identifies the electrode that increases in mass as the cell operates, and correctly explains why?

- (A) The Ag electrode, because $\text{Ag}^+(aq)$ in the solution is reduced to form $\text{Ag}(s)$. ✓
- (B) The Ag electrode, because Ag has a greater molar mass than Ni has.
- (C) The Ni electrode, because Ni is chemically more reactive than Ag is.
- (D) The Ni electrode, because $\text{Ni}^{2+}(aq)$ is reduced at a faster rate than $\text{Ag}^+(aq)$ is.

45. $2 \text{H}_2\text{S}(g) + \text{SO}_2(g) \rightleftharpoons 3 \text{S}(s) + 2 \text{H}_2\text{O}(g)$ $\Delta H_{rxn} < 0$ and $\Delta G_{rxn} < 0$ at 298 K

A 0.20 mol sample of $\text{H}_2\text{S}(g)$ and a 0.10 mol sample of $\text{SO}_2(g)$ are placed in a previously evacuated 10.0 L vessel at 298 K. Even though the reaction represented by the equation above is thermodynamically favorable, the formation of $\text{S}(s)$ was not observed. Which of the following best explains why $\text{S}(s)$ is not produced at 298 K?

- (A) At 298 K, some $\text{S}(s)$ must first be present for the reaction to occur.
- (B) At 298 K, the value of the equilibrium constant is less than 1.
- (C) At 298 K, the energy of most molecular collisions is lower than the activation energy for the reaction. ✓
- (D) At 298 K, the loss of entropy is too great to make molecular collisions likely to occur.

46. $\text{HCN}(aq) + \text{H}_2\text{O}(l) \rightleftharpoons \text{H}_3\text{O}^+(aq) + \text{CN}^-(aq)$ $K_a = 6.2 \times 10^{-10}$

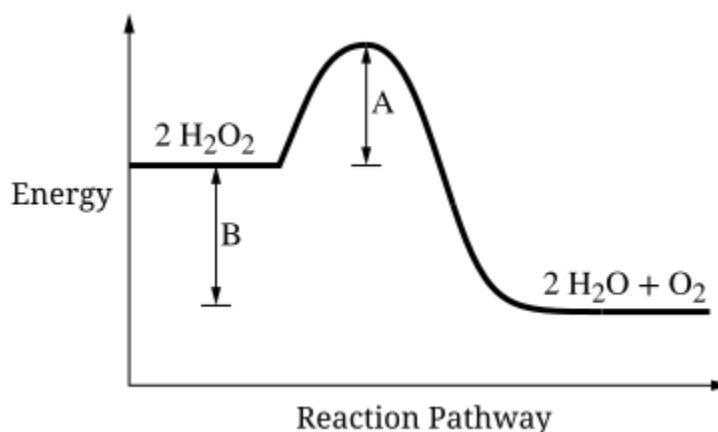


Based on the chemical equations given, which of the following statements is correct?

- (A) HCN is a weaker acid than H_2O .
- (B) CN^- is a stronger acid than HCN.
- (C) CN^- is a stronger base than H_2O . ✓
- (D) H_2O is a weaker base than HCN.

2023 Form I

47.



The potential energy diagram for the uncatalyzed decomposition of $\text{H}_2\text{O}_2(l)$ is shown above. The arrows labeled A and B represent different amounts of energy. When $\text{I}^-(aq)$ is used as a catalyst, how do the magnitudes of A and B in the new reaction energy diagram compare to the uncatalyzed diagram shown above?

	Energy A	Energy B
A	Larger	Larger
B	Smaller	Smaller
C	Smaller	Unchanged
D	Unchanged	Smaller

(A) A

(B) B

(C) C

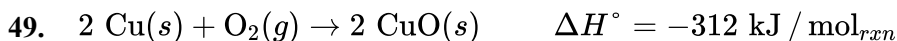
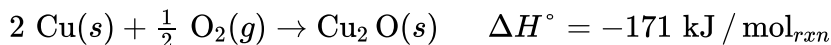
(D) D



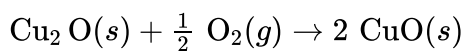
48. Based on the information in the table, which of the following substances produces the most energy per gram of substance combusted?

Substance	Molar Mass (g/mol)	Heat Released from Combustion of One Mole of Substance (kJ)
$\text{H}_2(l)$	2	290
$\text{CH}_4(l)$	16	900
$\text{C}_2\text{H}_5\text{OH}(l)$	46	1400
$\text{C}_{18}\text{H}_{38}(l)$	254	12,000

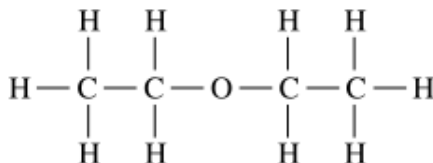
2023 Form I

(A) $\text{H}_2(l)$ (B) $\text{CH}_4(l)$ (C) $\text{C}_2\text{H}_5\text{OH}(l)$ (D) $\text{C}_{18}\text{H}_{38}(l)$ 

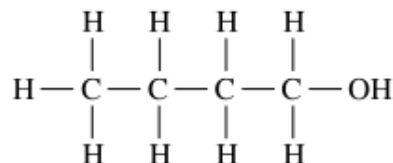
Based on the information above, what is the value of ΔH° for the following reaction?

(A) $-483 \text{ kJ/mol}_{rxn}$ (B) $-141 \text{ kJ/mol}_{rxn}$ (C) $+141 \text{ kJ/mol}_{rxn}$ (D) $+483 \text{ kJ/mol}_{rxn}$

50.



Compound 1



Compound 2

The structural formulas of two compounds that are liquids at room temperature are shown above. Which of the following statements best explains the observation that compound 1 boils at 35°C , whereas its structural isomer, compound 2, boils at 118°C ?

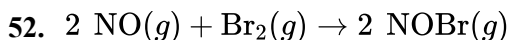
- (A) Molecules of compound 1 have a linear shape and no net dipole, whereas molecules of compound 2 have a bent shape and are polar.
- (B) Molecules of compound 1 are bent less than molecules of compound 2; thus they have weaker dipole-dipole attractions.
- (C) There are dipole-dipole attractions among molecules of compound 1, whereas there are only dispersion forces among molecules of compound 2.

(D) Although there are dipole-dipole attractions among molecules of both compound 1 and compound 2, the $-\text{OH}$ group in compound 2 allows strong hydrogen bonding to occur.



2023 Form I

51. Which of the following is the best method for preparing 100.0 mL of 1.00 M KCl(aq)?
- (A) Place 74.6 g of KCl(s) in a 100 mL graduated cylinder and fill to the 100.0 mL mark with water.
- (B) Place 7.46 g of KCl(s) in a 100 mL Erlenmeyer flask, add 92.54 g of water, and invert several times.
- (C) Place 7.46 g of KCl(s) in a 100 mL volumetric flask, partially fill with water, swirl flask to dissolve solid, fill to the 100.0 mL mark with water, and invert several times. ✓
- (D) Place 7.46 g of KCl(s) in a 100 mL volumetric flask, partially fill with water, swirl flask to dissolve solid, add 92.54 mL of water, and invert several times.



The two mechanisms in the table below have been proposed for the reaction represented above.

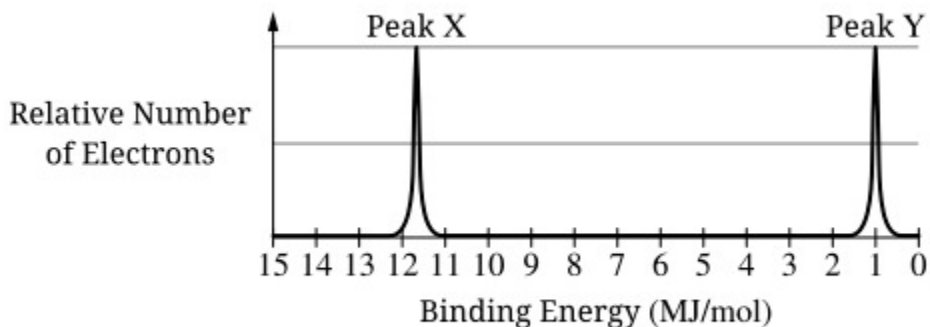
Mechanism 1	Mechanism 2
Step 1 : $\text{NO}(g) + \text{NO}(g) \rightarrow \text{N}_2\text{O}_2(g)$ <i>slow</i>	Step 1 : $\text{NO}(g) + \text{Br}_2(g) \rightarrow \text{NOBr}_2(g)$
Step 2 : $\text{N}_2\text{O}_2(g) + \text{Br}_2(g) \rightarrow 2 \text{ NOBr}(g)$ <i>fast</i>	Step 2 : $\text{NOBr}_2(g) + \text{NO}(g) \rightarrow 2 \text{ NOBr}(g)$

Which of the following observations would support mechanism 1 but not mechanism 2 ?

- (A) The reaction rate is independent of [NO].
- (B) The reaction rate is independent of [Br₂]. ✓
- (C) The reaction is exothermic.
- (D) The reaction is second order overall.

2023 Form I

53.



The complete photoelectron spectrum of a pure element is represented above. Which of the following correctly identifies both the element and the atomic orbitals represented by peak X and peak Y?

	Element	Peak X	Peak Y
A	Li	1s	2s
B	Li	2s	1s
C	Be	1s	2s
D	Be	2s	1s

(A) A

(B) B

(C) C

(D) D



54.

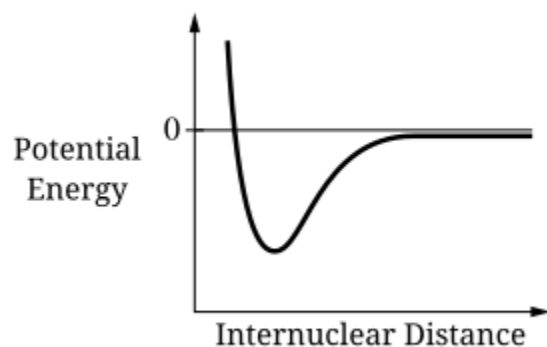
Acid	pK_a
$\text{HClO}_2(aq)$	1.92
$\text{HNO}_2(aq)$	3.25
$\text{HC}_3\text{H}_5\text{O}_2(aq)$	4.88
$\text{HOCl}(aq)$	7.42

Based on the information in the table, which of the following mixtures forms a buffer with a pH closest to 3 ?

2023 Form I

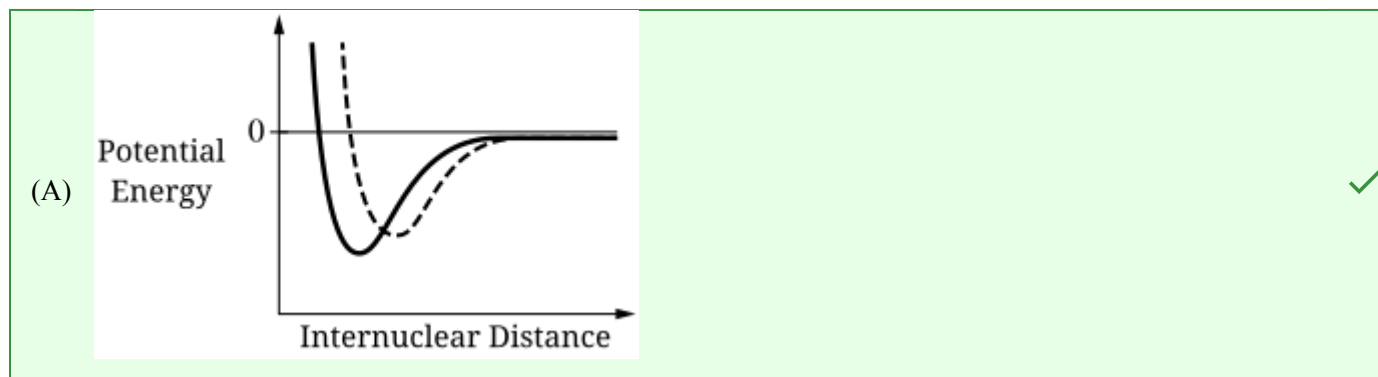
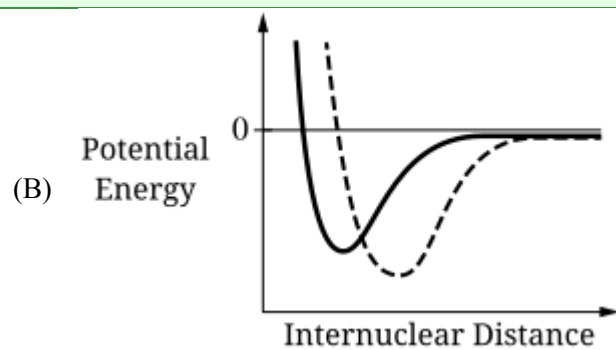
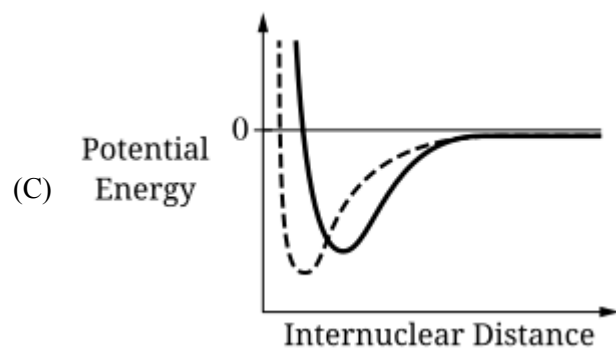
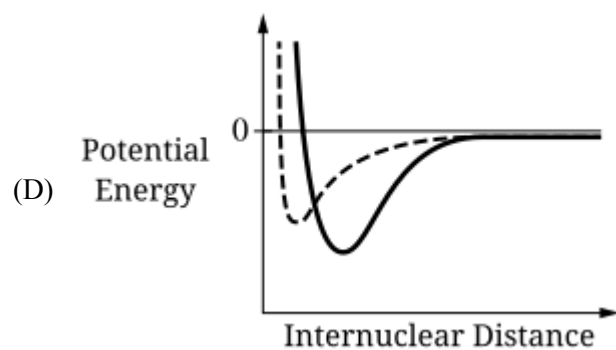
- (A) 50.0 mL of 0.10 M $\text{HClO}_2(aq)$ and 25.0 mL of 0.10 M $\text{NaOH}(aq)$
- (B) 50.0 mL of 0.20 M $\text{HNO}_2(aq)$ and 50.0 mL of 0.10 M $\text{NaOH}(aq)$ ✓
- (C) 50.0 mL of 0.10 M $\text{HC}_3\text{H}_5\text{O}_2(aq)$ and 50.0 mL of 0.050 M $\text{NaOH}(aq)$
- (D) 50.0 mL of 0.10 M $\text{HOCl}(aq)$ and 25.0 mL of 0.10 M $\text{NaOH}(aq)$

55.

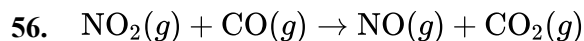


The graph of potential energy versus internuclear distance for the HCl molecule is shown. Which of the following graphs includes the plot for the HBr molecule, shown as a dashed line?

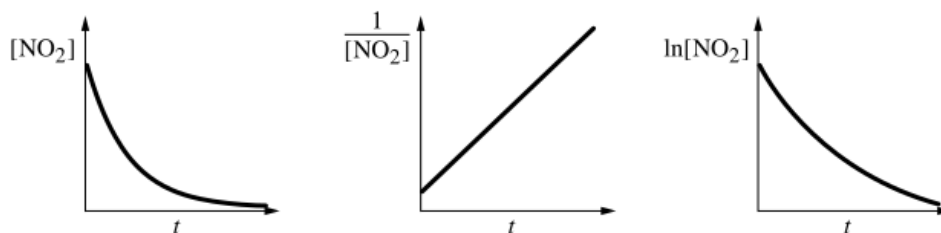
2023 Form I



2023 Form I



A group of students studied the rate of the reaction represented above at a fixed temperature. During the reaction, the concentration of CO was in large excess. The graphs shown below were created using the data collected by the students. Based on the graphs, which of the following is the rate law?



- (A) $\text{Rate} = k$
(B) $\text{Rate} = [\text{NO}_2]$
(C) $\text{Rate} = k[\text{NO}_2]$

(D) $\text{Rate} = k[\text{NO}_2]^2$



Equal volumes of 0.1 M solutions of $\text{Fe}^{3+}(aq)$ and $\text{SCN}^{-}(aq)$ are mixed and allowed to attain the equilibrium represented above at a temperature of 25°C . Which of the following statements is correct about the system at equilibrium?

(A) $[\text{SCN}^{-}] > [\text{FeSCN}^{2+}]$

(B) $[\text{SCN}^{-}] < [\text{FeSCN}^{2+}]$

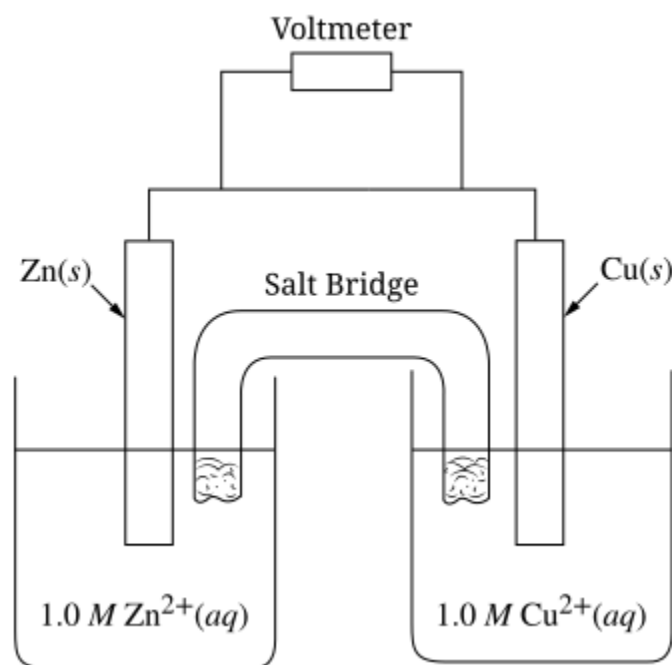
(C) $[\text{Fe}^{3+}] > [\text{FeSCN}^{2+}]$

(D) $[\text{Fe}^{3+}] = [\text{FeSCN}^{2+}]$



2023 Form I

58.



Half-Reaction	E° (V)
$\text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s)$	0.80
$\text{Cu}^{2+}(aq) + 2e^- \rightarrow \text{Cu}(s)$	0.34
$\text{Zn}^{2+}(aq) + 2e^- \rightarrow \text{Zn}(s)$	-0.76

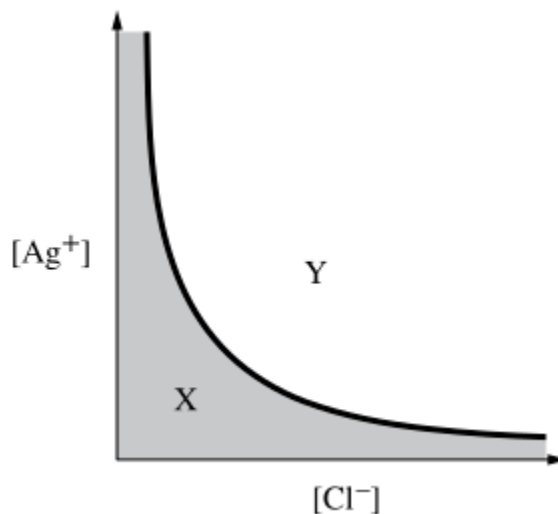
A student sets up a standard galvanic cell, as shown in the diagram, and measures a voltage of 1.10 V. Based on the standard reduction potentials in the table, which of the following will occur if the student makes a new standard cell but uses a silver wire in place of the salt bridge?

- (A) The voltage will be greater than 1.10 V.
- (B) The voltage will be 0. ✓
- (C) The silver wire will become thinner.
- (D) $\text{Zn}(s)$ and $\text{Cu}(s)$ will form on the silver wire.

2023 Form I



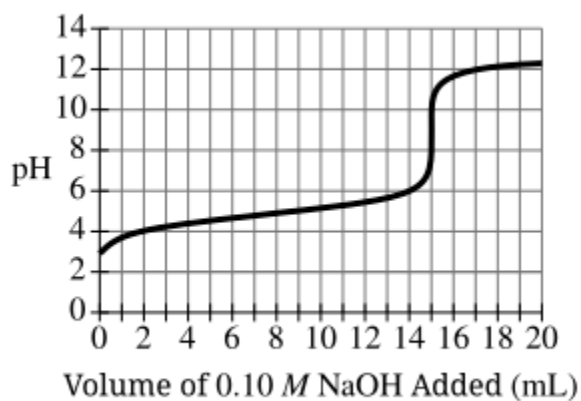
The preceding equation represents the equilibrium of a saturated solution of $\text{AgCl}(aq)$ in contact with $\text{AgCl}(s)$. All points on the curve in the following graph represent values of $[\text{Ag}^+]$ and $[\text{Cl}^-]$ for which the product $[\text{Ag}^+][\text{Cl}^-]$ is equal to the value of K_{sp} for AgCl . Which of the following provides the correct comparison of Q and K_{sp} and describes the net process that occurs at any point in region Y (unshaded) of the graph?



- (A) $Q > K_{sp}$ and dissolution of $\text{AgCl}(s)$ occurs.
- (B) $Q < K_{sp}$ and dissolution of $\text{AgCl}(s)$ occurs.
- (C) $Q > K_{sp}$ and precipitation of $\text{AgCl}(s)$ occurs. ✓
- (D) $Q < K_{sp}$ and precipitation of $\text{AgCl}(s)$ occurs.

2023 Form I

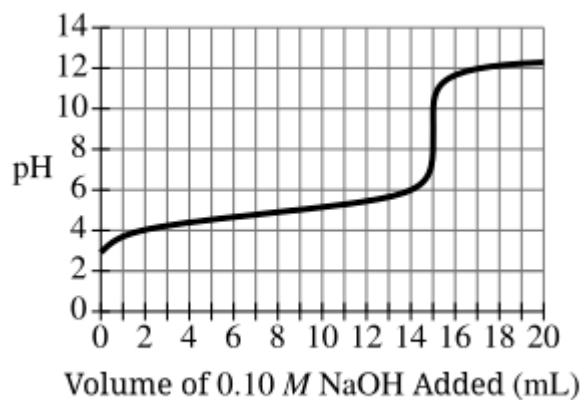
60.



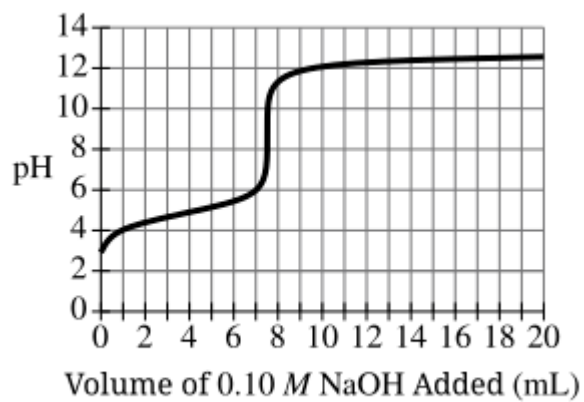
A 15.0 mL sample of 0.10 M $\text{HC}_2\text{H}_3\text{O}_2$ is titrated with 0.10 M NaOH , and the data are shown in the graph above. Which of the following graphs shows the change in pH when a 15.0 mL sample of 0.10 M HCl is titrated with 0.10 M NaOH ?

2023 Form I

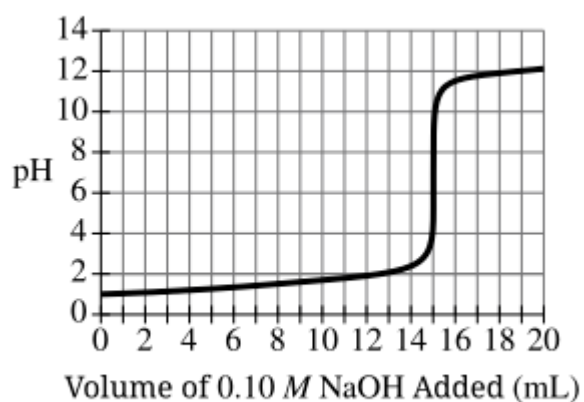
(A)



(B)

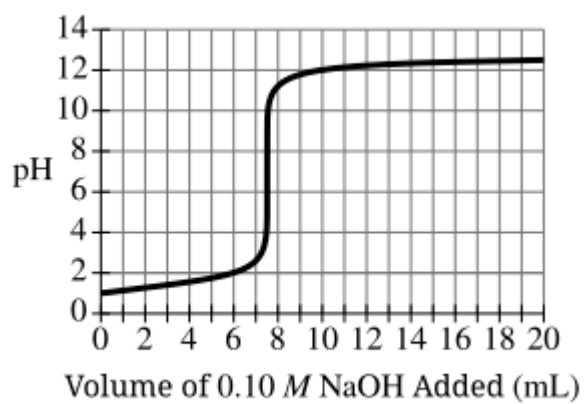


(C)



2023 Form I

(D)

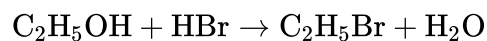


2023 Form I

61. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

Ethanol ($\text{C}_2\text{H}_5\text{OH}$) reacts with hydrobromic acid (HBr) to produce ethyl bromide ($\text{C}_2\text{H}_5\text{Br}$) and water according to the following balanced equation.



(a) At the conclusion of the reaction, the product mixture includes $\text{C}_2\text{H}_5\text{Br}$, H_2O , and excess unreacted $\text{C}_2\text{H}_5\text{OH}$.

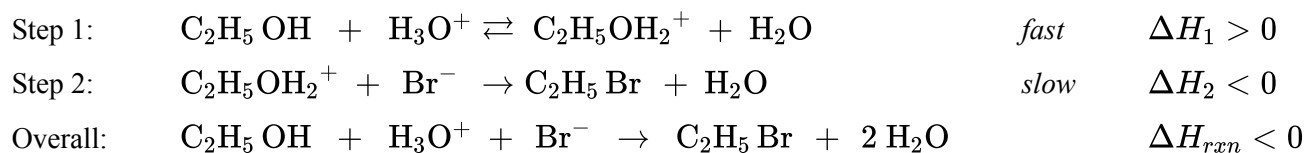
(i) Identify all of the types of intermolecular forces that can exist between one molecule of $\text{C}_2\text{H}_5\text{OH}$ and one molecule of $\text{C}_2\text{H}_5\text{Br}$ in the product mixture.

(ii) The aqueous solubility of $\text{C}_2\text{H}_5\text{OH}$ is greater than that of $\text{C}_2\text{H}_5\text{Br}$. Explain this observation based on the types and relative strengths of intermolecular forces between each solute and H_2O .

The reaction is found to be first order with respect to HBr when $\text{C}_2\text{H}_5\text{OH}$ is in excess. The following data were recorded showing how the concentration of HBr changes over time.

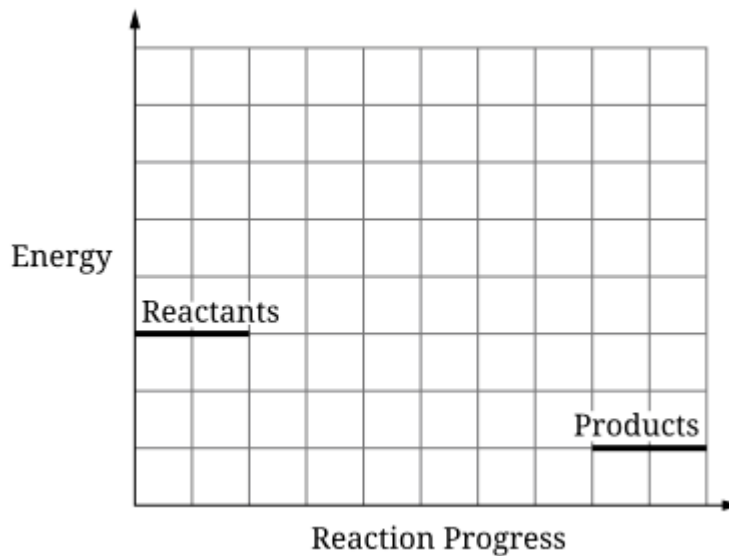
Time (min)	0	50.0	100.0	150.0	200.0
[HBr] (M)	2.00	1.80	1.62	1.46	1.32

- (b) Using the data provided, calculate the value of the rate constant, k , in min^{-1} .
- (c) Using the data provided, determine the half-life of the reaction, in minutes.
- (d) The experiment is repeated at a higher temperature.
- (i) Explain the effect, if any, that the higher temperature has on collisions between reactant particles.
- (ii) Identify the effect, if any, that the higher temperature has on the rate constant. Explain your reasoning.
- (e) The following reaction mechanism has been proposed for the reaction of $\text{C}_2\text{H}_5\text{OH}$ and HBr .



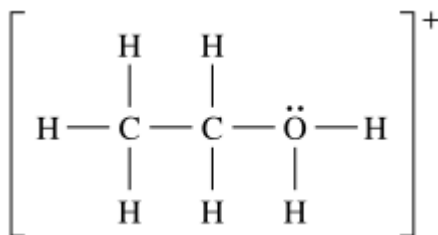
2023 Form I

(i) Sketch an energy diagram that represents this reaction mechanism on the axes given.



(ii) In step 2 of the mechanism, only the C—O bond is broken and the C—Br bond is formed. Given that $\Delta H_2 < 0$, a student claims that more energy is needed to break the C—O bond than is released when the C—Br bond forms. Do you agree or disagree? Justify your answer.

(iii) The following Lewis diagram is for the reaction intermediate, $\text{C}_2\text{H}_5\text{OH}_2^+$. On the Lewis diagram, circle an atom that has a formal charge of +1.

**Part A(i)**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0

1

The response provides the correct answer.

- London dispersion forces and dipole-dipole attractions

2023 Form I

Part A(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides a valid explanation.

- Only $\text{C}_2\text{H}_5\text{OH}$ molecules can engage in hydrogen bonding with H_2O molecules, which results in greater overall attractive forces, and thus, greater aqueous solubility than $\text{C}_2\text{H}_5\text{Br}$.

Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides a correct calculated value.

- Answers will range from $0.00202 - 0.00211 \text{ min}^{-1}$ depending on the data points selected from the table. See sample calculation:

$$k = \frac{-(\ln [\text{HBr}]_t - \ln [\text{HBr}]_0)}{t} = \frac{-(\ln(1.32) - \ln(2.00))}{(200.0 \text{ min} - 0 \text{ min})} = 0.00208 \text{ min}^{-1}$$

Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides a correct calculated value, consistent with B.

- $t_{1/2} = \frac{0.693}{k} = \frac{0.693}{0.00208 \text{ min}^{-1}} = 333 \text{ min}$

Part D(i)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

2023 Form I



0	1
---	---

The response provides a correct answer.

- At a higher temperature, reactant particles collide more frequently.

OR

- At a higher temperature, reactant particles collide with greater energy.

Part D(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides a correct answer and a valid explanation.

- The rate constant will increase. At higher temperature, a greater frequency of effective collisions will result in an increased probability of product formation, increasing the rate constant.

OR

- The rate constant will increase. The rate law for the reaction is $\text{rate} = k[\text{HBr}]$ (because $[\text{CH}_3\text{CH}_2\text{OH}]$ remains constant), so at the same concentration, the only way for the rate to increase is for the rate constant to increase.

Part E(i)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1	2
---	---	---

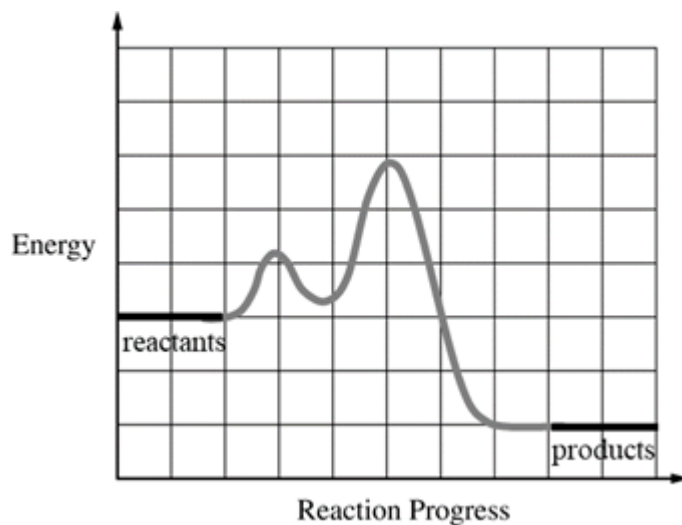
The response meets **both** of the following criteria.

- ☐ The response shows a curve with two activation energy peaks.
 - See example response below.
- ☐ The response shows a curve with an endothermic first step with lower activation energy than the second

2023 Form I

step.

- See example response below.



Part E(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct answer and a valid justification.

- Disagree. Given that step 2 is exothermic ($\Delta H_2 < 0$), the amount of energy required to break the C-O bond must be less than the amount of energy released when the C-Br bond forms.

OR

- Disagree. If the student's claim were correct, step 2 would be endothermic, not exothermic.

Part E(iii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

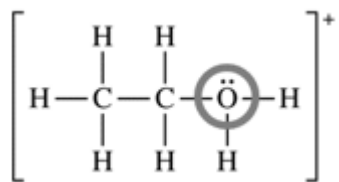


0	1
---	---

The response provides the correct answer.

- The O atom (and only the O atom) should be circled.

2023 Form I



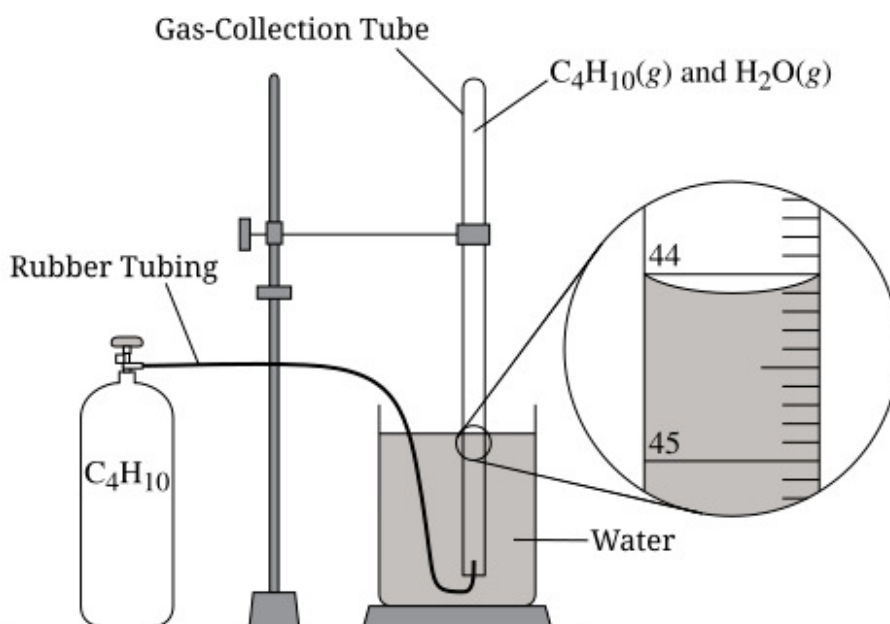
2023 Form I

62. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

A student performs an experiment to determine the molar mass of butane, C_4H_{10} .

- (a) To determine the molar mass, the student collects a sample of butane gas over water in a 50.00 mL gas-collection tube, as shown in the following diagram. The student then adjusts the position of the tube so the water level is the same inside and outside the tube. A partial data table for the experiment is also shown.



2023 Form I

Initial mass of C ₄ H ₁₀ container	25.012 g
Final mass of C ₄ H ₁₀ container	24.911 g
Initial volume of gas	0.00 mL
Final volume of gas	?
Atmospheric pressure	0.970 atm
Temperature	21.0 °C

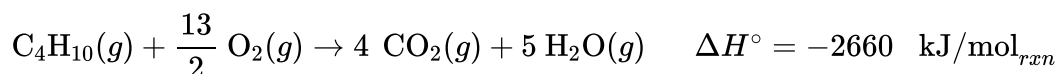
(i) What should the student record for the volume of the gas collected, in mL? _____

(ii) Given that the vapor pressure of water at 21.0 °C is 0.0246 atm, calculate the partial pressure, in atmospheres, of butane collected. Assume that the total pressure in the gas-collection tube is equal to the atmospheric pressure in the laboratory.

(iii) Calculate the number of moles of butane gas in the gas-collection tube.

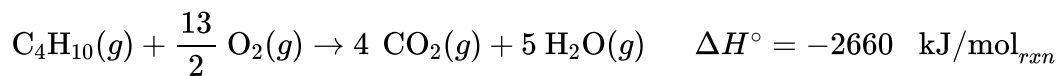
(b) The student then incorrectly determines the molar mass of butane by dividing the initial mass of the container with butane (25.012 g) by the number of moles of butane calculated in part (a)(iii). Assuming that the number of moles calculated in part (a)(iii) is accurate, describe how to correct the student's calculation.

Butane undergoes combustion according to the following balanced equation.



(c) Which species undergoes reduction in the combustion reaction? Justify your answer with oxidation numbers.

(d) Determine the sign of the entropy change for the reaction. Use particle reasoning to justify your answer.



(e) A student combusts 9.29×10^{-4} mol of butane as shown in the preceding equation in a calorimeter containing 100.0 g of water.

(i) Calculate the heat, in J, released during the combustion of butane.

(ii) Calculate the temperature change of the water in the calorimeter. (Assume that the calorimeter is perfectly insulated and all the heat released by the combustion of butane is transferred to the 100.0 g sample of water.) The specific heat capacity of water is 4.18 J/(g·°C).

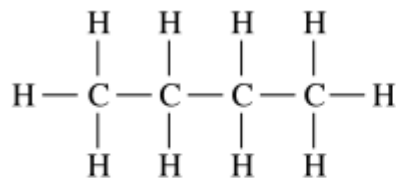
The student repeats the calorimetry experiment under the same conditions, replacing the butane with an equimolar amount of propane. The following reaction occurs.



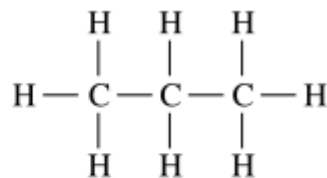
(f) Predict whether the change in temperature observed during the combustion would be greater than, less than, or

2023 Form I

equal to the change in part (e)(ii). Justify your answer.



Butane



Propane

(g) The Lewis diagrams for butane and propane are shown above. Both compounds exhibit London dispersion attractive forces. Explain why the London dispersion forces between molecules of butane are stronger than those between molecules of propane.

Part A(i)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct answer.

- 44.11mL

Part A(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct calculated value with the correct number of decimal places (thousandths).

- $0.970 \text{ atm} - 0.0246 \text{ atm} = 0.945 \text{ atm}$

Part A(iii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

2023 Form I



0	1
---	---

The response provides the correct calculated value consistent with A(i) and A(ii).

- $n = \frac{PV}{RT} = \frac{(0.945 \text{ atm})(0.04411 \text{ L})}{(0.08206 \frac{\text{L}\cdot\text{atm}}{\text{mol}\cdot\text{K}})(294 \text{ K})} = 1.73 \times 10^{-3} \text{ mol C}_4\text{H}_{10}$
- $25.012 \text{ g} - 24.911 \text{ g} = 0.101 \text{ g C}_4\text{H}_{10} \times \frac{1 \text{ mol}}{58.12 \text{ g}} = 1.74 \times 10^{-3} \text{ mol C}_4\text{H}_{10}$

Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct answer.

- The student should use the difference between the initial and final mass of the butane container, not the initial mass.

Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct answer and a valid justification.

- Oxygen. The oxidation number reduces from to -2 .

Part D

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct answer and a valid justification.

2023 Form I

- Positive. There is a greater number of moles of gaseous particles in the products than in the reactants. The products have greater dispersal (a larger number of possible microstates) than the reactants, thus, $\Delta S^\circ > 0$.

Part E(i)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct calculated value (sign not required)

$$\bullet \quad q_{sys} = 9.29 \times 10^{-4} \text{ mol C}_4\text{H}_{10} \times \frac{1 \text{ mol}_{rxn}}{1 \text{ mol C}_4\text{H}_{10}} \times \frac{-2660 \text{ kJ}}{1 \text{ mol}_{rxn}} = -2.47 \text{ kJ}$$

$$= -2470 \text{ J}$$

Part E(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct calculated value with the correct sign.

$$q_{surr} = -q_{sys} = +2470 \text{ J}$$

$$\bullet \quad q_{surr} = mc\Delta T$$

$$\Delta T = \frac{q_{surr}}{mc} = \frac{+2470 \text{ J}}{(100.0 \text{ g})(4.18 \frac{\text{J}}{\text{g}^\circ\text{C}})} = +5.91^\circ\text{C} = 5.91^\circ\text{C}$$

Part F

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct answer and a valid explanation.

- Less than. Propane releases less energy per mole of reaction, so a smaller quantity of heat is released, resulting in a smaller change in temperature.

OR

2023 Form I

•
$$q_{sys} = 9.29 \times 10^{-4} \text{ mol C}_3\text{H}_8 \times \frac{1 \text{ mol}_{rxn}}{1 \text{ mol C}_3\text{H}_8} \times \frac{-2040 \text{ kJ}}{1 \text{ mol}_{rxn}} = -1.90 \text{ kJ}$$
$$= -1900 \text{ J}$$

Propane releases less energy, so the temperature change will be smaller.

Part G

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response does not provide the correct answer and a valid justification.

- Butane molecules have more electrons and larger, more polarizable electron clouds than propane molecules have, so butane molecules experience greater London dispersion forces.

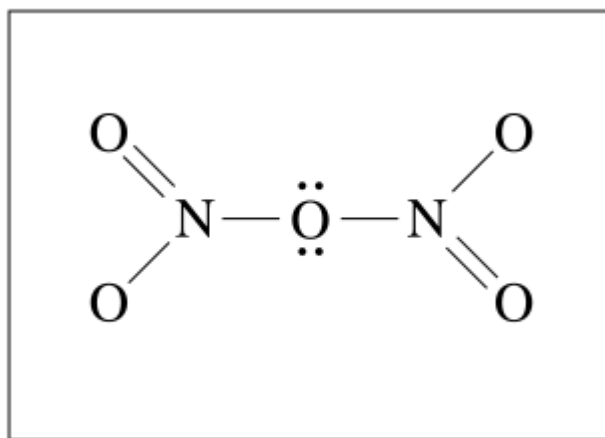
2023 Form I

63. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

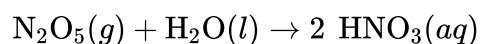
Answer the following questions related to N_2O_5 and HNO_3 .

- (a) An incomplete Lewis diagram for N_2O_5 is shown. Draw all of the remaining nonbonding electrons on the diagram.



- (b) Based on VSEPR theory and the molecular geometry around the central O atom, what is the predicted $\text{N} - \text{O} - \text{N}$ bond angle?

When $\text{N}_2\text{O}_5(g)$ is added to water, $\text{HNO}_3(aq)$ is formed according to the following equation.



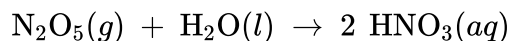
Thermodynamic data for the reaction at 298 K are given in the following table.

ΔH°	$-140. \text{ kJ} / \text{mol}_{rxn}$
ΔS°	$-124 \text{ J} / (\text{K} \cdot \text{mol}_{rxn})$

- (c) Calculate the value of ΔG° , in $\text{kJ} / \text{mol}_{rxn}$, at 298 K.
- (d) A student claims that lowering the temperature makes the value of ΔG° more negative. Do you agree or

2023 Form I

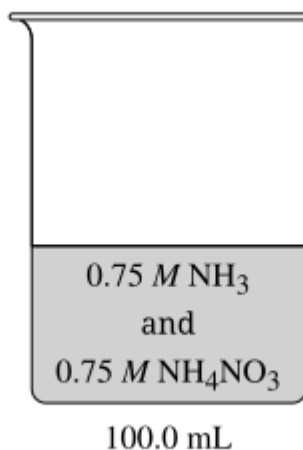
disagree? Justify your answer.



(e) Enough $\text{N}_2\text{O}_5(g)$ is added to distilled water to make 350. mL of $\text{HNO}_3(aq)$, as shown in the preceding equation. The resulting solution has a pH of 1.62.

(i) Calculate the value of $[\text{H}_3\text{O}^+]$ in the solution.

(ii) Assuming the $\text{HNO}_3(aq)$ is produced with 100% yield, calculate the mass of $\text{N}_2\text{O}_5(g)$ (molar mass 108.02 g/mol) that was added in part (e).



(f) A buffer solution is prepared in a beaker as shown. Calculate the pH of the solution in the beaker. The K_a of NH_4^+ is 5.6×10^{-10} .

(g) Four students are each given a different beaker containing 100.0 mL of a solution that contains 0.75 M NH_3 and 0.75 M NH_4NO_3 . Each student adds a different amount of 1.0 M HNO_3 and then correctly measures the pH of their solution, as shown in the following table.

Student	Volume of Buffer (mL)	Amount of HNO_3 Added (mL)	pH after HNO_3 Addition
A	100.0	20.	9.01
B	100.0	40.	8.73
C	100.0	60.	8.30
D	100.0	80.	1.56

(i) Write a balanced net ionic equation for the reaction that occurs when a small amount of HNO_3 is added to Student A's buffer solution.

2023 Form I

(ii) What evidence in the data table indicates that the buffer capacity is exceeded only in the solution prepared by Student D?

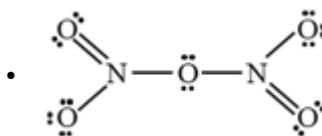
Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct diagram.



Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides a correct answer.

- A bond angle in the range $104^\circ - 114^\circ$

Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct calculated value.

- $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$

$$\Delta G^\circ = \frac{-140. \text{ kJ}}{1 \text{ mol}_{rxn}} - (298 \text{ K}) \left(\frac{-124 \text{ J}}{\text{K} \cdot \text{mol}_{rxn}} \right) \left(\frac{1 \text{ kJ}}{1000 \text{ J}} \right)$$

2023 Form I

$$\Delta G^\circ = -103 \text{ kJ/mol}_{rxn}$$

Part D

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct answer and/or a valid justification.

- Agree. The sign of ΔS° is negative, so in the equation $\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$, the value of ΔG° will become more negative as temperature decreases (the term $-T\Delta S^\circ$ becomes a smaller positive value added to the negative value of ΔH°).

Part E(i)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct calculated value.

- $\text{pH} = -\log [\text{H}_3\text{O}^+]$
 $[\text{H}_3\text{O}^+] = 10^{-1.62} = 2.4 \times 10^{-2} M = 0.024 M$

Part E(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1	2
---	---	---

The response meets **both** of the following criteria.

- ☐ The response provides the correct calculated value of moles, consistent with part E(i).

$$[\text{H}_3\text{O}^+] = [\text{HNO}_3] = 0.024 M$$

$$0.350 \text{ L} \times \frac{0.024 \text{ mol HNO}_3}{1 \text{ L}} = 0.0084 \text{ mol HNO}_3$$

- ☐ The response provides the correct calculated value of grams.

2023 Form I

$$\circ \quad 0.0084 \text{ mol HNO}_3 \times \frac{1 \text{ mol N}_2\text{O}_5}{2 \text{ mol HNO}_3} \times \frac{108.02 \text{ g N}_2\text{O}_5}{1 \text{ mol N}_2\text{O}_5} = 0.45 \text{ g N}_2\text{O}_5$$

Part F

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct calculated value.

- $\text{p}K_a = -\log(K_a) = -\log(5.6 \times 10^{-10}) = 9.25$

$$\text{pH} = \text{p}K_a + \log\left(\frac{[\text{NH}_3]}{[\text{NH}_4^+]}\right) = 9.25 + \log\left(\frac{0.75}{0.75}\right) = 9.25$$

OR

- Because $[\text{NH}_3] = [\text{NH}_4^+]$, $\text{pH} = \text{p}K_a = -\log(K_a) = -\log(5.6 \times 10^{-10}) = 9.25$

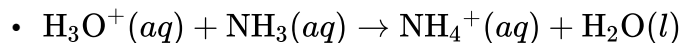
Part G(i)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

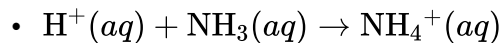


0	1
---	---

The response provides a correct balanced equation.



OR



Part G(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

2023 Form I

The response provides the correct answer.

- The pH in D is significantly lower than the similar pH readings in A, B, and C.

64. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

Answer the following questions about atomic structure and bonding.

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

(b) The Rb^+ ion has the same electron configuration as the neutral Kr atom. Which has the larger radius, the Rb^+ ion or the Kr atom? Justify your answer in terms of Coulomb's law.

(c) The composition of a sample of solid Rb containing a high percentage of the radioactive isotope Rb-83 is given in the following table.

Isotope	Isotopic Mass (amu)	Percentage of Sample	Isotope Half-Life
Rb - 83	82.92	32.5%	86 days
Rb-85	84.91	50.8%	stable
Rb-87	86.91	16.7%	stable

(i) Using the values in the table, calculate the average atomic mass, in amu, of Rb in the sample.

(ii) Rb-83 undergoes radioactive decay into gaseous Kr-83, which leaves the solid sample. Over time, how will the average atomic mass of the remaining sample compare to the value calculated in part (c)(i) ?

Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



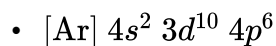
0	1
---	---

The response provides a correct answer.

- $1s^2 2s^2 2p^6 3s^2 3p^6 4s^2 3d^{10} 4p^6$

2023 Form I

OR



Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct answer and a valid justification.

- The Kr atom. The outermost electrons of and Kr occupy the same shell Rb^+ , but Kr has one less proton, resulting in a weaker Coulombic attraction between the Kr nucleus and its electrons; therefore, Kr has a larger radius than Rb^+ .

Part C(i)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct calculated value.

- $0.325(82.92) + 0.508(84.91) + 0.167(86.91) = 84.6 \text{ amu}$

Part C(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct answer.

- The average atomic mass will increase over time.

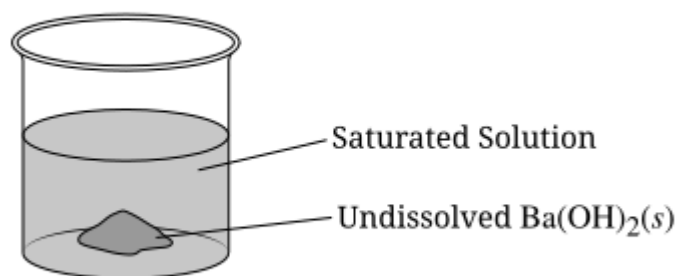
2023 Form I

65. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

To determine the value of the solubility product constant, K_{sp} , a student prepares a saturated solution by dissolving $\text{Ba}(\text{OH})_2(s)$ in water. The K_{sp} expression is $K_{sp} = [\text{Ba}^{2+}][\text{OH}^-]^2$.

- (a) Write the balanced equation for the dissociation reaction that is consistent with the K_{sp} expression.
- (b) The student determines that the solubility of $\text{Ba}(\text{OH})_2(s)$ is 18.5 g/L at 25 °C.
- (i) Calculate the molar solubility of $\text{Ba}(\text{OH})_2(s)$ in mol/L at 25 °C.
- (ii) Calculate the value of K_{sp} for $\text{Ba}(\text{OH})_2(s)$ at 25 °C.



- (c) The student creates a saturated solution of $\text{Ba}(\text{OH})_2$ in water, as shown in the diagram. The student claims that the amount of undissolved $\text{Ba}(\text{OH})_2(s)$ will decrease when $\text{HNO}_3(aq)$ is added. Do you agree or disagree with the student's claim? Justify your answer with a comparison of Q and K_{sp} .

Part A

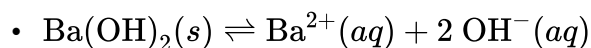
Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

2023 Form I



0	1
---	---

The response provides the correct balanced equation (state symbols not required).

**Part B(i)**

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct calculated value.

- $\frac{18.5 \text{ g}}{1 \text{ L}} \times \frac{1 \text{ mol}}{171.35 \text{ g}} = 0.108 \text{ mol/L}$

Part B(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides the correct calculated value, consistent with part B(i).

- $K_{sp} = [\text{Ba}^{2+}][\text{OH}^-]^2 = (s)(2s)^2 = 4s^3 = 4(0.108)^3 = 5.04 \times 10^{-3}$

Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

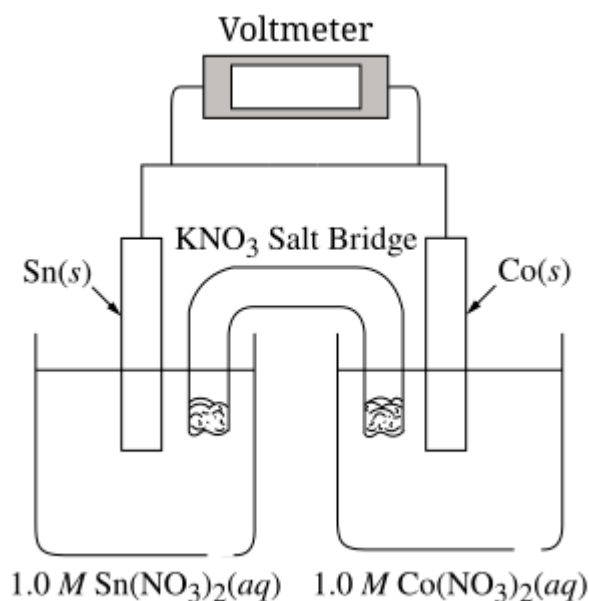
The response provides the correct answer and a valid justification.

- Agree. The H_3O^+ from the HNO_3 solution would react with OH^- , which would decrease $[\text{OH}^-]$, make $Q_{sp} < K_{sp}$, and result in greater dissolution of $\text{Ba}(\text{OH})_2(s)$.

2023 Form I

66. For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.



A student sets up a galvanic cell with one half-cell made with a tin electrode and a Sn^{2+} solution and the second half-cell made with a cobalt electrode and a Co^{2+} solution, as shown. The salt bridge contains $\text{KNO}_3(aq)$.

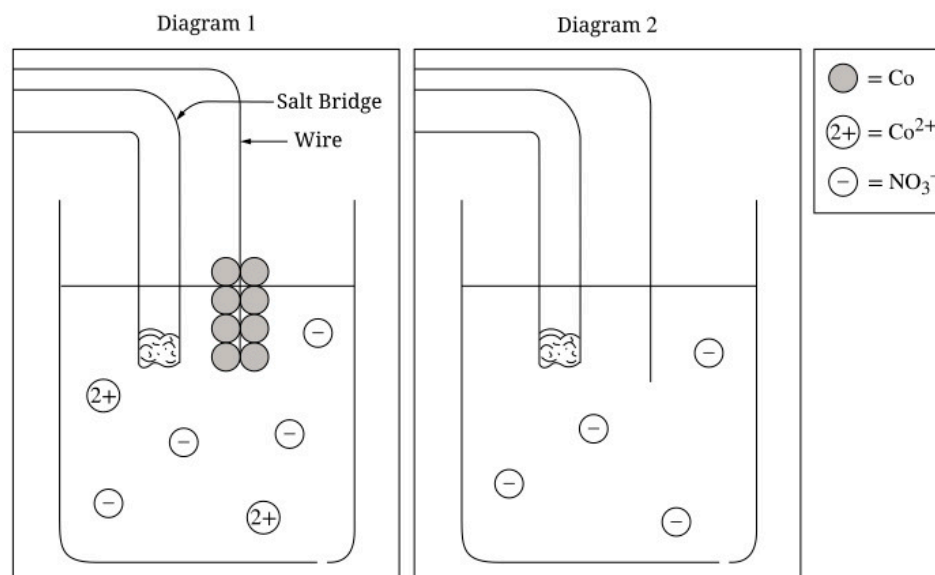
- (a) The following table provides standard reduction potentials.

Half-Reaction	E° (V)
$\text{Sn}^{2+} + 2e^- \rightarrow \text{Sn}$	-0.138
$\text{Co}^{2+} + 2e^- \rightarrow \text{Co}$	-0.277

- (i) Given the balanced equation $\text{Sn}^{2+} + \text{Co} \rightarrow \text{Sn} + \text{Co}^{2+}$, determine the standard cell potential, E°_{cell} .
- (ii) Is the value of ΔG° for the overall electrochemical reaction greater than, less than, or equal to zero? Justify your answer based on the value of E°_{cell} .
- (b) A representation of the cobalt half-cell before the reaction starts is shown in diagram 1. The student observes that as the cell operates, the solution becomes a darker shade of pink. In diagram 2, complete the representation of

2023 Form I

the cobalt half-cell after the cell has operated for a short time. Be sure that mass is conserved. The balance of charge is not necessary, and all species may not need to be shown in the drawing.



(c) A second galvanic cell is constructed such that $[\text{Sn}^{2+}] = 1.0\text{ M}$ and $[\text{Co}^{2+}] = 0.20\text{ M}$. How does the cell potential of this second galvanic cell compare to the cell potential of the first cell?

Part A(i)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0

1

The response provides the correct calculated value.

$$\bullet E_{\text{cell}}^{\circ} = -0.138\text{ V} - (-0.277\text{ V}) = 0.139\text{ V}$$

Part A(ii)

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

2023 Form I



0	1
---	---

The response provides the correct answer and a valid justification, consistent with part A(i).

- Less than zero. Because E_{cell}° is positive, the reaction is thermodynamically favorable, and ΔG° must be negative.

OR

- Based on the equation, $\Delta G^{\circ} = -nFE^{\circ}$ if E_{cell}° is positive, then ΔG° must be negative.

Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.

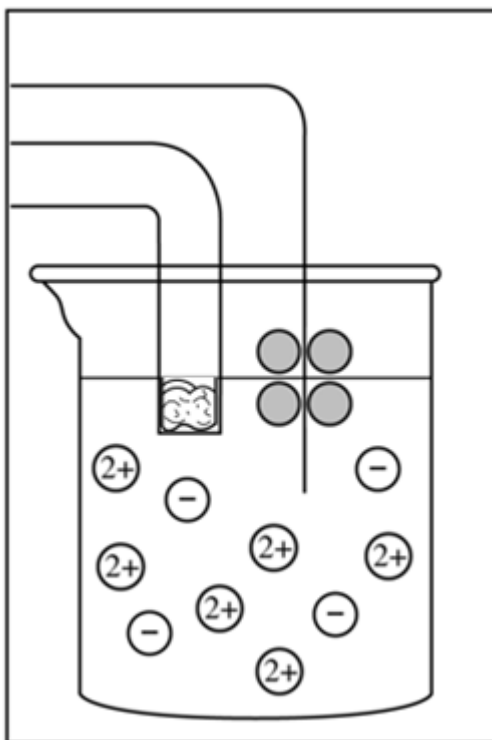


0	1
---	---

The response provides a correct drawing.

- The drawing should show a decrease in the number of Co particles on the electrode and a matching increase in the number of Co^{2+} ions.

2023 Form I



Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0

1

The response provides a correct answer.

- The cell potential will be higher.

OR

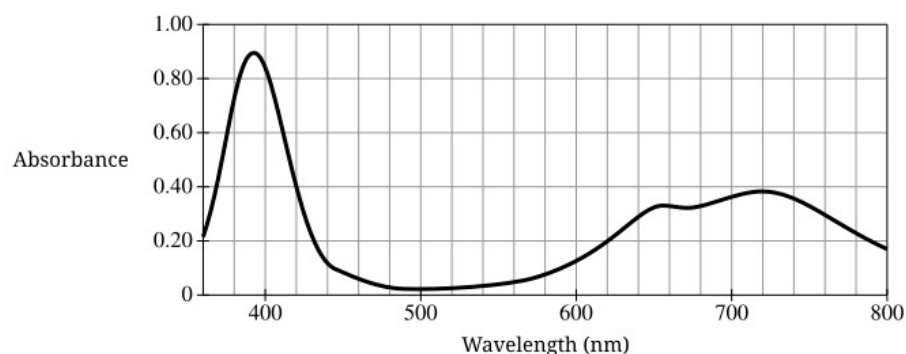
- In the new cell, $Q < 1$, so the value of E_{cell} will be higher than E_{cell}° .

2023 Form I

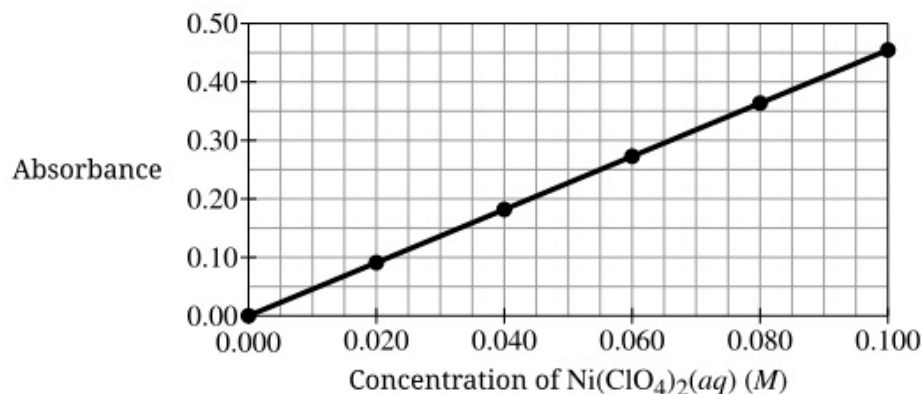
67. For parts of the free response question that require calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit for your answer. Examples and equations may be included in your answers where appropriate.

For parts of the free response question that require 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. Examples and equations may be included in your answers where appropriate.

A student performs a spectrophotometry experiment using solutions of $\text{Ni}(\text{ClO}_4)_2(aq)$. The student needs to make a standard curve and determine the concentration of $\text{Ni}(\text{ClO}_4)_2(aq)$ in a sample with an unknown concentration.

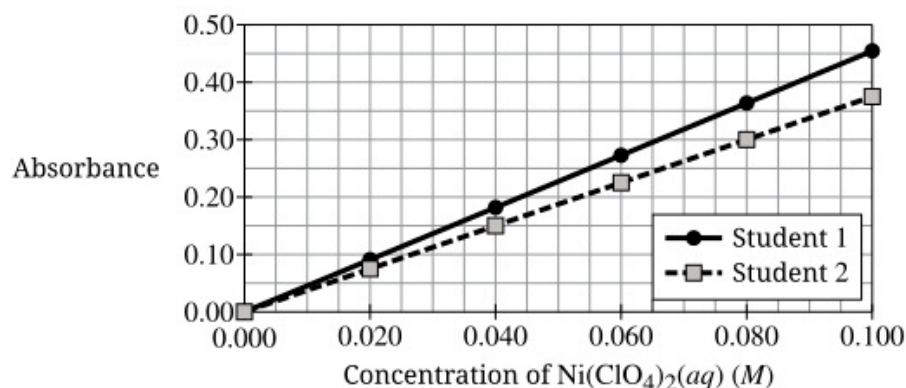


- (a) Based on the absorbance spectrum of $\text{Ni}(\text{ClO}_4)_2(aq)$ shown in the preceding graph, what wavelength should the student use in the experiment to achieve the greatest precision?
- (b) To make the standard curve, the student must prepare $\text{Ni}(\text{ClO}_4)_2(aq)$ solutions with different concentrations. The student has a standard solution of $\text{Ni}(\text{ClO}_4)_2(aq)$ with a concentration of 0.198 M . Calculate the volume, in mL, of 0.198 M $\text{Ni}(\text{ClO}_4)_2(aq)$ that is needed to prepare 250.0 mL of 0.0400 M $\text{Ni}(\text{ClO}_4)_2(aq)$.



2023 Form I

(c) The standard curve generated by the student is provided above. The student measures an absorbance of 0.30 for the unknown solution. Using the standard curve provided, determine the molarity of $\text{Ni}(\text{ClO}_4)_2(aq)$ in the unknown solution.



(d) A second student repeats the procedure using the same spectrophotometer but makes an error, which results in the dashed line shown in the graph above. Assuming that the first student's data (shown by the solid line) are correct, identify one error that could account for the second student's standard curve being less steep than that obtained by the first student.

Part A

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0

1

The response provides a correct answer.

- 391 nm (acceptable range: 385 nm – 395 nm)

Part B

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0

1

The response provides the correct calculated value.

2023 Form I

$$M_1 V_1 = M_2 V_2$$

$$V_2 = \frac{M_1 V_1}{M_2} = \frac{(0.0400 M)(250.0 \text{ mL})}{0.198 M} = 50.5 \text{ mL}$$

Part C

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides a correct value.

- $0.067 M$ (If reading from the graph, acceptable range is $0.065 - 0.068 M$)

OR

$$\frac{0.45}{0.100 M} = \frac{0.30}{x}, x = 0.067 M$$

Part D

Select a point value to view scoring criteria, solutions, and/or examples and to score the response.



0	1
---	---

The response provides a correct answer.

- Student 2 used a lower concentration of $\text{Ni}(\text{ClO}_4)_2(aq)$ (less concentrated stock solution, added too much water, used a wet cuvette, etc.)

OR

- Student 2 used a wavelength other than the wavelength of maximum absorbance.

OR

- Student 2 used a cuvette with a shorter path length.