CHEMISTRY

SECTION I

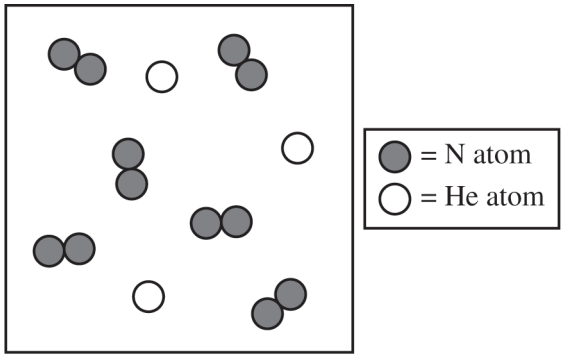
Time—1 hour and 30 minutes

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.

1. The ratio of gases in a mixture of $N_2(g)$ and $He(g)$ is represented by the following particle diagram.



What is the mole fraction of N_2 in this sample of gas?

(A) 0.33
(B) 0.50
(C) 0.67
(D) 0.80

Trial	Completion Time (seconds)
1	37
2	59

2. A student performed an experiment to study the rate of reaction between solid magnesium, $Mg(s)$, and aqueous hydrochloric acid, $HCl(aq)$. The student conducted two trials under different experimental conditions, using 0.10 mol of $Mg(s)$ and 1.00 mol of $HCl(aq)$ in each trial. Which of the following changes in conditions could account for the difference in the time for the reaction to go to completion in trial 1 and trial 2 ?

(A) The mixture of reactants was stirred in trial 2, but not in trial 1.
(B) The temperature of the hydrochloric acid was higher in trial 2.
(C) The concentration of the hydrochloric acid was greater in trial 2.
(D) The solid magnesium was a fine powder in trial 1 but a single chunk in trial 2.

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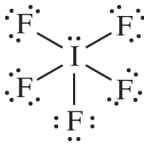
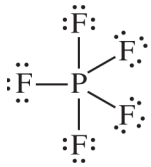
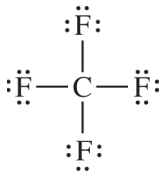
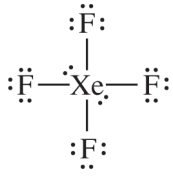
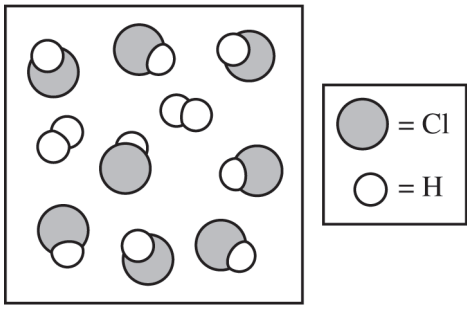
3. Which of the following represents a molecule with a trigonal bipyramidal geometry?

(A) 

(B) 

(C) 

(D) 



4. The diagram represents a mixture that results when samples of $Cl_2(g)$ and $H_2(g)$ are combined and react, producing $HCl(g)$. Which of the following identifies the limiting reactant and provides the best justification?

(A) H_2, because there is unreacted H_2 present.

(B) H_2, because it has a smaller molar mass than Cl_2.

(C) Cl_2, because there is no unreacted Cl_2 present.

(D) Cl_2, because it has a larger molar mass than H_2.

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5. A rigid container holds 0.50 mol of $Ar(g)$ and 0.75 mol of $O_2(g)$. How will the total pressure of the gases in the container and the partial pressure of $O_2(g)$ be affected by the addition of 0.25 mol of $He(g)$ at constant temperature?

   (A) Both the total pressure and the partial pressure of $O_2(g)$ will remain constant.

   (B) Both the total pressure and the partial pressure of $O_2(g)$ will increase.

   (C) The total pressure will increase, and the partial pressure of $O_2(g)$ will decrease.

   (D) The total pressure will increase, and the partial pressure of $O_2(g)$ will remain constant.

6. The ideal gas law best describes the properties of which of the following gases at 0°C and 1 atm ?

   (A) O_2

   (B) CF_4

   (C) SO_2

   (D) SF_6

7. Gallium, Ga, reacts with chlorine gas to produce gallium(III) chloride. When the equation for the reaction is balanced with lowest whole-number coefficients, the coefficient for gallium is

   (A) 1

   (B) 2

   (C) 3

   (D) 4

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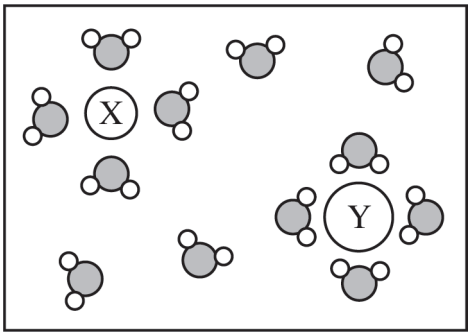

8. The diagram shown represents water molecules () as they interact with two ions, X and Y, in solution. Which of the following best identifies ions X and Y ?

	X	Y
A	Ba^{2+}	Cl^{-}
B	Cl^{-}	S^{2-}
C	S^{2-}	Na^{+}
D	Ba^{2+}	Na^{+}

(A) A
(B) B
(C) C
(D) D

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Reaction 1 : $NH_3(aq) + H^+(aq) \rightarrow NH_4{}^+(aq)$

Reaction 2 : $2\,H_2O_2(l) \rightarrow 2\,H_2O(l) + O_2(g)$

9. Which of the following statements about the reactions represented above is true?

   (A) Reaction 1 cannot be a redox reaction because total charge is conserved.

   (B) Reaction 1 is a redox reaction because the nitrogen atom transfers electrons to the H^+ ion.

   (C) Reaction 2 cannot be a redox reaction because both the reactant and the products have neutral charge.

   (D) Reaction 2 is a redox reaction because there is a transfer of electrons between the oxygen atoms.

10. Which of the following compounds has the strongest Coulombic attractions between its ions in the solid state?

    (A) MgO

    (B) CaO

    (C) $MgCl_2$

    (D) $CaCl_2$

$M(s) + 2\,HCl(aq) \rightarrow MCl_2(aq) + H_2(g)$

11. A student weighs a sample of a group 2 metal, M, and adds it to excess $HCl(aq)$ to react as represented in the equation. The student measures the volume of $H_2(g)$ produced by collecting the gas over water at 1.00 atm and 298 K, and uses the volume to calculate the moles of $H_2(g)$. Which of the following questions is most likely to be answered as a result of the experiment?

    (A) What is the value of ΔH°_{rxn} ?

    (B) What is the density of metal M ?

    (C) What is the molar mass of metal M ?

    (D) What is the value of the specific heat of metal M ?

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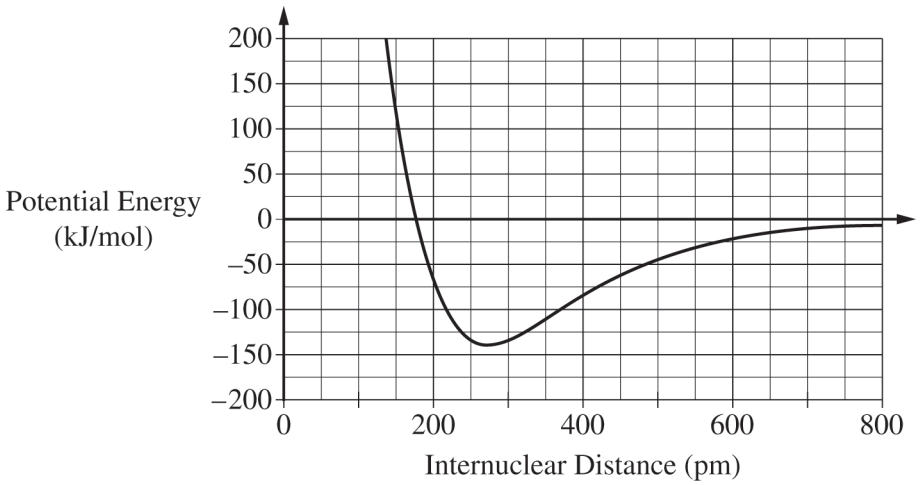

12. The graph shows the potential energy of two atoms as a function of internuclear distance. What is the approximate bond energy?

(A) 140 kJ/mol

(B) 170 kJ/mol

(C) 200 kJ/mol

(D) 270 kJ/mol

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Half-Reaction	$E°$
$Ni^{2+} + 2\ e^- \rightarrow Ni$	−0.28 V
$Fe^{2+} + 2\ e^- \rightarrow Fe$	−0.44 V
$Cr^{3+} + 3\ e^- \rightarrow Cr$	−0.74 V

13. Based on the reduction potentials in the table, which of the following reactions is thermodynamically favorable?

(A) $3\ Ni(s) + 2\ Cr^{3+}(aq) \rightarrow 3\ Ni^{2+}(aq) + 2\ Cr(s)$

(B) $3\ Fe(s) + 2\ Cr^{3+}(aq) \rightarrow 3\ Fe^{2+}(aq) + 2\ Cr(s)$

(C) $3\ Ni^{2+}(aq) + 2\ Cr(s) \rightarrow 3\ Ni(s) + 2\ Cr^{3+}(aq)$

(D) $3\ Fe^{2+}(aq) + 2\ Ni(s) \rightarrow 3\ Fe(s) + 2\ Ni^{2+}(aq)$

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$$2\,HI(g) \rightarrow I_2(g) + H_2(g)$$

14. The decomposition of $HI(g)$ into $I_2(g)$ and $H_2(g)$ is represented by the equation. The reaction is second order with respect to $HI(g)$. Assuming all other conditions are held constant, which initial concentration of $HI(g)$ will result in an initial rate of formation of $H_2(g)$ that is 16 times higher than that in trial 1, as shown in the table?

Trial	Initial [HI]	Rate of Formation of $H_2(g)$
1	0.20 *M*	*x*
2	?	16*x*

(A) 0.40 *M*
(B) 0.80 *M*
(C) 1.6 *M*
(D) 3.2 *M*

15. A pure sample of which of the following compounds has the highest boiling point?

(A) LiCl
(B) Cl_2
(C) PCl_3
(D) CCl_4

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Questions 16 - 18 refer to the following information.

$$CaC_2(s) + 2\ H_2O(l) \rightarrow C_2H_2(g) + Ca(OH)_2(s) \quad \Delta H^\circ = -128\ \text{kJ / mol}_{rxn}$$

When a 0.64 g sample of $CaC_2(s)$ (molar mass 64 g / mol) is added to 100. mL of water at 25°C in a calorimeter, all of the $CaC_2(s)$ reacts with water as represented by the equation.

16. Which of the following is true of the reaction system when 0.64 g of $CaC_2(s)$ reacts?

    (A) 1.3 kJ of energy is absorbed.
    (B) 1.3 kJ of energy is released.
    (C) 82 kJ of energy is absorbed.
    (D) 82 kJ of energy is released.

17. Which of the following statements about the thermodynamic favorability of the reaction at 25°C is correct?

    (A) The high activation energy results in the reaction being thermodynamically unfavorable.
    (B) Only the ΔH° of the reaction contributes to the reaction being thermodynamically favorable.
    (C) Only the ΔS° of the reaction contributes to the reaction being thermodynamically favorable.
    (D) Both the ΔH° and the ΔS° of the reaction contribute to the reaction being thermodynamically favorable.

18. At the completion of the reaction, the pH of the product mixture is measured to be above 7. Which of the following can be concluded from this result?

    (A) $Ca(OH)_2(s)$ is slightly soluble in water.
    (B) $C_2H_2(g)$ is a proton donor.
    (C) $H_2O(l)$ is the limiting reactant.
    (D) The final temperature of the mixture is below 25°C.

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19. Which of the following lists chemical species in order from largest to smallest radius?

(A) $S^{2-} > O > F$

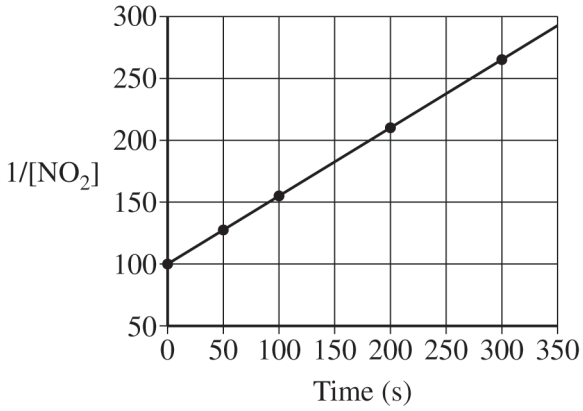
(B) $O > O^{2-} > Ne$

(C) $K^{+} > Ar > Cl$

(D) $Na > Mg^{2+} > Mg$

$$NO_2(g) \rightarrow NO(g) + \frac{1}{2} O_2(g)$$

20. The following graph shows data from an experiment in which $NO_2(g)$ decomposes as represented by the equation.



The graph could be used to support which of the following statements?

(A) The half-life of the reaction is constant.

(B) The magnitude of the rate constant, k, is approximately 10.

(C) The unit of the rate constant, k, is s^{-1}.

(D) The rate law for the reaction is

$rate = k[NO_2]^2$.

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$$CO(g) + 2\,H_2(g) \rightleftarrows CH_3OH(g) \quad \Delta H^\circ = -90\ \text{kJ/mol}_{rxn}$$

21. The system represented by the equation shown is at equilibrium in a rigid container. Which of the following would decrease the amount of the reactant $CO(g)$ in the container?

    (A) Increasing the temperature
    (B) Decreasing the temperature
    (C) Adding $CH_3OH(g)$ to the container
    (D) Removing $H_2(g)$ from the container

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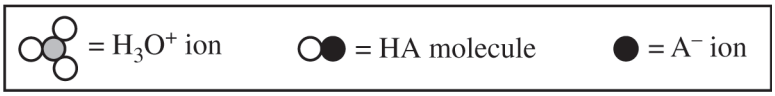
Questions 22 through 25 refer to the following.

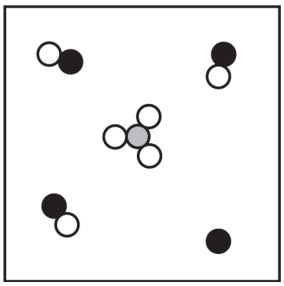
The table contains information about four samples of different monoprotic acids with the general formula HA.

Sample	Volume (mL)	Concentration (M)	pH at 25°C
1	10.0	0.10	1.0
2	5.0	0.10	2.3
3	10.0	0.10	4.7
4	20.0	0.10	2.3

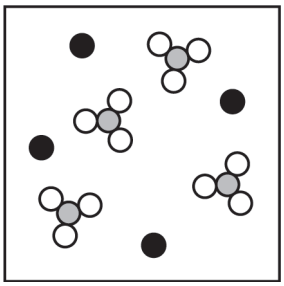
22. Which particle drawing best represents a portion of sample 1 ? (Note that water molecules are omitted.)



(A)



(B)



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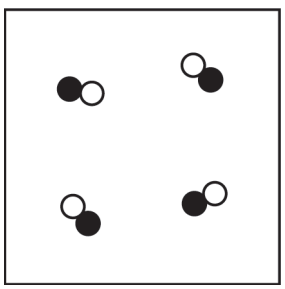

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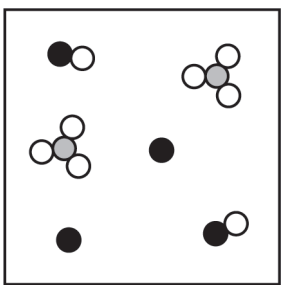

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23. Which sample of acid would require the largest number of moles of NaOH to neutralize it completely?

(A) Sample 1
(B) Sample 2
(C) Sample 3
(D) Sample 4

24. Which sample of acid has the smallest value of K_a ?

(A) Sample 1
(B) Sample 2
(C) Sample 3
(D) Sample 4

25. Which statement correctly explains why the pH value of sample 3 is the greatest?

(A) It has the smallest value of $[H_3O^+]$.
(B) It has the smallest value of $[OH^-]$.
(C) It has the weakest conjugate base.
(D) It is the strongest acid.

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$O_2,\ H_2O,\ C_3H_8,\ CF_4$

26. Of the substances listed above, which has the highest boiling point, and why?

(A) O_2, because its molecules have a double bond between the oxygen atoms.

(B) H_2O, because hydrogen bonds form between its molecules.

(C) C_3H_8, because multiple hydrogen bonds can form between its molecules.

(D) CF_4, because its molecules have the largest dipole moment, since C−F bonds are highly polar.

$$2\ NO(g) + Br_2(g) \rightleftarrows 2\ NOBr(g)$$

27. Which of the following is the expression for the equilibrium constant, K_c, for the reaction represented by the balanced chemical equation shown?

(A) $K_c = \dfrac{[NO][Br_2]}{[NOBr]}$

(B) $K_c = \dfrac{[NOBr]}{[NO][Br_2]}$

(C) $K_c = \dfrac{[NO]^2[Br_2]}{[NOBr]^2}$

(D) $K_c = \dfrac{[NOBr]^2}{[NO]^2[Br_2]}$

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$$\Delta H^\circ = +495 \text{ kJ/mol}_{rxn}$$

28. Which of the following best explains why the enthalpy change of the reaction represented above is positive?

(A) The reaction is endothermic because breaking the O=O bond requires energy.

(B) The reaction is endothermic because breaking the O=O bond releases energy.

(C) The reaction is exothermic because breaking the O=O bond requires energy.

(D) The reaction is exothermic because breaking the O=O bond releases energy.

Mass of metal	15 g
Initial temperature of metal	80.0°C
Mass of water	50. g
Initial temperature of water	18.0°C
Final temperature of water	20.0°C
Specific heat capacity of water	4.18 J /(g · °C)

29. A calorimetry experiment is conducted to determine the specific heat capacity of a metal. Based on the results shown in the table, what is the specific heat capacity of the metal?

(A) 0.042 J / (g · °C)

(B) 0.35 J / (g · °C)

(C) 0.46 J / (g · °C)

(D) 1.39 J / (g · °C)

$$2\ SO_2(g) + O_2(g) \rightleftarrows 2\ SO_3(g)$$
$$K_p = 2.5 \times 10^{-2} \text{ at } 896 \text{ K}$$

30. Samples of $SO_2(g)$, $O_2(g)$, and $SO_3(g)$ are placed in a previously evacuated reaction vessel. In the vessel, initially P_{SO_2} is 4.0 atm, P_{O_2} is 10. atm, and P_{SO_3} is 2.0 atm. If the temperature is held constant, which of the following predicts what will happen to P_{O_2} when the reaction represented above occurs and best explains why?

(A) P_{O_2} will increase, because $K_p < 1$.

(B) P_{O_2} will decrease, because the total number of moles of reactants is less than the number of moles of product, and the reaction will proceed to form more product.

(C) P_{O_2} will decrease, because the initial P_{SO_3} is lowest, and the reaction will proceed in the forward direction.

(D) P_{O_2} will not change, because the system is already at equilibrium.

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$$2\,PCl_3(g) + O_2(g) \rightarrow 2\,POCl_3(g)$$

31. At 398 K the reaction shown has a ΔH° of -543 kJ / mol_{rxn} and a ΔS° of -178 J / (K $\cdot$ mol_{rxn}). The reaction is run at both 398 K and 798 K. Which of the following correctly identifies the thermodynamic favorability for the reaction at the two temperatures? (Assume that ΔH° and ΔS° do not change with temperature.)

	At 398 K	At 798 K
A	Unfavorable	Favorable
B	Unfavorable	Unfavorable
C	Favorable	Favorable
D	Favorable	Unfavorable

(A) A
(B) B
(C) C
(D) D

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32. A student determines the concentration of an $NaBr(aq)$ solution by adding $AgNO_3(aq)$ until no more $AgBr(s)$ precipitate is formed. The precipitate is filtered out of the solution and then dried and weighed. The student uses the mass of the precipitate to determine the concentration of the $NaBr(aq)$ solution. Which of the following could result in the student calculating a concentration of $NaBr(aq)$ that is higher than the actual concentration?

(A) The $AgBr(s)$ was not completely dried before being weighed.
(B) Some of the $AgBr(s)$ fell off the filter paper onto the balance while being weighed.
(C) An insufficient amount of $AgNO_3(aq)$ was added, so some $NaBr(aq)$ was left in solution.
(D) The filter paper had a hole in it, and some of the $AgBr(s)$ precipitate washed through the filter paper.

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$$C_2H_5Cl(g) \rightarrow C_2H_4(g) + HCl(g)$$

33. A scientist performed two trials in a study of the decomposition reaction of compound C_2H_5Cl, represented by the equation shown. Based on the data table below, which of the following outcomes will provide the best evidence that the decomposition reaction is first order?

	$[C_2H_5Cl]_0$	Initial Rate	Half-Life
Trial 1	1.0 *M*	R_1	t_1
Trial 2	2.0 *M*	R_2	t_2

(A) $R_2 = R_1,\ t_2 = t_1$
(B) $R_2 = R_1,\ t_2 \neq t_1$
(C) $R_2 \neq R_1,\ t_2 = t_1$
(D) $R_2 \neq R_1,\ t_2 \neq t_1$

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34. $N_2(g)$ reacts with $F_2(g)$ in a sealed, rigid container to produce $NF_3(g)$ according to the following balanced equation.

$$N_2(g) + 3\,F_2(g) \rightarrow 2\,NF_3(g)$$

The $N_2(g)$ had an initial partial pressure of 1.00 atm, and the $F_2(g)$ had an initial partial pressure of 1.80 atm. Assuming that the reaction goes to completion and the temperature remains constant, what is the maximum partial pressure of $NF_3(g)$ that could be produced?

(A) 0.50 atm

(B) 1.20 atm

(C) 2.00 atm

(D) 2.80 atm



Structure 1 Structure 2

35. Both structure 1 and structure 2 shown are needed to describe the N_2O molecule. Which of the following indicates the better resonance structure and best explains why? (Formal charges are provided in circles on the diagrams.)

(A) Structure 1, because it has two double bonds and is therefore more symmetrical.

(B) Structure 1, because the negative formal charge is on the more electronegative element.

(C) Structure 2, because the triple bond between the two nitrogen atoms is stronger than the double bond.

(D) Structure 2, because the negative formal charge is on the more electronegative element.

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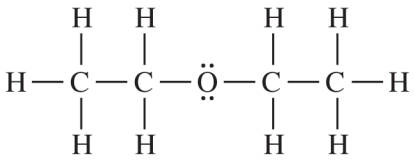
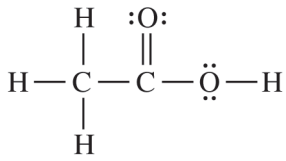
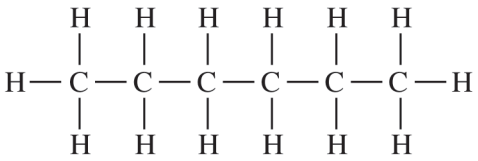
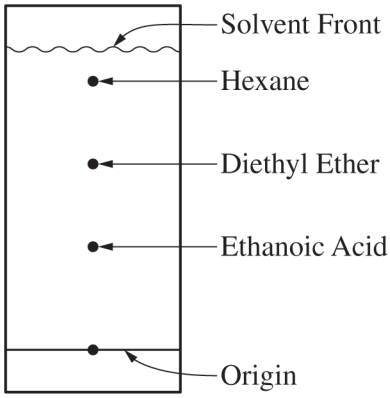
Diethyl Ether	Ethanoic Acid	Hexane
		



36. A mixture of diethyl ether, ethanoic acid, and hexane is separated using a thin-layer chromatography experiment. The Lewis diagrams of the compounds in the mixture and the results of the experiment are shown. A student determines the identity of the compound in each spot shown. Based on this information, which of the following conclusions can be drawn about the polarity of the stationary phase and mobile phase used in this experiment?

	Stationary Phase	Mobile Phase
A	Nonpolar	Polar
B	Nonpolar	Nonpolar
C	Polar	Polar
D	Polar	Nonpolar

(A) A
(B) B
(C) C
(D) D

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37. CHF_3 has a normal boiling point of −82.1°C, and $CHCl_3$ has a normal boiling point of 61.2°C. Which of the following best helps to explain why $CHCl_3$ has a higher boiling point?

(A) $CHCl_3$ has dipole-dipole forces, but CHF_3 does not.

(B) $CHCl_3$ experiences hydrogen bonding, but CHF_3 does not.

(C) $CHCl_3$ has stronger London dispersion forces than CHF_3 does.

(D) $CHCl_3$ has stronger covalent bonds than CHF_3 does.

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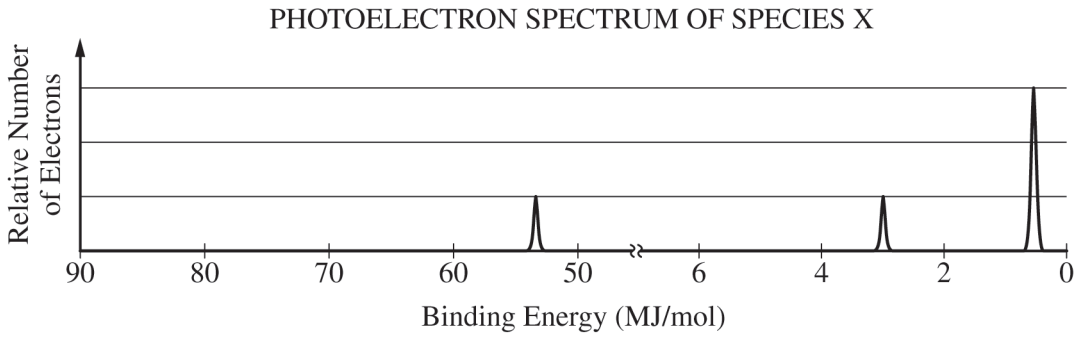

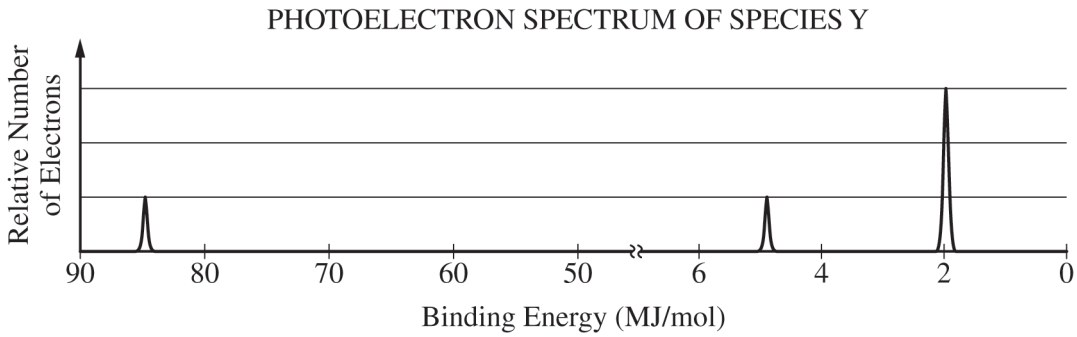

38. The complete photoelectron spectra for two species, X and Y, are represented above. One of the species is a neutral atom and the other species is a negatively charged ion. Both species have the same electron configuration. Which of the following can be inferred from the spectra?

(A) X has a larger nuclear charge than Y has; therefore, X is neutral and Y is negatively charged.

(B) X has a larger nuclear charge than Y has; therefore, Y is neutral and X is negatively charged.

(C) X has a smaller nuclear charge than Y has; therefore, X is neutral and Y is negatively charged.

(D) X has a smaller nuclear charge than Y has; therefore, Y is neutral and X is negatively charged.

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Container	A	B	C	D
Pressure	2.0 atm	1.0 atm	1.5 atm	3.0 atm
Temperature	200 K	300 K	300 K	200 K
Volume	1.0 L	2.0 L	1.0 L	0.50 L

39. Four containers each hold a sample of $O_2(g)$. Based on the information in the table, which container has the largest number of $O_2(g)$ molecules?

(A) A
(B) B
(C) C
(D) D

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Compound	Lattice Enthalpy (kJ/mol)
LiF	1030
LiCl	834
$MgCl_2$	2510
$SrCl_2$	2127

40. Lattice enthalpy can be defined as the $\Delta H°$ associated with the separation of a solid crystal into gaseous ions. Which of the following statements about lattice enthalpy is consistent with the information in the table above?

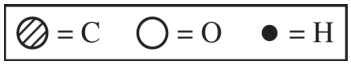
(A) It increases with the increasing radii of the ions in the compound.

(B) It increases with the decreasing radii of the ions in the compound.

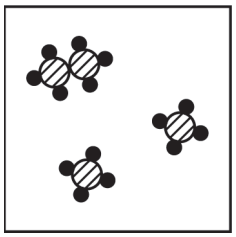
(C) It increases with the decreasing charge of the ions.

(D) It increases with the decreasing electronegativity of the atoms.

41. Which of the following samples contains the greatest percentage of carbon by mass?



(A)



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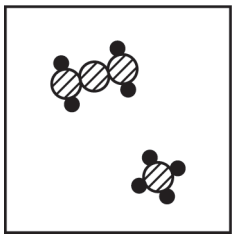
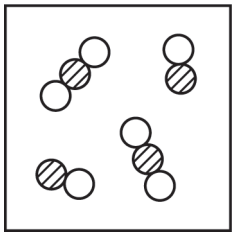
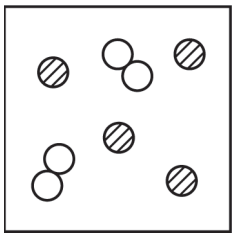


(C)



(D)



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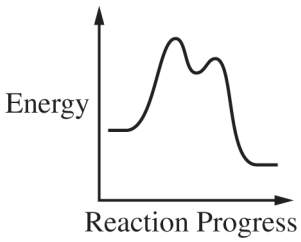
42. The reaction $NO_2 + CO \rightarrow NO + CO_2$ is exothermic. A proposed mechanism for this reaction is shown.

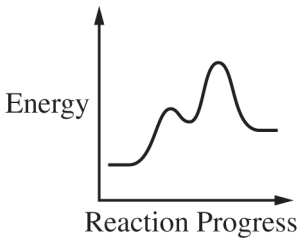
$$NO_2 + NO_2 \rightarrow NO_3 + NO \ (slow)$$
$$NO_3 + CO \rightarrow NO_2 + CO_2 \ (fast)$$

Which of the following energy profiles is most consistent with the exothermic nature of the reaction and the proposed mechanism?

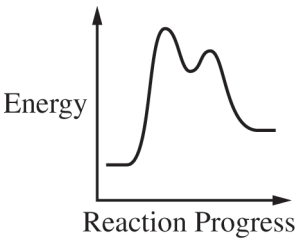
(A)



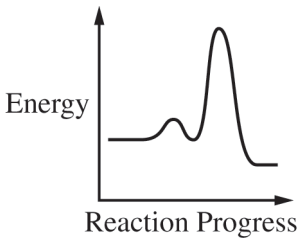
(B)



(C)



(D)



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43. Which of the following processes results in a decrease in entropy of a system?

(A) A pot of water is boiled.
(B) Water is frozen into ice cubes.
(C) Carbon dioxide gas is released from a pressurized container into the atmosphere.
(D) A container of pressurized carbon dioxide is heated to a higher temperature.

$C_2H_5OH(l) + 3\ O_2(g) \rightarrow 2\ CO_2(g) + 3\ H_2O(l) \quad \Delta H° = -1368\ \text{kJ/mol}_{rxn}$

44. Based on the reaction and data table shown, what is the value of ΔH_f° of $C_2H_5OH(l)$?

Substance	ΔH_f° (kJ / mol)
$CO_2(g)$	−394
$H_2O(l)$	−286
$O_2(g)$	0

(A) −688 kJ / mol
(B) −278 kJ / mol
(C) 278 kJ / mol
(D) 688 kJ / mol

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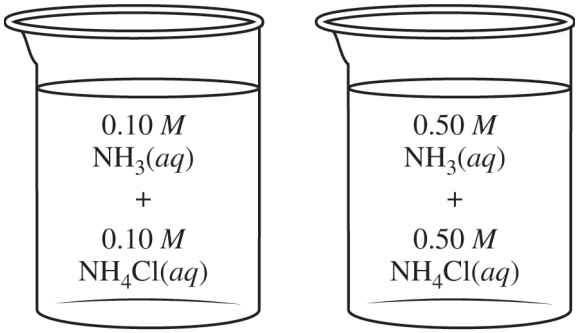


Buffer X Buffer Y

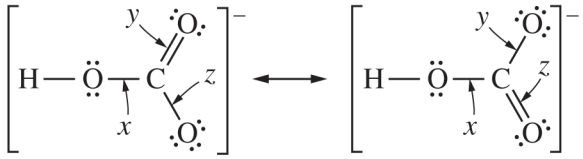
45. Two buffers are represented in the diagram. How do the pH and buffer capacity of buffer X compare to those of buffer Y ?

(A) Buffer X has the same pH as buffer Y and a smaller buffer capacity than buffer Y.

(B) Buffer X has the same pH as buffer Y and the same buffer capacity as buffer Y.

(C) Buffer X has a lower pH than buffer Y and a smaller buffer capacity than buffer Y.

(D) Buffer X has a higher pH than buffer Y and a larger buffer capacity than buffer Y.



46. The two primary resonance structures for HCO_3^- are shown. What are the relative lengths of the carbon-to-oxygen bonds in this ion?

(A) Bonds y and z are equal in length and longer than bond x.

(B) Bonds y and z are equal in length and shorter than bond x.

(C) Bonds x and z are equal in length and longer than bond y.

(D) All three bonds are equal in length.

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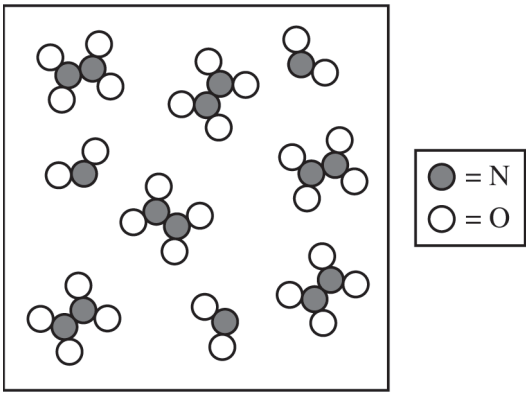


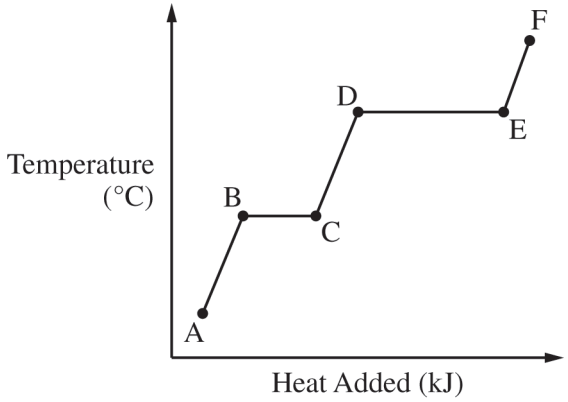
47. The particle diagram shown represents a mixture of NO_2 and N_2O_4 at equilibrium according to the reaction $2\ NO_2(g) \rightleftarrows N_2O_4(g)$. Which of the following is the value of K_p for the reaction? (Assume that each particle represents a partial pressure of 1.0 atm for that substance.)

(A) 0.50
(B) 0.67
(C) 1.5
(D) 2.0

48. Which of the following compounds would be most effective in decreasing the pH when added to a sample of water that has a pH of 10.3 ?

(A) KCl
(B) $NaNO_3$
(C) NH_4NO_3
(D) $NaC_2H_3O_2$

49. A pure substance begins as a solid at point A and is heated at a constant rate. Which of the following best describes the process occurring from point B to point C on the heating curve shown?



(A) The average kinetic energy of the particles in the system is increasing as the substance melts.
(B) The average kinetic energy of the particles in the system is increasing as the substance boils.
(C) The potential energy of the particles in the system is increasing as the substance melts.
(D) The potential energy of the particles in the system is increasing as the substance boils.

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Substance	Cl_2	I_2
Boiling point (K)	239	457

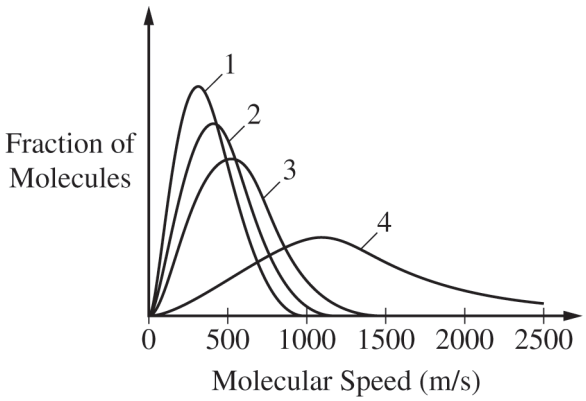
50. The boiling points of two diatomic elements are listed in the table shown. Which statement best explains the observed difference in the boiling points?

(A) Iodine has the larger electron cloud, so molecules of I_2 are more polarizable.

(B) Iodine has the lower electronegativity, so molecules of I_2 are more polar.

(C) Chlorine has the smaller atomic radius, so molecules of Cl_2 contain weaker bonds.

(D) Chlorine has the higher electronegativity, so molecules of Cl_2 are more polar.



51. The curves in the figure above represent the distribution of the molecular speeds for the gases H_2, O_2, N_2, and CH_4 at the same temperature. Which curve corresponds to the distribution for CH_4 ?

(A) 1

(B) 2

(C) 3

(D) 4

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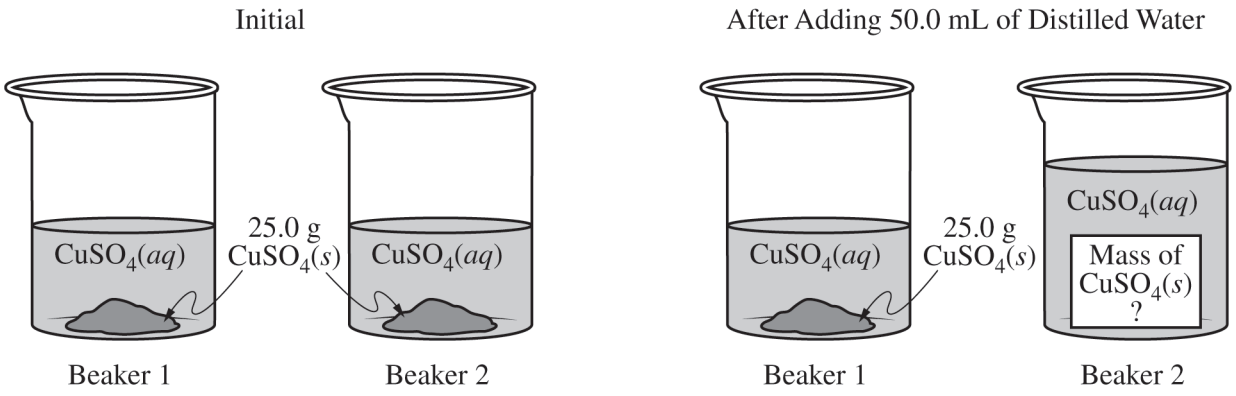

52. Beaker 1 and beaker 2 each contain 100.0 mL of saturated $CuSO_4(aq)$ and 25.0 g of undissolved $CuSO_4(s)$. A 50.0 mL sample of distilled water is added to beaker 2, the contents are stirred for several minutes, and $CuSO_4(s)$ is observed at the bottom of the beaker. After stirring, which of the following is true about the contents of the beakers? (Assume temperature remains constant.)

(A) The concentration of $CuSO_4(aq)$ in beaker 2 is less than in beaker 1.

(B) The concentration of $CuSO_4(aq)$ in beaker 2 is greater than in beaker 1.

(C) The mass of undissolved $CuSO_4(s)$ in beaker 2 is less than in beaker 1.

(D) The mass of undissolved $CuSO_4(s)$ in beaker 2 is greater than in beaker 1.

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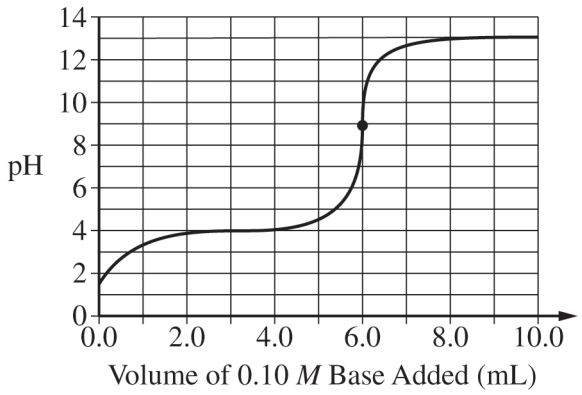
Questions 53 through 55 refer to the following.

The curve shows the results of an acid-base titration.



53. Which of the following is closest to the pK_a of the acid for which the titration curve is shown?

(A) 2
(B) 4
(C) 8
(D) 13

54. In addition to the information provided in the titration curve, what other value is needed to determine the concentration of the acid used in the titration?

(A) The molar mass of the acid
(B) The density of the acid
(C) The volume of the acid
(D) The initial temperature of the acid

55. Which of the following molecular equations could represent the reaction used to generate the titration curve?

(A) $H_3PO_4(aq) + 3\,LiOH(aq) \rightarrow 3\,H_2O(l) + Li_3PO_4(aq)$
(B) $HCl(aq) + KOH(aq) \rightarrow H_2O(l) + KCl(aq)$
(C) $HF(aq) + NaOH(aq) \rightarrow H_2O(l) + NaF(aq)$
(D) $HNO_3(aq) + NH_3(aq) \rightarrow NH_4NO_3(aq)$

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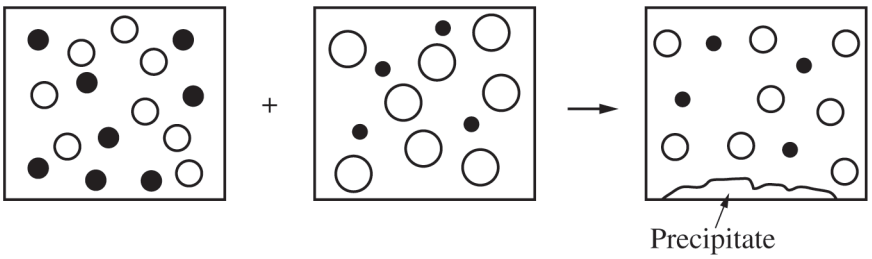

Key
● Positive ions in aqueous solution
○ Negative ions in aqueous solution

56. Which of the following chemical changes is best represented by the particle diagram shown? (Water molecules are omitted for clarity.)

(A) $2\ AgNO_3(aq) + MgI_2(aq) \rightarrow 2\ AgI(s) + Mg(NO_3)_2(aq)$

(B) $AgNO_3(aq) + KCl(aq) \rightarrow AgCl(s) + KNO_3(aq)$

(C) $2\ HCl(aq) + Ba(OH)_2(aq) \rightarrow BaCl_2(s) + 2\ H_2O(l)$

(D) $MnSO_4(aq) + K_2S(aq) \rightarrow MnS(aq) + K_2SO_4(aq)$

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57. A reversible reaction at standard conditions has a negative enthalpy change ($\Delta H° < 0$) and a positive entropy change ($\Delta S° > 0$). Which of the following must be true for the equilibrium constant, K, and the standard cell potential, $E°$, for the forward reaction?

	K	$E°$
A	Greater than 1	Positive
B	Greater than 1	Negative
C	Less than 1	Positive
D	Less than 1	Negative

(A) A
(B) B
(C) C
(D) D

58. A 15.0 g sample of $H_2O(l)$ initially at 20.0°C absorbs 4.60 kJ of heat. The final temperature of the $H_2O(l)$ is closest to which of the following? (Assume the specific heat capacity of $H_2O(l)$ is constant at 4.18 J/ (g·°C).)

(A) 20.1°C
(B) 36.5°C
(C) 73.4°C
(D) 93.4°C

59. Which of the following elements has the largest first ionization energy?

(A) Be
(B) Li
(C) Na
(D) Mg

Mass of Isotope	Percent Abundance
185 amu	37%
187 amu	63%

60. A certain element has two naturally occurring isotopes, as shown in the table. The element's average atomic mass is closest to which of the following?

(A) 185.0 amu
(B) 185.6 amu
(C) 186.3 amu
(D) 187.0 amu

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CHEMISTRY

SECTION II

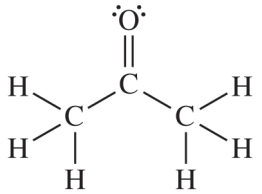
Time—1 hour and 45 minutes

7 Questions

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

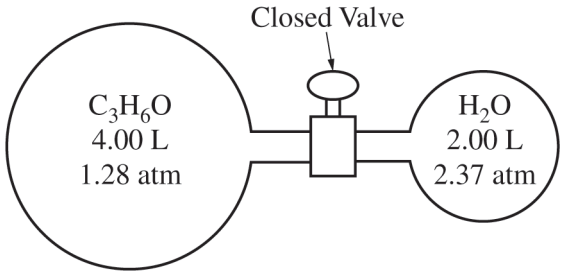
For each question, show your work for each part in the space provided after that part. Examples and equations may be included in your responses where appropriate. For calculations, clearly show the method used and the steps involved in arriving at your answers. You must show your work to receive credit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

1. Answer the following questions about acetone, C_3H_6O, which is represented in the following Lewis diagram.



(a) The bonding in an acetone molecule can be modeled using sigma and pi bonds. Based on the Lewis diagram, identify the number of sigma bonds and the number of pi bonds.

Sigma bonds: _____
Pi bonds: _____



(b) While held at a constant temperature of 800. K, a sample of $C_3H_6O(g)$ and a sample of $H_2O(g)$ are in containers separated by a closed valve, as shown in the diagram.

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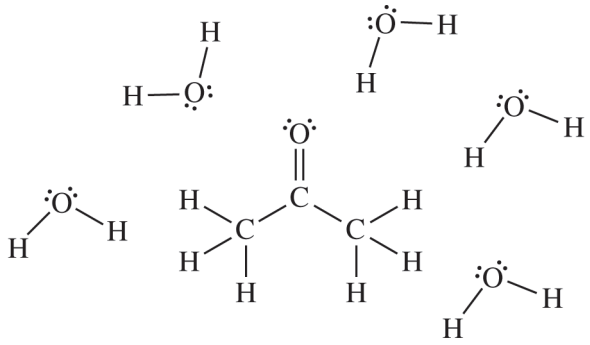
(i) Assuming ideal behavior, constant temperature, and initial volumes of 4.00 L and 2.00 L for the gases shown, what is the partial pressure, in atm, of the $C_3H_6O(g)$ after the valve is opened and the gases have mixed?

(ii) After the gases mix, the system is cooled to 400. K. What is the ratio of the acetone partial pressures, $\frac{P_{400\,K}}{P_{800\,K}}$, at the two temperatures? $\frac{P_{400\,K}}{P_{800\,K}} =$ _____

(c) After the gases are cooled to 400. K, the measured pressure of the system is significantly lower than the predicted value, partially because of strong interactions between molecules of C_3H_6O and molecules of H_2O.

(i) Draw a single dashed line (---) on the following diagram to indicate the location of the strongest interaction between a molecule of C_3H_6O and a molecule of H_2O.



(ii) Using principles of kinetic molecular theory, explain why the attraction between molecules of C_3H_6O and H_2O results in a pressure that is lower than the predicted value.

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$$C_3H_6O(aq) + I_2(aq) \xrightarrow{H_3O^+} C_3H_5IO(aq) + HI(aq)$$

Acetone, C_3H_6O, reacts with I_2 in acidic solution, as represented by the preceding equation. A student conducts several trials at constant temperature using different concentrations of the reactants. The results of the student's experiment are provided in the following table.

Trial	$[C_3H_6O]$ (M)	$[I_2]$ (M)	$[H_3O^+]$ (M)	Initial Rate (M/s)
1	1.33	0.00100	0.162	8.11×10^{-6}
2	1.33	0.00100	0.323	16.6×10^{-6}
3	0.667	0.00100	0.323	8.25×10^{-6}

(d) Explain how the data in the table support that the reaction is first order with respect to C_3H_6O.

(e) The reaction is found to be zero order with respect to I_2. Use the data to determine the overall rate law for the reaction.

(f) Using the data from trial 3, calculate the value of the rate constant, k, in $M^{-1}\,s^{-1}$.

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(g) When the reaction occurs at a higher temperature, the value of the rate constant, k, increases. Based on collision theory, explain why the value of k increases with temperature.

(h) The following mechanism was proposed for the reaction. Explain how this mechanism is consistent with the reaction being zero order with respect to I_2.

Step 1: $C_3H_6O + H_3O^+ \rightleftarrows C_3H_6OH^+ + H_2O$ *slow*

Step 2: $C_3H_6OH^+ + H_2O \rightleftarrows C_3H_5OH + H_3O^+$ *fast*

Step 3: $C_3H_5OH + I_2 \rightarrow C_3H_5IO + HI$ *fast*

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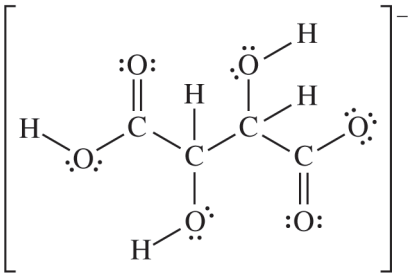
2. Answer the following questions about potassium hydrogen tartrate, $KHC_4H_4O_6$.

When $KHC_4H_4O_6$ dissolves in water, it dissociates into K^+ and $HC_4H_4O_6^-$ ions. The Lewis diagram of $HC_4H_4O_6^-$ is shown.



(a) In the diagram, circle the atom that detaches when $HC_4H_4O_6^-$ acts as a proton donor.

The $HC_4H_4O_6^-$ ion can act as a proton donor and a proton acceptor. The ionization reactions of $HC_4H_4O_6^-(aq)$ in water and their corresponding K values are provided.

$$HC_4H_4O_6^-(aq) + H_2O(l) \rightleftarrows C_4H_4O_6^{2-}(aq) + H_3O^+(aq) \qquad K_a = 4.5 \times 10^{-5}$$

$$HC_4H_4O_6^-(aq) + H_2O(l) \rightleftarrows H_2C_4H_4O_6(aq) + OH^-(aq) \qquad K_b = 9.5 \times 10^{-12}$$

(b) Calculate the pK_a of $HC_4H_4O_6^-(aq)$.

(c) When $HC_4H_4O_6^-$ is dissolved in water, $\left[C_4H_4O_6^{2-}\right]$ is greater than $\left[H_2C_4H_4O_6\right]$. Explain this observation based on the information provided.

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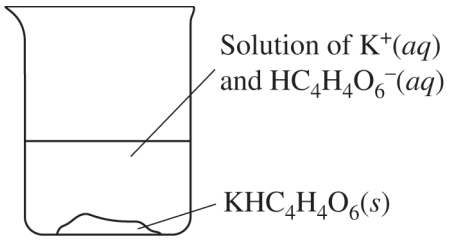
Unlike many potassium salts, $KHC_4H_4O_6$ is only slightly soluble in water. It dissociates according to the following equation. The K_{sp} expression is given.

$$KHC_4H_4O_6(s) \rightleftarrows K^+(aq) + HC_4H_4O_6^-(aq) \qquad K_{sp} = [K^+][HC_4H_4O_6^-]$$

In order to determine the K_{sp} of this salt, a student prepares a saturated solution as shown in diagram 1.

Diagram 1
Approximately 2.0 g of $KHC_4H_4O_6$ is mixed with 150 mL of water in a beaker. The mixture is stirred overnight and then allowed to settle. The beaker is shown after the contents have settled.


(d) What observation can the student make to confirm that the solution in the beaker is saturated?

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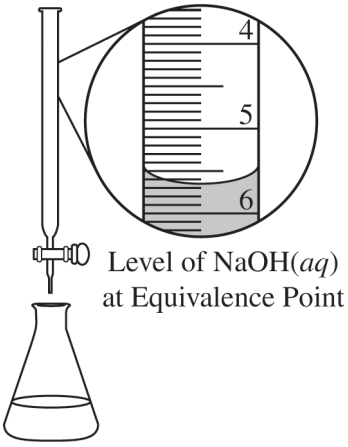
(e) The student continues the experiment by filtering the saturated solution and then titrating it with NaOH(aq). These steps are shown in diagrams 2 and 3.

Diagram 2	Diagram 3
The mixture is filtered to separate the solid from the solution.	A 25.00 mL sample of the solution is transferred to an Erlenmeyer flask and titrated with 0.1376 *M* NaOH(aq).
	

The magnified view in diagram 3 shows part of the buret at the equivalence point of the titration. The remaining data are shown in the following table.

Volume of $KHC_4H_4O_6$ solution in the flask	25.00 mL
Initial buret reading of NaOH(aq)	0.00 mL
Final buret reading of NaOH(aq)	?
Concentration of NaOH(aq) in the buret	0.1376 *M*

(i) Based on the magnified view in diagram 3, what should the student record as the final volume reading of NaOH(aq) in the buret?

_____ mL

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(ii) Using the data from the titration, calculate the value of $[HC_4H_4O_6^-]$ in the $KHC_4H_4O_6$ solution. The equation shown represents the reaction that occurs during the titration.

$$HC_4H_4O_6^-(aq) + OH^-(aq) \rightarrow C_4H_4O_6^{2-}(aq) + H_2O(l)$$

(iii) Using the data from the experiment, calculate the value of K_{sp} for $KHC_4H_4O_6$, given that $K_{sp} = [K^+][HC_4H_4O_6^-]$.

(f) A second student performs the same experiment, but some $KHC_4H_4O_6(s)$ passes around the filter paper and remains in the 25.00 mL sample that is titrated. As a result, the second student requires a greater volume of $NaOH(aq)$ to reach the equivalence point of the titration.

(i) Assuming no other errors occurred, explain why the presence of the $KHC_4H_4O_6(s)$ increases the volume of $NaOH(aq)$ needed to reach the equivalence point.

(ii) Would the second student's calculated value of K_{sp} be larger, smaller, or the same as the first student's calculated value of K_{sp} obtained in part (e)(iii) ? Justify your answer.

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3. Piperidine, $C_5H_{10}NH$, is a weak organic base. The reaction of $C_5H_{10}NH(aq)$ with $H_2O(l)$ is represented by the following equation.

$$C_5H_{10}NH(aq) + H_2O(l) \rightleftarrows C_5H_{10}NH_2^{+}(aq) + OH^{-}(aq)$$

(a) Identify one Brønsted-Lowry conjugate acid-base pair in the reaction of piperidine with water. Be sure to label which species is the acid and which is the base.

(b) Write the expression for the equilibrium constant, K_b, for piperidine, $C_5H_{10}NH$.

(c) A 20.0 mL sample of 0.750 M $C_5H_{10}NH(aq)$ is prepared at 25°C.

(i) The equilibrium concentration of $OH^{-}(aq)$ in the solution is $3.09 \times 10^{-2}\ M$. Calculate the pH of the 0.750 M $C_5H_{10}NH(aq)$ solution at 25°C.

(ii) What is the percent ionization of piperidine in the 0.750 M solution?

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(d) When a small volume of strong acid is added to the 0.750 M $C_5H_{10}NH(aq)$ solution, the number of moles of $C_5H_{10}NH_2^+$ increases.

(i) Write the balanced net ionic equation for the reaction that occurs between major species in solution when the strong acid is added.

(ii) Using Q and K, explain why the moles of $C_5H_{10}NH_2^+$ increase when a small amount of strong acid is added to the solution.

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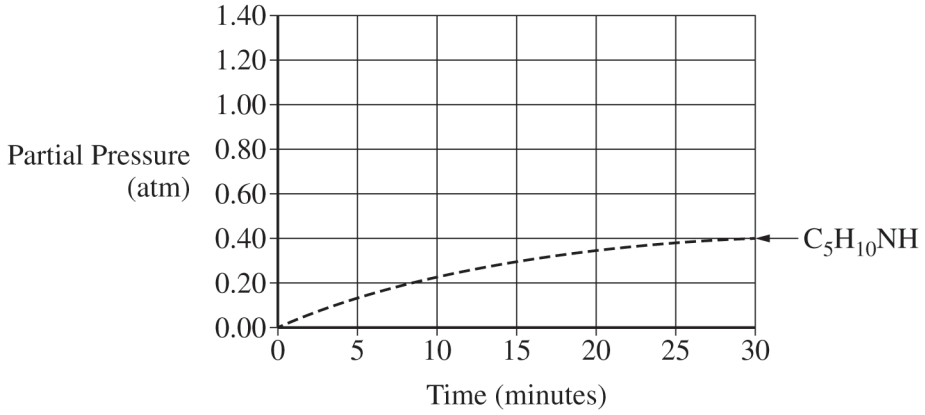
A scientist prepares piperidine, $C_5H_{10}NH$, by reacting C_5H_5N and H_2 in a nickel-coated container at 400. K according to the following reaction equation.

$$C_5H_5N(g) + 3\ H_2(g) \rightleftarrows C_5H_{10}NH(g) \qquad \Delta G° = -42.8\ \text{kJ / mol}_{rxn}$$

The scientist fills a previously evacuated, sealed, rigid container with 1.40 atm of C_5H_5N and 1.40 atm of H_2 and records the partial pressure of $C_5H_{10}NH(g)$ as the reaction progresses. The data are shown in the following graph.



(e) On the graph, sketch a single curve that represents the partial pressure of $H_2(g)$ as the reaction proceeds from 0 minutes to 30 minutes. Your curve should reflect

(i) the rate of change of $H_2(g)$ compared to that of $C_5H_{10}NH(g)$ and
(ii) the initial partial pressure of $H_2(g)$ and the partial pressure of $H_2(g)$ at 30 minutes.

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(f) In this reaction, 4 mol of gaseous reactants produce 1 mol of gaseous product. Based on this fact, a student claims that the entropy change of the forward reaction, ΔS°_{rxn}, is negative.

(i) Use particulate-level reasoning to explain why the student's claim is correct.

(ii) Given the signs of ΔG°_{rxn} and ΔS°_{rxn} at 400. K, is the sign of ΔH°_{rxn} positive or negative? Justify your answer.

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4. A student conducts a calorimetry experiment using $CaBr_2(s)$ (molar mass 199.88 g / mol) to determine the enthalpy of solution. The student prepares the solution by dissolving $CaBr_2(s)$ in water. The following data table includes the information from the experiment.



Mass of water	46.00 g
Mass of $CaBr_2$	7.11 g
Initial temperature	23.5°C
Final temperature	44.0°C

(a) Other than preventing the solution from splashing out, explain why it is important to keep the lid on the calorimeter during the experiment.

(b) Based on the data in the table, what is the sign of the enthalpy of solution, $\Delta H^{\circ}_{solution}$? Justify your answer.

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(c) Using the data from the experiment, calculate the magnitude of thermal energy, q, in joules, transferred in the dissolution of $CaBr_2$. Assume that the mixture in the calorimeter has a specific heat capacity of 3.61 J/ $(g \cdot °C)$.

(d) Using the data from the experiment, calculate the magnitude of $\Delta H^{\circ}_{solution}$ of $CaBr_2$ in kJ /mol.

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5. Answer the following questions about magnesium nitrate and sodium carbonate.

When a student combines equal volumes of 0.1 M aqueous solutions of magnesium nitrate, $Mg(NO_3)_2$, and sodium carbonate, Na_2CO_3, a white solid forms.

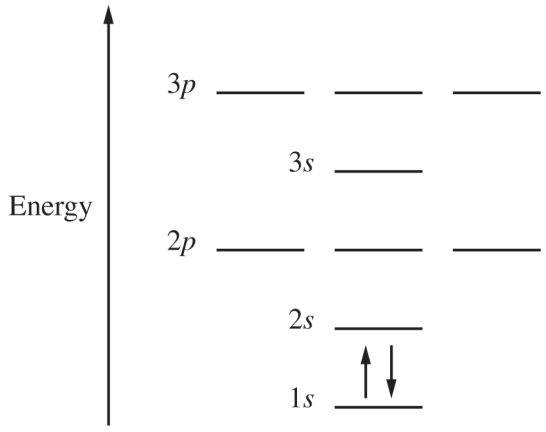
(a) Write the balanced net ionic equation for the reaction.

(b) A student filters the mixture from part (a) to remove the solid from the solution. Describe an experimental technique that the student can use to demonstrate that ions remain in the filtered solution.

(c) The $Na_2CO_3(aq)$ used in the reaction has a 2:1 ratio of cations to anions. Identify a metallic element, M, other than sodium that results in a compound that has a formula of M_2CO_3.

_____

(d) An incomplete orbital energy diagram for the magnesium cation in the ground state is shown. Using arrows to represent electrons, complete the diagram with the correct number of electrons in the cation. The arrows for the 1s sublevel are already shown.



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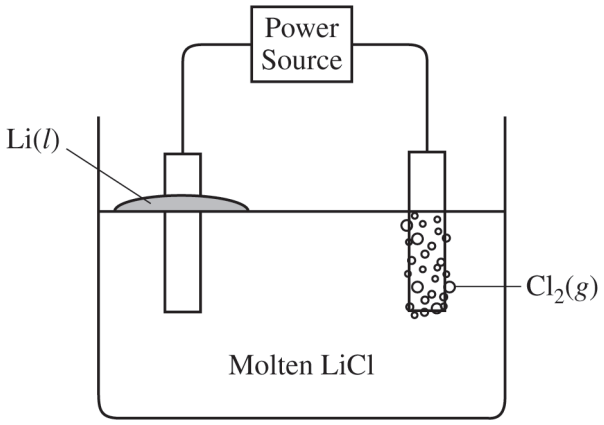
6. Molten lithium chloride, $LiCl(l)$, is electrolyzed using an external power supply and inert electrodes, as represented in the following diagram. Liquid lithium metal and chlorine gas are produced.



The reduction potentials for the half-reactions associated with this process are shown in the following table.

Half-Reaction	E (V)
$Cl_2 + 2\ e^- \rightarrow 2\ Cl^-$	−1.36
$Li^+ + e^- \rightarrow Li$	−2.10

(a) On the diagram, draw an arrow to show the direction of electron flow in the wire.

(b) Use the half-reactions in the table to write the balanced net ionic equation for the reaction that occurs in the electrolytic cell.

(c) Calculate the average current, in C/s, that must flow through the cell to produce 0.18 g of lithium metal in 3200. seconds.

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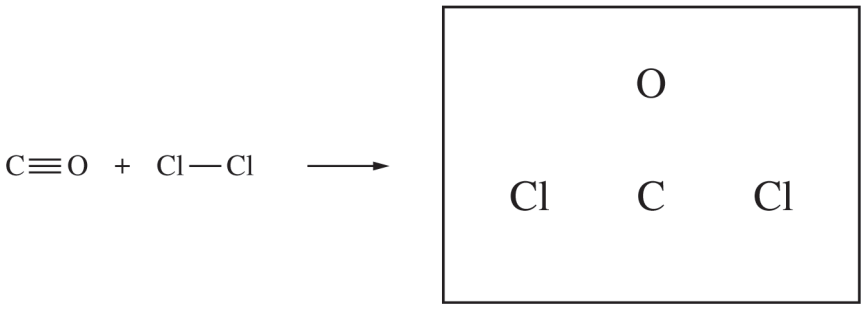
7. Phosgene gas ($COCl_2$) can be synthesized in the reaction represented by the following equation.



(a) Complete the Lewis diagram for phosgene in which the formal charge on each atom is zero. Include all bonding and nonbonding valence electrons.

(b) A student claims that the hybridization of the carbon atom is the same in CO and $COCl_2$. Do you agree or disagree with the student's claim? Justify your answer in terms of the hybridization of the C atom in each structure.

(c) When CO and Cl_2 are combined, no reaction is observed to occur. The reaction is initiated by exposing the reactants to ultraviolet light that has a frequency of $8.67 \times 10^{14}\ s^{-1}$. Calculate the energy of 1.00 mol of photons at this frequency. Include units with your answer.

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