CHEMISTRY

Section I

50 Questions

Time—90 minutes

CALCULATORS ARE NOT ALLOWED FOR SECTION I.

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. In which of the following liquids do the intermolecular forces include dipole-dipole forces?

   (A) $F_2(l)$
   (B) $CH_4(l)$
   (C) $CF_4(l)$
   (D) $CH_2F_2(l)$

2. Which of the following best helps explain why an increase in temperature increases the rate of a chemical reaction?

   (A) At higher temperatures, reactions have a lower activation energy.
   (B) At higher temperatures, reactions have a higher activation energy.
   (C) At higher temperatures, every collision results in the formation of product.
   (D) At higher temperatures, high-energy collisions happen more frequently.

3. A sample of a hard, solid binary compound at room temperature did not conduct electricity as a pure solid but became highly conductive when dissolved in water. Which of the following types of interactions is most likely found between the particles in the substance?

   (A) Ionic bonds
   (B) Metallic bonds
   (C) Covalent bonds
   (D) Hydrogen bonds

$$N_2(g) + 3\ H_2(g) \rightleftarrows 2\ NH_3(g) \qquad \Delta H < 0$$

4. $NH_3(g)$ was synthesized at 200°C in the presence of a powdered $Os(s)$ catalyst, leading to the equilibrium system represented above. Which of the following changes would result in more $NH_3(g)$ in the mixture after equilibrium is reestablished?

   (A) Replacing the powdered $Os(s)$ with a solid cube of $Os(s)$ of the same total mass
   (B) Increasing the temperature of the system to 250°C at constant pressure
   (C) Removing some $H_2(g)$
   (D) Adding some $N_2(g)$

5. Which of the following arranges the molecules N_2, O_2, and F_2 in order of their bond enthalpies, from least to greatest?

   (A) $F_2 < O_2 < N_2$
   (B) $O_2 < N_2 < F_2$
   (C) $N_2 < O_2 < F_2$
   (D) $N_2 < F_2 < O_2$

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Ion	Ionic Radius (pm)
Li^+	60
Na^+	95
Ca^{2+}	99
In^{3+}	81

6. Based on Coulomb's law and the information in the table above, which of the following cations is most likely to have the weakest interaction with an adjacent water molecule in an aqueous solution?

   (A) Li^+
   (B) Na^+
   (C) Ca^{2+}
   (D) In^{3+}

Element	Electronegativity
H	2.1
C	2.5
S	2.5
F	4.0
Cl	3.0
Si	1.8

7. On the basis of the information above, which of the following arranges the binary compounds in order of increasing bond polarity?

   (A) $CH_4 < SiCl_4 < SF_4$
   (B) $CH_4 < SF_4 < SiCl_4$
   (C) $SF_4 < CH_4 < SiCl_4$
   (D) $SiCl_4 < SF_4 < CH_4$

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$$X(g) \rightarrow X^{+}(g) + e^{-} \qquad IE_1 = 740 \text{ kJ/mol}$$
$$X^{+}(g) \rightarrow X^{2+}(g) + e^{-} \qquad IE_2 = 1450 \text{ kJ/mol}$$
$$X^{2+}(g) \rightarrow X^{3+}(g) + e^{-} \qquad IE_3 = 7730 \text{ kJ/mol}$$

8. For element X represented above, which of the following is the most likely explanation for the large difference between the second and third ionization energies?

   (A) The effective nuclear charge decreases with successive ionizations.
   (B) The shielding of outer electrons increases with successive ionizations.
   (C) The electron removed during the third ionization is, on average, much closer to the nucleus than the first two electrons removed were.
   (D) The ionic radius increases with successive ionizations.

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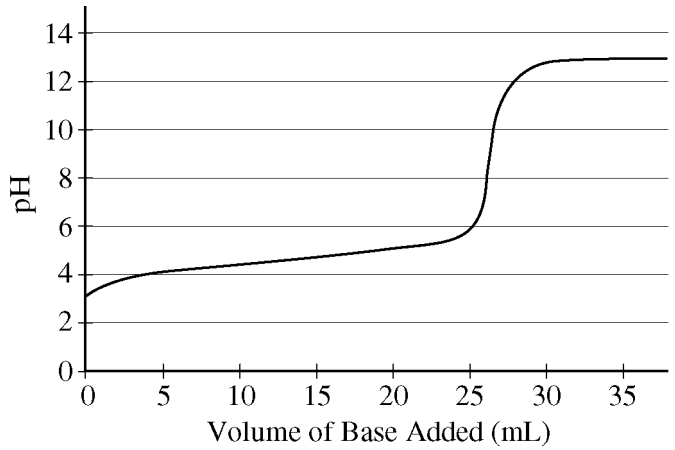

9. A student performs an acid-base titration and plots the experimental results in the graph above. Which of the following statements best explains the experimental findings?

   (A) A strong acid was titrated with a strong base, as evidenced by the equivalence point at pH = 7.

   (B) A strong acid was titrated with a strong base, as evidenced by the equivalence point at pH > 7.

   (C) A weak acid was titrated with a strong base, as evidenced by the equivalence point at pH > 7.

   (D) A weak acid was titrated with a weak base, as evidenced by the equivalence point at pH approximately 7.

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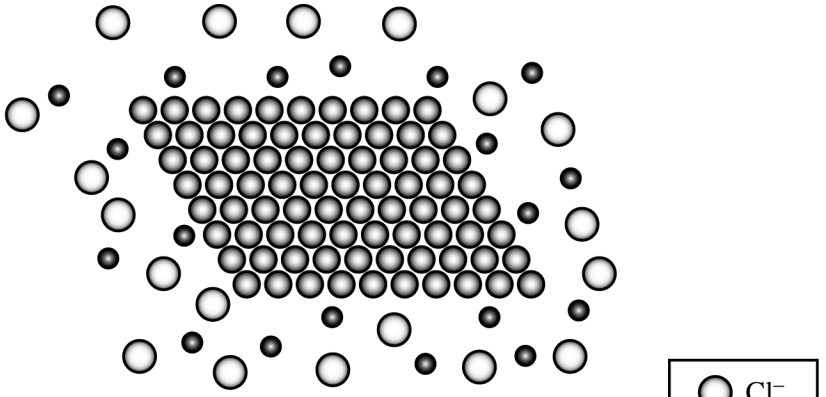

Figure 1

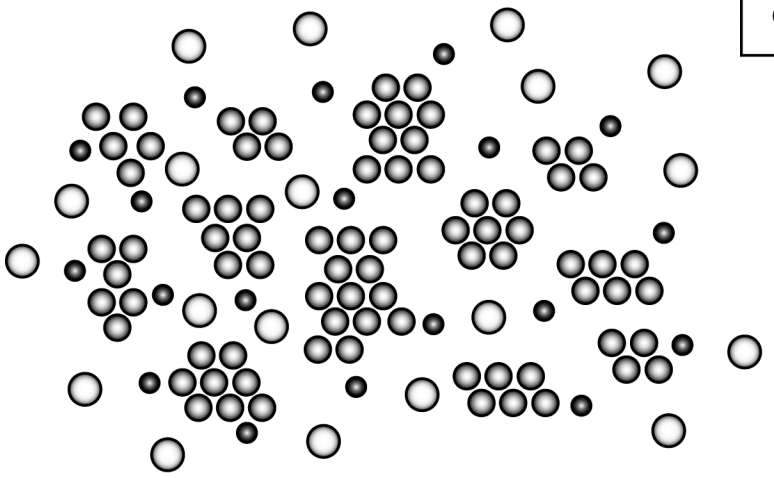

Figure 2

10. Two samples of Mg(*s*) of equal mass were placed in equal amounts of HCl(*aq*) contained in two separate reaction vessels. Particle representations of the mixing of Mg(*s*) and HCl(*aq*) in the two reaction vessels are shown in Figure 1 and Figure 2 above. Water molecules are not included in the particle representations. Which of the reactions will initially proceed faster, and why?

    (A) The reaction in Figure 1, because the atoms of Mg are more concentrated than those in Figure 2

    (B) The reaction in Figure 1, because the Mg(*s*) in Figure 1 has a larger mass than the Mg(*s*) in Figure 2

    (C) The reaction in Figure 2, because more Mg atoms are exposed to HCl(*aq*) in Figure 2 than in Figure 1

    (D) The reaction in Figure 2, because the Mg(*s*) in Figure 2 has less surface area than the Mg(*s*) in Figure 1

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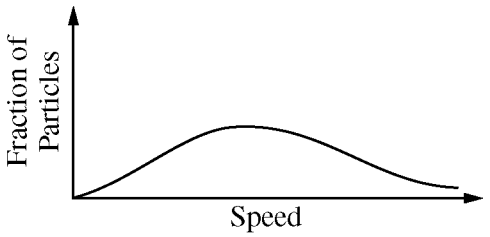
11. A 23.0 g sample of a compound contains 12.0 g of C, 3.0 g of H, and 8.0 g of O. Which of the following is the empirical formula of the compound?

(A) CH_3O
(B) C_2H_6O
(C) $C_3H_9O_2$
(D) $C_4H_{12}O_2$

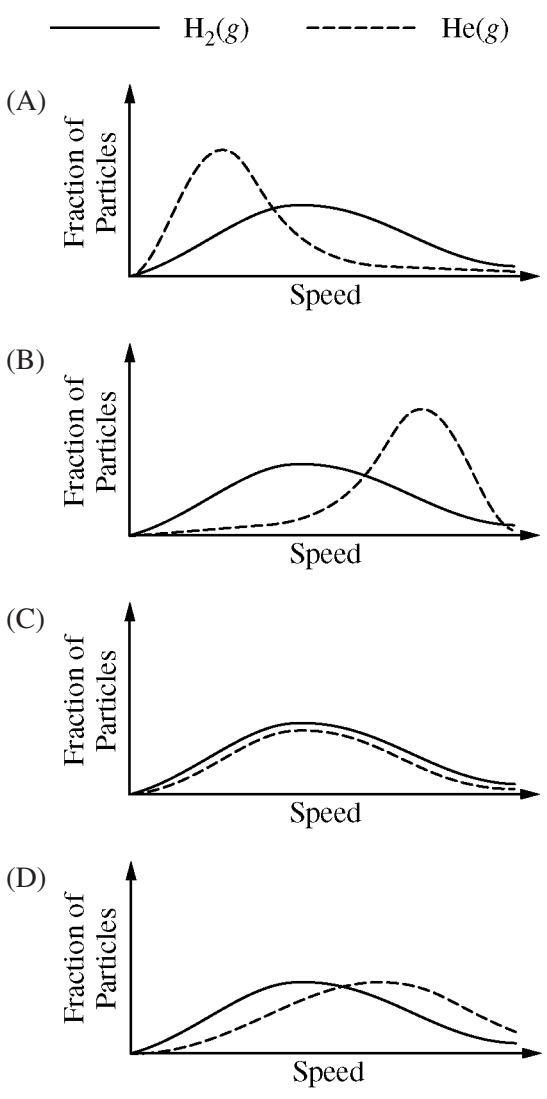
Compound	K_{sp}
$PbCl_2$	1.2×10^{-5}
CuCl	1.6×10^{-7}
AgCl	1.8×10^{-10}
Hg_2Cl_2	1.4×10^{-18}

12. Based on the K_{sp} values in the table above, a saturated solution of which of the following compounds has the highest $[Cl^-]$?

(A) $PbCl_2$
(B) CuCl
(C) AgCl
(D) Hg_2Cl_2



13. The distribution of speeds of $H_2(g)$ molecules at 273 K and 1 atm is shown in the diagram above. Which of the following best shows the speed distribution of $He(g)$ atoms under the same conditions of temperature and pressure?



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Questions 14-15 refer to the following information.

$$2\ H_2O_2(aq) \rightarrow 2\ H_2O(l) + O_2(g) \qquad E^\circ = 0.55\ V$$

The equation and standard cell potential for the decomposition of $H_2O_2(aq)$ in acidic solution at 25°C is given above. The reduction half-reactions for the process are listed below.

$$O_2(g) + 4\ H^+(aq) + 4\ e^- \rightarrow 2\ H_2O(l) \qquad E^\circ = 1.23\ V$$

$$O_2(g) + 2\ H^+(aq) + 2\ e^- \rightarrow H_2O_2(aq) \qquad E^\circ = ?$$

$$O_2(g) + 2\ H^+(aq) + 2\ e^- \rightarrow H_2O_2(aq)$$

14. What is the standard reduction potential for the half-reaction represented above?

(A) −1.78 V
(B) −0.68 V
(C) +0.68 V
(D) +1.78 V

15. Which of the following is true for the decomposition of $H_2O_2(aq)$?

(A) $\Delta G^\circ > 0$ and $K_{eq} > 1$
(B) $\Delta G^\circ > 0$ and $K_{eq} < 1$
(C) $\Delta G^\circ < 0$ and $K_{eq} > 1$
(D) $\Delta G^\circ < 0$ and $K_{eq} < 1$

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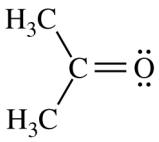
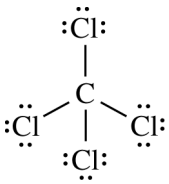
$$C_2H_4(g) + H_2(g) \rightarrow C_2H_6(g)$$

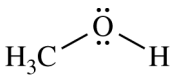
16. Which of the following will most likely increase the rate of the reaction represented above?

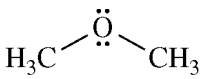
(A) Decreasing the temperature of the reaction system
(B) Adding a heterogeneous catalyst to the reaction system
(C) Increasing the volume of the reaction vessel using a piston
(D) Removing some $H_2(g)$ from the reaction system

17. Which of the following molecules is least soluble in water?

(A) 

(B) 

(C) 

(D) 

18. At room temperature $I_2(s)$ is a molecular solid. Which of the following provides a characteristic of $I_2(s)$ with a correct explanation?

(A) It has a high melting point because it has weak intermolecular forces.
(B) It is hard because it forms a three-dimensional covalent network.
(C) It is not a good conductor of electricity because its valence electrons are localized in bonding and nonbonding pairs.
(D) It is very soluble in water because its molecules are polar.

	Molar Mass (g/mol)	Boiling Point (°C)
$CS_2(l)$	76	46.5
$CCl_4(l)$	154	76.7

19. Based on the information in the table above, which liquid, $CS_2(l)$ or $CCl_4(l)$, has the higher equilibrium vapor pressure at 25°C, and why?

(A) $CS_2(l)$, because it has stronger London dispersion forces
(B) $CS_2(l)$, because it has weaker London dispersion forces
(C) $CCl_4(l)$, because it has stronger London dispersion forces
(D) $CCl_4(l)$, because it has weaker London dispersion forces

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$$HX(aq) + Y^-(aq) \rightleftarrows HY(aq) + X^-(aq) \qquad K_{eq} > 1$$

20. Based on the information given above, which of the following is the strongest acid?

(A) $HX(aq)$
(B) $Y^-(aq)$
(C) $HY(aq)$
(D) $X^-(aq)$

$$AgNO_3(aq) + NaCl(aq) \rightarrow AgCl(s) + NaNO_3(aq)$$

21. A student performed an analysis to determine the amount of $AgNO_3(aq)$ in a solution. Excess $NaCl(aq)$ was added to the solution, and the $Ag^+(aq)$ precipitated as $AgCl(s)$. The precipitate was collected by gravity filtration and dried in an oven. Three trials were performed, and in each case, according to the instructor, the mass of precipitate recovered was 5 percent higher than the actual mass of $AgCl(s)$ that should have formed. Which of the following could account for the error?

(A) The pores in the filter paper were too large.
(B) Not all of the precipitate was transferred to the filter paper.
(C) The $NaCl(aq)$ solution was too concentrated.
(D) The precipitate was not rinsed with deionized water before drying.

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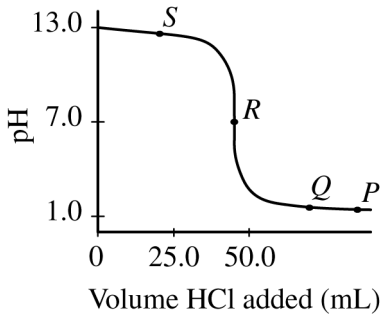
Questions 22-25 refer to the following information.

$$NaOH(aq) + HCl(aq) \rightarrow NaCl(aq) + H_2O(l)$$

To determine the concentration of a $NaOH(aq)$ solution, a student titrated a 50. mL sample with 0.10 *M* $HCl(aq)$. The reaction is represented by the equation above. The titration is monitored using a pH meter, and the experimental results are plotted in the graph below.



22. At the point labeled *R* on the pH curve, which of the following ions are present in the reaction mixture at a concentration greater than 0.01 *M* ?

    (A) Na^+ and Cl^- only
    (B) Na^+, Cl^-, and H^+ only
    (C) Na^+, Cl^-, and OH^- only
    (D) Na^+, Cl^-, H^+, and OH^-

23. One student titrated the $NaOH(aq)$ with 1.0 *M* $HCl(aq)$ instead of 0.10 *M* $HCl(aq)$. How would the student's titration curve differ from the original curve?

    (A) The initial pH would be 11 instead of 13.
    (B) The pH at the equivalence point would be 5 instead of 7.
    (C) The pH far beyond the equivalence point would be higher than in the original curve.
    (D) The pH far beyond the equivalence point would be lower than in the original curve.

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Trial	Volume of 0.10 *M* HCl	Volume of 0.10 *M* NaOH	Amount of Heat Released
1	50. mL	50. mL	X
2	100. mL	50. mL	Y

24. A student conducted an experiment to determine ΔH°_{rxn} for the reaction between HCl(*aq*) and NaOH(*aq*). The student ran two trials using the volumes of HCl(*aq*) and NaOH(*aq*) indicated in the table above, and determined the amount of heat released. Which of the following best explains the relationship between X and Y?

    (A) $Y = 2X$, because the volume of HCl(*aq*) used in trial 2 is twice the volume used in trial 1.

    (B) $Y = X$, because the number of moles of acid and base reacting with each other is the same in both trials.

    (C) $Y = \frac{2X}{3}$, because the heat is distributed over more particles in trial 2 than in trial 1.

    (D) The relationship between X and Y cannot be predicted.

25. A student mixes a 10.0 mL sample of 1.0 *M* NaOH(*aq*) with a 10.0 mL sample of 1.0 *M* HCl(*aq*) in a polystyrene container. The temperature of the solutions before mixing was 20.0°C. If the final temperature of the mixture is 26.0°C, what is the experimental value of ΔH°_{rxn}? (Assume that the solution mixture has a specific heat of 4.2 J/(g·K) and a density of 1.0 g/mL.)

    (A) $-50.\ \text{kJ/mol}_{rxn}$

    (B) $-25\ \text{kJ/mol}_{rxn}$

    (C) $-5.0 \times 10^4\ \text{kJ/mol}_{rxn}$

    (D) $-5.0 \times 10^2\ \text{kJ/mol}_{rxn}$

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$$2\ NO_2(g)\ +\ F_2(g)\ \rightarrow\ 2\ NO_2F(g)$$

26. The rate law for the reaction represented by the equation above is rate = $k\ [NO_2][F_2]$. Which of the following could be the first elementary step of a two-step mechanism for the reaction if the first step is slow and the second step is fast?

(A) $F_2(g)\ \rightarrow\ 2\ F(g)$

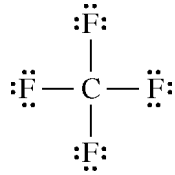
(B) $NO_2(g)\ +\ F_2(g)\ \rightarrow\ NO_2F(g)\ +\ F(g)$

(C) $NO_2(g)\ +\ F(g)\ \rightarrow\ NO_2F(g)$

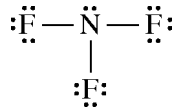
(D) $2\ NO_2(g)\ +\ F_2(g)\ \rightarrow\ 2\ NO_2F(g)$

27. Which of the following Lewis electron-dot diagrams represents the molecule that contains the smallest bond angle?

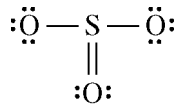
(A)



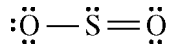
(B)



(C)



(D)



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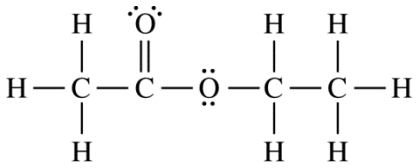
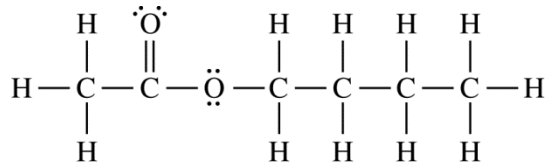


Ethyl Acetate



Butyl Acetate

28. A mixture containing equal numbers of moles of ethyl acetate and butyl acetate was separated using distillation. Based on the diagrams shown above, which of the following identifies the substance that would be initially present in higher concentration in the distillate and correctly explains why that occurs?

(A) Ethyl acetate, because it has fewer C–C bonds to break
(B) Ethyl acetate, because it has a shorter carbon chain and weaker London dispersion forces
(C) Butyl acetate, because it has more C–C bonds to break
(D) Butyl acetate, because it has a longer carbon chain and weaker dipole-dipole attractions

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Questions 29-31 refer to the investigation described below.

$$\underset{violet}{C_{25}H_{30}N_3^+(aq)} + OH^-(aq) \rightarrow \underset{colorless}{C_{25}H_{30}N_3OH(aq)}$$

The reaction between $C_{25}H_{30}N_3^+(aq)$ and $OH^-(aq)$, as represented above, is first order with respect to $C_{25}H_{30}N_3^+(aq)$ in the presence of excess $OH^-(aq)$. A 10.0 mL sample of 0.10 *M* NaOH(*aq*) is mixed with a 10.0 mL sample of 2.5×10^{-5} *M* $C_{25}H_{30}N_3^+(aq)$. A 5.0 mL sample of the mixture is quickly transferred to a clean cuvette and placed in a spectrophotometer, and the progress of the reaction is measured. The data are given in the table below.

Time (s)	0	30	60	90	120	150	180	210	240	270	300
Absorbance	0.62	0.54	0.47	0.41	0.36	0.31	0.27	0.23	0.20	0.17	0.15

29. Approximately how long did it take for 75 percent of the initial amount of $C_{25}H_{30}N_3^+(aq)$ to react?

(A) 75 s
(B) 225 s
(C) 300 s
(D) 600 s

30. What would be the effect on the reaction rate if the solution of $C_{25}H_{30}N_3^+(aq)$ is diluted by a factor of two?

(A) It would be higher.
(B) It would be lower.
(C) It would not change.
(D) It would initially be higher but then rapidly decrease.

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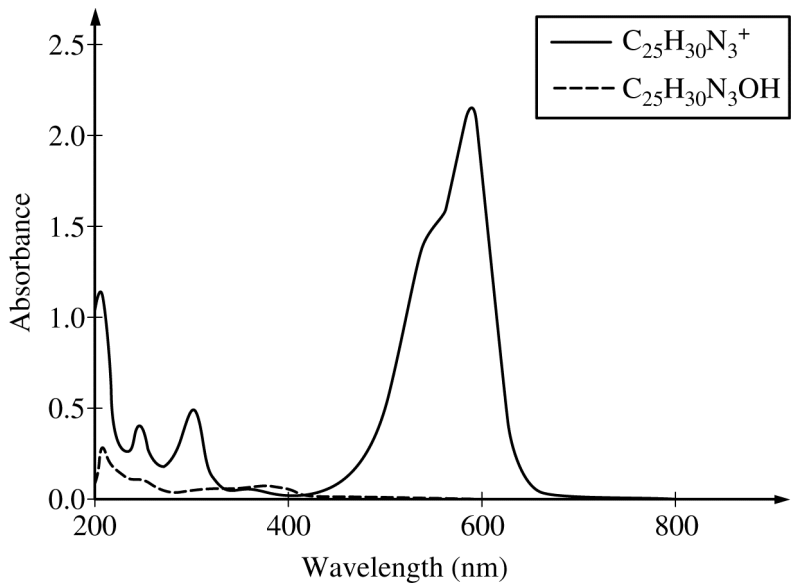
31. To choose a wavelength to analyze the progress of the reaction, a student records the absorbance spectra of both $C_{25}H_{30}N_3^+(aq)$ and $C_{25}H_{30}N_3OH(aq)$ in the range of 200-800 nm. The two spectra are presented in the graph below.



The student wants to use the spectrophotometer to measure $[C_{25}H_{30}N_3^+]$ with the greatest sensitivity as the reaction progresses. Which of the following indicates the best wavelength setting and explains why it is best?

(A) 205 nm, because the colorless form of the molecule will absorb significantly at this wavelength
(B) 205 nm, because both forms of the molecule will absorb significantly at this wavelength
(C) 590 nm, because only the violet form of the molecule will absorb significantly at this wavelength
(D) 590 nm, because this wavelength falls in the violet region of the visible light spectrum

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$$CO(g) + H_2O(g) \rightleftarrows CO_2(g) + H_2(g) \qquad K_c = 1.5 \times 10^3$$

32. A 2.0 mol sample of $CO(g)$ and a 2.0 mol sample of $H_2O(g)$ are introduced into a previously evacuated 100. L rigid container, and the temperature is held constant as the reaction represented above reaches equilibrium. Which of the following is true at equilibrium?

(A) $[H_2O] > [CO]$ and $[CO_2] > [H_2]$
(B) $[H_2O] > [H_2]$
(C) $[CO_2] > [CO]$
(D) $[CO] = [H_2O] = [CO_2] = [H_2]$

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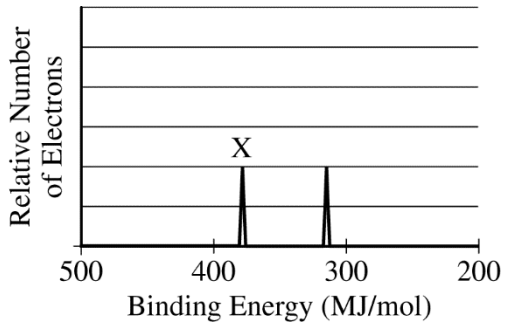
Compound	K_{sp} at 298 K
Ag_2SO_4	1×10^{-5}
$PbSO_4$	1×10^{-8}

33. A 1.0 L solution of $AgNO_3(aq)$ and $Pb(NO_3)_2(aq)$ has a Ag^+ concentration of 0.020 *M* and a Pb^{2+} concentration of 0.0010 *M*. A 0.0010 mol sample of $K_2SO_4(s)$ is added to the solution. Based on the information in the table above, which of the following will occur? (Assume that the volume change of the solution is negligible.)

(A) No precipitate will form.
(B) Only $Ag_2SO_4(s)$ will precipitate.
(C) Only $PbSO_4(s)$ will precipitate.
(D) Both $Ag_2SO_4(s)$ and $PbSO_4(s)$ will precipitate.

34. The pH of a 0.01 *M* $HNO_2(aq)$ solution is in which of the following ranges? (For $HNO_2(aq)$, $K_a = 4.0 \times 10^{-4}$)

(A) Between 1 and 2
(B) Between 2 and 3
(C) Between 4 and 5
(D) Between 6 and 7



35. The photoelectron spectra of the 1*s* electrons of two isoelectronic species, Ca^{2+} and Ar, are shown above. Which of the following correctly identifies the species associated with peak X and provides a valid justification?

(A) Ar, because it has completely filled energy levels
(B) Ar, because its radius is smaller than the radius of Ca^{2+}
(C) Ca^{2+}, because its nuclear mass is greater than that of Ar
(D) Ca^{2+}, because its nucleus has two more protons than the nucleus of Ar has

36. A vessel contains Ar(*g*) at a high pressure. Which of the following statements best helps to explain why the measured pressure is significantly greater than the pressure calculated using the ideal gas law?

(A) The molar mass of Ar is relatively large.
(B) A significant number of Ar_2 molecules form.
(C) The attractive forces among Ar atoms cause them to collide with the walls of the container with less force.
(D) The combined volume of the Ar atoms is too large to be negligible compared with the total volume of the container.

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Questions 37-39 refer to the following information.

When water is added to a mixture of $Na_2O_2(s)$ and $S(s)$, a redox reaction occurs, as represented by the equation below.

$$2\ Na_2O_2(s) + S(s) + 2\ H_2O(l) \rightarrow 4\ NaOH(aq) + SO_2(aq) \qquad \Delta H^\circ_{298} = -610\ \text{kJ/mol}_{rxn}\ ;\ \Delta S^\circ_{298} = -7.3\ \text{J/(K}\cdot\text{mol}_{rxn})$$

37. Two trials are run, using excess water. In the first trial, 7.8 g of $Na_2O_2(s)$ (molar mass 78 g/mol) is mixed with 3.2 g of $S(s)$. In the second trial, 7.8 g of $Na_2O_2(s)$ is mixed with 6.4 g of $S(s)$. The $Na_2O_2(s)$ and $S(s)$ react as completely as possible. Both trials yield the same amount of $SO_2(aq)$. Which of the following identifies the limiting reactant and the heat released, q, for the two trials at 298 K?

	Limiting Reactant	q
(A)	S	30. kJ
(B)	S	61 kJ
(C)	Na_2O_2	30. kJ
(D)	Na_2O_2	61 kJ

38. Atoms of which element are reduced in the reaction?

(A) S; each atom loses four electrons
(B) Na in Na_2O_2; each atom loses one electron
(C) O in Na_2O_2; each atom gains one electron
(D) O in H_2O; each atom gains one electron

39. Which of the following statements about the thermodynamic favorability of the reaction at 298 K is correct?

(A) It is thermodynamically unfavorable.
(B) It is thermodynamically favorable and is driven by ΔS° only.
(C) It is thermodynamically favorable and is driven by ΔH° only.
(D) It is thermodynamically favorable and is driven by both ΔH° and ΔS°.

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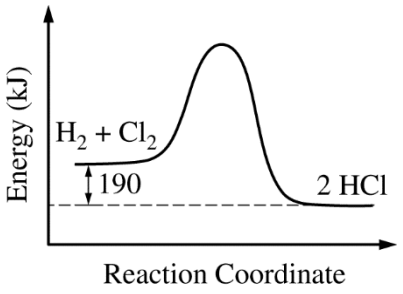
Bond	Bond Energy (kJ/mol)
H−H	430
Cl−Cl	240
H−Cl	430

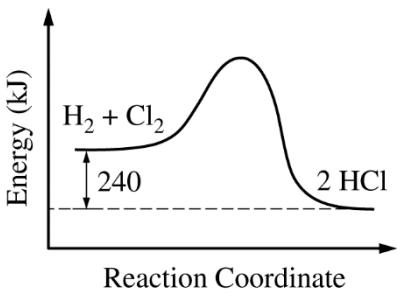
40. Based on the bond energies shown in the table above, which of the following diagrams best represents the change in energy as the reaction represented below proceeds?

$$H_2(g) + Cl_2(g) \rightarrow 2\ HCl(g)$$

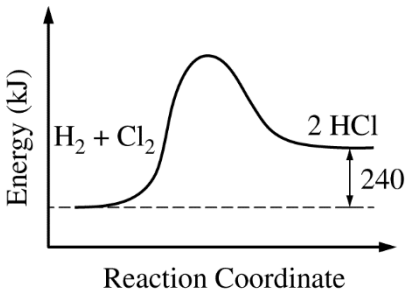
(A)



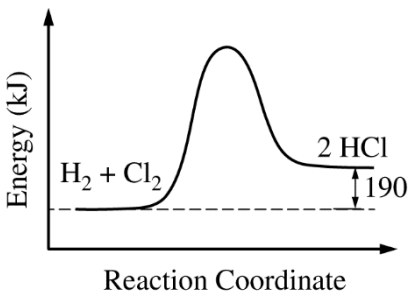
(B)



(C)



(D)



	Ionization Energy (kJ/mol)
First	577
Second	1,816
Third	2,745
Fourth	11,577
Fifth	14,482

41. Based on the ionization energies of element X given in the table above, which of the following is most likely the empirical formula of an oxide of element X?

(A) XO_2
(B) X_2O
(C) X_2O_3
(D) X_2O_5

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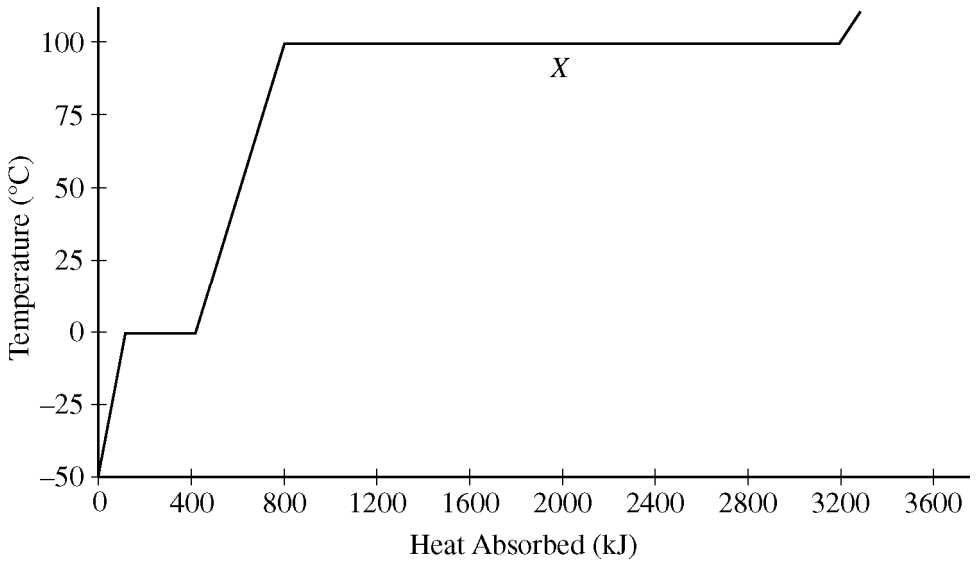
$$2\ H_2S(g) + CH_4(g) \rightleftarrows CS_2(g) + 4\ H_2(g) \qquad K_c = 3.4 \times 10^{-4}$$

42. A 0.10 mol sample of each of the four species in the reaction represented above is injected into a rigid, previously evacuated 1.0 L container. Which of the following species will have the highest concentration when the system reaches equilibrium?

(A) $H_2S(g)$
(B) $CH_4(g)$
(C) $CS_2(g)$
(D) $H_2(g)$



43. At 1.0 atm a sample of ice is heated to liquid water and then to water vapor. The heating curve is shown in the graph above. Which of the following lists the signs for the changes in enthalpy and entropy for the process corresponding to segment *X*, going from left to right?

	$\Delta H°$	$\Delta S°$
(A)	Positive	Negative
(B)	Positive	Positive
(C)	Negative	Negative
(D)	Negative	Positive

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Questions 44-47 refer to the following.

$$CH_3OH(g) \rightarrow CO(g) + 2\,H_2(g) \qquad \Delta H^\circ = +91\ \text{kJ/mol}_{rxn}$$

The reaction represented above goes essentially to completion. The reaction takes place in a rigid, insulated vessel that is initially at 600 K.

44. What happens to the temperature of the contents of the vessel as the reaction occurs?

(A) The temperature must increase, because according to Le Châtelier's principle, an increase in temperature causes more products to form.
(B) The temperature must decrease, because the reaction takes place at a temperature above room temperature.
(C) The temperature must decrease, because the reaction is endothermic.
(D) The temperature does not change, because the vessel is insulated.

45. A sample of $CH_3OH(g)$ is placed in the previously evacuated vessel with a pressure of P_1 at 600 K. What is the final pressure in the vessel after the reaction is complete and the contents of the vessel are returned to 600 K?

(A) $\frac{P_1}{9}$
(B) $\frac{P_1}{3}$
(C) P_1
(D) $3P_1$

46. What can be inferred about ΔS° for the reaction at 600 K?

(A) It must be positive, since the reaction is thermodynamically unfavorable at 600 K.
(B) It must be negative, since there are more moles of products than reactants.
(C) It must be positive, since ΔG° is negative and ΔH° is positive.
(D) It must be negative, since ΔG° is positive and ΔH° is positive.

47. Which of the following statements about the bonds in the reactants and products is most accurate?

(A) The sum of the bond enthalpies of the bonds in the reactant is greater than the sum of the bond enthalpies of the bonds in the products.
(B) The sum of the bond enthalpies of the bonds in the reactant is less than the sum of the bond enthalpies of the bonds in the products.
(C) The length of the bond between carbon and oxygen in CH_3OH is shorter than the length of the bond between carbon and oxygen in CO.
(D) All of the bonds in the reactant and products are polar.

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Acid	Concentration	pH
X	0.005 *M*	2.3
Y	2.0 *M*	2.8
Z	3.0 *M*	2.8

48. Which of the following correctly ranks the three monoprotic acids listed in the table above from the weakest to the strongest?

(A) X < Y < Z
(B) X < Z < Y
(C) Y < Z < X
(D) Z < Y < X

Element	Known Oxides
H	H_2O, H_2O_2
Li	Li_2O, Li_2O_2
Na	Na_2O, Na_2O_2, NaO_2
K	K_2O, K_2O_2, KO_2

49. Based on the information above and periodic trends, which of the following is the best hypothesis regarding the oxide(s) formed by Rb?

(A) Rb will form only Rb_2O.
(B) Rb will form only RbO_2.
(C) Rb will form only Rb_2O and Rb_2O_2.
(D) Rb will form Rb_2O, Rb_2O_2, and RbO_2.

$$Fe(s) + 2\,HCl(aq) \rightarrow FeCl_2(aq) + H_2(g)$$

50. When a student adds 30.0 mL of 1.00 *M* HCl to 0.56 g of powdered Fe, a reaction occurs according to the equation above. When the reaction is complete at 273 K and 1.0 atm, which of the following is true?

(A) HCl is in excess, and 0.100 mol of HCl remains unreacted.
(B) HCl is in excess, and 0.020 mol of HCl remains unreacted.
(C) 0.015 mol of $FeCl_2$ has been produced.
(D) 0.22 L of H_2 has been produced.

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CHEMISTRY

Section II

7 Questions

Time—1 hour and 45 minutes

YOU MAY USE YOUR CALCULATOR FOR THIS SECTION.

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

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

$$CaO(s) + H_2O(l) \rightarrow Ca(OH)_2(s) \qquad \Delta H^\circ_{rxn} = -63.7 \text{ kJ/mol}_{rxn}$$

1. Calcium oxide, $CaO(s)$, has been proposed as a substance that can be used to heat water quickly for portable heating packs or for cooking. When placed in water, $CaO(s)$ reacts as shown by the equation above.

   (a) A student wants to design a heating pad that could heat a 150.0 g sample of water from 25.0°C to 60.0°C.

   (i) Calculate the amount of heat, in joules, that the water must absorb for its temperature to change by this amount. (Assume that the specific heat capacity of the water is 4.18 J/(g·°C).)

   (ii) Calculate the minimum mass of $CaO(s)$ that the student would need to use in order to cause this temperature change.

   (b) The student hypothesizes that the design of the heating pad could be changed to enable it to heat 150.0 g of water from 25.0°C to 90.0°C by using a greater mass of $CaO(s)$.

   (i) Use the data in the table below to determine the standard entropy change, ΔS°_{rxn}, in J/(K·mol$_{rxn}$) for the reaction.

Substance	Absolute Entropy at 25°C (J/(K·mol))
$CaO(s)$	83
$H_2O(l)$	70.
$Ca(OH)_2(s)$	40.

   (ii) Is the reaction thermodynamically favorable at 90.0°C? Justify your answer with a calculation. (Assume that both ΔS°_{rxn} and ΔH°_{rxn} are constant between 25.0°C and 90.0°C.)

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The student learns that the $Ca(OH)_2$ produced from the reaction is relatively insoluble and that it dissolves in water according to the equation below.

$$Ca(OH)_2(s) \rightarrow Ca^{2+}(aq) + 2\ OH^{-}(aq)$$

(c) The student prepares a saturated solution of $Ca(OH)_2$ and determines that the $[Ca^{2+}]$ is 0.011 *M*. Calculate the value of K_{sp} for $Ca(OH)_2$.

The student wishes to significantly increase the molar solubility of the $Ca(OH)_2(s)$ and has access to the following substances.

15 mL of distilled water	15 mL of 1.0 *M* KOH(*aq*)
15 mL of 1.0 *M* $CaCl_2(aq)$	15 mL of 1.0 *M* HCl(*aq*)

(d) Which substance, when added to the $Ca(OH)_2$ mixture, would increase the molar solubility most significantly? Justify your choice based on concepts of chemical equilibrium, such as Le Châtelier's principle.

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ADDITIONAL PAGE FOR ANSWERING QUESTION 1

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ADDITIONAL PAGE FOR ANSWERING QUESTION 1

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$$2\ NaHCO_3(s) \rightarrow Na_2CO_3(s) + CO_2(g) + H_2O(g)$$

2. $NaHCO_3(s)$ (baking soda) decomposes upon heating to produce $Na_2CO_3(s)$ and two gaseous products, as shown by the equation above.

(a) A student claims that the reaction is an oxidation-reduction reaction because the oxidation number of carbon changes. Do you agree with the claim? In your answer include the oxidation number of carbon in each of the three carbon-containing species in the reaction.

The student conducts an experiment to determine the composition of a mixture of $NaHCO_3$ (molar mass 84.01 g/mol) and Na_2CO_3 (molar mass 105.99 g/mol). The student places a sample of the mixture into a preweighed test tube that is attached to a container that holds a drying agent. The student heats the test tube strongly with a Bunsen burner for 10 minutes, during which time all of the water produced by the reaction is captured by the drying agent. The following table shows the data the student recorded during the experiment.

Mass of empty test tube	15.825 g
Mass of test tube and mixture before heating	17.648 g
Mass of drying agent before reaction	2.134 g
Mass of drying agent and water after reaction	2.303 g

(b) Calculate the number of moles of $NaHCO_3(s)$ present in the mixture in the test tube before the reaction was initiated.

(c) Determine the mass percent of $NaHCO_3(s)$ in the mixture.

(d) If the student spills some of the mixture out of the test tube after weighing the test tube and mixture and before heating, how would this error affect the mass percent of $NaHCO_3$ calculated in part (c) ? Justify your answer.

When a sample of pure Na_2CO_3 is placed in distilled water, the student observes that the pH of the solution increases significantly. This process is represented by the balanced net-ionic equation shown below.

$$CO_3^{2-}(aq) + H_2O(l) \rightleftarrows HCO_3^{-}(aq) + OH^{-}(aq)$$

(e) The student prepares a 0.10 M $Na_2CO_3(aq)$ solution and measures the pH of the solution to be 11.65.

(i) Calculate $[OH^-]$ in the $Na_2CO_3(aq)$ solution.

(ii) Write the expression for K_b for the carbonate ion.

(iii) Calculate the value of K_b for the carbonate ion.

The student adds some 1.0 M $Sr(NO_3)_2(aq)$ to the 0.10 M $Na_2CO_3(aq)$ and observes the formation of a precipitate.

(f) Write the balanced net-ionic equation for the reaction between $Sr(NO_3)_2$ and Na_2CO_3 that produces the precipitate.

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PAGE FOR ANSWERING QUESTION 2

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ADDITIONAL PAGE FOR ANSWERING QUESTION 2

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$$H_3BO_3(aq) + 4\ HF(g) \rightarrow H_3O^+(aq) + BF_4^-(aq) + 2\ H_2O(l)$$

3. Tetrafluoroboric acid is a strong acid with the formula HBF_4. The acid can be prepared by reacting the weak acid H_3BO_3 (molar mass 61.83 g/mol) with HF according to the equation above.

(a) To prepare a solution of $BF_4^-(aq)$, $HF(g)$ is bubbled into a solution containing 50.0 g of H_3BO_3 in a 1 L reaction vessel.

(i) Calculate the maximum number of moles of $BF_4^-(aq)$ that can be produced.

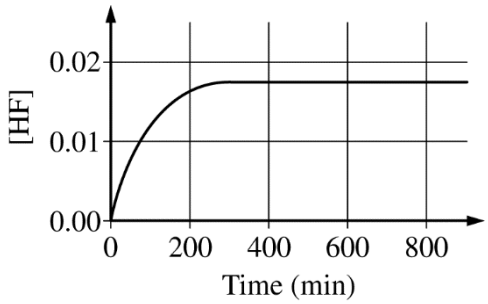
(ii) Calculate the number of liters of $HF(g)$, measured at 273 K and 1.00 atm, that will be consumed if all the H_3BO_3 reacts.

(iii) Will the pH of the solution increase, decrease, or remain the same during the course of the reaction? Justify your answer.

In another experiment, a 0.150 *M* $BF_4^-(aq)$ solution is prepared by dissolving $NaBF_4(s)$ in distilled water. The $BF_4^-(aq)$ ions in the solution slowly react with $H_2O(l)$ in the reversible reaction represented below.

$$BF_4^-(aq) + H_2O(l) \rightleftarrows BF_3OH^-(aq) + HF(aq)$$

The concentration of HF is monitored over time, as shown in the graph below.



[HF] reaches a constant value of 0.0174 *M* when the reaction reaches equilibrium. For the forward reaction, the rate law is $rate = k_f[BF_4^-]$. The value of the rate constant k_f was experimentally determined to be $9.00 \times 10^{-4}\ min^{-1}$.

(b) Calculate the rate of the forward reaction after 600. minutes. Include units with your answer.

The rate law for the reverse reaction is $rate = k_r[BF_3OH^-][HF]$.

(c) A student claims that the initial rate of the reverse reaction is equal to zero. Do you agree or disagree with this claim? Justify your answer in terms of the rate law for the reverse reaction.

(d) At equilibrium the forward and reverse reaction rates are equal. Calculate the value of the rate constant for the reverse reaction.

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PAGE FOR ANSWERING QUESTION 3

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ADDITIONAL PAGE FOR ANSWERING QUESTION 3

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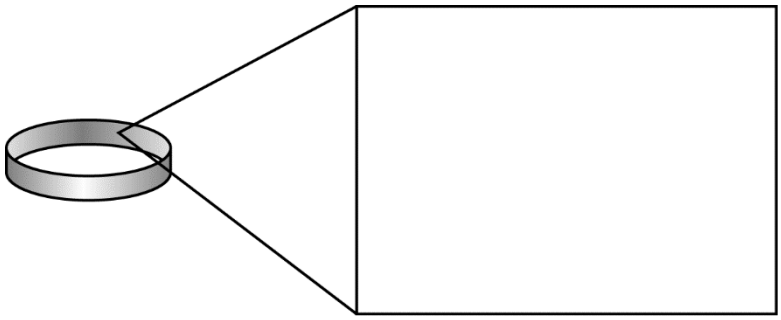
Element	Atomic Radius (pm)
Au	135
Pd	140

4. White gold is a common alloy of gold and palladium that is often used in jewelry. The atomic radii of the metals are given in the table above.

   (a) A particular ring is made from an alloy that is 75 mole percent gold and 25 mole percent palladium. Using the box below, draw a particle-level diagram of the solid alloy consisting of 12 atoms with a representative proportion of atom types. Your diagram should clearly indicate whether the alloy is interstitial or substitutional. Use empty circles for gold and shaded circles for palladium.



White-gold jewelry is often coated with rhodium to modify the color and durability.

   (b) A student hypothesizes that placing the ring in a 1.0 *M* solution of $Rh(NO_3)_3(aq)$ will result in a reaction in which Rh metal is deposited on the white-gold ring. Based on the information in the table below, calculate $E°$ for the reactions that may occur between ions in the solution and atoms in the ring, and indicate whether or not the student's hypothesis is correct.

Half-Reaction	$E°$ (V)
$Au^{3+}(aq) + 3\,e^- \rightarrow Au(s)$	1.50
$Pd^{2+}(aq) + 2\,e^- \rightarrow Pd(s)$	0.92
$Rh^{3+}(aq) + 3\,e^- \rightarrow Rh(s)$	0.76

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ADDITIONAL PAGE FOR ANSWERING QUESTION 4

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Element	First Ionization Energy (J/mol)
Na	4.95×10^5
K	4.19×10^5

5. The first ionization energies for Na and K are given in the table above. Na metal reacts vigorously with water to form hydrogen gas and a metal hydroxide. K metal reacts vigorously as well, but it bursts into a violet-colored flame.

   (a) Write the electron configuration for a K^+ ion.

   (b) Based on principles of atomic structure, explain why the first ionization energy of K is lower than the first ionization energy of Na.

   (c) A student hypothesizes that the flame is violet colored because violet light consists of photons that have the energy needed to ionize K atoms. The wavelength of the violet light is measured to be 423 nm.

      (i) Calculate the energy, in J, of one photon of violet light with a wavelength of 423 nm.

      (ii) Is the energy of one photon of the violet light sufficient to cause the ionization of a K atom? Justify your answer.

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ADDITIONAL PAGE FOR ANSWERING QUESTION 5

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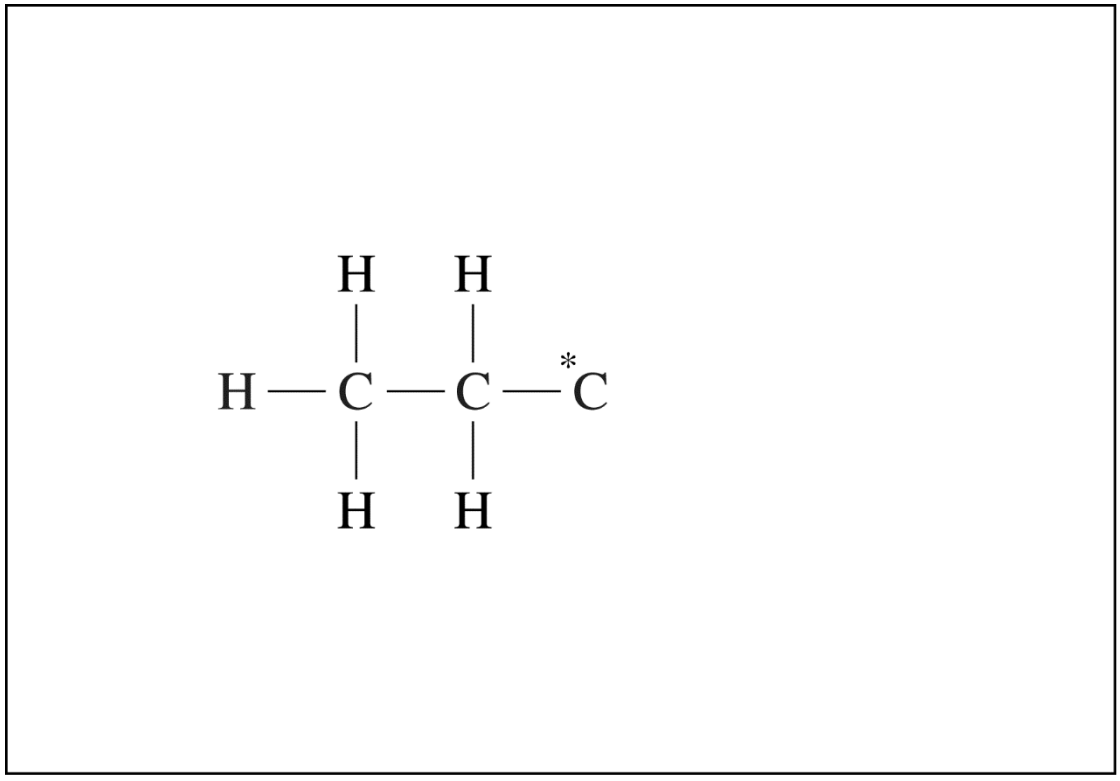
6. Propanoic acid, C_2H_5COOH, is an organic acid that is a liquid at room temperature.

(a) An incomplete Lewis diagram for the propanoic acid molecule is provided in the box below. Complete the diagram, showing how the remaining atoms in the molecule are arranged around the carbon atom marked with an asterisk (*). Your structure should minimize formal charge and include any lone pairs of electrons.



(b) Identify the hybridization of the carbon atom marked with the asterisk.

(c) Propanoic acid has a lower boiling point than butanoic acid, C_3H_7COOH.

(i) Identify all the types of intermolecular forces present among the molecules in propanoic acid.

(ii) Which of the types of intermolecular forces that you identified in part (c)(i) is most responsible for the difference in boiling points of the two acids?

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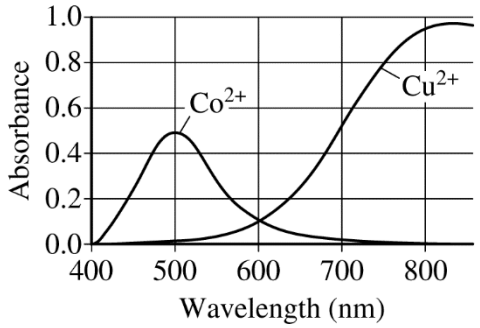
7. A student has 100. mL of 0.400 *M* $CuSO_4(aq)$ and is asked to make 100. mL of 0.150 *M* $CuSO_4(aq)$ for a spectrophotometry experiment. The following laboratory equipment is available for preparing the solution: centigram balance, weighing paper, funnel, 10 mL beaker, 150 mL beaker, 50 mL graduated cylinder, 100 mL volumetric flask, 50 mL buret, and distilled water.

   (a) Calculate the volume of 0.400 *M* $CuSO_4(aq)$ required for the preparation.

   (b) Briefly describe the essential steps to most accurately prepare the 0.150 *M* $CuSO_4(aq)$ from the 0.400 *M* $CuSO_4(aq)$ using the equipment listed above.

   The student plans to conduct a spectrophotometric analysis to determine the concentration of $Cu^{2+}(aq)$ in a solution. The solution has a small amount of $Co(NO_3)_2(aq)$ present as a contaminant. The student is given the diagram below, which shows the absorbance curves for aqueous solutions of $Co^{2+}(aq)$ and $Cu^{2+}(aq)$.



   (c) The spectrophotometer available to the student has a wavelength range of 400 nm to 700 nm. What wavelength should the student use to minimize the interference from the presence of the $Co^{2+}(aq)$ ions?

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ADDITIONAL PAGE FOR ANSWERING QUESTION 7

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DO NOT DETACH FROM BOOK.

PERIODIC TABLE OF THE ELEMENTS

1																	18
1 **H** 1.008	2											13	14	15	16	17	2 **He** 4.00
3 **Li** 6.94	4 **Be** 9.01											5 **B** 10.81	6 **C** 12.01	7 **N** 14.01	8 **O** 16.00	9 **F** 19.00	10 **Ne** 20.18
11 **Na** 22.99	12 **Mg** 24.30	3	4	5	6	7	8	9	10	11	12	13 **Al** 26.98	14 **Si** 28.09	15 **P** 30.97	16 **S** 32.06	17 **Cl** 35.45	18 **Ar** 39.95
19 **K** 39.10	20 **Ca** 40.08	21 **Sc** 44.96	22 **Ti** 47.87	23 **V** 50.94	24 **Cr** 52.00	25 **Mn** 54.94	26 **Fe** 55.85	27 **Co** 58.93	28 **Ni** 58.69	29 **Cu** 63.55	30 **Zn** 65.38	31 **Ga** 69.72	32 **Ge** 72.63	33 **As** 74.92	34 **Se** 78.97	35 **Br** 79.90	36 **Kr** 83.80
37 **Rb** 85.47	38 **Sr** 87.62	39 **Y** 88.91	40 **Zr** 91.22	41 **Nb** 92.91	42 **Mo** 95.95	43 **Tc** (97)	44 **Ru** 101.1	45 **Rh** 102.91	46 **Pd** 106.42	47 **Ag** 107.87	48 **Cd** 112.41	49 **In** 114.82	50 **Sn** 118.71	51 **Sb** 121.76	52 **Te** 127.60	53 **I** 126.90	54 **Xe** 131.29
55 **Cs** 132.91	56 **Ba** 137.33	57 ***La** 138.91	72 **Hf** 178.49	73 **Ta** 180.95	74 **W** 183.84	75 **Re** 186.21	76 **Os** 190.2	77 **Ir** 192.2	78 **Pt** 195.08	79 **Au** 196.97	80 **Hg** 200.59	81 **Tl** 204.38	82 **Pb** 207.2	83 **Bi** 208.98	84 **Po** (209)	85 **At** (210)	86 **Rn** (222)
87 **Fr** (223)	88 **Ra** (226)	89 **†Ac** (227)	104 **Rf** (267)	105 **Db** (270)	106 **Sg** (271)	107 **Bh** (270)	108 **Hs** (277)	109 **Mt** (276)	110 **Ds** (281)	111 **Rg** (282)	112 **Cn** (285)	113 **Uut** (285)	114 **Fl** (289)	115 **Uup** (288)	116 **Lv** (293)	117 **Uus** (294)	118 **Uuo** (294)

*Lanthanoid Series	58 **Ce** 140.12	59 **Pr** 140.91	60 **Nd** 144.24	61 **Pm** (145)	62 **Sm** 150.4	63 **Eu** 151.97	64 **Gd** 157.25	65 **Tb** 158.93	66 **Dy** 162.50	67 **Ho** 164.93	68 **Er** 167.26	69 **Tm** 168.93	70 **Yb** 173.05	71 **Lu** 174.97
†Actinoid Series	90 **Th** 232.04	91 **Pa** 231.04	92 **U** 238.03	93 **Np** (237)	94 **Pu** (244)	95 **Am** (243)	96 **Cm** (247)	97 **Bk** (247)	98 **Cf** (251)	99 **Es** (252)	100 **Fm** (257)	101 **Md** (258)	102 **No** (259)	103 **Lr** (262)

AP® CHEMISTRY EQUATIONS AND CONSTANTS

Throughout the exam the following symbols have the definitions specified unless otherwise noted.

L, mL	=	liter(s), milliliter(s)	mm Hg	=	millimeters of mercury
g	=	gram(s)	J, kJ	=	joule(s), kilojoule(s)
nm	=	nanometer(s)	V	=	volt(s)
atm	=	atmosphere(s)	mol	=	mole(s)

ATOMIC STRUCTURE

$E = h\nu$

$c = \lambda\nu$

E = energy
ν = frequency
λ = wavelength

Planck's constant, $h = 6.626 \times 10^{-34}$ J s
Speed of light, $c = 2.998 \times 10^{8}$ m s^{-1}
Avogadro's number = 6.022×10^{23} mol^{-1}
Electron charge, $e = -1.602 \times 10^{-19}$ coulomb

EQUILIBRIUM

$K_c = \dfrac{[C]^c[D]^d}{[A]^a[B]^b}$, where $a\ A + b\ B \rightleftarrows c\ C + d\ D$

$K_p = \dfrac{(P_C)^c(P_D)^d}{(P_A)^a(P_B)^b}$

$K_a = \dfrac{[H^+][A^-]}{[HA]}$

$K_b = \dfrac{[OH^-][HB^+]}{[B]}$

$K_w = [H^+][OH^-] = 1.0 \times 10^{-14}$ at 25°C

$= K_a \times K_b$

$pH = -\log[H^+]$, $pOH = -\log[OH^-]$

$14 = pH + pOH$

$pH = pK_a + \log\dfrac{[A^-]}{[HA]}$

$pK_a = -\log K_a$, $pK_b = -\log K_b$

Equilibrium Constants

K_c (molar concentrations)
K_p (gas pressures)
K_a (weak acid)
K_b (weak base)
K_w (water)

KINETICS

$\ln[A]_t - \ln[A]_0 = -kt$

$\dfrac{1}{[A]_t} - \dfrac{1}{[A]_0} = kt$

$t_{1/2} = \dfrac{0.693}{k}$

k = rate constant
t = time
$t_{1/2}$ = half-life

GASES, LIQUIDS, AND SOLUTIONS

$$PV = nRT$$

$$P_A = P_{\text{total}} \times X_A, \text{ where } X_A = \frac{\text{moles A}}{\text{total moles}}$$

$$P_{total} = P_A + P_B + P_C + \ldots$$

$$n = \frac{m}{\boldsymbol{M}}$$

$$\text{K} = ^\circ\text{C} + 273$$

$$D = \frac{m}{V}$$

$$KE \text{ per molecule} = \frac{1}{2}mv^2$$

Molarity, M = moles of solute per liter of solution

$$A = abc$$

P = pressure
V = volume
T = temperature
n = number of moles
m = mass
$\boldsymbol{M}$ = molar mass
D = density
KE = kinetic energy
v = velocity
A = absorbance
a = molar absorptivity
b = path length
c = concentration

Gas constant, R = 8.314 J mol^{-1} K^{-1}
= 0.08206 L atm mol^{-1} K^{-1}
= 62.36 L torr mol^{-1} K^{-1}

1 atm = 760 mm Hg = 760 torr

STP = 273.15 K and 1.0 atm

Ideal gas at STP = 22.4 L mol^{-1}

THERMODYNAMICS / ELECTROCHEMISTRY

$$q = mc\Delta T$$

$$\Delta S^\circ = \sum S^\circ \text{ products} - \sum S^\circ \text{ reactants}$$

$$\Delta H^\circ = \sum \Delta H_f^\circ \text{ products} - \sum \Delta H_f^\circ \text{ reactants}$$

$$\Delta G^\circ = \sum \Delta G_f^\circ \text{ products} - \sum \Delta G_f^\circ \text{ reactants}$$

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$
$$= -RT \ln K$$
$$= -nFE^\circ$$

$$I = \frac{q}{t}$$

q = heat
m = mass
c = specific heat capacity
T = temperature
S° = standard entropy
H° = standard enthalpy
G° = standard Gibbs free energy
n = number of moles
E° = standard reduction potential
I = current (amperes)
q = charge (coulombs)
t = time (seconds)

Faraday's constant, F = 96,485 coulombs per mole of electrons

$$1 \text{ volt} = \frac{1 \text{ joule}}{1 \text{ coulomb}}$$