

**2018**

**AP<sup>®</sup>**

**CollegeBoard**

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# **AP Chemistry**

## **Free-Response Questions**

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**DO NOT DETACH FROM BOOK.**

$$\frac{18}{2}$$

|    |   |    |      |    |    |       |    |    |       |    |    |       |    |    |        |    |    |       |     |     |       |
|----|---|----|------|----|----|-------|----|----|-------|----|----|-------|----|----|--------|----|----|-------|-----|-----|-------|
| 18 | 2 | He | 4.00 | 10 | Ne | 20.18 | 18 | Ar | 39.95 | 36 | Kr | 83.80 | 54 | Xe | 131.29 | 86 | Rn | (222) | 118 | Uuo | (294) |
|----|---|----|------|----|----|-------|----|----|-------|----|----|-------|----|----|--------|----|----|-------|-----|-----|-------|

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

|           |           |          |           |           |           |           |           |           |           |           |           |           |           |
|-----------|-----------|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 90        | 91        | 92       | 93        | 94        | 95        | 96        | 97        | 98        | 99        | 100       | 101       | 102       | 103       |
| <b>Th</b> | <b>Pa</b> | <b>U</b> | <b>Np</b> | <b>Pu</b> | <b>Am</b> | <b>Cm</b> | <b>Bk</b> | <b>Cf</b> | <b>Es</b> | <b>Fm</b> | <b>Md</b> | <b>No</b> | <b>Lr</b> |
| 232.04    | 231.04    | 238.03   | (237)     | (244)     | (243)     | (247)     | (247)     | (251)     | (252)     | (257)     | (258)     | (259)     | (262)     |

## AP<sup>®</sup> CHEMISTRY EQUATIONS AND CONSTANTS

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

L, mL = liter(s), milliliter(s)  
g = gram(s)  
nm = nanometer(s)  
atm = atmosphere(s)

mm Hg = millimeters of mercury  
J, kJ = joule(s), kilojoule(s)  
V = volt(s)  
mol = mole(s)

### ATOMIC STRUCTURE

$$E = h\nu$$

$$c = \lambda\nu$$

$E$  = energy  
 $\nu$  = frequency  
 $\lambda$  = wavelength

Planck's constant,  $h = 6.626 \times 10^{-34}$  J s

Speed of light,  $c = 2.998 \times 10^8$  m s<sup>-1</sup>

Avogadro's number =  $6.022 \times 10^{23}$  mol<sup>-1</sup>

Electron charge,  $e = -1.602 \times 10^{-19}$  coulomb

### EQUILIBRIUM

$$K_c = \frac{[C]^c[D]^d}{[A]^a[B]^b}, \text{ where } aA + bB \rightleftharpoons cC + dD$$

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

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

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

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

$$= K_a \times K_b$$

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

$$14 = \text{pH} + \text{pOH}$$

$$\text{pH} = \text{p}K_a + \log \frac{[A^-]}{[HA]}$$

$$\text{p}K_a = -\log K_a, \text{ p}K_b = -\log K_b$$

#### Equilibrium Constants

$K_c$  (molar concentrations)

$K_p$  (gas pressures)

$K_a$  (weak acid)

$K_b$  (weak base)

$K_w$  (water)

### KINETICS

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

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

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

$k$  = rate constant

$t$  = time

$t_{1/2}$  = half-life

## GASES, LIQUIDS, AND SOLUTIONS

$$PV = nRT$$

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

$$P_{\text{total}} = P_A + P_B + P_C + \dots$$

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

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

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

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

Molarity,  $M$  = moles of solute per liter of solution

$$A = abc$$

$P$  = pressure

$V$  = volume

$T$  = temperature

$n$  = number of moles

$m$  = mass

$M$  = molar mass

$D$  = density

$KE$  = kinetic energy

$v$  = velocity

$A$  = absorbance

$a$  = molar absorptivity

$b$  = path length

$c$  = concentration

$$\begin{aligned}\text{Gas constant, } R &= 8.314 \text{ J mol}^{-1} \text{ K}^{-1} \\ &= 0.08206 \text{ L atm mol}^{-1} \text{ K}^{-1} \\ &= 62.36 \text{ L torr mol}^{-1} \text{ K}^{-1}\end{aligned}$$

$$1 \text{ atm} = 760 \text{ mm Hg} = 760 \text{ torr}$$

$$\text{STP} = 273.15 \text{ K and } 1.0 \text{ atm}$$

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

## 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

$S^\circ$  = standard entropy

$H^\circ$  = standard enthalpy

$G^\circ$  = standard Gibbs free energy

$n$  = number of moles

$E^\circ$  = standard reduction potential

$I$  = current (amperes)

$q$  = charge (coulombs)

$t$  = time (seconds)

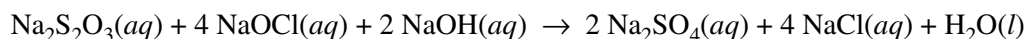
Faraday's constant,  $F$  = 96,485 coulombs per mole of electrons

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

**2018 AP<sup>®</sup> CHEMISTRY FREE-RESPONSE QUESTIONS****CHEMISTRY****Section II****Time—1 hour and 45 minutes****7 Questions****YOU MAY USE YOUR CALCULATOR FOR THIS SECTION.**

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

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



1. A student performs an experiment to determine the value of the enthalpy change,  $\Delta H_{rxn}^\circ$ , for the oxidation-reduction reaction represented by the balanced equation above.
  - (a) Determine the oxidation number of Cl in NaOCl.
  - (b) Calculate the number of grams of  $\text{Na}_2\text{S}_2\text{O}_3$  needed to prepare 100.00 mL of 0.500 M  $\text{Na}_2\text{S}_2\text{O}_3(aq)$ .

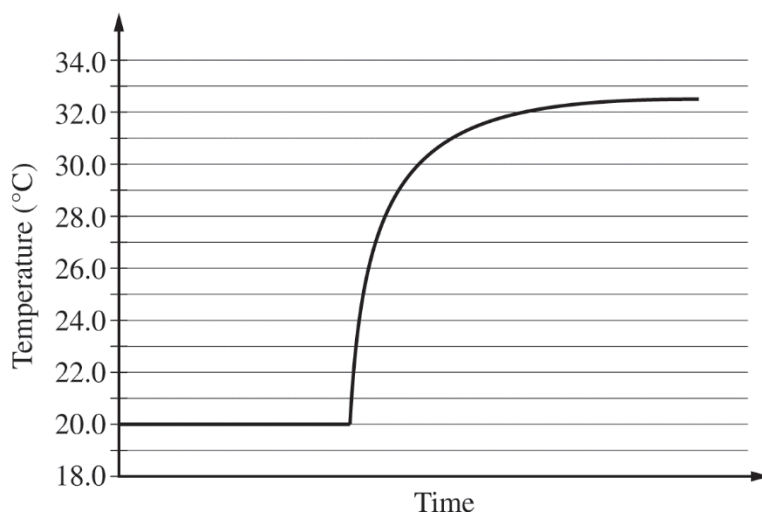
In the experiment, the student uses the solutions shown in the table below.

| Solution                              | Concentration<br>(M) | Volume<br>(mL) |
|---------------------------------------|----------------------|----------------|
| $\text{Na}_2\text{S}_2\text{O}_3(aq)$ | 0.500                | 5.00           |
| $\text{NaOCl}(aq)$                    | 0.500                | 5.00           |
| $\text{NaOH}(aq)$                     | 0.500                | 5.00           |

- (c) Using the balanced equation for the oxidation-reduction reaction and the information in the table above, determine which reactant is the limiting reactant. Justify your answer.

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The solutions, all originally at 20.0°C, are combined in an insulated calorimeter. The temperature of the reaction mixture is monitored, as shown in the graph below.



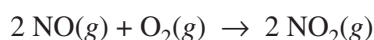
- (d) According to the graph, what is the temperature change of the reaction mixture?
- (e) The mass of the reaction mixture inside the calorimeter is 15.21 g.
- Calculate the magnitude of the heat energy, in joules, that is released during the reaction. Assume that the specific heat of the reaction mixture is  $3.94 \text{ J/(g}\cdot^{\circ}\text{C)}$  and that the heat absorbed by the calorimeter is negligible.
  - Using the balanced equation for the oxidation-reduction reaction and your answer to part (c), calculate the value of the enthalpy change of the reaction,  $\Delta H_{\text{rxn}}^{\circ}$ , in  $\text{kJ/mol}_{\text{rxn}}$ . Include the appropriate algebraic sign with your answer.

The student repeats the experiment, but this time doubling the volume of each of the reactants, as shown in the table below.

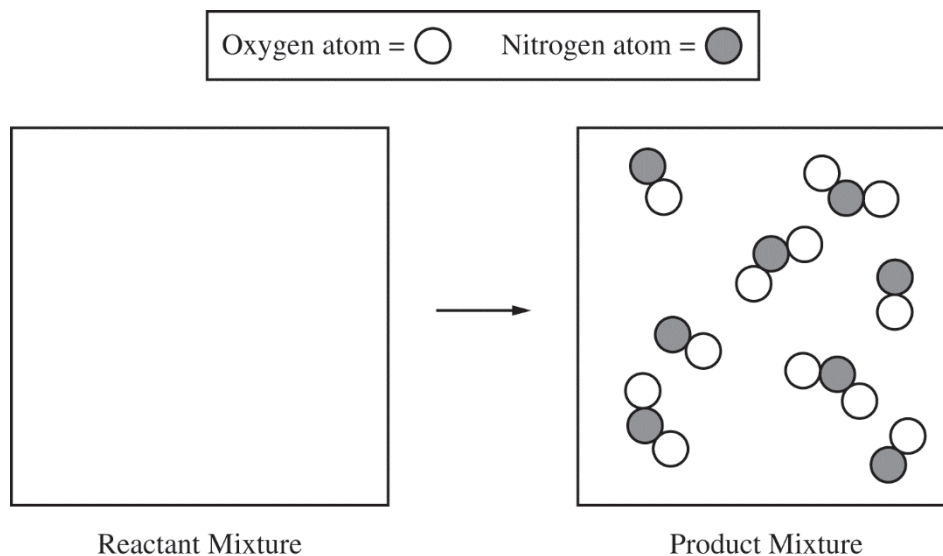
| Solution                                     | Concentration (M) | Volume (mL) |
|----------------------------------------------|-------------------|-------------|
| $\text{Na}_2\text{S}_2\text{O}_3(\text{aq})$ | 0.500             | 10.0        |
| $\text{NaOCl}(\text{aq})$                    | 0.500             | 10.0        |
| $\text{NaOH}(\text{aq})$                     | 0.500             | 10.0        |

- (f) The magnitude of the enthalpy change,  $\Delta H_{\text{rxn}}^{\circ}$ , in  $\text{kJ/mol}_{\text{rxn}}$ , calculated from the results of the second experiment is the same as the result calculated in part (e)(ii). Explain this result.
- (g) Write the balanced net ionic equation for the given reaction.

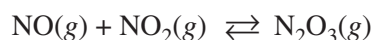
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2. A student investigates the reactions of nitrogen oxides. One of the reactions in the investigation requires an equimolar mixture of  $\text{NO}(g)$  and  $\text{NO}_2(g)$ , which the student produces by using the reaction represented above.
- (a)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



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

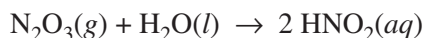


| $\Delta H_{298}^\circ$              | $\Delta S_{298}^\circ$                               | $\Delta G_{298}^\circ$             |
|-------------------------------------|------------------------------------------------------|------------------------------------|
| $-40.4 \text{ kJ/mol}_{\text{rxn}}$ | $-138.5 \text{ J/(K} \cdot \text{mol}_{\text{rxn}})$ | $0.87 \text{ kJ/mol}_{\text{rxn}}$ |

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

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



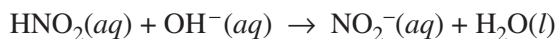
(d) The skeletal structure of the  $\text{HNO}_2$  molecule is shown in the box below.

- (i) Complete the Lewis electron-dot diagram of the  $\text{HNO}_2$  molecule in the box below, including any lone pairs of electrons.

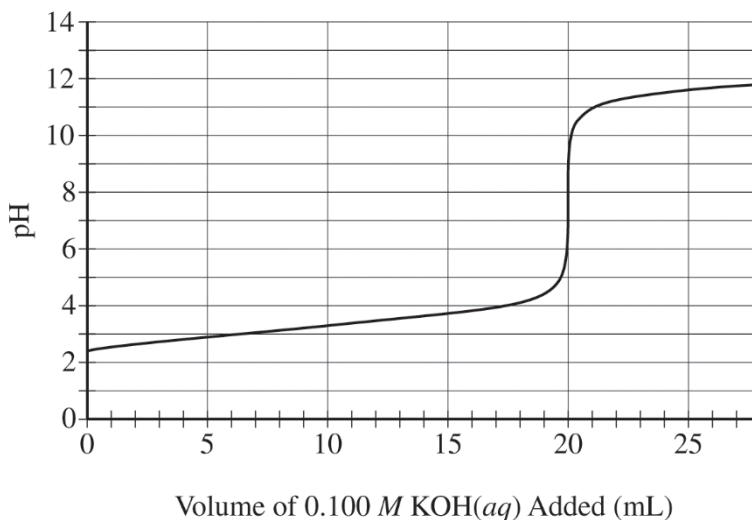


- (ii) Based on your completed diagram above, identify the hybridization of the nitrogen atom in the  $\text{HNO}_2$  molecule.

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



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



(e) Use the titration curve and the information above to

- (i) determine the initial concentration of the  $\text{HNO}_2(aq)$  solution
- (ii) estimate the value of  $\text{p}K_a$  for  $\text{HNO}_2(aq)$

(f) During the titration, after a volume of 15 mL of 0.100 M  $\text{KOH}(aq)$  has been added, which species,  $\text{HNO}_2(aq)$  or  $\text{NO}_2^-(aq)$ , is present at a higher concentration in the solution? Justify your answer.

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3. Answer the following questions relating to Fe and its ions, Fe<sup>2+</sup> and Fe<sup>3+</sup>.

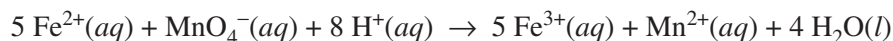
(a) Write the ground-state electron configuration of the Fe<sup>2+</sup> ion.

| Ion              | Ionic Radius (pm) |
|------------------|-------------------|
| Fe <sup>2+</sup> | 92                |
| Fe <sup>3+</sup> | 79                |

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

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

A student obtains a solution that contains an unknown concentration of Fe<sup>2+</sup>(aq). To determine the concentration of Fe<sup>2+</sup>(aq) in the solution, the student titrates a sample of the solution with MnO<sub>4</sub><sup>−</sup>(aq), which converts Fe<sup>2+</sup>(aq) to Fe<sup>3+</sup>(aq), as represented by the following equation.



(d) Write the balanced equation for the half-reaction for the oxidation of Fe<sup>2+</sup>(aq) to Fe<sup>3+</sup>(aq).

(e) The student titrates a 10.0 mL sample of the Fe<sup>2+</sup>(aq) solution. Calculate the value of [Fe<sup>2+</sup>] in the solution if it takes 17.48 mL of added 0.0350 M KMnO<sub>4</sub>(aq) to reach the equivalence point of the titration.

To deliver the 10.0 mL sample of the Fe<sup>2+</sup>(aq) solution in part (e), the student has the choice of using one of the pieces of glassware listed below.

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

(f) Explain why the 25 mL volumetric flask would be a poor choice to use for delivering the required volume of the Fe<sup>2+</sup>(aq) solution.

In a separate experiment, the student is given a sample of powdered Fe(s) that contains an inert impurity. The student uses a procedure to oxidize the Fe(s) in the sample to Fe<sub>2</sub>O<sub>3</sub>(s). The student collects the following data during the experiment.

|                                                     |         |
|-----------------------------------------------------|---------|
| Mass of Fe(s) with inert impurity                   | 6.724 g |
| Mass of Fe <sub>2</sub> O <sub>3</sub> (s) produced | 7.531 g |

(g) Calculate the number of moles of Fe in the Fe<sub>2</sub>O<sub>3</sub>(s) produced.

(h) Calculate the percent by mass of Fe in the original sample of powdered Fe(s) with the inert impurity.

(i) If the oxidation of the Fe(s) in the original sample was incomplete so that some of the 7.531 g of product was FeO(s) instead of Fe<sub>2</sub>O<sub>3</sub>(s), would the calculated mass percent of Fe(s) in the original sample be higher, lower, or the same as the actual mass percent of Fe(s)? Justify your answer.

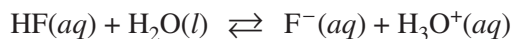
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|                                                                                                 |                                                                                                 |                                                                                                   |
|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|
| Sulfur atom =  | Carbon atom =  | Oxygen atom =  |
|-------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------|

| Compound        | Molecular Structure                                                               | Boiling Point at 1 atm (K) |
|-----------------|-----------------------------------------------------------------------------------|----------------------------|
| CS <sub>2</sub> |  | 319                        |
| COS             |  | 223                        |

4. The table above gives the molecular structures and boiling points for the compounds CS<sub>2</sub> and COS.
- (a) In terms of the types and relative strengths of all the intermolecular forces in each compound, explain why the boiling point of CS<sub>2</sub>(*l*) is higher than that of COS(*l*).
- (b) A 10.0 g sample of CS<sub>2</sub>(*l*) is put in an evacuated 5.0 L rigid container. The container is sealed and heated to 325 K, at which temperature all of the CS<sub>2</sub>(*l*) has vaporized. What is the pressure in the container once all of the CS<sub>2</sub>(*l*) has vaporized?

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5. The ionization of  $\text{HF}(aq)$  in water is represented by the equation above. In a  $0.0350\text{ M}$   $\text{HF}(aq)$  solution, the percent ionization of  $\text{HF}$  is 13.0 percent.
- (a) Two particulate representations of the ionization of  $\text{HF}$  molecules in the  $0.0350\text{ M}$   $\text{HF}(aq)$  solution are shown below in Figure 1 and Figure 2. Water molecules are not shown. Explain why the representation of the ionization of  $\text{HF}$  molecules in water in Figure 1 is more accurate than the representation in Figure 2. (The key below identifies the particles in the representations.)

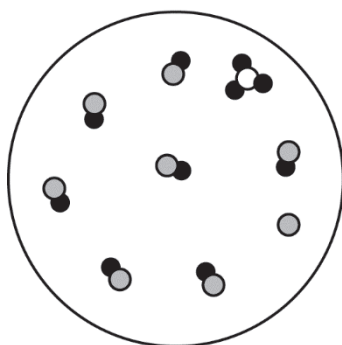
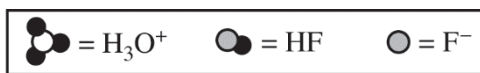


Figure 1

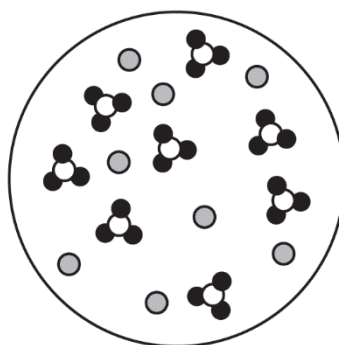
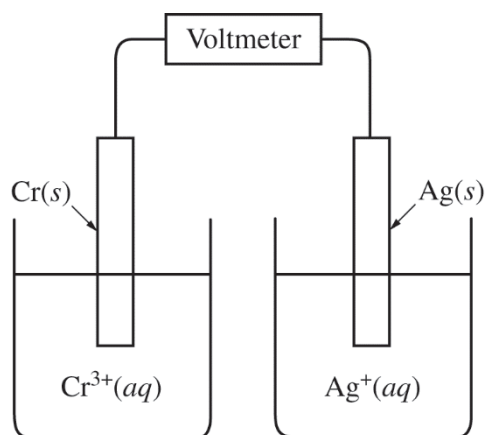


Figure 2

- (b) Use the percent ionization data above to calculate the value of  $K_a$  for  $\text{HF}$ .
- (c) If  $50.0\text{ mL}$  of distilled water is added to  $50.0\text{ mL}$  of  $0.035\text{ M}$   $\text{HF}(aq)$ , will the percent ionization of  $\text{HF}(aq)$  in the solution increase, decrease, or remain the same? Justify your answer with an explanation or calculation.

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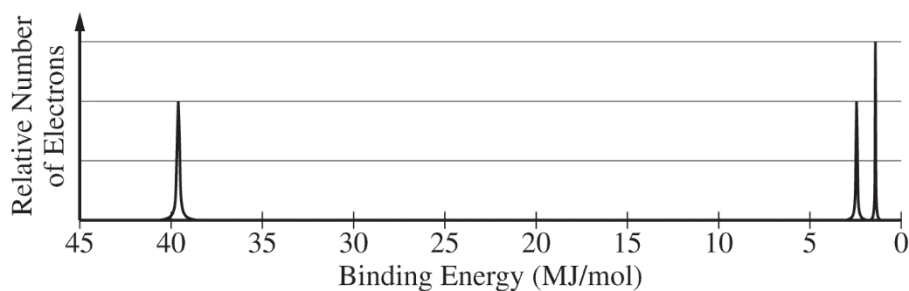


6. A student sets up a galvanic cell at 298 K that has an electrode of  $\text{Ag}(s)$  immersed in a 1.0  $M$  solution of  $\text{Ag}^+(aq)$  and an electrode of  $\text{Cr}(s)$  immersed in a 1.0  $M$  solution of  $\text{Cr}^{3+}(aq)$ , as shown in the diagram above.
- (a) The student measures the voltage of the cell shown above and discovers that it is zero. Identify the missing component of the cell, and explain its importance for obtaining a nonzero voltage.

| Half-Reaction                                         | $E^\circ$ (V) |
|-------------------------------------------------------|---------------|
| $\text{Ag}^+(aq) + e^- \rightarrow \text{Ag}(s)$      | + 0.80        |
| $\text{Cr}^{3+}(aq) + 3 e^- \rightarrow \text{Cr}(s)$ | ?             |

- (b) The student adds the missing component to the cell and measures  $E^\circ_{\text{cell}}$  to be +1.54 V. As the cell operates,  $\text{Ag}^+$  ions are reduced. Use this information and the information in the table above to do the following.
- Calculate the value of  $E^\circ$  for the half-reaction  $\text{Cr}^{3+}(aq) + 3 e^- \rightarrow \text{Cr}(s)$ .
  - Write the balanced net-ionic equation for the overall reaction that occurs as the cell operates.
  - Calculate the value of  $\Delta G^\circ$  for the overall cell reaction in  $\text{J/mol}_{\text{rxn}}$ .

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7. The complete photoelectron spectrum of an element is represented above.

(a) Identify the element.

A radioactive isotope of the element decays with a half-life of 10. minutes.

(b) Calculate the value of the rate constant,  $k$ , for the radioactive decay. Include units with your answer.

(c) If 64 atoms of the radioactive isotope are originally present in a sample, what is the expected amount of time that will pass until only one atom of the isotope remains? Show how you arrived at your answer.

**STOP**

**END OF EXAM**