13.7: End-of-Chapter Material

Exercises (Chemical Equilibrium)

1. Define the law of mass action.

2. What is an equilibrium constant for a chemical reaction? How is it constructed?

3. Write the Keq expression for each reaction.

   a. $H_2 + Cl_2 \rightleftarrows 2HCl$
   b. $NO + NO_2 \rightleftarrows N_2O_3$

4. Write the Keq expression for each reaction.

   a. $C_2H_5OH + NaI \rightleftarrows C_2H_5I + NaOH$
   b. $PCl_3 + Cl_2 \rightleftarrows PCl_5$

5. Write the KP expression for each reaction.

   a. $2H_2(g) + O_2(g) \rightleftarrows 2H_2O(g)$
   b. $2H_2O_2(g) \rightleftarrows 2H_2O(g) + O_2(g)$

6. Write the KP expression for each reaction.

   a. $CH_4(g) + 2O_2(g) \rightleftarrows CO_2(g) + 2H_2O(g)$
   b. $CH_4(g) + 4Cl_2(g) \rightleftarrows CCl_4(g) + 4HCl(g)$

7. The following reaction is at equilibrium:

   $PBr_3 + Br_2 \rightleftarrows PBr_5$

The equilibrium $[Br_2]$ and $[PBr_5]$ are $2.05 M$ and $0.55 M$, respectively. If the Keq_{eq} is 1.65 , what is the equilibrium $[PBr3]$?

8. The following reaction is at equilibrium:

   $CO + Cl_2 \rightleftarrows CoCl_2$

The equilibrium [CO] and $[Cl_2]$ are $0.088 M$ and $0.103 M$, respectively. If the K_{eq} is 0.225 , what is the equilibrium $[COCl_2]$?

9. The following reaction is at equilibrium:

   $CH_4 + 2Cl_2 \rightleftarrows CH_2Cl_2 + 2HCl$

If $[CH_4]$ is $0.250 M$, $[Cl_2]$is $0.150 M$, and $[CH_2Cl_2]$ is $0.175 M$ at equilibrium, what is [HCl] at equilibrium if the K_{eq} is 2.30 ?

10. The following reaction is at equilibrium:

    $4HBr + O_2 \rightleftarrows 2H_2O + 2Br_2$

If $[HBr]$ is $0.100 M$, $[O_2]$is $0.250 M$, and $[H_2O]$ is $0.0500 M$ at equilibrium, what is [Br2] at equilibrium if the K_{eq} is 0.770 ?

11. Write the KP expression for the following gas-phase reaction:

    $4NO_2(g) + O_2(g) \rightleftarrows 2\ N_2O_5(g)$

12. Write the KP expression for the following gas-phase reaction:

    $ClO(g) + O_3(g) \rightleftarrows ClO_2(g) + O_2(g)$

13. What is the equilibrium partial pressure of $COBr_2$ if the equilibrium partial pressures of CO and Br_2 are $0.666\ atm$ and $0.235\ atm$ and the KP_P for this equilibrium is 4.08 ?

    $CO(g) + Br_2(g) \rightleftarrows COBr_2(g)$

14. What is the equilibrium partial pressure of O_3 if the equilibrium partial pressure of O_2 is $0.0044\ atm$ and KP_P for this equilibrium is 0.00755 ?

    $3O_2(g) \rightleftarrows 2O_3(g)$

15. Calculate the K_P for this reaction at 298 K if the $K_{eq} = 1.76 \times 10^{-3}$.
$3O_2(g) \rightleftarrows 2O_3(g)$

16. Calculate the K_P for this reaction at 310 K if the $K_{eq} = 6.22 \times 10^{3}$.
$4NO_2(g) + O_2(g) \rightleftarrows 2\,N_2O_5(g)$

17. Calculate the K_{eq} for this reaction if the $K_P = 5.205 \times 10^{-3}$ at 660°C.
$CO(g) + F_2(g) \rightleftarrows COF_2(g)$

18. Calculate the K_{eq} for this reaction if the $KP = 78.3$ at 100°C.
$4HCl(g) + O_2(g) \rightleftarrows 2H_2O(g) + 2Cl_2(g)$

19. Write the correct K_{eq} expression for this reaction.
$NaOH(aq) + HCl(aq) \rightleftarrows NaCl(aq) + H_2O(\ell)$

20. Write the correct K_{eq} expression for this reaction.
$AgNO_3(aq) + NaCl(aq) \rightleftarrows AgCl(s) + NaNO_3(aq)$

21. Write the correct KP expression for this reaction.
$CaCO_3(s) \rightleftarrows CaO(s) + CO_2(g)$

22. Write the correct KP expression for this reaction.

Answers

1. the relationship between the concentrations of reactants and products of a chemical reaction at equilibrium

3. a. $K_{eq} = \dfrac{[HCl]^2}{[H_2]\,[Cl_2]}$

b. $K_{eq} = \dfrac{[N_2O_3]}{[NO]\,[NO_2]}$

5. a. $K_P = \dfrac{P^2_{H_2O}}{P^2_{H_2} P_{O_2}}$

b. $K_P = \dfrac{P^2_{H_2O} P_{O_2}}{P^2_{H_2O_2}}$

7. 0.163M

9. 0.272M

11. $K_P = \dfrac{P^2_{N_2O_5}}{P^4_{NO_2} P_{O_2}}$

13. $0.639\ \text{atm}$

15. 7.20×10^{-5}

17. $K_{eq} = 3.98 \times 10^{-1}$

19. $K_{eq} = \dfrac{[NaCl]}{[NaOH][HCl]}$

21. $KP = P_{CO}$

Exercises (Le Chatelier's principle)

1. Define Le Chatelier's principle.

2. What is meant by a stress? What are some of the ways an equilibrium can be stressed?

3. Given this equilibrium, predict the direction of shift for each stress.
$H_2(g) + I_2(s) + 53\ \text{kJ} \rightleftarrows 2HI(g)$

a. decreased temperature
b. increased pressure
c. removal of HI

4. Given this equilibrium, predict the direction of shift for each stress.

$$\mathrm{H_2(\,g) + F_2(\,g) \rightleftarrows 2HF(g) + 546\ kJ}$$

a. increased temperature
b. addition of $\mathrm{H_2}$
c. decreased pressure

5. Given this equilibrium, predict the direction of shift for each stress.

$$\mathrm{2SO_2(\,g) + O_2(\,g) \rightleftarrows 2SO_3(\,g) + 196\ kJ}$$

a. removal of $\mathrm{SO_3}$
b. addition of $\mathrm{O_2}$
c. decreased temperature

6. Given this equilibrium, predict the direction of shift for each stress listed.

$$\mathrm{CO_2(\,g) + C(s) + 171\ kJ \rightleftarrows 2CO(g)}$$

a. addition of CO
b. increased pressure
c. addition of a catalyst

7. The synthesis of $\mathrm{NH_3}$ uses this chemical reaction.

$$\mathrm{N_2(\,g) + 3H_2(\,g) \rightleftarrows 2NH_3(\,g) + 92\ kJ}$$

Identify three stresses that can be imposed on the equilibrium to maximize the amount of $\mathrm{NH_3}$.

8. The synthesis of $\mathrm{CaCO_3}$ uses this chemical reaction.

$$\mathrm{CaO(s) + CO_2(\,g) \rightleftarrows CaCO_3(\,s) + 180\ kJ}$$

Identify three stresses that can be imposed on the equilibrium to maximize the amount of $\mathrm{CaCO_3}$.

Answers

1. When an equilibrium is stressed, the equilibrium shifts to minimize that stress.

3.

a. toward reactants
b. toward reactants
c. toward products

5.

a. toward products
b. toward products
c. toward products

7. increased pressure, decreased temperature, removal of $\mathrm{NH_3}$

Exercises (Calculating Equilibrium Constant Values)

1. Describe the three parts of an ICE chart.
2. What is the relationship between the equilibrium row in an ICE chart and the other two rows?
3. Set up (but do not solve) an ICE chart for this reaction, given the initial conditions.

$$\begin{array}{c} \mathrm{3O_2(\,g)} \\ \mathrm{0.075M} \end{array} \rightleftarrows \mathrm{2O_3(\,g)}$$

4. Set up (but do not solve) an ICE chart for this reaction, given the initial conditions.

$$\begin{array}{c} \mathrm{CH_4(\,g) + 2O_2(\,g)} \rightleftarrows \mathrm{CO_2(\,g) + 2H_2O(g)} \\ \mathrm{0.750M \quad 0.450M} \end{array}$$

5. Given that pure solids and liquids do not appear in Keq expressions, set up the ICE chart for this reaction, given the initial

conditions.

$$\underset{0.0060\text{M}}{\text{CH}_4(\text{ g})} + \underset{0.055\text{M}}{2\text{O}_2(\text{ g})} \rightarrow \underset{0}{0.05\text{CO}_2(\text{ g})} + 2\text{H}_2\text{O}(\ell)$$

6. Given that pure solids and liquids do not appear in Keq expressions, set up the ICE chart for this reaction, given the initial conditions.

$$\text{N}_2\text{H}_4(\ell) + \text{O}_2(\text{ g}) \rightleftarrows \text{N}_2(\text{ g}) + 2\text{H}_2\text{O}(\ell)$$

$2.33\text{M} \quad 1.09\text{M}$

7. Determine the equilibrium concentrations for this chemical reaction with the given Keq.

$$\underset{2.00\text{M}}{\text{HCN(g)}} \rightleftarrows \text{HNC(g)} \quad K_{\text{eq}} = 4.50$$

8. Determine the equilibrium concentrations for this chemical reaction with the given K_{eq}.

$$\text{IF}_3(\text{ g}) + \text{F}_2(\text{ g}) \rightleftarrows \text{IF}_5(\text{ g}) \quad K_{\text{eq}} = 7.59$$

$1.0\text{M} \quad 0.50\text{M}$

9. Determine the equilibrium concentrations for this chemical reaction with the given K_{eq}.

$$\text{N}_2\text{O}_3(\text{ g}) \rightleftarrows \text{NO(g)} + \text{NO}_2(\text{ g}) \quad K_{\text{eq}} = 2.50$$

0.0663M

10. Determine the equilibrium concentrations for this chemical reaction with the given K_{eq}.

$$\text{CO(g)} + \text{H}_2\text{O(g)} \rightleftarrows \text{CO}_2(\text{ g}) + \text{H}_2(\text{ g}) \quad K_{\text{eq}} =$$

$0.750\text{M} \quad 0.750\text{M}$

11. Determine the equilibrium concentrations for this chemical reaction with the given Keq.

$$\underset{0.882\text{M}}{\text{H}_2\text{ S}(\text{ g})} \rightleftarrows \text{H}_2(\text{ g}) + \text{S(s)} \quad K_{\text{eq}} = 0.055$$

12. Determine the equilibrium concentrations for this chemical reaction with the given K_{eq}.

$$2\text{AgCl(s)} + \underset{1.99\text{M}}{\text{F}_2(\text{ g})} \rightleftarrows 2\text{AgF(s)} + \text{Cl}_2(\text{ g}) \quad K_{\text{eq}} =$$

Answers

1. $\text{I} =$ initial concentrations; $\text{C} =$ change in concentrations; $\text{E} =$ equilibrium concentrations

3.

	$3O_2$	$\rightleftarrows$	$2O_3$
I	0.075		0
C	-3 x		+2 x
E	0.075-3 x		+2 x

5.

	CH_4	+	$2\ O_2$	$\rightleftarrows$	CO_2	+	$2H_2O$	
I	0.0060		0.055		0		0	
C	-x		-2 x		+x		-	
E	0.0060-x		.055-2 x		+x		-	

7. $[\text{HCN}] = 0.364\text{M}; [\text{HNC}] = 1.64\text{M}$

9. $[\text{N}_2\text{O}_3] = 0.0017\text{M}; [\text{NO}] = [\text{NO}_2] = 0.0646\text{M}$

11. $[\text{H}_2\text{ S}] = 0.836\text{M}; [\text{H}_2] = 0.046\text{M}$

Exercises (Some Special Types of Equilibria)

1. Explain the difference between the K_{eq} and the K_{sp}.

2. Explain the difference between the K_a and the Kb.

3. Write the balanced chemical equation that represents the equilibrium between $\mathrm{HF(aq)}$ as reactants and $\mathrm{H^+(aq)}$ and $\mathrm{F^-(aq)}$ as products.

4. Write the balanced chemical equation that represents the equilibrium between $\mathrm{CaF_2(\,s)}$ as reactants and $\mathrm{Ca^{2+}(aq)}$ and $\mathrm{F^-(aq)}$ as products.

5. Assuming that all species are dissolved in solution, write the Keq expression for the chemical equation in Exercise 3.

6. Noting the phase labels, write the K_{Sp} expression for the chemical equation in Exercise 4.

7. Determine the concentrations of all species in the ionization of $0.100\mathrm{M}\,\mathrm{HClO_2}$ in $\mathrm{H_2O}$. The $\mathrm{Ka_a}$ for $\mathrm{HClO_2}$ is 1.1×10^{-2}.

8. Determine the concentrations of all species in the ionization of $0.0800\mathrm{M}\,\mathrm{HCN}$ in $\mathrm{H_2O}$. The $\mathrm{K_a}$ for HCN is 6.2×10^{-10}.

9. Determine the pH of a $1.00\mathrm{M}$ solution of $\mathrm{HNO_2}$. The $\mathrm{Ka_a}$ for $\mathrm{HNO_2}$ is 5.6×10^{-4}.

10. Determine the pH of a $3.35\mathrm{M}$ solution of $\mathrm{HC_2H_3O_2}$. The $\mathrm{Ka_a}$ for $\mathrm{HC_2H_3O_2}$ is 1.8×10^{-5}.

11. Write the chemical equations and K_a expressions for the stepwise dissociation of $\mathrm{H_3PO_4}$.

12. Write the chemical equations and K_a expressions for the stepwise dissociation of $\mathrm{H_3C_6H_5O_7}$.

13. If the $\mathrm{Ka_a}$ for $\mathrm{HNO_2}$ is 5.6×10^{-4}, what is the $\mathrm{Kb_b}$ for $\mathrm{NO_2^-(aq)}$?

14. If the $\mathrm{K_a}$ for HCN is 6.2×10^{-10}, what is the $\mathrm{Kb_b}$ for $\mathrm{CN^-(aq)}$?

15. What is $\left[\mathrm{OH^-}\right]$ in a solution whose $\left[\mathrm{H^+}\right]$ is $3.23 \times 10^{-6}\mathrm{M}$?

16. What is $\left[\mathrm{OH^-}\right]$ in a solution whose $\left[\mathrm{H^+}\right]$ is $9.44 \times 10^{-11}\mathrm{M}$?

17. What is $\left[\mathrm{H^+}\right]$ in a solution whose $\left[\mathrm{OH^-}\right]$ is $2.09 \times 10^{-2}\mathrm{M}$?

18. What is $\left[\mathrm{H^+}\right]$ in a solution whose $\left[\mathrm{OH^-}\right]$ is $4.07 \times 10^{-7}\mathrm{M}$?

19. Write the balanced chemical equation and the K_{sp} expression for the slight solubility of $\mathrm{Mg(OH)_2(\,s)}$.

20. Write the balanced chemical equation and the K_{sp} expression for the slight solubility of $\mathrm{Fe_2(SO_4)_3(\,s)}$.

21. What are $\left[\mathrm{Sr^{2+}}\right]$ and $\left[\mathrm{SO_4{}^{2-}}\right]$ in a saturated solution of $\mathrm{SrSO_4(\,s)}$? The $\mathrm{K_{Sp}}$ of $\mathrm{SrSO_4(\,s)}$ is 3.8×10^{-4}.

22. What are $\left[\mathrm{Ba^{2+}}\right]$ and $\left[\mathrm{F^-}\right]$ in a saturated solution of $\mathrm{BaF_2(\,s)}$? The K_{sp} of $\mathrm{BaF_2(\,s)}$ is 1.8×10^{-7}.

23. What are $\left[\mathrm{Ca^{2+}}\right]$ and $\left[\mathrm{OH^-}\right]$ in a saturated solution of $\mathrm{Ca(OH)_2(\,s)}$? The $\mathrm{K_{sp}}$ of $\mathrm{Ca(OH)_2(\,s)}$ is 5.0×10^{-6}.

24. What are $\left[\mathrm{Pb^{2+}}\right]$ and $\left[\mathrm{I^-}\right]$ in a saturated solution of $\mathrm{PbI_2}$? The K_{sp} for $\mathrm{PbI_2}$ is 9.8×10^{-9}.

Answers

1. The K_{sp} is a special type of the K_{eq} and applies to compounds that are only slightly soluble.

3. $\mathrm{HF(aq)} \rightleftarrows \mathrm{H^+(aq)} + \mathrm{F^-(aq)}$

5. $K_{eq} = \dfrac{\left[H^+\right]\left[F^-\right]}{\left[HF\right]}$

7. $\left[HClO_2\right] = 0.0719M; \left[H^+\right] = \left[ClO_2^-\right] = 0.0281M$

9. 1.63

11.

$$H_3PO_4(aq) \rightleftarrows H^+(aq) + H_2PO_4{}^-(aq); K_a = \frac{\left[H^+\right]\left[H_2PO_4^-\right]}{\left[H_3PO_4\right]}$$

$$H_2PO_4{}^-(aq) \rightleftarrows H^+(aq) + HPO_4{}^{2-}(aq); K_a = \frac{\left[H^+\right]\left[HPO_4{}^{2-}\right]}{\left[H_2PO_4{}^-\right]}$$

$$HPO_4{}^{2-}(aq) \rightleftarrows H^+(aq) + PO_4{}^{3-}(aq); K_a = \frac{\left[H^+\right]\left[PO_4{}^{3-}\right]}{\left[HPO_4{}^{2-}\right]}$$

13. 1.8×10^{-11}

15. $3.10 \times 10^{-9}M$

17. $4.78 \times 10^{-13}M$

19. $MgOH_2(\,s) \rightleftarrows Mg^{2+}(aq) + 2OH^-(aq); Ksp = \left[Mg^{2+}\right]\left[OH^-\right]^2$

21. $\left[Sr^{2+}\right] = \left[SO_4{}^{2-}\right] = 1.9 \times 10^{-2}M$

23. $\left[Ca^{2+}\right] = 0.011M; \left[OH^-\right] = 0.022M$

Additional Exercises

1. What is the relationship between the K_{sp} expressions for a chemical reaction and its reverse chemical reaction?

2. What is the relationship between the K_w value for H_2O and its reverse chemical reaction?

3. For the equilibrium

$$PCl_3(g) + Cl^{2+}(g) \rightleftharpoons PCl_5(g) + 60kJ$$

list four stresses that serve to increase the amount of PCl_5.

4. For the equilibrium

$$N_2O_4 + 57kJ \rightleftharpoons 2NO_2$$

list four stresses that serve to increase the amount of NO_2.

5. Does a very large K_{eq} favor the reactants or the products? Explain your answer.

6. Is the K_{eq} for reactions that favor reactants large or small? Explain your answer.

7. Show that $K_a \times K_b = K_w$ by determining the expressions for these two reactions and multiplying them together.

$$HX(aq) \rightleftharpoons H^+(aq) + X^-(aq)$$
$$X^+(aq) + H_2O(l) \rightleftharpoons HX(aq) + OH^-(aq)$$

8. Is the conjugate base of a strong acid weak or strong? Explain your answer.

9. What is the solubility in moles per liter of AgCl? Use data from Table 13.7.2- Solubility Product Constants for Slightly Soluble Ionic Compounds.

10. What is the solubility in moles per liter of $Ca(OH)_2$? Use data from Table 13.7.2- Solubility Product Constants for Slightly Soluble Ionic Compounds.

11. Under what conditions is $K_{eq} = K_P$?

12. Under what conditions is $K_{eq} > K_P$ when the temperature is 298 K?

13. What is the pH of a saturated solution of $Mg(OH)_2$? Use data from Table 13.7.2- Solubility Product Constants for Slightly Soluble Ionic Compounds.

14. What are the pH and the pOH of a saturated solution of $Fe(OH)_3$? The K_{sp} of $Fe(OH)_3$ is 2.8×10^{-39}.

15. For a salt that has the general formula MX, an ICE chart shows that the K_{sp} is equal to x^2, where x is the concentration of the cation. What is the appropriate formula for the K_{sp} of a salt that has a general formula of MX_2?

16. Referring to Exercise 15, what is the appropriate formula for the K_{sp} of a salt that has a general formula of M_2X_3 if the concentration of the cation is defined as $2x$, rather than x?

17. Consider a saturated solution of $PbBr_2(s)$. If $[Pb^{2+}]$ is 1.33×10^{-5} M, find each of the following.
    a. $[Br^-]$
    b. the K_{sp} of $PbBr_2(s)$

18. Consider a saturated solution of $Pb_3(PO_4)_2(s)$. If $[Pb^{2+}]$ is 7.34×10^{-14} M, find each of the following.
    a. $[PO_4^{3-}]$
    b. the K_{sp} of $Pb_3(PO_4)_2(s)$

Answers

1. They are reciprocals of each other.

3. increase the pressure; decrease the temperature; add PCl_3; add Cl_2; remove PCl_5

5. favor products because the numerator of the ratio for the K_{eq} is larger than the denominator

9. 1.3×10^{-5} mol/L

11. $K_{eq} = K_P$ when the number of moles of gas on both sides of the reaction is the same.

13. 10.35

15. $4x^3$

17. a. 2.66×10^{-5}M
    b. 9.41×10^{-15}