CHAPTER 7   CHEMICAL SYSTEMS IN EQUILIBRIUM

Reflect on Your Learning

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1. This is not an example of dynamic equilibrium because there are no opposing processes taking place – even at the microscopic level. "Dynamic" implies change, or movement.
2. Household examples of dynamic equilibrium are:
   • dissolved carbon dioxide in soft drinks in equilibrium with gaseous carbon dioxide in the air space above the soft drink in the bottle;
   • undissolved sugar at the bottom of a cup of tea in equilibrium with dissolved sugar;
   • the temperature of a house staying steady as the furnace warms the air inside, but heat leaks out through cracks and by radiation.
3. The presence of the iodide ion prevents some of the lead iodide from dissolving.
4. (a) The double arrow implies that two opposite chemical reactions are occurring at the same rate.
   (b) Heating the container would decrease the production of carbon dioxide since the reverse reaction consumes the applied heat.
5. (Most students will probably conclude that they are not able to answer the question at this stage.) The reaction should proceed spontaneously as written because its products are in a more random state than the reactant.

Try This Activity: Shakin' the Blues

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(a) Some chemical reactions are reversible.
(b) The solution turns blue after being shaken and then returns to colourless after being allowed to stand for a few moments. This cycle can be repeated.
(c) The colour changes will continue forever.
(d) The blue–colourless cycle continues even after 10 cycles. (Note: After a considerable amount of time, the solution turns yellow and the colour changes stop.)

7.1   DYNAMIC EQUILIBRIUM IN CHEMICAL SYSTEMS

Try This Activity: The Coin Exchange: Establishing Dynamic Equilibrium

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(a) The player with the smaller exchange rate gained pennies until a maximum was reached. The player with the larger exchange rate lost pennies until a minimum number was reached.
(b) Groups with the largest difference in the initial amount of pennies had the most exchanges before the equilibrium was established. Groups with exchange rates that were similar took longer to reach equilibrium. This is because the pennies from one side were replacing almost all the pennies taken from the other pile.
(c) The partner with the larger exchange rate always had less pennies. The number of pennies never reaches zero because some are always returned.
(d) During the course of the activity, the number of pennies approaches a constant value.

Try This Activity: Digesting a Precipitate

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(a) The settling time decreases over the course of one week.
(b) The size of the crystals increases.
(c) For the system to be at equilibrium, two opposing reactions need to be occurring at the same rate in the closed system. The solution had to be saturated because crystals were always present at the bottom of the flask. Over the course of the week the crystals grew, implying that crystallization was still occurring. However, the number of crystals also decreased, proof that dissolving was occurring. If the rate of crystallization and dissolving were not equal, the crystals would have either disappeared or grown in number and size.

PRACTICE

Understanding Concepts

1. Evaporating water molecules cannot escape from the plastic bag. The saturation of the air inside the bag with water vapour prevents the towel from drying completely as a dynamic equilibrium becomes established.
2. Dissolution and crystallization continue to occur at the same rate, resulting in no visible changes.
3. Stirring removes solute as it dissolves, lowering the concentration in the region of the solute, allowing further dissolution to occur.

Making Connections

4. Hot moist air can escape from the clothes dryer through the exhaust vent, to be replaced by drier air.
5. Resealing carbonated soft drink bottles prevents carbon dioxide gas from leaving the solution. Equilibrium is quickly reestablished between dissolved CO_2 and gaseous CO_2 in the air space above the soft drink.

PRACTICE

Understanding Concepts

6. $[CO_{2(g)}]_{initial} = \dfrac{2.0 \text{ mol}}{5.0 \text{ L}}$

$[CO_{2(g)}]_{initial} = 0.40 \text{ mol/L}$

ICE Table for the Decomposition of Carbon Dioxide			
	$2\ CO_{2(g)} \rightleftharpoons$	$2\ CO_{(g)} +$	$O_{2(g)}$
Initial concentration (mol/L)	0.4	0	0
Change in concentration (mol/L)	$-2x$	$+2x$	$+x$
Equilibrium concentration (mol/L)	0.39		

At equilibrium:

$[CO_{2(g)}] = 0.40 \text{ mol/L} - 2x$

$[CO_{2(g)}] = 0.39$

$2x = 0.01$

$[CO_{(g)}] = 2x$

$[CO_{(g)}] = 0.01 \text{ mol/L}$

$[O_{2(g)}] = x$

$x = 0.005$

The concentration of carbon monoxide is 0.01 mol/L and the concentration of oxygen is 0.005 mol/L.

7. $[NOC1_{(g)}]_{initial} = \dfrac{2.0 \text{ mol}}{2.0 \text{ L}}$

$[NOC1_{(g)}]_{initial} = 1.0 \text{ mol/L}$

ICE Table for the Decomposition of NOCl			
	$2\ NOCl_{(g)} \rightleftharpoons$	$2\ NO_{(g)} +$	$Cl_{2(g)}$
Initial concentration (mol/L)	1.0		
Change in concentration (mol/L)	$-2x$	$+2x$	$+x$
Equilibrium concentration (mol/L)		0.032	

At equilibrium:

$$[NO_{(g)}] = 0.32 \text{ mol/L}$$

$$[NO_{(g)}] = 2x$$

$$x = 0.16 \text{ mol/L}$$

$$[NOC1_{(g)}] = 1.0 - 2x$$

$$= 1.0 - 0.32$$

$$[NOC1_{(g)}] = 0.68 \text{ mol/L}$$

$$[Cl_{2(g)}] = x$$

$$= 0.16 \text{ mol/L}$$

The concentration of $NO_{(g)}$ and $Cl_{2(g)}$ are 0.68 mol/L and 0.16 mol/L, respectively.

SECTION 7.1   QUESTIONS

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Understanding Concepts

1. (a) No observable changes occur.
    (b) Equilibrium is considered to be "dynamic" because changes are still occurring at the microscopic level.
    (c) The rates of the two opposing processes are equal.
2. (Answers will vary. Possible examples include:)
    • undissolved sugar at the bottom of cup of tea (dynamic equilibrium)
    • an ice cube floating in water at 0°C (dynamic equilibrium)
    • carbon dioxide gas in equilibrium with dissolved carbon dioxide in soft drinks (dynamic equilibrium)
    • preparing a saturated sugar solution when making "rock" candy (dynamic equilibrium)

3. (a) $CH_{4(g)} + Cl_{2(g)} \rightleftharpoons CH_3Cl_{(g)} + 2 HCl_{(g)}$

    (b) percent reaction $= \dfrac{\text{actual product yield}}{\text{theoretical product yield}} \times 100\%$

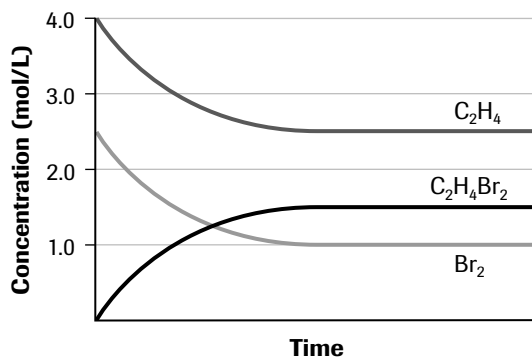 $$= \dfrac{1.4}{2.0} \times 100\%$$

    percent reaction $= 70\%$
    The percent reaction of this equilibrium is 70%. This equilibrium favours the products.

4. (a)

ICE Table for the Reaction $C_2H_{4(g)}$ with $Br_{2(g)}$			
	$C_2H_{4(g)}$ +	$Br_{2(g)}$ $\rightleftharpoons$	$C_2H_4Br_{2(g)}$
Initial concentration (mol/L)	4.00	2.50	0
Change in concentration (mol/L)	−1.50	−1.50	+1.50
Equilibrium concentration (mol/L)	2.50	1.50	1.50

   (b)
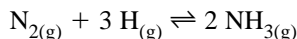**Reaction of Ethene**
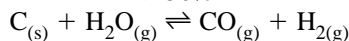
(c) percent reaction $= \dfrac{\text{actual product yield}}{\text{theoretical product yield}} \times 100\%$

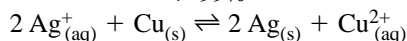$= \dfrac{1.5}{2.5} \times 100\%$

percent reaction $= 60\%$

5. (a) $< 50\%$
$N_{2(g)} + 3\ H_{(g)} \rightleftharpoons 2\ NH_{3(g)}$

(b) $> 50\%$
$C_{(s)} + H_2O_{(g)} \rightleftharpoons CO_{(g)} + H_{2(g)}$

(c) $> 99\%$
$2\ Ag^+_{(aq)} + Cu_{(s)} \rightleftharpoons 2\ Ag_{(s)} + Cu^{2+}_{(aq)}$

(d) $> 50\%$
$2\ SO_{2(g)} + O_{2(g)} \rightleftharpoons 2\ SO_{3(g)}$
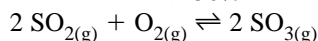
6. The addition reactions of halogens and alkenes are generally quantitative, so for the reaction of bromine with ethene (ethylene) a >99% yield of products is predicted.

7. (a) $n_{HI} = 2.00\ L \times 0.00\ mol/L$

$n_{HI} = 0.00\ mol$

$n_{H_2} = 2.00\ L \times 6.0\ mol/L$

$n_{H_2} = 12.0\ mol$

$n_{I_2} = 2.00\ L \times 6.0\ mol/L$

$n_{I_2} = 12.0\ mol$

(b)

ICE Table for the Reaction of Hydrogen and Iodine			
	$H_{2(g)}$ +	$I_{2(g)}$ $\rightleftharpoons$	$2\ HBr_{(g)}$
Initial concentration (mol/L)	6.0	4.0	0.0
Change in concentration (mol/L)	3.6	3.6	7.2
Equilibrium concentration (mol/L)	2.4	0.4	7.2

At equilibrium, 14.4 mol of hydrogen iodide had formed.

(c) Since iodine is the limiting reagent, the maximum possible yield of hydrogen iodide is calculated as

$n_{HI} = 8.0\ mol \times \dfrac{2\ mol}{1\ mol}$

$n_{HI} = 16.0\ mol$

percent reaction $= \dfrac{14.4\ mol}{16.0\ mol} \times 100\%$

percent reaction $= 90\%$

(d) At equilibrium, the rate of the forward reaction is equal to the rate of the reverse reaction. In this case, at equilibrium, the rate of reaction of hydrogen with iodine is equal to the rate of decomposition of hydrogen.

8.

ICE Table for the Decomposition of $PCl_{5(g)}$			
	$PCl_{5(g)}$ $\rightleftharpoons$	$PCl_{3(g)}$ +	$Cl_{2(g)}$
Initial concentration (mol/L)	1.00	0	0
Change in concentration (mol/L)	−0.100	+0.100	+0.100
Equilibrium concentration (mol/L)	0.90	0.100	0.100

9. (a) The concentrations of $PCl_{3(g)}$ and $Cl_{2(g)}$ are both 0.100 mol/L.

ICE Table for the Production of Methanol			
	$CO_{(g)}$ +	$2 H_{2(g)} \rightleftharpoons$	$CH_3OH_{(g)}$
Initial concentration (mol/L)	0.100	0.200	0
Change in concentration (mol/L)	–0.040	–0.080	+0.040
Equilibrium concentration (mol/L)	0.060	0.120	0.040

The concentrations of carbon monoxide and methanol are 0.060 mol/L and 0.0400 mol/L, respectively.

(b)　$\text{percent reaction} = \dfrac{\text{actual product yield}}{\text{theoretical product yield}} \times 100\%$

$= \dfrac{0.0400}{0.100} \times 100\%$

$\text{percent reaction} = 40\%$

10. (a) The saturated solution is in a state of dynamic equilibrium. Even though the appearance of the system did not change, the evidence suggests that some radioactive iodine became incorporated into the original sample of iodine. Furthermore, the radioactivity of the solution implies that some radioactive iodine had dissolved.

Making Connections

11. (a) Immediately following a fructose-rich meal, a net amount of diffusion of fructose will occur into the (surrounding) intestinal cells because the concentration of fructose in the intestinal tract is higher than the concentration of fructose in the intestinal cells. Diffusion into the cells continues until the concentration of fructose inside the intestinal cells and the intestinal tract are equal. At this point, a dynamic equilibrium is reached; the rate of fructose diffusing into the cells equals the rate of fructose diffusing out of the cells. Thus, a certain amount of fructose remains in the intestinal tract (unabsorbed).

(b) Cells use active transport mechanisms to pump nutrient molecules such as glucose and amino acids (digested protein). These systems require the use of cell membrane proteins and cell energy in the form of adenosine triphosphate (ATP). Using energy to actively pump certain nutrients against a concentration gradient ensures that intestinal cells absorb the majority of nutrient molecules.

7.2 EQUILIBRIUM LAW IN CHEMICAL REACTIONS

PRACTICE

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Understanding Concepts

1. (a) $K = \dfrac{[SO_{3(g)}]^2}{[SO_{2(g)}]^2[O_{2(g)}]}$

(b) $4 NH_{3(g)} + 3 O_{2(g)} \rightleftharpoons 2 N_{2(g)} + 6 H_2O_{(g)}$

$K = \dfrac{[N_{2(g)}]^2[H_2O_{(g)}]^6}{[NH_{3(g)}]^4[O_{2(g)}]^3}$

(c) $K = \dfrac{[NO_{(g)}]^2[Br_{2(g)}]}{[NOBr_{(g)}]^2}$

PRACTICE

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Understanding Concepts

2. $CO_{(g)} + 2 H_{2(g)} \rightleftharpoons CH_3OH_{(g)}$