

accordance with the law of conservation of mass. The number of atoms of each element in the reactants must equal the number in the products.

5. Stoichiometry is the quantitative study of products and reactants in chemical reactions. Stoichiometric calculations are best done by expressing both the known and unknown quantities in terms of moles and then converting

to other units if necessary. A limiting reagent is the reactant that is present in the smallest stoichiometric amount. It limits the amount of product that can be formed. The amount of product obtained in a reaction (the actual yield) may be less than the maximum possible amount (the theoretical yield). The ratio of the two multiplied by 100 percent is expressed as the percent yield.

KEY WORDS

Actual yield, p. 83	Chemical reaction, p. 73	Mole method, p. 77	Reactant, p. 73
Atomic mass, p. 59	Excess reagent, p. 81	Molecular mass, p. 64	Stoichiometric amount, p. 81
Atomic mass unit (amu), p. 59	Limiting reagent, p. 81	Percent composition, p. 68	Stoichiometry, p. 77
Avogadro's number (N_A), p. 60	Molar mass (M), p. 61	Percent yield, p. 84	Theoretical yield, p. 83
Chemical equation, p. 73	Mole (mol), p. 60	Product, p. 73	

QUESTIONS AND PROBLEMS

Atomic Mass

Review Questions

- What is an atomic mass unit? Why is it necessary to introduce such a unit?
- What is the mass (in amu) of a carbon-12 atom? Why is the atomic mass of carbon listed as 12.01 amu in the table on the inside front cover of this book?
- Explain clearly what is meant by the statement "The atomic mass of gold is 197.0 amu."
- What information would you need to calculate the average atomic mass of an element?

Problems

- The atomic masses of $^{35}_{17}\text{Cl}$ (75.53 percent) and $^{37}_{17}\text{Cl}$ (24.47 percent) are 34.968 amu and 36.956 amu, respectively. Calculate the average atomic mass of chlorine. The percentages in parentheses denote the relative abundances.
- The atomic masses of ^6_3Li and ^7_3Li are 6.0151 amu and 7.0160 amu, respectively. Calculate the natural abundances of these two isotopes. The average atomic mass of Li is 6.941 amu.
- What is the mass in grams of 13.2 amu?
- How many amu are there in 8.4 g?

Avogadro's Number and Molar Mass

Review Questions

- Define the term "mole." What is the unit for mole in calculations? What does the mole have in common

with the pair, the dozen, and the gross? What does Avogadro's number represent?

- What is the molar mass of an atom? What are the commonly used units for molar mass?

Problems

- Earth's population is about 6.5 billion. Suppose that every person on Earth participates in a process of counting identical particles at the rate of two particles per second. How many years would it take to count 6.0×10^{23} particles? Assume that there are 365 days in a year.
- The thickness of a piece of paper is 0.0036 in. Suppose a certain book has an Avogadro's number of pages; calculate the thickness of the book in light-years. (*Hint:* See Problem 1.38 for the definition of light-year.)
- How many atoms are there in 5.10 moles of sulfur (S)?
- How many moles of cobalt (Co) atoms are there in 6.00×10^9 (6 billion) Co atoms?
- How many moles of calcium (Ca) atoms are in 77.4 g of Ca?
- How many grams of gold (Au) are there in 15.3 moles of Au?
- What is the mass in grams of a single atom of each of the following elements? (a) Hg, (b) Ne.
- What is the mass in grams of a single atom of each of the following elements? (a) As, (b) Ni.
- What is the mass in grams of 1.00×10^{12} lead (Pb) atoms?

- 3.20 How many atoms are present in 3.14 g of copper (Cu)?
- 3.21 Which of the following has more atoms: 1.10 g of hydrogen atoms or 14.7 g of chromium atoms?
- 3.22 Which of the following has a greater mass: 2 atoms of lead or 5.1×10^{-23} mole of helium?

Molecular Mass

Problems

- 3.23 Calculate the molecular mass or formula mass (in amu) of each of the following substances: (a) CH_4 , (b) NO_2 , (c) SO_3 , (d) C_6H_6 , (e) NaI , (f) K_2SO_4 , (g) $\text{Ca}_3(\text{PO}_4)_2$.
- 3.24 Calculate the molar mass of the following substances: (a) Li_2CO_3 , (b) CS_2 , (c) CHCl_3 (chloroform), (d) $\text{C}_6\text{H}_8\text{O}_6$ (ascorbic acid, or vitamin C), (e) KNO_3 , (f) Mg_3N_2 .
- 3.25 Calculate the molar mass of a compound if 0.372 mole of it has a mass of 152 g.
- 3.26 How many molecules of ethane (C_2H_6) are present in 0.334 g of C_2H_6 ?
- 3.27 Calculate the number of C, H, and O atoms in 1.50 g of glucose ($\text{C}_6\text{H}_{12}\text{O}_6$), a sugar.
- 3.28 Urea [$(\text{NH}_2)_2\text{CO}$] is used for fertilizer and many other things. Calculate the number of N, C, O, and H atoms in 1.68×10^4 g of urea.
- 3.29 Pheromones are a special type of compound secreted by the females of many insect species to attract the males for mating. One pheromone has the molecular formula $\text{C}_{19}\text{H}_{38}\text{O}$. Normally, the amount of this pheromone secreted by a female insect is about 1.0×10^{-12} g. How many molecules are there in this quantity?
- 3.30 The density of water is 1.00 g/mL at 4°C . How many water molecules are present in 2.56 mL of water at this temperature?

Mass Spectrometry

Review Questions

- 3.31 Describe the operation of a mass spectrometer.
- 3.32 Describe how you would determine the isotopic abundance of an element from its mass spectrum.

Problems

- 3.33 Carbon has two stable isotopes, $^{12}_6\text{C}$ and $^{13}_6\text{C}$, and fluorine has only one stable isotope, $^{19}_9\text{F}$. How many peaks would you observe in the mass spectrum of the positive ion of CF_4^+ ? Assume that the ion does not break up into smaller fragments.
- 3.34 Hydrogen has two stable isotopes, ^1_1H and ^2_1H , and sulfur has four stable isotopes, $^{32}_{16}\text{S}$, $^{33}_{16}\text{S}$, $^{34}_{16}\text{S}$, and $^{36}_{16}\text{S}$. How many peaks would you observe in the mass

spectrum of the positive ion of hydrogen sulfide, H_2S^+ ? Assume no decomposition of the ion into smaller fragments.

Percent Composition and Chemical Formulas

Review Questions

- 3.35 Use ammonia (NH_3) to explain what is meant by the percent composition by mass of a compound.
- 3.36 Describe how the knowledge of the percent composition by mass of an unknown compound can help us identify the compound.
- 3.37 What does the word "empirical" in empirical formula mean?
- 3.38 If we know the empirical formula of a compound, what additional information do we need to determine its molecular formula?

Problems

- 3.39 Tin (Sn) exists in Earth's crust as SnO_2 . Calculate the percent composition by mass of Sn and O in SnO_2 .
- 3.40 For many years chloroform (CHCl_3) was used as an inhalation anesthetic in spite of the fact that it is also a toxic substance that may cause severe liver, kidney, and heart damage. Calculate the percent composition by mass of this compound.
- 3.41 Cinnamic alcohol is used mainly in perfumery, particularly in soaps and cosmetics. Its molecular formula is $\text{C}_9\text{H}_{10}\text{O}$. (a) Calculate the percent composition by mass of C, H, and O in cinnamic alcohol. (b) How many molecules of cinnamic alcohol are contained in a sample of mass 0.469 g?
- 3.42 All of the substances listed below are fertilizers that contribute nitrogen to the soil. Which of these is the richest source of nitrogen on a mass percentage basis?
- Urea, $(\text{NH}_2)_2\text{CO}$
 - Ammonium nitrate, NH_4NO_3
 - Guanidine, $\text{HNC}(\text{NH}_2)_2$
 - Ammonia, NH_3
- 3.43 Alliin is the compound responsible for the characteristic smell of garlic. An analysis of the compound gives the following percent composition by mass: C: 44.4 percent; H: 6.21 percent; S: 39.5 percent; O: 9.86 percent. Calculate its empirical formula. What is its molecular formula given that its molar mass is about 162 g?
- 3.44 Peroxyacetyl nitrate (PAN) is one of the components of smog. It is a compound of C, H, N, and O. Determine the percent composition of oxygen and the empirical formula from the following percent composition by mass: 19.8 percent C, 2.50 percent H, 11.6 percent N. What is its molecular formula given that its molar mass is about 120 g?

- 3.45 The formula for rust can be represented by Fe_2O_3 . How many moles of Fe are present in 24.6 g of the compound?
- 3.46 How many grams of sulfur (S) are needed to react completely with 246 g of mercury (Hg) to form HgS ?
- 3.47 Calculate the mass in grams of iodine (I_2) that will react completely with 20.4 g of aluminum (Al) to form aluminum iodide (AlI_3).
- 3.48 Tin(II) fluoride (SnF_2) is often added to toothpaste as an ingredient to prevent tooth decay. What is the mass of F in grams in 24.6 g of the compound?
- 3.49 What are the empirical formulas of the compounds with the following compositions? (a) 2.1 percent H, 65.3 percent O, 32.6 percent S, (b) 20.2 percent Al, 79.8 percent Cl.
- 3.50 What are the empirical formulas of the compounds with the following compositions? (a) 40.1 percent C, 6.6 percent H, 53.3 percent O, (b) 18.4 percent C, 21.5 percent N, 60.1 percent K.
- 3.51 The anticaking agent added to Morton salt is calcium silicate, CaSiO_3 . This compound can absorb up to 2.5 times its mass of water and still remains a free-flowing powder. Calculate the percent composition of CaSiO_3 .
- 3.52 The empirical formula of a compound is CH. If the molar mass of this compound is about 78 g, what is its molecular formula?
- 3.53 The molar mass of caffeine is 194.19 g. Is the molecular formula of caffeine $\text{C}_4\text{H}_5\text{N}_2\text{O}$ or $\text{C}_8\text{H}_{10}\text{N}_4\text{O}_2$?
- 3.54 Monosodium glutamate (MSG), a food-flavor enhancer, has been blamed for "Chinese restaurant syndrome," the symptoms of which are headaches and chest pains. MSG has the following composition by mass: 35.51 percent C, 4.77 percent H, 37.85 percent O, 8.29 percent N, and 13.60 percent Na. What is its molecular formula if its molar mass is about 169 g?

Chemical Reactions and Chemical Equations

Review Questions

- 3.55 Use the formation of water from hydrogen and oxygen to explain the following terms: chemical reaction, reactant, product.
- 3.56 What is the difference between a chemical reaction and a chemical equation?
- 3.57 Why must a chemical equation be balanced? What law is obeyed by a balanced chemical equation?
- 3.58 Write the symbols used to represent gas, liquid, solid, and the aqueous phase in chemical equations.

Problems

- 3.59 Balance the following equations using the method outlined in Section 3.7:

- (a) $\text{C} + \text{O}_2 \longrightarrow \text{CO}$
 (b) $\text{CO} + \text{O}_2 \longrightarrow \text{CO}_2$
 (c) $\text{H}_2 + \text{Br}_2 \longrightarrow \text{HBr}$
 (d) $\text{K} + \text{H}_2\text{O} \longrightarrow \text{KOH} + \text{H}_2$
 (e) $\text{Mg} + \text{O}_2 \longrightarrow \text{MgO}$
 (f) $\text{O}_3 \longrightarrow \text{O}_2$
 (g) $\text{H}_2\text{O}_2 \longrightarrow \text{H}_2\text{O} + \text{O}_2$
 (h) $\text{N}_2 + \text{H}_2 \longrightarrow \text{NH}_3$
 (i) $\text{Zn} + \text{AgCl} \longrightarrow \text{ZnCl}_2 + \text{Ag}$
 (j) $\text{S}_8 + \text{O}_2 \longrightarrow \text{SO}_2$
 (k) $\text{NaOH} + \text{H}_2\text{SO}_4 \longrightarrow \text{Na}_2\text{SO}_4 + \text{H}_2\text{O}$
 (l) $\text{Cl}_2 + \text{NaI} \longrightarrow \text{NaCl} + \text{I}_2$
 (m) $\text{KOH} + \text{H}_3\text{PO}_4 \longrightarrow \text{K}_3\text{PO}_4 + \text{H}_2\text{O}$
 (n) $\text{CH}_4 + \text{Br}_2 \longrightarrow \text{CBr}_4 + \text{HBr}$

- 3.60 Balance the following equations using the method outlined in Section 3.7:

- (a) $\text{N}_2\text{O}_5 \longrightarrow \text{N}_2\text{O}_4 + \text{O}_2$
 (b) $\text{KNO}_3 \longrightarrow \text{KNO}_2 + \text{O}_2$
 (c) $\text{NH}_4\text{NO}_3 \longrightarrow \text{N}_2\text{O} + \text{H}_2\text{O}$
 (d) $\text{NH}_4\text{NO}_2 \longrightarrow \text{N}_2 + \text{H}_2\text{O}$
 (e) $\text{NaHCO}_3 \longrightarrow \text{Na}_2\text{CO}_3 + \text{H}_2\text{O} + \text{CO}_2$
 (f) $\text{P}_4\text{O}_{10} + \text{H}_2\text{O} \longrightarrow \text{H}_3\text{PO}_4$
 (g) $\text{HCl} + \text{CaCO}_3 \longrightarrow \text{CaCl}_2 + \text{H}_2\text{O} + \text{CO}_2$
 (h) $\text{Al} + \text{H}_2\text{SO}_4 \longrightarrow \text{Al}_2(\text{SO}_4)_3 + \text{H}_2$
 (i) $\text{CO}_2 + \text{KOH} \longrightarrow \text{K}_2\text{CO}_3 + \text{H}_2\text{O}$
 (j) $\text{CH}_4 + \text{O}_2 \longrightarrow \text{CO}_2 + \text{H}_2\text{O}$
 (k) $\text{Be}_2\text{C} + \text{H}_2\text{O} \longrightarrow \text{Be}(\text{OH})_2 + \text{CH}_4$
 (l) $\text{Cu} + \text{HNO}_3 \longrightarrow \text{Cu}(\text{NO}_3)_2 + \text{NO} + \text{H}_2\text{O}$
 (m) $\text{S} + \text{HNO}_3 \longrightarrow \text{H}_2\text{SO}_4 + \text{NO}_2 + \text{H}_2\text{O}$
 (n) $\text{NH}_3 + \text{CuO} \longrightarrow \text{Cu} + \text{N}_2 + \text{H}_2\text{O}$

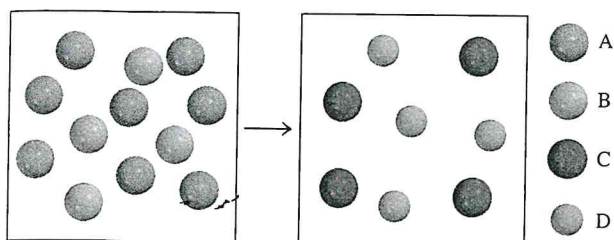
Amounts of Reactants and Products

Review Questions

- 3.61 On what law is stoichiometry based? Why is it essential to use balanced equations in solving stoichiometric problems?
- 3.62 Describe the steps involved in the mole method.

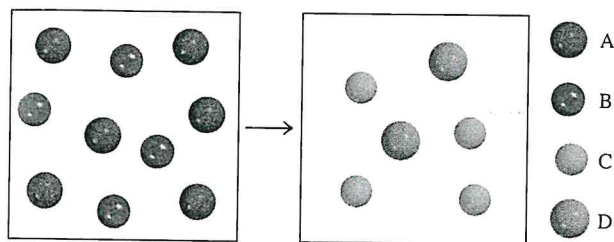
Problems

- 3.63 Which of the following equations best represents the reaction shown in the diagram?
- (a) $8\text{A} + 4\text{B} \longrightarrow \text{C} + \text{D}$
 (b) $4\text{A} + 8\text{B} \longrightarrow 4\text{C} + 4\text{D}$
 (c) $2\text{A} + \text{B} \longrightarrow \text{C} + \text{D}$
 (d) $4\text{A} + 2\text{B} \longrightarrow 4\text{C} + 4\text{D}$
 (e) $2\text{A} + 4\text{B} \longrightarrow \text{C} + \text{D}$

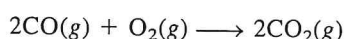


3.64 Which of the following equations best represents the reaction shown in the diagram?

- $A + B \longrightarrow C + D$
- $6A + 4B \longrightarrow C + D$
- $A + 2B \longrightarrow 2C + D$
- $3A + 2B \longrightarrow 2C + D$
- $3A + 2B \longrightarrow 4C + 2D$

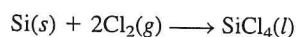


3.65 Consider the combustion of carbon monoxide (CO) in oxygen gas



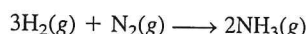
Starting with 3.60 moles of CO, calculate the number of moles of CO_2 produced if there is enough oxygen gas to react with all of the CO.

3.66 Silicon tetrachloride (SiCl_4) can be prepared by heating Si in chlorine gas:



In one reaction, 0.507 mole of SiCl_4 is produced. How many moles of molecular chlorine were used in the reaction?

3.67 Ammonia is a principal nitrogen fertilizer. It is prepared by the reaction between hydrogen and nitrogen.



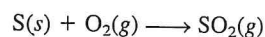
In a particular reaction, 6.0 moles of NH_3 were produced. How many moles of H_2 and how many moles of N_2 were reacted to produce this amount of NH_3 ?

3.68 Consider the combustion of butane (C_4H_{10}):



In a particular reaction, 5.0 moles of C_4H_{10} are reacted with an excess of O_2 . Calculate the number of moles of CO_2 formed.

3.69 The annual production of sulfur dioxide from burning coal and fossil fuels, auto exhaust, and other sources is about 26 million tons. The equation for the reaction is



How much sulfur (in tons), present in the original materials, would result in that quantity of SO_2 ?

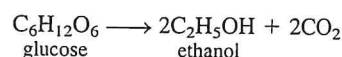
3.70 When baking soda (sodium bicarbonate or sodium hydrogen carbonate, NaHCO_3) is heated, it releases carbon dioxide gas, which is responsible for the rising of cookies, donuts, and bread. (a) Write a balanced equation for the decomposition of the compound (one of the products is Na_2CO_3). (b) Calculate the mass of NaHCO_3 required to produce 20.5 g of CO_2 .

3.71 When potassium cyanide (KCN) reacts with acids, a deadly poisonous gas, hydrogen cyanide (HCN), is given off. Here is the equation:



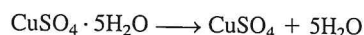
If a sample of 0.140 g of KCN is treated with an excess of HCl, calculate the amount of HCN formed, in grams.

3.72 Fermentation is a complex chemical process of wine making in which glucose is converted into ethanol and carbon dioxide:



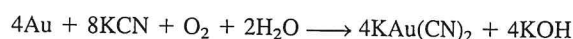
Starting with 500.4 g of glucose, what is the maximum amount of ethanol in grams and in liters that can be obtained by this process? (Density of ethanol = 0.789 g/mL.)

3.73 Each copper(II) sulfate unit is associated with five water molecules in crystalline copper(II) sulfate pentahydrate ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$). When this compound is heated in air above 100°C , it loses the water molecules and also its blue color:



If 9.60 g of CuSO_4 are left after heating 15.01 g of the blue compound, calculate the number of moles of H_2O originally present in the compound.

3.74 For many years the recovery of gold—that is, the separation of gold from other materials—involved the use of potassium cyanide:



What is the minimum amount of KCN in moles needed to extract 29.0 g (about an ounce) of gold?