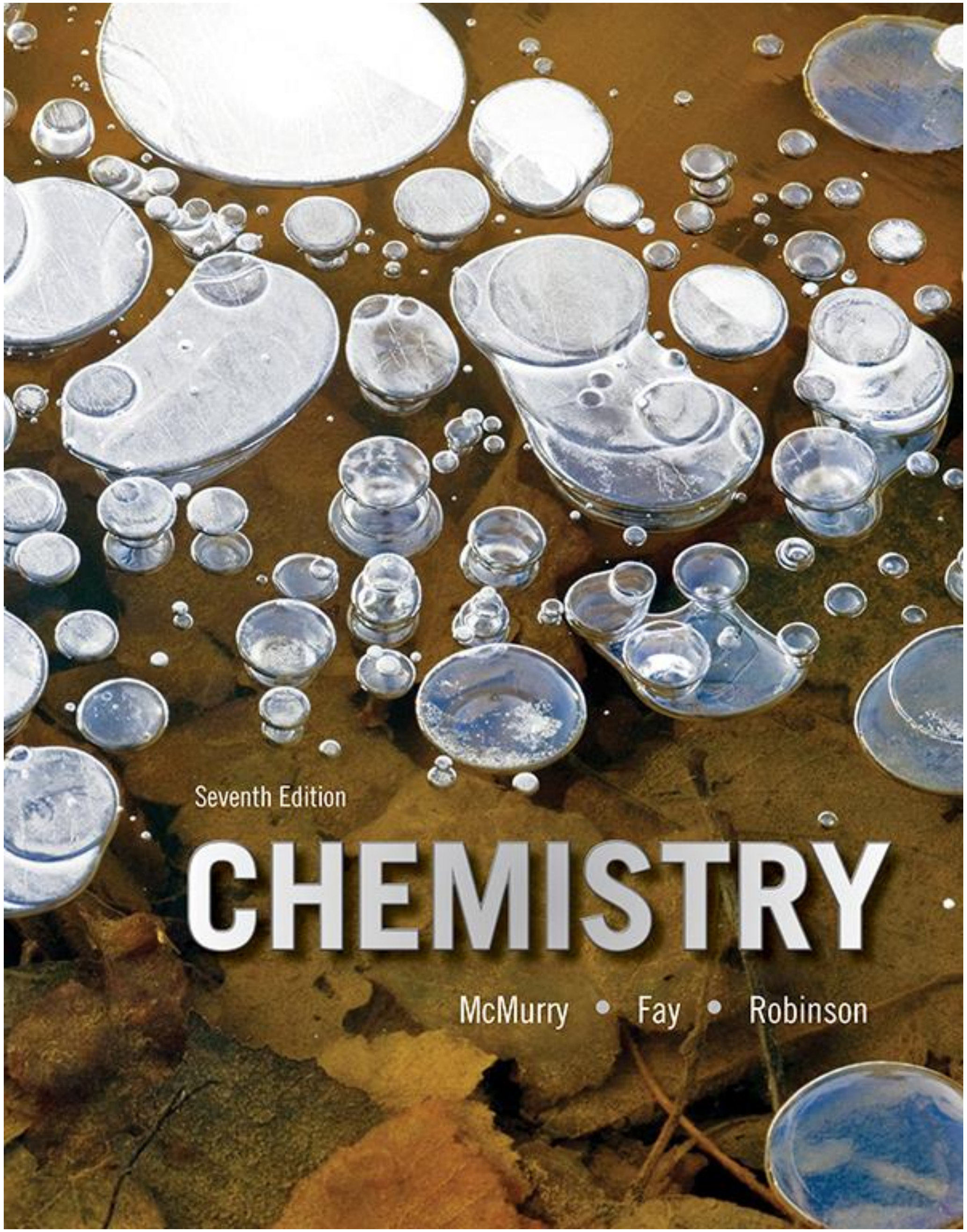

Lecture Presentation

Chapter 3

Mass Relationships in Chemical Reactions

HW: 3.3, 3.5, 3.7, 3.9, 3.10, 3.11, 3.13, 3.15, 3.17, 3.23, 3.27, 3.30, 3.38, 3.42, 3.54, 3.60, 3.70, 3.84, 3.106, 3.114

John E. McMurry
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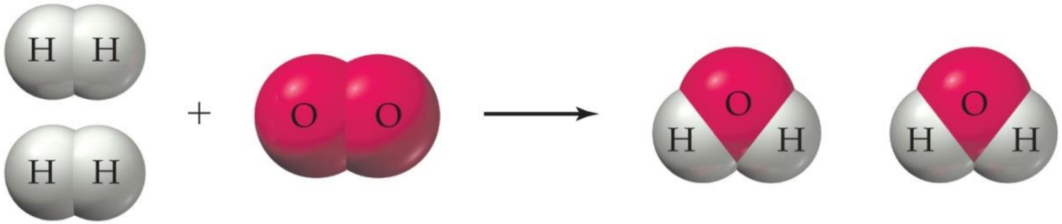
John E. McMurry, Robert C. Fay, Jill Robinson

Representing Chemistry on Different Levels

$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

Microscopic: 2 molecules of hydrogen gas react with 1 molecule of oxygen gas to yield 2 molecules of liquid water.



Representing Chemistry on Different Levels

$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

Microscopic: 2 *molecules* of hydrogen gas react with 1 *molecule* of oxygen gas to yield 2 *molecules* of liquid water.

Macroscopic: 2 *moles* of hydrogen gas react with 1 *mole* of oxygen gas to yield 2 *moles* of liquid water. (lab scale)

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Need to Know: elements that exist in nature as diatomics (memorize list)

HON + halogens

Hydrogen (H_2)
Oxygen (O_2)
Nitrogen (N_2)
Halogens (F_2, Cl_2, Br_2, I_2)

Balancing Chemical Equations

A balanced chemical equation follows the **law of conservation of mass**.

In a **balanced** chemical equation, the numbers and kinds of atoms on both sides of the reaction arrow are identical.

$$2Na(s) + Cl_2(g) \longrightarrow 2NaCl(s)$$

left side:	right side:
reactant	product
2 Na	2 Na
2 Cl	2 Cl

Balancing Chemical Equations

$$Hg(NO_3)_2(aq) + 2KI(aq) \longrightarrow HgI_2(s) + 2KNO_3(aq)$$

left side:	right side:
1 Hg	1 Hg
2 N	2 I
6 O	2 K
2 K	2 N
2 I	6 O

How to Balance Chemical Equations

1. Write the unbalanced equation using the correct chemical formula for each reactant and product.

$$H_2(g) + O_2(g) \longrightarrow H_2O(l)$$

2. Change coefficients—the numbers placed before formulas to indicate how many formula units of each substance are required to balance the equation. (leave the subscripts alone – otherwise change ID of molecule)

$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

Balancing Chemical Equations

3. Reduce the coefficients to their smallest whole-number values, if necessary, by dividing them all by a common divisor.

$$4H_2(g) + 2O_2(g) \longrightarrow 4H_2O(l)$$

$$\downarrow$$

divide all coefficients by 2 (or any common divisor

$$\downarrow$$

$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

Balancing Chemical Equations

4. Check your answer by making sure that the numbers and kinds of atoms are the same on both sides of the equation.

$$2H_2(g) + O_2(g) \longrightarrow 2H_2O(l)$$

left side:	right side:
4 H	4 H
2 O	2 O

note: (g) = gas (l) = liquid (s) = solid
(aq) = aqueous or dissolved in water

Likely balancing chemical equation question on quiz or exam. (fill in blank or MC)

a. Balance the following by filling in the blanks

$$\_\_\_ \ NH_3 + 5\ O_2 \rightarrow 4\ NO + \_\_\_ \ H_2O$$

b. Write down the number of each type of atom on both the reactant and product side of the reaction.

HW: Balancing reaction. Do only (a).

- Balance the following reaction. Give # of each type of atom in both reactants & products. (keep polyatomic ions together) (start with polyatomics, end with water)

a) $AgNO_3(aq) + H_2SO_4(aq) \rightarrow Ag_2SO_4(s) + HNO_3(aq)$

b) $Ca(OH)_2(aq) + H_3PO_4(aq) \rightarrow H_2O(l) + Ca_3(PO_4)_2(s)$

HW: Balancing chemical reactions.

- For balanced RXN, give # of each type of atom on reactant & product. (keep polyatomic ions together) [do (b) on own]

a) $AgNO_3(aq) + H_2SO_4(aq) \rightarrow Ag_2SO_4(s) + HNO_3(aq)$

$2AgNO_3(aq) + H_2SO_4(aq) \rightarrow Ag_2SO_4(s) + 2HNO_3(aq)$

b) $Ca(OH)_2(aq) + H_3PO_4(aq) \rightarrow H_2O(l) + Ca_3(PO_4)_2(s)$

$3Ca(OH)_2(aq) + 2H_3PO_4(aq) \rightarrow 6H_2O(l) + Ca_3(PO_4)_2(s)$

Chemical Arithmetic: Stoichiometry

Molecular Mass: Sum of atomic masses of all atoms in a molecule (for covalent molecule) (some texts use term molecular weight MW or MM)

Formula Mass: Sum of atomic masses of all atoms in a formula unit of any compound, molecular or ionic (for any compound) (some texts use term formula weight FW or FM)

HCl: 1.0 amu + 35.5 amu = 36.5 amu
(H) (Cl)

C_2H_4: 2(12.0 amu) + 4(1.0 amu) = 28.0 amu
(C) (H)

Chemical Arithmetic: Stoichiometry

Cl	one atom = 35.5 amu 1 mole = 35.5 g molar mass 6.022×10^{23} atoms = 35.5 g

HCl:	one formula = 36.5 amu 1 mole = 36.5 g molar mass 6.022×10^{23} molecules = 36.5 g

$\mathbf{C_2H_4}$:	one molecule = 28.0 amu 1 mole = 28.0 g molar mass 6.022×10^{23} molecules = 28.0 g

Chemical Arithmetic: Stoichiometry

Stoichiometry: The chemical arithmetic needed for mole to mass conversions (convert amount of one chemical to amount of another chemical – using conversion factor)

$$aA + bB \longrightarrow cC + dD$$

Grams of A → Moles of A → Moles of B → Grams of B

- Grams of A → Moles of A: Molar mass of A
- Moles of A → Moles of B: Mole ratio between A and B (coefficients) Change A to B
- Moles of B → Grams of B: Molar mass of B

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Chemical Arithmetic: Stoichiometry

$$2NaOH(aq) + Cl_2(g) \longrightarrow NaOCl(aq) + NaCl(aq) + H_2O(l)$$

How many grams of NaOH are needed to react with 25.0 g Cl_2?

using balanced chemical equation as conversion factor

Grams of Cl_2 → Moles of Cl_2 → Moles of NaOH → Grams of NaOH

Molar mass of Cl_2

Mole ratio between Cl_2 and NaOH

Molar mass of NaOH

Chemical Arithmetic: Stoichiometry

$$2NaOH(aq) + Cl_2(g) \longrightarrow NaOCl(aq) + NaCl(aq) + H_2O(l)$$

FM 40.0 g/mol FM 70.9g/mol

End 9/19 R D section

How many grams of NaOH are needed to react with 25.0 g Cl_2? 2 mole NaOH = 1 mole Cl_2

$$25.0 \text{ g } Cl_2 \times \frac{1 \text{ mol } Cl_2}{70.9 \text{ g } Cl_2} \times \frac{2 \text{ mol NaOH}}{1 \text{ mol } Cl_2} \times \frac{40.0 \text{ g NaOH}}{1 \text{ mol NaOH}}$$

= 28.2 g NaOH

HW: If I want to make 15.0 g iron, how many grams of iron (III) oxide is needed ?

$$Fe_2O_3(s) + 2Al(s) \rightarrow 2Fe(l) + Al_2O_3(s)$$

FM 159.7 g/mol FM 55.9 g/mol

conversion factors:

1 mole Fe = 55.9 g Fe

1 mole Fe_2O_3 = 159.7 g Fe_2O_3

1 mole Fe_2O_3 = 2 moles Fe

HW: If I want to make 15.0 g iron, how many grams of iron (III) oxide is needed ?

$$Fe_2O_3(s) + 2Al(s) \rightarrow 2Fe(l) + Al_2O_3(s)$$

Mass of iron (III) oxide = 21.5 g

End F section
9/20 Friday

Yields of Chemical Reactions

Actual Yield: The amount actually formed in a reaction

Theoretical Yield: The amount predicted by calculations

$$\textbf{Percent Yield} = \frac{\text{Actual yield of product}}{\text{Theoretical yield of product}} \times 100\%$$

Experimental yield is almost never the same as theoretically expected yield.

End F section
9/23 M

Examples: calculating % yield

A reaction should produce 23.2 grams of iron metal from the reactant amount. The reaction experimentally only yields 19.3 grams of iron metal. What is your percent yield ?

End G section 9/20/19, 9/23M

$$\% \text{ yield} = \left[\frac{19.3 \text{ grams experimental yield}}{23.2 \text{ grams theoretical yield}} \right] * 100 = 83.2\ \%$$

Reactions with Limiting Amounts of Reactants

Limiting Reactant: The reactant that is present in limiting amount. The extent to which a chemical reaction takes place depends on the limiting reactant.

Excess Reactant: Any of the other reactants still present after using up all of the limiting reactant

How Many Cookies Can I Make?

- You can make cookies until you run out of one of the ingredients.
- Once this family runs out of sugar, they will stop making cookies (at least any cookies you would want to eat).

How Many Cookies Can I Make?

- In this example the sugar would be the limiting reactant, because it will limit the amount of cookies you can make.

Stoichiometric Calculations

2 bread slices + 1 salami slices $\rightarrow$ 1 salami sandwich

What is the theoretical yield of salami sandwiches from 4 bread slices and 3 salami slices ? Which is the limiting reagent ?

(a) salami sandwiches (b) bread slices (c) salami slices (d) b & c

$$4 \text{ bread} \times \frac{1 \text{ sandwich}}{2 \text{ bread}} = 2 \text{ sandwiches}$$

$$3 \text{ salami} \times \frac{1 \text{ sandwich}}{1 \text{ salami}} = 3 \text{ sandwiches}$$

Stoichiometric Calculations

2 bread slices + 1 salami slices $\rightarrow$ 1 salami sandwich

What is the theoretical yield of salami sandwiches from 4 bread slices and 3 salami slices ? Which is the limiting reagent ?

(a) salami sandwiches (b) bread slices (c) salami slices (d) b & c

$$4 \text{ bread} \times \frac{1 \text{ sandwich}}{2 \text{ bread}} = 2 \text{ sandwiches}$$

$$3 \text{ salami} \times \frac{1 \text{ sandwich}}{1 \text{ salami}} = 3 \text{ sandwiches}$$

bread is Limiting Reagent

Theoretical Yield is 2 sandwiches.

Stoichiometric Calculations

$$3\ H_2 + N_2 \rightarrow 2\ NH_3$$

What is the theoretical yield of NH_3 in grams from 8.22 grams H_2 and 31.5 g of N_2 ? (NOT 8.22 g NH_3, NOT 31.5 g NH_3) Which is the limiting reagent ? (NOT necessarily H_2)

(a) NH_3 (b) H_2 (c) N_2 (d) b & c

__Needed__ must have formula masses because chemical equation is in molar or number of molecule ratios

- FM of NH_3 = 14.01(N) + 3*1.01(H) = 17.04 g NH_3/mol NH_3
- FM of H_2 = 2*1.01(H) = 2.02 g H_2/mol H_2
- FM of N_2 = 2*14.01(N) = 28.02 g N_2/mol N_2

Stoichiometric Calculations

$3\ H_2 + N_2 \rightarrow 2\ NH_3$

(1) What is the theoretical yield of NH_3 (17.04 g NH_3/mol NH_3) in grams from 8.22 grams H_2 (2.02 g H_2/mol H_2) and 31.5 g of N_2 (28.02 g N_2/mol N_2) ? (2) Which is the limiting reagent ?

(a) NH_3 (b) H_2 (c) N_2 (d) b & c

$$8.22\ \text{g}\ H_2 \times \frac{1\ \text{mol H2}}{2.02\ \text{g H2}} \times \frac{2\ \text{mol NH3}}{3\ \text{mol H2}} \times \frac{17.04\ \text{g NH3}}{1\ \text{mol NH3}} = 46.2\ \text{g}\ NH_3$$

$$31.5\ \text{g}\ N_2 \times \frac{1\ \text{mol N2}}{28.02\ \text{g N2}} \times \frac{2\ \text{mol NH3}}{1\ \text{mol N2}} \times \frac{17.04\ \text{g NH3}}{1\ \text{mol NH3}} = 38.3\ \text{g}\ NH_3$$

Stoichiometric Calculations

$3\ H_2 + N_2 \rightarrow 2\ NH_3$

(1) What is the theoretical yield of NH_3 (17.04 g NH_3/mol NH_3) in grams from 8.22 grams H_2 (2.02 g H_2/mol H_2) and 31.5 g of N_2 (28.02 g N_2/mol N_2) ? (2) Which is the limiting reagent ?

(a) NH_3 (b) H_2 (c) N_2 (d) b & c

- Using 8.22 g H_2 gives 46.2 g NH_3
- Using 31.5 g N_2 gives 38.3 g NH_3
- Which is limiting reagent ? Not NH_3 (product never limiting reagent)
- H_2 or N_2 (Which gives less products ?)

(2) Which is limiting reagent ? (c) N_2

(1) What is Theoretical Yield ? 38.3 g NH_3

Reactions with Limiting Amounts of Reactants

Lithium oxide is used aboard the space shuttle to remove water from the air supply according to the equation

$$Li_2O(s) + H_2O(g) \longrightarrow 2LiOH(s)$$

29.88 g/mol	18.02 g/mol	23.95 g/mol	FM values

If 80.0 g of water is to be removed and 65.0 g of Li_2O is available, which reactant is limiting? How many grams of excess reactant remain? How many grams of LiOH are produced? (theoretical yield of LiOH)

Reactions with Limiting Amounts of Reactants

$$Li_2O(s) + H_2O(g) \longrightarrow 2LiOH(s)$$

Which reactant is limiting?

Amount of H_2O that will react with 65.0 g Li_2O:

$$65.0 \text{ g } Li_2O \times \frac{1 \text{ mol } Li_2O}{29.9 \text{ g } Li_2O} \times \frac{1 \text{ mol } H_2O}{1 \text{ mol } Li_2O} = \boxed{2.17 \text{ mol } H_2O}$$

Amount of H_2O given:

$$80.0 \text{ g } H_2O \times \frac{1 \text{ mol } H_2O}{18.0 \text{ g } H_2O} = 4.44 \text{ mol } H_2O$$

Li_2O is limiting.

Reactions with Limiting Amounts of Reactants

$$Li_2O(s) + H_2O(g) \longrightarrow 2LiOH(s)$$

How many grams of excess H_2O remain?

$$2.17 \text{ mol } H_2O \times \frac{18.0 \text{ g } H_2O}{1 \text{ mol } H_2O} = 39.1 \text{ g } H_2O \text{ (consumed)}$$

$$80.0 \text{ g } H_2O - 39.1 \text{ g } H_2O = \boxed{40.9 \text{ g } H_2O}$$

initial — consumed — **remaining**

Reactions with Limiting Amounts of Reactants

$$Li_2O(s) + H_2O(g) \longrightarrow 2LiOH(s)$$

How many grams of LiOH are produced?

$$2.17 \text{ mol } H_2O \times \frac{2 \text{ mol LiOH}}{1 \text{ mol } H_2O} \times \frac{23.9 \text{ g LiOH}}{1 \text{ mol LiOH}} = \boxed{104 \text{ g LiOH}}$$

End 9/25 D section

Limiting Reagent HW:

Suppose 68.5 kg CO(g) is reacted with 8.60 kg H_2. (a) Which is limiting reagent ? (b) What is the theoretical yield of methanol (in grams) ?

$$2\,H_2(g) + CO(g) \rightarrow CH_3OH(l)$$

FM 2.02 g/mol 28.01 g/mol 32.05 g/mol

End F, G section 9/25/19 W
End D section 9/26R

Solution (continued from last page)

Limiting Reagent is the H_2. The maximum amount of CH_3OH that can be formed is 6.82×10^4 g (theoretical yield)

Percent Composition and Empirical Formulas

Percent Composition: gives the mass percent of each element in a compound.

Empirical Formula: gives the smallest whole-number (molar) ratios of the atoms in the compound.

Molecular Formula: gives the actual numbers of atoms in a compound (molecule). (can be the empirical formula or a multiple of the empirical formula)

Types of Chemical Formulas

- An **empirical formula** gives the *relative* number of atoms of each element in a compound. (just ratio of elements)
- A **molecular formula** gives the *actual* number of atoms of each element in the molecule of a compound. (ratio **AND** exactly how many of each atom in a molecule)

(for molecular formulas H_2O_2 B_2H_6 CCl_4)

(a) For H_2O_2, the greatest common factor is 2. The **empirical formula is HO**.

(b) For B_2H_6, the greatest common factor is 2. The **empirical formula is BH_3**.

(c) For CCl_4, the only common factor is 1, so the **empirical formula and the molecular formula are identical.**

Empirical Formula – gives lowest ratio of elements in a compound

- Molecular formula = (empirical formula)$_n$
- n = integer (1,2,3…)
- Example:

  C H (empirical formula)

  $(C H)_6$ = C_6H_6 (molecular formula)

Molecular Formulas for Compounds

- The molecular formula is a whole-number multiple of the empirical formula.
- To determine the molecular formula, you need to know the empirical formula and the molar mass of the compound.

Molecular formula = (empirical formula)***n***,

*where **n** is a positive integer.*

$$n = \frac{\text{molar mass}}{\text{empirical formula molar mass}}$$

HW: Determining Empirical & Molecular Formulas from molar mass and molecular formula mass

- Empirical formula of styrene is CH (molar mass of CH is 13.02 g/mol); its molecular molar mass is 104.1 g/mol

  - What is the molecular formula of styrene?

    a. C_2H_4
    b. C_8H_8
    c. $C_{10}H_{10}$
    d. C_6H_6

HW: Determining Empirical & Molecular Formulas from molar mass and molecular formula mass

- Empirical formula of styrene is CH (molar mass of CH is 13.02 g/mol); its molecular molar mass is 104.1 g/mol

  - What is the molecular formula of styrene?

    a. C_2H_4
    b. C_8H_8 *
    c. $C_{10}H_{10}$
    d. C_6H_6

Example: Determining Empirical & Molecular Formulas from % elements

- A compound has 43.64% phosphorus and 56.36% oxygen by mass (assume 100 grams of compound)
  - Compound has a molar mass of 283.88 g/mol
  - What are the compound's empirical and molecular formulas?

Example on doc camera

Example: Determining Empirical & Molecular Formulas from % elements

- What is the mass of each element in 100.00 g of compound?
  - Mass of P = 43.64 g
  - Mass of O = 56.36 g

Example: Determining Empirical & Molecular Formulas from % elements

- What are the moles of each element in 100.00 g of compound? (divide mass by atomic mass of each element)

$$43.64\ \cancel{g\,P} \times \frac{1\ \text{mol P}}{30.97\ \cancel{g\,P}} = 1.409\ \text{mol P}$$

$$56.36\ \cancel{g\,O} \times \frac{1\ \text{mol O}}{16.00\ \cancel{g\,O}} = 3.523\ \text{mol O}$$

- What is the empirical formula for the compound?
  - Dividing each mole value by the smaller one gives

$$\frac{1.409}{1.409} = 1\ \text{P} \quad \text{and} \quad \frac{3.523}{1.409} = 2.5\ \text{O}$$

Example: Determining Empirical & Molecular Formulas from % elements

- Gives $PO_{2.5}$
- Multiply both numbers by 2 to give the empirical formula P_2O_5

Example: Determining Empirical & Molecular Formulas from % elements

- What is the molecular formula for the compound?
  - Compare the empirical formula mass to the molar mass of molecule.

Empirical formula mass = 141.94 g/mol
Given molar mass = 283.88 g/mol

$$\frac{\text{Molar mass}}{\text{Empirical formula mass}} = \frac{283.88}{141.94} = 2$$

- Molecular formula is $(P_2O_5)_2$, or P_4O_{10}

Summary: Calculating Empirical & Molecular Formulas Given % Composition & Molecular Formula Mass

- To Calculate Empirical Formula from % composition:

1. assume 100 grams of compound
2. divide each element mass by element atomic mass to convert to molar ratio of elements = empirical formula

- To Calculate Molecular Formula from Empirical Formula and molar mass

1. Calculate empirical formula mass
2. Divide molecular formula mass by empirical formula mass to calculate n factor
3. Molecular formula = (empirical formula)* n

HW: Percent Composition and Empirical Formulas

A colorless liquid has a composition of 84.1% carbon and 15.9% hydrogen by mass. (a) What is the empirical formula. (assume 100 grams of compound) (b) If the molar mass of this compound is 114.2 g/mol, what is the molecular formula of this compound.

Percent Composition and Empirical Formulas

Assume 100.0 g of the substance:

Mole of carbon:

$$84.1\text{ g C} \times \frac{1\text{ mol C}}{12.0\text{ g C}} = 7.01\text{ mol C}$$

Mole of hydrogen:

$$15.9\text{ g H} \times \frac{1\text{ mol H}}{1.0\text{ g H}} = 15.9\text{ mol H}$$

Percent Composition and Empirical Formulas

Empirical formula:

$C_{7.01}H_{15.9}$

smallest value for the ratio → $\dfrac{C_{7.01}}{7.01}\dfrac{H_{15.9}}{7.01} = C_1H_{2.27}$

$C_1H_{2.27}$

0.27 nearly 0.25 or 1/4

need whole numbers → $C_{1\times4}H_{2.27\times4} = C_4H_9$

[(12.0*4) + (1.0*9)]=57.0
C H

Molecular formula:

$$\text{multiple} = \frac{114.2}{57.0} = 2$$

$C_{4\times2}H_{9\times2} = C_8H_{18}$

End 9/27F F section

Determining Empirical Formulas: Elemental Analysis (instrument that gives % elements)

Combustion Analysis: A compound of unknown composition is burned with oxygen to produce the volatile combustion products CO_2 and H_2O, which are separated and have their amounts determined by an automated instrument.

$$\text{hydrocarbon} + O_2(g) \longrightarrow xCO_2(g) + yH_2O(g)$$

carbon → $xCO_2(g)$

hydrogen → $yH_2O(g)$

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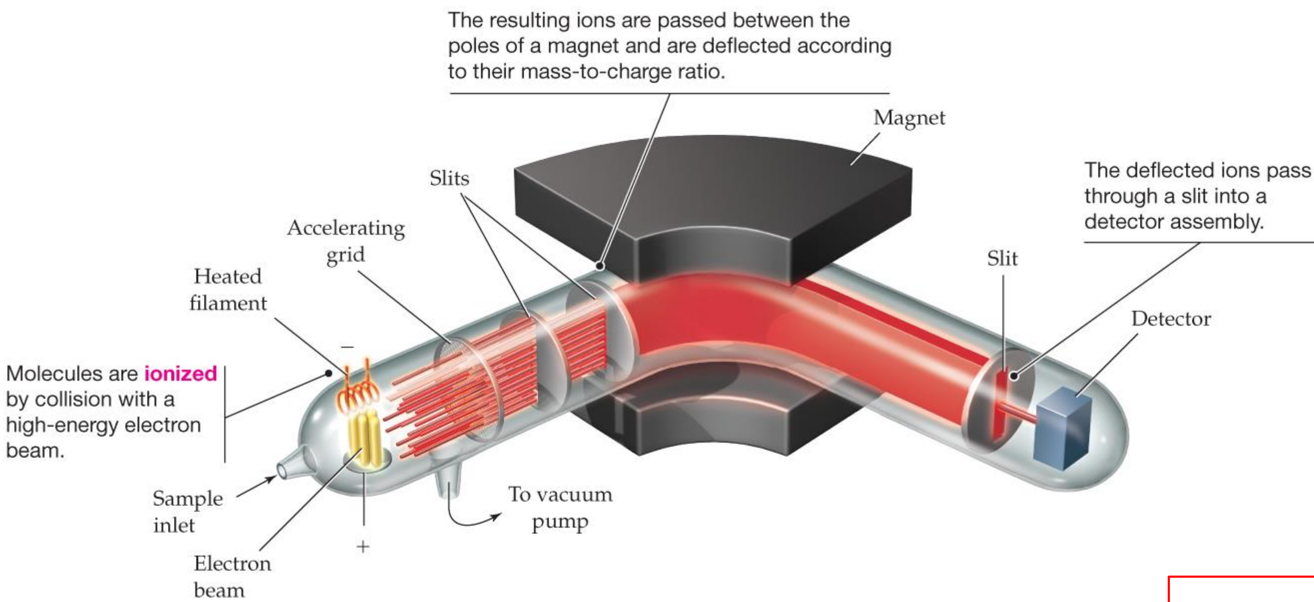
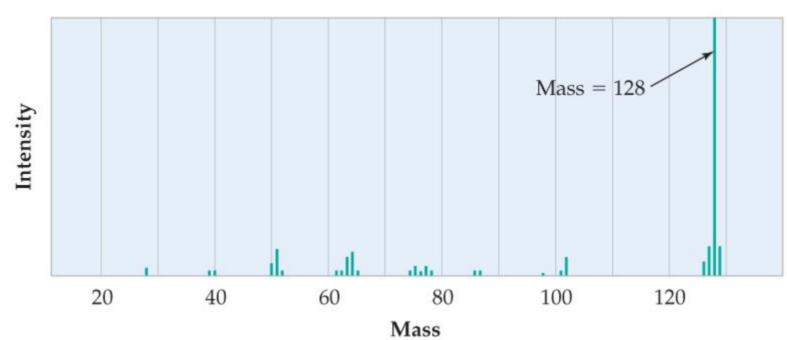
Determining Molecular Masses: Mass Spectrometry – spectra for getting FM

(a) A mass spectrometer



(b) A mass spectrum for naphthalene



End 9/27F
G section