Chapter 8 – Chemical Equations

In Chapte4, Section 2 we first saw chemical reactions expressed as chemical equations. In this chapter we go into much greater depth by considering why reactions proceed as written, how they are balanced, and classification of reactions.

8.1 The Chemical Equation

The basic structure of chemical equations is fairly straightforward. The chemical formula of materials that react are written separated by "plus" (+) signs. Then an arrow pointing to the right is written, followed by the materials that are produced in the reaction, separated by plus signs. Coefficients are added to indicate how many units of each compound are present. The physical phases (solid, ℓiquid, gas) of each material is indicated following the material's formula. Sometimes, conditions are placed above or below the arrow. Conditions include warming the reaction (Δ), shining light on it ($h\nu$), or providing the solvent (In CHM 111, 211, 212, the solvent will be presumed to be water. If the solvent is something else, it might be written over/under the arrow. Chemical equations are important because they present a great deal of information in a compact form.

The combustion of methane provides an example of these rules.

$$CH_{4\,(g)} + 3\ O_{2\,(g)} \rightarrow CO_{2\,(g)} + 2\ H_2O_{(\ell)}$$

One final point relating to chemical equations: the total mass of the reacting species must equal the total mass of the product species. This is called the law of conservation of matter. It is sometimes expressed as matter may neither be created nor destroyed (in chemical reactions). It is also the First Law of Thermodynamics.

8.2 Writing and Balancing Chemical Equations

Chemical equations must be "balanced" to be truly valuable. Balancing simply means that the number and kind of atom on each side of the arrow must be the same. Using the burning of methane example from a few lines ago, the equation is balanced because each side has 1 carbon atom, 4 hydrogen atoms, and 6 oxygen atoms. The chemical reaction changes the atoms to which they are connected, but not the number or identity of the atoms. The process for balancing shown here differs a little from the book's description, but this method provides an added filter that simplifies the process.

Begin by knowing the reactants and products in the reaction mixture. The steps are:

1) Write out all reactants and products on the correct sides of the arrow.
2) Count out how many atoms of each element (or group) appear on either side of the arrow.
3) Choose the element (or group) that appears in the fewest number of places <u>and</u> has different numbers on either side of the arrow. Balance using coefficients.
4) Repeat with the remaining atoms/groups.
5) Make all coefficients whole numbers by multiplying through by the least common denominator of the existing coefficients.

Examples: (The **blue** atoms are being balanced.)

__ P + __ $Cl_2 \longrightarrow$ __ PCl_3

P + 3 $Cl_2 \longrightarrow$ 2 PCl_3

2 P + 3 $Cl_2 \longrightarrow$ 2 PCl_3

__ C_7H_{14} + __ $O_2 \longrightarrow$ __ CO_2 + __ H_2O

C_7H_{14} + $O_2 \longrightarrow$ 7 CO_2 + H_2O

C_7H_{14} + $O_2 \longrightarrow$ 7 CO_2 + 7 H_2O

C_7H_{14} + $^{21}/_2$ $O_2 \longrightarrow$ 7 CO_2 + 7 H_2O

` 2 C_7H_{14} + 21 $O_2 \longrightarrow$ 14 CO_2 + 14 H_2O

There are a couple of important points to add: (1) Never change subscripts in formulas. Doing so changes the identity of the substance. For example, H_2O is water, but H_2O_2 is hydrogen peroxide. CH_2O is formaldehyde, while $C_6H_{12}O_6$ is glucose. (2) Coefficients should not have a common divisor. That is, reaction between hydrogen and oxygen to form water is **<u>not</u>** properly balanced as: 4 H_2 + 2 $O_2 \rightarrow$ 4 H_2O because each coefficient is an even number. To balance it correctly, you must divide by 2 (point 5 above).

There are a couple of final points about chemical equations worth remembering.

(1) Chemical equations provide no information on reaction rate (speed) and

(2) Chemical equations provide no information about how the reactants interact with one another. This is called the reaction mechanism and describes at the atomic level the path from reactants to products. Most reactions take several steps to complete. For example, looking at the combustion of C_7H_{14} above, what is the likelihood that 23 molecules react (collide) in one step?

8.3 Why Do Chemical Reactions Occur?

The short answer to this question is: In almost all cases, reactions occur because, collectively, the products are more stable than the reactants. This section is very short and you'll see that nothing like that statement appears in the book's answer.

The language the book uses is important. It really doesn't address "why" the reaction occurs, but rather how to empirically decide whether a reaction will proceed as written. It is usually the case that in reactions in which none of the reactants are gasses and at least one product is a gas, the reaction will proceed as written. Does that make sense/sound reasonable?

Let's answer that question with an example. Consider reacting zinc metal with hydrochloric acid in an open container:

$$Zn_{(s)} + 2\ HCl_{(aq)} \rightarrow ZnCl_{2\ (aq)} + H_{2\ (g)}$$

Why does having a gas on the right suggest that the reaction proceeds as written, rather than the reverse? Imagine in your mind's eye doing the reaction. You have a beaker with a clear, colorless HCl solution and stir in some gray zinc powder. What happens next? Either the solid sinks to the bottom, consistent with no reaction occurring or hydrogen gas forms bubbles that float to the top of the solution and escape into the atmosphere. Once the H_2 leaves the solution, it is unavailable for reaction, meaning there is no buildup of hydrogen that would allow the reverse reaction to proceed. The result is the reaction proceeds to the right/forms products because there is no viable return pathway.

Thus, formation of a gas is frequently viewed as a driving force for a reaction because when the product separates from the reaction solution, the reverse reaction isn't possible. The same basic logic applies to the formation of solids (precipitates) and liquids in reactions, but the explanation for why it works is more complicated.

8.4 Types of Chemical Reactions

As you've seen, there is a huge amount of information that must be retained in chemistry and much of it looks similar. Grouping information makes remembering it easier. To some degree, grouping occurs in nomenclature, where there are ionic and molecular compounds and acids for three groups.

Reactions are grouped to highlight similarities between them. Your book lists five very common collections of reaction types and we will look at them individually.

Synthesis/Combination Reactions

These reactions result in two or more materials forming a single product. "Combination" is more commonly used than "synthesis" because chemists frequently use the term synthesis to mean any reaction that leads to a sought-after product. Combination is a better term because this reaction arises when two or more reactant molecules merge into a single product. (Note: When balancing, there may be two or more of the product molecule.) Formation of sodium chloride from its constituent elements is a classic example of a combination reaction.

$$2\ Na_{(s)} + Cl_{2\,(g)} \rightarrow 2\ NaCl_{(s)}$$

Combustion Reactions

A combustion reaction is any reaction that produces a flame. (Do not use your book's definition.) Nearly all combustion reactions involve an organic compound reacting with oxygen. Organic compounds are those made of carbon, hydrogen, and possibly other, nonmetallic elements. The prototypical combustion reaction is the burning of methane shown earlier in these notes.

$$CH_{4\,(g)} + 3\ O_{2\,(g)} \rightarrow CO_{2\,(g)} + 2\ H_2O_{(\ell)}$$

Decomposition reactions

Decomposition reactions occur when one compound breaks up into two or more compounds. They are the reverse of combination reactions. Heating limestone to form lime is a classic decomposition reaction.

$$CaCO_{3\,(s)} \xrightarrow{\Delta} CaO_{(s)} + CO_{2\,(g)}$$

Much of the destruction of ancient Greek temples occurred when people tore down the structures and burned the limestone for heat. In general, decomposition reactions require the input of energy, usually as heat.

Single Displacement Reactions

A single displacement reaction occurs when an element replaces another element in a compound. Note that the reactant is an element in its native form.

A straightforward example would be replacing the copper ion in copper(II) sulfate with iron.

$$Fe_{(s)} + CuSO_{4\,(aq)} \rightarrow Cu_{(s)} + FeSO_{4\,(aq)}$$

The reaction of iron filings with hydrochloric acid provides a slightly more complicated example because the balancing coefficients don't have to be 1:

$$Fe_{(s)} + 2\,HCl_{(aq)} \rightarrow H_{2\,(g)} + FeCl_{2\,(aq)}$$

The reaction between an alkali metal and water provides a single displacement that is more involved.

$$Na_{(s)} + 2\,H_2O_{(\ell)} \rightarrow H_{2\,(g)} + 2\,NaOH_{(aq)}$$

This may not look like a displacement reaction at first, but if water is viewed as H-OH, then the sodium is displacing the "H" that is bound to the -OH.

Double Displacement Reactions

Double displacement reactions occur when the cations and anions in two compounds that form ions when they dissolve exchange places. They are sometimes called metathesis reactions. The "driving forces" discussed in Section 8.3 play a prominent role in double displacement reactions. In nearly all of these reactions, both reactants are soluble, while one of the products is a solid, gas, or non-ionic molecule, with the other product being a soluble salt. An example of each of these appears below.

$$AgNO_{3\,(aq)} + HCl_{(aq)} \rightarrow AgCl_{(s)} + HNO_{3\,(aq)}$$

$$ZnS_{(s)} + 2\,HCl_{(aq)} \rightarrow ZnCl_{2\,(aq)} + H_2S_{(g)}$$

$$HCl_{(aq)} + Na(OH)_{(aq)} \rightarrow H_2O_{(\ell)} + NaCl_{(aq)}$$

Occasionally, metathesis reaction yield products that later decompose as part of the driving force process. For example,

$$Na_2CO_{3\,(aq)} + 2\,HCl_{(aq)} \rightarrow H_2CO_{3\,(aq)} + 2\,NaCl_{(aq)}$$

Carbonic acid is a molecule so is sufficient to be a driving force, but it is very unstable and breaks up into water and carbon dioxide.

8.5 Heat in Chemical Reactions

In this section, we return to the role energy, specifically heat, plays in chemical reactions. In the discussion of driving forces, the idea that mixtures of chemicals typically react when the products of a reaction are more stable than the reactant was introduced. Remember that this is reasonable from your personal experience. Putting energy into systems (e.g. heating them) makes them less stable. Lifting a glass from the ground to a shelf requires the input of energy and makes the glass less stable. We will now examine energy changes in a little more detail.

The direction of the flow of energy is named. Systems that release heat energy to the surroundings are called exothermic, while those that extract heat from their surroundings are called endothermic. Systems that are exothermic in one direction will be endothermic in the reverse direction and *vice-versa*. Does this sound reasonable? Let's go back to the glass example. If a glass is on the floor and you lift it onto a shelf, you input some amount of energy. If the glass falls to the floor, how much energy is released? The same amount.

The same is true of chemical reactions. Hydrogen reacts with oxygen to produce water according to the reaction:

$$2\,H_{2(g)} + O_{2\,(g)} \rightarrow 2\,H_2O_{(g)}\ \Delta H = -286\ kJ$$

To break water up into hydrogen and oxygen, the reverse reaction, would look like this:

$$2\ H_2O_{(g)} \longrightarrow 2\ H_{2\,(g)} + O_{2\,(g)} \quad \Delta H = +286\ kJ$$

This phenomenon of a reaction and its reverse having the same magnitude of energy change, but with the sign reversed is always true. (Industry is looking at making this particular cycle a way of creating and storing clean energy. It works like this: during the day, solar energy is used to drive the second reaction and convert water to hydrogen and oxygen. That energy is released later when the hydrogen and oxygen are reacted to from water.)

The energy change associated with a chemical reaction is called its heat of reaction (or more formally its enthalpy of reaction).

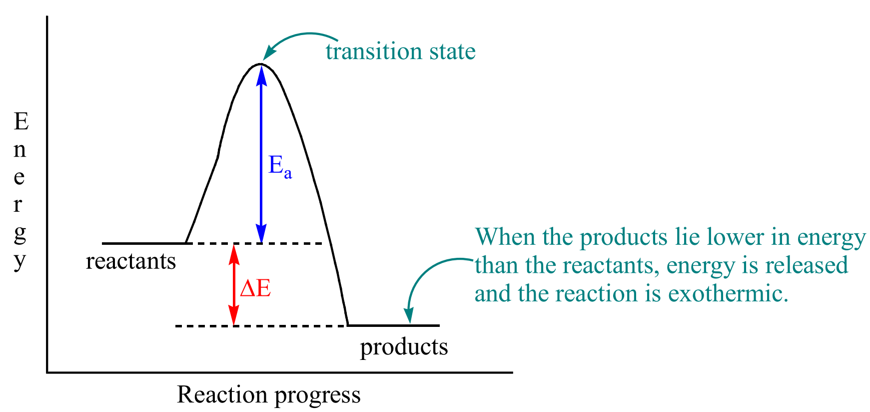
Finally, we need to think about how a reaction actually occurs at the atomic level. Consider the decomposition of NOCl, to nitrogen monoxide gas and chlorine gas:

$$2NOCl_{(g)} \rightarrow 2NO_{(g)} + Cl_{2\,(g)}$$

which occurs in a single step. Imagine in your mind's eye what a single molecule of NOCl would look like. What would the reaction look like if you could record a video of it happening?

The molecule would look a little like a three Nerf® balls pushed together in a line. The reaction would be complicated because the molecules would have to align properly for a reaction. (E.g. The two chlorine atoms would have to collide. Other orientations would result in the two molecules bouncing off one another. Does this sound reasonable?

Implicit in this discussion is something that you accepted without thinking about. The NOCl molecule is stable. That is, it will react with other NOCl molecules under the right conditions, but otherwise it exists. What this means energetically is that there is a barrier to the reaction getting started otherwise the compound couldn't be prepared and stored. That energy barrier is called the activation energy, E_a, and is seen pictorially as



Is it reasonable that an energy barrier exists? Think about it this way. Molecules exist because atoms bind to one another. That binding is an attractive interaction (force). A reaction requires that the bond be broken and that requires an input of energy. The reason why there is a net loss of heat energy for almost all reactions (exothermic) is because for the reaction to proceed, the atoms will be bound more strongly than in the starting chemicals. That makes the reverse reaction more difficult.

8.6 Climate Change: The Greenhouse Effect

Read on your own. One question that people frequently relates to the amount of carbon dioxide that human activity puts into the atmosphere. Here is a calculation you can do to get a perspective. A typical car or truck has a 15-20 gallon gas tank. What mass of carbon dioxide forms from burning 15 gallons of gasoline if the gasoline is 100% octane (C_8H_{18}) and its density is 0.75 g/mL. Now consider how many times per year you fill your tank. Typical tanker trucks hold about 9,000 gallons.

August 21, 2023