Tutorial 5

NET IONIC EQUATIONS

The efficiency and extent of a chemical reaction is very much dependent upon the physical state (solid, liquid, gas, or solution) of reactants and products. Not surprisingly, the most efficient reactions are those that take place in the gas phase. But the most familiar and frequently encountered reactions are those that occur in solution and in particular, water. (Your text devotes an entire chapter (4) to this subject.) This tutorial is designed to give you additional insight into reactions that occur in water and to equip you with the necessary tools for writing net ionic equations from observations of chemical phenomena in the laboratory. Use this tutorial in conjunction with your textbook; as noted, solution based reactions including net ionic equations are discussed in chapter 4 of the text.

Water is the medium for many different kinds of reactions. These reactions involve substances dissolved in water – solutes, and include reactions between solutes or reactions of solutes with solids, liquids, or gases:

(1) $NaCl\ (aq) + AgNO_3\ (aq) \rightarrow NaNO_3\ (aq) + AgCl\ (s)$

(2) $Ba(NO_3)_2\ (aq) + Na_2CO_3\ (aq) \rightarrow BaCO_3\ (s) + 2NaNO_3\ (aq)$

(3) $HC_2H_3O_2\ (aq) + NaOH\ (aq) \rightarrow NaC_2H_3O_2\ (aq) + H_2O\ (l)$

(4) $MgO\ (s) + 2HCl\ (aq) \rightarrow MgCl_2\ (aq) + H_2O\ (l)$

(5) $FeS\ (s) + H_2SO_4\ (aq) \rightarrow FeSO_4\ (aq) + H_2S\ (g)$

(6) $Cl_2\ (aq) + 2KBr\ (aq) \rightarrow 2KCl\ (aq) + Br_2\ (l)$

(7) $Zn\ (s) + CuSO_4\ (aq) \rightarrow ZnSO_4\ (aq) + Cu\ (s)$

A careful examination of these reactions reveals that some solutes are dissolved ionic substances (*e.g.* NaCl, $AgNO_3$, etc.) while others are dissolved molecular species (eg. $HC_2H_3O_2$, HCl, Cl_2, etc.). When an ionic substance dissolves in water, it completely dissociates into ions. For example, an aqueous solution of sodium chloride consists of Na^+ (aq) and Cl^- (aq) ions and essentially no associated sodium chloride (NaCl (aq)).

Molecular substances will either remain as molecules or partially or completely dissociate when dissolved in water. To predict how a molecule will behave when dissolved in water requires an understanding of its molecular and electronic properties. In time you will have a more complete understanding of these properties; for now, we will identify which molecular species that dissociate and to what extent.

Strong acids are molecular substances that completely dissociate into ions when dissolved in water. Hydrogen chloride, HCl, is an example; it is a molecule and a gas at room temperature. An aqueous solution of hydrogen chloride (hydrochloric acid), consists of hydrogen ions (H^+)

and chloride ions (Cl^-). Other common strong acids are: HBr, HI, HNO_3, H_2SO_4, and $HClO_4$. These acids are completely dissociated into ions in water.
Weak acids and weak bases are only partially dissociated in water. A typical weak acid is acetic acid, $HC_2H_3O_2$. (Generally, any acid or base not listed as strong [lecture text, Table 4.2, p 115, or above for acids] can be assumed to be weak.) A typical weak base is ammonia, NH_3.

All other molecular substances remain undissociated in aqueous solution.

The chemical events described by reactions 1-6 illustrate the variety of water based reactions that you will encounter in your study of chemistry. These reactions are frequently identified and categorized by some characteristic feature or "driving force".

Reactions (1) and (2) are called metathesis (or double displacement or double decomposition) reactions; precipitate formation is the driving force and is the result of ions exchanging partners. Reaction (3) is also a metathesis reaction but all species remain in solution; this is an acid-base reaction and is called a neutralization reaction. The driving force is the formation of water as a product. Reactions (4) and (5) are reactions between acids and insoluble bases; two examples of acid-base reactions, but usually called dissolution reactions because a solid dissolves during the course of the reaction. The production of water (4) and a gas (5) help drive these reactions to completion. Reactions (6) and (7) are examples of oxidation-reduction (redox) reactions. A free element displaces the ion of another element from solution; these reactions are called (single) displacement reactions. The driving force in these reactions is known as the reduction potential – a measurable quantity, and the separation of products from solution as an insoluble liquid (6) and solid (7).

Please note: The reaction types described are not intended to be exclusive; indeed, most reactions possess multiple features (*e.g.* redox accompanied by precipitation). Classification, therefore, can be seemingly arbitrary but is usually determined by the predominant characteristic.

We can now use this knowledge to simplify chemical equations for reactions in aqueous solution. Consider the reaction:

(8m) $$BaCl_2\,(aq) + Na_2SO_4\,(aq) \rightarrow BaSO_4\,(s) + 2NaCl\,(aq)$$

This is the molecular equation. Since the ions in solution are independent of one another let's write them that way:

(8) $$Ba^{2+}\,(aq) + 2Cl^-\,(aq) + 2Na^+\,(aq) + SO_4^{2-}\,(aq) \rightarrow$$
$$BaSO_4\,(s) + 2Na^+\,(aq) + 2Cl^-\,(aq)$$

Soluble ionic substances $BaCl_2$, Na_2SO_4, and NaCl are ionized; $BaSO_4$ is insoluble in water, as indicated by the (s). Note what happens to the numerical subscripts in going from a molecular formula to ions in solution: $BaCl_2$ and Na_2SO_4. The (aq) should be included with the ions.

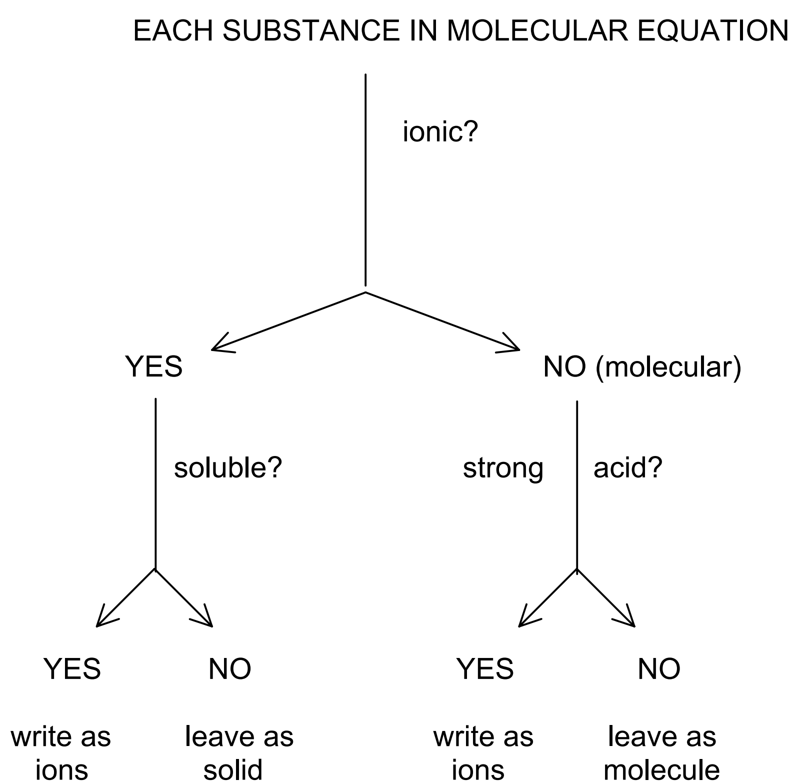
Equation (8) can be simplified: Na^+ (aq) and Cl^- (aq) are the same on both sides of the equation so have not undergone any chemical change; they can be removed, leaving

$$\text{(8i)} \qquad Ba^{2+}\,(aq) + SO_4^{2-}\,(aq) \rightarrow BaSO_4\,(s)$$

This equation contains only those chemical species which have reacted and is called the net ionic equation. A reaction has occurred because ions which were capable of independent movement when present in reactant solutions are now immobilized in a solid: a precipitate has formed.

To go from a molecular to a net ionic equation you must know for each substance in the equation: (1) is it ionic or molecular; (2) if ionic, is it soluble; (3) if molecular, does it dissociate. You must know the symbols and charges of the common ions; these are given in Tutorial 2, p T-7. Similarly, you must know whether or not a particular substance is soluble in water. A set of solubility rules can be found on p 111, Table 4.1, of the lecture text.

A virtually infallible scheme to follow is:



NOTE: A similar flow chart for deciding whether or not a substance is an electrolyte is presented in Figure 4.7, p 116, of the lecture text.

Write the net ionic equation for the reacton:

$$\text{(9m)} \qquad NaC_2H_3O_2\,(aq) + HCl\,(aq) \rightarrow NaCl\,(aq) + HC_2H_3O_2\,(aq)$$

Using the scheme outlined above we write the appropriate substances in ionic form:

(9) $Na^+ (aq) + C_2H_3O_2^- (aq) + H^+ (aq) + Cl^- (aq) \rightarrow$

$Na^+ (aq) + Cl^- (aq) + HC_2H_3O_2 (aq)$

Note: $HC_2H_3O_2$ is covalent and a weak acid; it is undissociated in aqueous solution.

Canceling common ions from both sides of the equation leaves

(9i) $C_2H_3O_2^- (aq) + H^+ (aq) \rightarrow HC_2H_3O_2 (aq)$

Consider the following equations in their molecular and net ionic forms:

(10m) $Ag_2SO_4 (s) + 4NH_3 (aq) \rightarrow [Ag(NH_3)_2]_2SO_4 (aq)$

(10i) $Ag_2SO_4 (s) + 4NH_3 (aq) \rightarrow 2[Ag(NH_3)_2]^+ (aq) + SO_4^{2-} (aq)$

(11m) $[Ag(NH_3)_2]_2SO_4 (aq) + BaCl_2 (aq) \rightarrow BaSO_4 (s) + 2NH_4NO_3 (aq)$

(11i) $SO_4^{2-} (aq) + Ba^{2+} (aq) \rightarrow BaSO_4 (s)$

(12m) $[Ag(NH_3)_2]Cl (aq) + 2HNO_3 (aq) \rightarrow AgCl (s) + 2NH_4NO_3 (aq)$

(12i) $[Ag(NH_3)_2]^+ (aq) + Cl^- (aq) + 2H^+ (aq) \rightarrow AgCl (s) + 2NH_4^+ (aq)$

Square brackets around a group of atoms indicates a complex ion and this group stays together throughout a reaction, unless, of course, it is destroyed in the reaction. $[Ag(NH_3)_2]^+$ is a complex ion in the above equations. Equations (10) show the formation of the complex ion; equations (11) show the maintenance of its integrity during a reaction; and equations (12) show its destruction.

In a displacement reaction a free element displaces the ion of another from aqueous solution. Metals displace other metal ions, nonmetals displace other nonmetal ions. Whether or not one element displaces another depends on their relative positions on the so-called "activity series." An activity series for some common metals and another for Group VII nonmetals are given in the left margin. An element will displace another on the list below it. For example, consider the reaction between zinc and copper ion depicted in equation (7). Zinc is above copper on the activity series of metals so a reaction occurs. (The reverse reaction will not occur.) Zinc metal dissolves to form zinc ion; the net ionic reaction is:

(7i) $Zn\ (s) + Cu^{2+}\ (aq) \rightarrow Zn^{2+}\ (aq) + Cu\ (s)$

Aluminum is above zinc on the activity series so it will displace zinc:

(13m) $2Al\ (s) + 3ZnSO_4\ (aq) \rightarrow Al_2(SO_4)_3\ (aq) + 3Zn\ (s)$

(13i) $2Al\ (s) + 3Zn^{2+}\ (aq) \rightarrow 2Al^{3+}\ (aq) + 3Zn\ (s)$

Aluminum dissolves to form aluminum ion.

Hydrogen, a nonmetal, is on the activity series with the metals. It is displaced from some acids by metal above it on the series:

(14m) $Zn\ (s) + H_2SO_4\ (aq) \rightarrow ZnSO_2\ (aq) + H_2\ (g)$

(14i) $Zn\ (s) + 2H^{+}\ (aq) \rightarrow Zn^{2+}\ (aq) + H_2\ (g)$

(15m) $2Al\ (s) + 6HCl\ (aq) \rightarrow 2AlCl_3\ (aq) + 3H_2\ (g)$

(15i) $2Al\ (s) + 6H^{+}\ (aq) \rightarrow 2Al^{3+}\ (aq) + 3H_2\ (g)$

Among themselves Group VII nonmetals undergo displacement reactions:

(16m) $Cl_2\ (aq) + 2NaBr\ (aq) \rightarrow 2NaCl\ (aq) + Br_2\ (s)$

(16i) $Cl_2\ (aq) + 2Br^{-}\ (aq) \rightarrow 2Cl^{-}\ (aq) + Br_2\ (s)$

One word of caution regarding net ionic equations for displacement reactions. In equation (7i): Zn (s) and Zn^{2+} (aq) are not the same and do not cancel; likewise Cu^{2+} (aq) and Cu (s) are not the same. Similar statements apply to the elemental and corresponding ionic species in equations (13i), (14i), (15i) and (16i).

In an oxidation-reduction, or redox, reaction electrons are transferred from one species to another. All displacement reactions are redox reactions: the presence of a free element indicates redox. Consider this more complex redox reaction in molecular and net ionic forms:

(17m) $6FeSO_2\ (aq)\ +\ K_2Cr_2O_7\ (aq)\ +\ 7H_2SO_4\ (aq)\ \rightarrow$

$3Fe_2(SO_4)_3\ (aq)\ +\ Cr_2(SO_4)_3\ (aq)\ +\ K_2SO_4\ (aq)\ +\ 7H_2O\ (l)$

(17i) $6Fe^{2+}\ (aq)\ +\ Cr_2O_7^{2-}\ (aq)\ +\ 14H^+\ (aq)\ \rightarrow$

$6Fe^{3+}\ (aq)\ +\ 2Cr^{3+}\ (aq)\ +\ 7H_2O\ (l)$

PLEASE NOTE: In equation (17i): $Fe^{2+}(aq)$ and $Fe^{3+}(aq)$ are not the same and do not cancel.

Write the net ionic equation for each of the following:

1) $MgO\ (s) + 2HCl\ (aq) \rightarrow MgCl_2\ (aq) + H_2O\ (l)$

2) $2Al(OH)_3\ (s) + 3H_2SO_4\ (aq) \rightarrow Al_2(SO_4)_3\ (aq) + 6H_2O\ (l)$

3) $BaCO_3\ (s) + 2HClO_4\ (aq) \rightarrow Ba(ClO_4)_2\ (aq) + H_2O\ (l) + CO_2\ (g)$

4) $AgCl\ (s) + 2Na_2S_2O_3\ (aq) \rightarrow Na_3[Ag(S_2O_3)_2]\ (aq) + NaCl\ (aq)$

5) $2Ce(NO_3)_4\ (aq) + H_2O_2\ (aq) \rightarrow 2Ce(NO_3)_3\ (aq) + O_2\ (g) + 2HNO_3\ (aq)$

6) $[Cu(NH_3)_4](OH)_2\ (aq) + 2H_2SO_4\ (aq) \rightarrow Cu(OH)_2\ (s) + 2(NH_4)_2SO_4\ (aq)$

7) $[Fe(SCN)]Cl_2\ (aq) + 6KF\ (aq) \rightarrow K_3[FeF_6]\ (aq) + 2KCl\ (aq) + K(SCN)\ (aq)$

Complete and balance the following equations in molecular form. Then write the net ionic equation for each. All are metathesis or displacement reactions.

8) $BaCl_2\ (aq) + H_2SO_4\ (aq) \rightarrow$

9) $AlCl_3\ (aq) + KOH\ (aq) \rightarrow$

10) $AgNO_3\ (aq) + CaBr_2\ (aq) \rightarrow$

11) $Mg\ (aq) + AgNO_3\ (aq) \rightarrow$

12) $KOH\ (aq) + H_2SO_4\ (aq) \rightarrow$

13) $Al\ (s) + SnCl_2\ (aq) \rightarrow$

14) $Br_2\ (aq) + KI\ (aq) \rightarrow$

15) $Fe(OH)_3\ (s) + HCl\ (aq) \rightarrow$

16) $CaCl_2\ (aq) + K_3PO_4\ (aq) \rightarrow$

17) $(NH_4)_2SO_4\ (aq) + Ba(NO_3)_2\ (aq) \rightarrow$

Answers to Problems

1) $MgO (s) + 2H^+ (aq) \rightarrow Mg^{2+} (aq) + H_2O (l)$

2) $Al(OH)_3 (s) + 3H^+ (aq) \rightarrow Al^{3+} (aq) + 3H_2O (l)$

3) $BaCO_3 (s) + 2H^+ (aq) \rightarrow Ba^{2+} (aq) + H_2O (l) + CO_2 (g)$

4) $AgCl (s) + 2S_2O_3^{2-} (aq) \rightarrow [Ag(S_2O_3)_2]^{3-} (aq) + Cl^- (aq)$

5) $2Ce^{4+} (aq) + H_2O_2 (aq) \rightarrow 2Ce^{3+} (aq) + O_2 (g) + 2H^+ (aq)$

6) $[Cu(NH_3)_4]^{2+} (aq) + 2OH^- (aq) + 4H^+ (aq) \rightarrow Cu(OH)_2 (s) + 4NH_4^+ (aq)$

7) $[Fe(SCN)]^{2+} (aq) + 6F^- (aq) \rightarrow [FeF_6]^{3-} (aq) + (SCN)^- (aq)$

8m) $BaCl_2 (aq) + H_2SO_4 (aq) \rightarrow BaSO_4 (s) + 2HCl (aq)$

8i) $Ba^{2+} (aq) + SO_4^{2-} (aq) \rightarrow BaSO_4 (s)$

9m) $AlCl_3 (aq) + 3KOH (aq) \rightarrow Al(OH)_3 (s) + KCl (aq)$

9i) $Al^{3+} (aq) + 3OH^- (aq) \rightarrow Al(OH)_3 (s)$

10m) $2AgNO_3 (aq) + CaBr_2 (aq) \rightarrow 2AgBr (s) + Ca(NO_3)_2 (aq)$

10i) $Ag^+ (aq) + Br^- (aq) \rightarrow AgBr (s)$

11m) $Mg (s) + 2AgNO_3 (aq) \rightarrow Mg(NO_3)_2 (aq) + 2Ag (s)$

11i) $Mg (s) + 2Ag^+ (aq) \rightarrow Mg^{2+} (aq) + 2Ag (s)$

12m) $2KOH (aq) + H_2SO_4 (aq) \rightarrow K_2SO_4 (aq) + 2H_2O (l)$

12i) $OH^- (aq) + H^+ (aq) \rightarrow H_2O (l)$

13m) $2Al (s) + 3SnCl_2 (aq) \rightarrow 2AlCl_3 (aq) + 3Sn (s)$

13i) $2Al (s) + 3Sn^{2+} (aq) \rightarrow 2Al^{3+} (aq) + 3Sn (s)$

14m) $Br_2 (aq) + 2KI (aq) \rightarrow 2KBr (aq) + I_2 (aq)$

14i) $Br_2 (aq) + 2I^- (aq) \rightarrow 2Br^- (aq) + I_2 (aq)$

15m) $Fe(OH)_3 (s) + 3HCl (aq) \rightarrow FeCl_3 (aq) + 3H_2O (l)$

15i) $Fe(OH)_3 (s) + 3H^+ (aq) \rightarrow Fe^{3+} (aq) + 3H_2O (l)$

16m) $3CaCl_2 (aq) + 2K_3PO_4 (aq) \rightarrow Ca_3(PO_4)_2 (s) + 6KCl (aq)$

16i) $3Ca^{2+} (aq) + 2PO_4^{3-} (aq) \rightarrow Ca_3(PO_4)_2 (s)$

17m) $(NH_4)_2SO_4 (aq) + Ba(NO_3)_2 (aq) \rightarrow BaSO_4 (s) + 2NH_4NO_3 (aq)$

17i) $SO_4^{2-} (aq) + Ba^{2+} (aq) \rightarrow BaSO_4 (s)$