Inorganic Chemistry
Lesson 8

Acids and their reaction with metals. Activity of metals. Salts.

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1 Reaction of metals with acids.

1.1 Reactivity series.

As we already know, hydrogen is formed during a reaction between sulfuric acid and zinc. How general this type reaction is? To check that, let's do some experiments.

Experiment 14

Pour 5 mL of dilute sulfuric acid into five test tubes. In each tube add one of the following metals: magnesium, zinc, iron, tin, copper (in that order). Describe your observations.

In four cases, we observe evolution of some gas (is it is easy to demonstrate it is hydrogen):

$$\mathrm{Mg + H_2SO_4 = MgSO_4 + H_{2(g)}} \tag{1}$$

$$\mathrm{Zn + H_2SO_4 = ZnSO_4 + H_{2(g)}} \tag{2}$$

$$\mathrm{Fe + H_2SO_4 = FeSO_4 + H_{2(g)}} \tag{3}$$

$$\mathrm{Sn + H_2SO_4 = SnSO_4 + H_{2(g)}} \tag{4}$$

It is easy to see that magnesium reacts with sulfuric acid violently, zinc is less reactive, iron reacts slowly, and the reaction of tin is barely seen. No bubbles is observed when sulfuric acid is added to copper. Obviously, all these five metals have different activity towards sulfuric acid. It is possible to arrange all metals in a reactivity series as follows:

Reactivity series of metals (reactivity decreases from left to right)
K, Na, Li, Ca, Mg, Al, Ti, Mn, Zn, Cr, Fe, Co, Ni, Sn, Pb (H) Cu, W, Hg, Ag, Au, Pt

Only the most important metals were added to this series. In addition to the metals we are already familiar with, I added potassium (K), lithium (Li), titanium (Ti), manganese (Mn), chromium (Cr), nickel (Ni), lead (Pb), tungsten (W), gold (Au), and platinum (Pt). Try to memorize their names and chemical symbols, because we will use them in future.

In addition to the metals, you also see the hydrogen symbol (H) in this series. What does it mean? Than means the metals left of hydrogen are capable of substitution of hydrogen during the reaction with acids (in other words, they are more active than hydrogen). In contrast, the metals in the right part of the reactivity series are less active than hydrogen, and they cannot produce hydrogen in reaction with acids *under no circumstances*.

> *One may ask: "If all metals right of hydrogen do not produce hydrogen in a reaction with acids, according to which trait have they been arranged in this particular order? Why does platinum occupy the right position, and why is copper closer to hydrogen?" That is a good question. Actually, this reactivity series reflects not only the reactivity of metals towards acids, but their reactivity in general. Thus, platinum is extremely resistive to almost all corrosive chemicals. In contrast, copper can rust in a moist atmosphere. Another experiment can demonstrate that.*

Experiment 15

Take clean copper and platinum wire and put them into the propane torch fire. After few minutes, remove them from a fire and let to cool down. Look at the surface of both metals. What do you see?

At high temperature, copper reacts with oxygen and produces copper (II) oxide (we already know about that reaction). In contrast, platinum remains totally unchanged. That is quite unusual, because overwhelming majority of metals react with oxygen at elevated temperatures (and some of them, such as magnesium or iron, even burn violently). However, platinum doesn't. So inert this metal is that it is found in nature mostly in a form of pure metal, not as some ore: imagine, billions of years after the Earth formation appeared to be insufficiently long for platinum to react with atmospheric oxygen, water, or another chemical substance. That is why platinum is called a king among all metals.

1.2 Activity of acids. Strong and weak acids.

As we have demonstrated, different metals show different activity in the reaction with sulfuric acid. Do other acids react similarly? Let's check that.

Experiment 16

Into three test tubes pour 5 mL of one of the following acids: dilute acetic, dilute sulfuric, and dilute hydrochloric acids. To each acid, add a small piece of zinc. Describe your observations.

In this experiment, similarly to the previous one, we observe that the evolution of gas proceeds at different rates: reaction of zinc and acetic acid is very slow, sulfuric acid reacts with zinc much faster, and hydrochloric acid "dissolves" zinc vigorously.[1] It is natural to conclude that zinc reacts with these three acids differently because they have different activity, or strength.

> **Depending on their ability to donate hydrogen (and, accordingly, on their ability to react with metals), acids can be subdivided onto strong, medium and weak**.

It is easy to see form the Experiment 15, that hydrochloric acid (HCl) is very strong. Sulfuric acid is also strong, although it is somewhat weaker than HCl. Among other acids we are familiar with, nitric acid and perchloric acid also belong to strong acids. Phosphoric acid is a medium strength acids. Most organic acids, such as acetic acid, citric acid (found in lemons), or malic acid (found in apples[2]) are weak acids. Carbonic acid is so weak that we even can barely feel its acidic taste when we are drinking a soda water[3].

Can acidity be predicted based on the acid's chemical structure? Actually, yes, although that is not as straightforward as one may think. Definitely, acidity does not correlate with the number of hydrogen atoms in the acid's molecule. Indeed, lets compare three acids, carbonic acid (H_2CO_3), sulfurous acid (H_2SO_3), and sulfuric acid (H_2SO_4). There are two hydrogen atoms in each of these acids. However, the first acid is very weak, the second one, a sulfurous acid, is a medium strength acid, whereas a sulfuric acid is strong.

Phosphoric acid (H_3PO_4 has three hydrogens, but it is just a medium acid. In contrast, hydrochloric acid has just one hydrogen, but it is very strong. To understand why does it happen, we need to know a little bit more about the electronic structure of molecules, therefore, it is better to return to this question later. However, it is still possible to formulate some empirical rule[4] that connect acid's composition and its strength.

> **If some element forms more than one oxygen containing acid, its "ic" acid (the acid where it has a higher valence) is stronger than its "ous" acids; "per" acid are among the strongest ones.**

As we already know, sulfuric acid is stronger than sulfurous acid. Accordingly, nitric acid is stronger than nitrous one, phosphoric acid is stronger that prosphorous one. Perchloric acid is the strongest chlorine acid (and among the strongest acids known to chemists). Note, that rule does not work for non-oxygen acids: for example, hydrosulfuric acid (H_2S, aka hydrogen sulfide) is a *very* weak acid.

2 Salts

Let's look at the reaction between zinc and sulfuric acid again.

$$Zn + H_2SO_4 = ZnSO_4 + H_{2(g)} \tag{5}$$

[1]It can be easily demonstrated that that variation is not due to the difference on concentration of the acids: even a very concentrated acetic acid is very inactive, whereas a dilute hydrochloric acid is still able to react with zinc.

[2]Both these acids were first isolated by a discoverer of oxygen, Carl Wilhelm Scheele in 1785.

[3]Soda water is a water solution of carbonic acid.

[4]An empirical rule is a rule that summarizes some experimental facts. In contrast to theories, empirical rules provide no explanations for the facts they summarize.

One reactant and one product of this reaction are elementary substances (elements). A second reactant belongs to the class of compounds called acids. What about the fourth substance? Clearly, it is not an elementary substance, it is a compound, but which class of compounds it belongs to? Let's look at its substance. We can obtain it from the reaction mixture after all zinc is dissolved. If we evaporate this liquid, we will obtain from it a white crystalline water soluble substance ($ZnSO_4$) resembling a table salt.

This compound is a representative of a third major class of inorganic compounds (after oxides and acids). This class of compounds is called ***"salts"***.

Salts are the compounds formed by substitution of hydrogen atoms in acids with the atoms of some metal[5]

Salts are among the most abundant substances on the Earth: if you look at chemical formulas of almost every rock or mineral in the Earth's crust, you will see that it is a salt. Indeed, limestone and marble ($CaCO_3$) is a salt of calcium and carbonic acid, a gypsum and calcite (both have a formula $CaSO_4$) is a salt of calcium and sulfuric acid, apatite ($CaHPO_4$) is a salt of calcium and phosphoric acid, magnesite ($MgCO_3$) is a salt of magnesium and carbonic acid, dolomite ($CaCO_3 \cdot MgCO_3$), a mixed calcium-magnesium carbonate. Even such an abundant artificial material as concrete is mainly a salt of calcium and silicic acid (Ca_2SiO_3[6]).

Figure 1: Dolomite Alps. $CaCO_3 \cdot MgCO_3$, a mineral dolomite, is responsible for the characteristic shapes and color of these mountains

Why "salts"?
Indeed, why had this name been chosen for this class of compounds, and did that name have any connection with an ordinary table salt? Yes, there is a connection, and this connection is pretty straightforward: a table salt was the first representative of this class of inorganic compounds known to humans. A table salt is known from pre-historical times, however, since antiquity people started to find (mostly in dry deserts) some substances that looked as a common salt, but that were not a salt. Initially, people thought those new substances were variations of a common salt ("The Salt"), and, to distinguish them from a genuine salt, they started to give them separate names, such as "saltpeter" (KNO_3, literally, "stone salt"), etc. By the beginning of XVIII century, scientists identified a huge number of various salts, each of which had something in common with a table salt: all of them were hard crystalline bodies, many of them were soluble in water (although others were not). Finally, scientists came to a conclusion that all those compounds form a separate class of substances, and our common table salt is

[5] Actually, only simple salts fit this definition. A modern definition is broader. However, to avoid a confusion, let's stick with this definition for a while.

[6] An approximate formula. The exact composition depends on the cement's type

just a one representative of this class (and not the most interesting one, by the way). However, there was no reason to change the generic name of this class, so we still are using the name “salt” for all salts.

Homework

1. Try to memorize the reactivity series. That will be useful during future classes.
2. Both platinum and tin are white, soft metals. You have a sack of platinum coins. You also know that there are several fake tin coins in the sack. You need to remove fake coins. How can you do that without analyzing each coin separately?
3. Draw the chemical equations of the reaction between water and the following acidic oxides: (a) Cl_2O_3, (b) Cl_2O, (c) SO_2. Draw structures of all intermediates. You may use simplified structural formulas if you want for all intermediates and products formed during these reactions.
4. Draw the chemical equations of the reactions between (a) hydrochloric acid and chromium, (b) sulfuric acid and nickel[7], (c) tungsten and hydrochloric acid, (d) Aluminum and hydrochloric acid.
5. At room temperature and under atmospheric pressure, two grams of hydrogen occupy 22.4 L.[8] You have seven following ingots: a zinc, a copper, a tin, a magnesium, an aluminum, an iron, and a silver ingot. Each ingot weighs 28 grams, you can take just one ingot, and you cannot cut it. You have to choose one ingot, dissolve it is HCl, and collect all hydrogen. Which ingot do you have to take to obtain 10 L of hydrogen as exactly as possible?
6. 40 grams of zinc wire and 45 grams of copper shavings were added to a solution of 200 g of sulfuric acid in 1 L of water. What will be the maximal volume of hydrogen that forms during this reaction?

As usually, I would be grateful if you sent me your homework by evening of next Saturday. My e-mail is mark.lukin@gmail.com.

[7]in those reactions, all these metals are divalent

[8]Again, this is a general law: if a mass of one molecule of some gas is X Da, then X *grams* of this gas will occupy a volume of 22.4 L at standard temperature and pressure.