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INTRODUCTION TO THE INORGANIC CHEMISTRY

Study Guide

Minsk BSMU 2015

МИНИСТЕРСТВО ЗДРАВООХРАНЕНИЯ РЕСПУБЛИКИ БЕЛАРУСЬ
БЕЛОРУССКИЙ ГОСУДАРСТВЕННЫЙ МЕДИЦИНСКИЙ УНИВЕРСИТЕТ
КАФЕДРА ОБЩЕЙ ХИМИИ

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ВВЕДЕНИЕ В НЕОРГАНИЧЕСКУЮ ХИМИЮ

INTRODUCTION TO THE INORGANIC CHEMISTRY

Учебно-методическое пособие

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Содержит теоретический материал и примеры задач по неорганической химии.

Предназначено для иностранных студентов подготовительного отделения. Может быть использовано в качестве дополнительного источника информации иностранными студентами 1-го курса фармацевтического факультета по предмету «Общая и неорганическая химия».

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PREFACE

The book provides an introduction into the Inorganic Chemistry. It is necessary for foreign students who are going to pass the Chemistry exam into the Belorussian State Medical University in English.

The material from this book is enough for answering questions and solving tasks on the chemistry of elements from the entrance exam. Moreover, this book is good for students of pharmaceutical faculty who are studying «General and Inorganic Chemistry» subject.

Authors are looking forward to receive any feedback from readers and colleagues regarding style and content of the book.

LESSON 1

1.1 HYDROGEN

Hydrogen is a unique element in the Periodic Table. 92 % of all the atoms in our Universe are hydrogen atoms (while 8 % of atoms are Helium atoms). There is still no agreement even about its position in the Periodic Table. Just like alkali metals it has a single electron on its valence shell. On the other hand, hydrogen needs just a single electron to complete its valence shell, just like halogens do. That is why hydrogen can demonstrate some common chemical features with both halogens and alkali metals.

Hydrogen behaves as a reducer in reactions with the most of nonmetals.

$H_2 + F_2 \rightarrow 2HF$

$H_2 + Cl_2 \rightarrow 2HCl$

$H_2 + Br_2 \rightleftarrows 2HBr$

$H_2 + I_2 \rightleftarrows 2HI$

$2H_2 + O_2 \rightarrow 2H_2O$

$H_2 + S \rightleftarrows H_2S$

$3H_2 + N_2 \rightleftarrows 2NH_3$

$2H_2 + C \rightleftarrows CH_4$

Hydrogen can reduce metals from their oxides. Only those metals which are situated after zinc (including the zinc) in the electrochemical series of metals may be produced from their oxides in the reaction with hydrogen.

$CuO + H_2 \rightarrow Cu + H_2O\uparrow$

$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O\uparrow$

Of course, hydrogen can reduce many other compounds. For example, molecular nitrogen can be produced from nitrogen oxide (II) in the reaction with hydrogen.

$2NO + 2H_2 \rightarrow N_2 + 2H_2O$

Hydrogen can also reduce iron and copper chlorides in their water solutions.

$2FeCl_3 + H_2 \rightarrow 2FeCl_2 + 2HCl$

$CuCl_2 + H_2 \rightarrow Cu\downarrow + 2HCl$

As an oxidizer hydrogen reacts with alkali and alkali-earth metals. In those reactions hydrides of metals are produced.

$2K + H_2 \rightarrow 2KH$

$Ca + H_2 \rightarrow CaH_2$

In normal conditions hydrogen gas can react with active metals and fluorine gas only.

Hydrides easily react with water and produce alkali and molecular hydrogen.

$KH + H_2O \rightarrow KOH + H_2\uparrow$

$CaH_2 + 2H_2O \rightarrow Ca(OH)_2 + 2H_2\uparrow$

Hydrides also react with molecular oxygen. In those reactions hydroxides are produced.

$CaH_2 + O_2 \rightarrow Ca(OH)_2$

The most common reactions to produce hydrogen in laboratory are listed below.

$CaH_2 + 2H_2O \rightarrow Ca(OH)_2 + 2H_2\uparrow$

$2Al + 2NaOH + 6H_2O \rightarrow 2Na[Al(OH)_4] + 3H_2\uparrow$

$Si + 2NaOH + H_2O \rightarrow Na_2SiO_3 + 2H_2\uparrow$

$Zn + H_2SO_4 \rightarrow ZnSO_4 + H_2\uparrow$

There are also several ways to produce hydrogen in industry.

$H_2O + C \rightarrow CO + H_2$

$CH_4 + H_2O \rightarrow CO + 3H_2$

$2CH_4 + O_2 \rightarrow 2CO + 4H_2$

$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2$

However, the most common way is to perform electrolysis of pure water or sodium chloride solution.

$2H_2O \text{ (electrolysis)} \rightarrow 2H_2\uparrow + O_2\uparrow$

$2NaCl + 2H_2O \text{ (electrolysis)} \rightarrow 2NaOH + Cl_2\uparrow + H_2\uparrow$

Exercises

a. Classic chains of chemical reactions.

$H_2 \rightarrow HCl \rightarrow H_2 \rightarrow H_2O \rightarrow H_2$

$CaH_2 \rightarrow Ca(OH)_2 \rightarrow H_2O \rightarrow Na[Al(OH)_4] \rightarrow H_2O$

b. Calculate the sum of molecular masses for hydrogen containing compounds B and D from the chain of chemical reactions.

$$H_2 \xrightarrow{+Cl_2} A \xrightarrow{+Zn} B \xrightarrow{+O_2} C \xrightarrow{+CaO} D$$

$$H_2 \xrightarrow{+O_2} A \xrightarrow[-KOH]{+K} B \xrightarrow{+Cl_2} C \xrightarrow{+Mg} D$$

$$H_2 \xrightarrow{+S} A \xrightarrow[-1H_2O]{+1KOH} B \xrightarrow[-K_2S]{+KOH} C \xrightarrow[-Ca(OH)_2]{+Ca} D$$

c. How many liters of molecular hydrogen (in form of gas) will be produced in the reaction between hydrochloric acid and 36 g of: a) potassium; b) calcium; c) aluminum?

d. Calculate the mass of NaOH which is required to produce 20 L of H_2 in the reaction with: a) aluminum; b) silicon.

e. Calculate the mass of water produced in the reaction between 11.2 L of hydrogen and 10 g of: a) copper oxide (I); b) copper oxide (II).

1.2 WATER

The shape of water molecule is nonlinear. The angle between two bonds is equal to 104.45° (figure 1). That shape can be explained by the hypothesis of sp^3 hybridization of oxygen electron orbitals. Two of those sp^3 orbitals already contain electron pairs. Electron pairs of the oxygen atom from water molecule are able to form hydrogen bonds with hydrogen atoms of other water molecules. Finally, one molecule of water can participate in formation of four hydrogen bonds (figure 2).

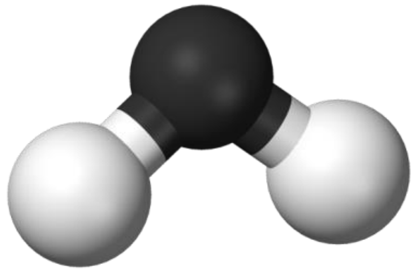


Figure 1. The shape of water molecule. Oxygen atom is black, hydrogen atoms are grey

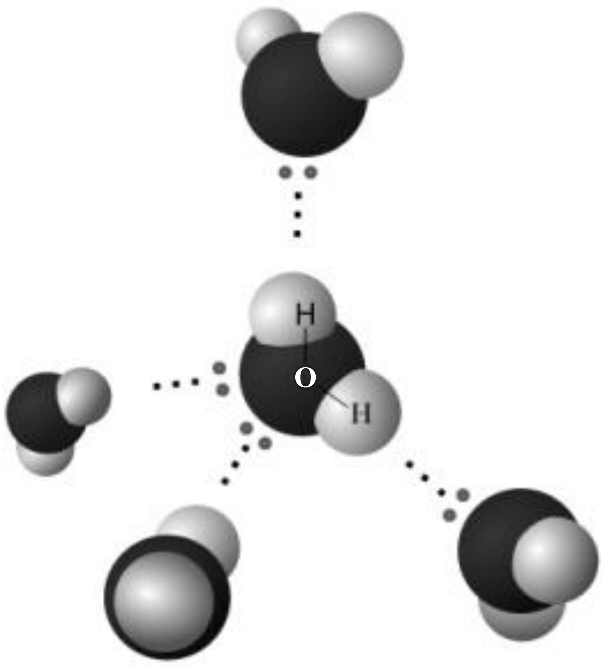


Figure 2. Formation of hydrogen bonds by water molecules. Oxygen atom is black, hydrogen atoms are grey

Consequences of hydrogen bonds formation by water molecules are numerous: higher freezing and boiling temperatures (relative to other hydrides of nonmetals), the highest heat capacity and strong surface tension.

As an oxidizer water interacts with alkali metals and alkaline-earth metals.

$2K + 2H_2O \rightarrow 2KOH + H_2\uparrow$

$Ba + 2H_2O \rightarrow Ba(OH)_2 + H_2\uparrow$

Aluminum also interacts with water in a similar way in case if protective oxide surface (Al_2O_3) has already been removed.

$2Al + 6H_2O \rightarrow 2Al(OH)_3 + 3H_2\uparrow$

Magnesium shows an odd behavior relative to other metals from IIA group. It reacts very slowly with a cool water. With a hot water it reacts just like other metals (except alkali and alkaline-earth ones) do.

$Mg + H_2O \rightarrow MgO + H_2\uparrow$

$Zn + H_2O \rightarrow ZnO + H_2\uparrow$

$3Fe + 4H_2O \rightarrow Fe_3O_4 + 4H_2\uparrow$

Only magnesium powder can interact with water and produce magnesium hydroxide.

$Mg\ (powder) + 2H_2O \rightarrow Mg(OH)_2 + H_2\uparrow$

Water cannot oxidize those metals which are situated after hydrogen in the reactivity series of metals. In contrast, water can oxidize some nonmetals presented in form of pure chemical elements (in certain conditions).

$Si + 2H_2O \rightarrow SiO_2 + 2H_2\uparrow$

$C + H_2O \rightarrow CO + H_2$

Such nonmetals as chlorine (chlorine gas) and phosphorus also react with water, while water molecules neither reduce, nor oxidize those pure chemical elements.

$Cl_2 + H_2O \rightarrow HCl + HClO$

Hydrochloric and hypochlorous acids are the products of the reaction between chlorine gas and water.

$4P + 6H_2O \rightarrow PH_3\uparrow + 3H_3PO_2$

Phosphine and hypophosphorous acid are the products of the reaction between phosphorus and water.

However, water can reduce chlorine gas being heated up.

$2Cl_2 + 2H_2O \rightarrow 4HCl + O_2$

Water hydrates both basic and acidic anhydrates to produce basic and acidic hydroxides, respectively.

$CaO + H_2O \rightarrow CaO\cdot H_2O = Ca(OH)_2$

$SO_3 + H_2O \rightarrow SO_3\cdot H_2O = H_2SO_4$

Salts can also be hydrated by water. A salt with associated water of crystallization is known as a hydrate. Water molecules can be included in the coordination sphere of metals ($[Mn(H_2O)_4]Cl_2$), or they can be just co-crystallized with salt ($CaCl_2\cdot 2H_2O$). In the majority of cases some water molecules are included in coordination sphere, while others are co-crystallized with salt ($[Mn(H_2O)_4]Cl_2\cdot 2H_2O$).

Water can hydrolyze many substances including inorganic salts, carbides and organic di- and polymeric molecules.

$Al_2S_3 + 6H_2O \rightarrow 2Al(OH)_3\downarrow + 3H_2S\uparrow$

$CaC_2 + 2H_2O \rightarrow Ca(OH)_2 + C_2H_2\uparrow$

Exercises

a. Calculate the mass percentage of oxygen in $CuSO_4 \cdot 5H_2O$.

b. Calculate the mass percentage of water in $CuSO_4 \cdot 5H_2O$.

c. Calculate the mass percentage of oxygen in $CuSO_4 \cdot 5H_2O$.

d. Calculate the mass percentage of water in $CaCl_2 \cdot 2H_2O$.

e. What mass of $CuSO_4 \cdot 5H_2O$ should be taken to prepare 250 ml of 0.1 M $CuSO_4$ solution?

f. What mass of $CaCl_2 \cdot 2H_2O$ should be taken to produce 100 g of 15 % $CaCl_2$ solution?

g. What mass of $Na_2SO_4 \cdot 10H_2O$ should be taken to produce 300 g of 5 % Na_2SO_4 solution?

h. What substances react with water? Write down possible chemical reactions with: CaO, K, NaOH, Cl_2, Si, Mg, HNO_3, SO_2, Al_2S_3, Au.

LESSON 2

2.1 HALOGENS

The halogens or halogen elements are the 17th (VIIA) group in the periodic table consisting of five chemically related elements: fluorine (F), chlorine (Cl), bromine (Br), iodine (I), and astatine (At). The group of halogens is the only periodic table group which contains elements in all three familiar states of matter at standard temperature and pressure: fluorine (F_2) and chlorine (Cl_2) are gases, bromine (Br_2) is liquid, while iodine (I_2) is solid. Astatine is thought to be solid.

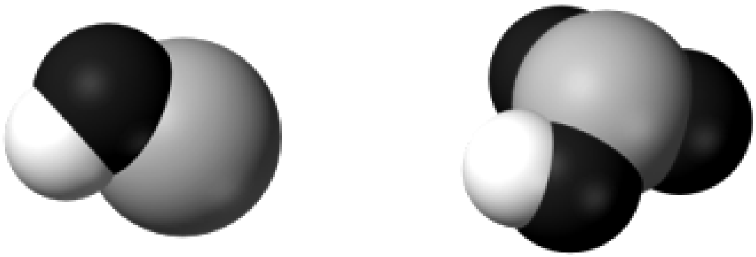
Halogens react with hydrogen and form diatomic molecules which demonstrate acidic properties in water solutions.

$H_2 + Cl_2 \rightarrow 2HCl$

At room temperature halogens (except fluorine) react with water and produce two acids: hydrochloric acid (HCl) and hypochlorous acid (HClO) in case of chlorine (figure 3, *a*).

$Cl_2 + H_2O \rightarrow HCl + HClO$

Resulting solution can be used as a disinfectant or bleach.



a ***b***

Figure 3. Structures of HClO (hypochlorous) and $HClO_3$ (chloric) acids. Chlorine atoms are dark grey, oxygen atoms are black, and hydrogen atoms are light grey

Hydrochlorous acid is instable: it spontaneously forms hydrochloric acid and atomic oxygen, which is a free radical able to oxidize many substances including proteins of pathogenic bacteria.

At higher temperature the mixture of hydrochloric acid HCl and chloric acid ($HClO_3$) is formed (figure 3, *b*).

$3Cl_2 + 3H_2O \rightarrow 5HCl + HClO_3$

Bromine slowly reacts with water to form hydrogen bromide (HBr) and hypobromous acid (HBrO), while iodine is minimally soluble in water and does not react with it. However, iodine will form an aqueous solution in the presence of iodide ion, such as by addition of potassium iodide (KI), because the triiodide ion ($I_2 + I^- \rightarrow I_3^-$) is formed.

Halogens oxidize metals and produce salts.

$2Na + I_2 \rightarrow 2NaI$

$2Fe + 3Cl_2 \rightarrow 2FeCl_3$

A halogen with lower atomic number is able to oxidize anions of halogens with higher atomic numbers.

$Cl_2 + 2KBr \rightarrow 2KCl + Br_2$

$Br_2 + 2KCl \neq$

$Cl_2 + 2NaI \rightarrow 2NaCl + I_2$

$I_2 + 2NaCl \neq$

$Br_2 + 2KI \rightarrow 2KBr + I_2$

$I_2 + 2KBr \neq$

Hydrogen chloride can be produced from solid chlorides of metals in the reaction with concentrated sulfuric acid, unlike hydrogen bromide and iodide. HBr and HI are easily oxidized by concentrated sulfuric acid.

$2NaCl(solid) + H_2SO_4(concentrated) \rightarrow Na_2SO_4 + 2HCl\uparrow$

$2NaBr(solid) + 2H_2SO_4(concentrated) \rightarrow Na_2SO_4 + SO_2\uparrow + Br_2 + 2H_2O$

Chlorine gas can be produced in laboratory from hydrochloric acid in the reaction with oxidizer (for example, with manganese oxide (IV) or potassium permanganate).

$MnO_2 + 4HCl \rightarrow MnCl_2 + Cl_2\uparrow + 2H_2O$

$2KMnO_4 + 16HCl \rightarrow 2MnCl_2 + 5Cl_2\uparrow + 2KCl + 8H_2O$

Potassium iodide is a strong reducer. Aged and impure samples of that salt are yellow because of aerial oxidation of the iodide to elemental iodine.

$4KI + 2CO_2 + O_2 \rightarrow 2K_2CO_3 + 2I_2$

Chlorine gas reacts with alkali and produces different sets of salts depending on the temperature.

$Cl_2 + 2KOH \rightarrow KCl + KClO + H_2O$ (when the temperature is low)

$3Cl_2 + 6KOH \rightarrow 5KCl + KClO_3 + 3H_2O$ (when the temperature is high)

Potassium iodate (KlO_3) which is sometimes used for iodination of table salt can be produced in a similar reaction.

$3l_2 + 6KOH \rightarrow 5Kl + KlO_3 + 3H_2O$

Exercises

a. Classic chains of chemical reactions.

$NaOH \rightarrow NaI \rightarrow NaBr \rightarrow NaCl \rightarrow NaF$

$K \rightarrow KI \rightarrow KBr \rightarrow KCl \rightarrow KNO_3$

$NaI \rightarrow I_2 \rightarrow KI \rightarrow I_2 \rightarrow KIO_3$

b. Calculate the sum of molecular masses for compounds A, B, C and D from the chain of chemical reactions.

$$I_2 \xrightarrow{+Na} A \xrightarrow[-I_2]{+Br_2} B \xrightarrow[-Br_2]{+Cl_2} C \xrightarrow[-Cl_2]{+F_2} D$$

c. Determine the mass of potassium iodide (KI) produced from 1 kg of molecular iodine in its reaction with pure potassium.

d. Determine the mass of potassium iodide (KI) produced from 1 kg of molecular iodine in its reaction with potassium hydroxide.

e. Mass percentages of potassium, chlorine and oxygen in the compound are equal to 32 %, 29 % and 39 %, respectively. Determine the simplest formula of that compound.

2.2 HYDROCHLORIC ACID

Hydrogen chloride in normal conditions exists as a gas. The bond between hydrogen and chlorine is covalent polar, but not ionic. When hydrogen chloride is being dissolved in water the bond between hydrogen and chlorine becomes more polar and finally hydrogen chloride molecule breaks in two ions (H^+ and Cl^-). Resulting water solution is called «hydrochloric acid». In Russian hydrochloric acid has a common name which can be translated into English as «salty acid». That name came from the reaction of HCl formation from the table salt (NaCl).

$2NaCl(solid) + H_2SO_4(concentrated) \rightarrow Na_2SO_4 + 2HCl\uparrow$

Hydrochloric acid demonstrates all the common properties of acids. It reacts with alkali and basic oxides to produce salts and water.

$HCl + KOH \rightarrow KCl + H_2O$

$2HCl + K_2O \rightarrow 2KCl + H_2O$

Hydrochloric acid reacts with metals situated before hydrogen in the reactivity series.

$Zn + 2HCl \rightarrow ZnCl_2 + H_2\uparrow$

$Cu + HCl \neq$

Reaction between hydrochloric acid and salt is possible in case if insoluble salt or gas is produced.

$HCl + AgNO_3 \rightarrow AgCl\downarrow + HNO_3$

$2HCl + CaSO_3 \rightarrow CaCl_2 + SO_2\uparrow + H_2O$

The presence of Cl^- ions in the solution can be checked by the addition of Ag^+ ions ($AgNO_3$ solution is used since it is one of the very few soluble salts of silver). AgCl is a white precipitate. Bromine and iodide anions also form precipitates with Ag^+, but of a different color (AgBr is light yellow, while AgI is yellow).

$NaCl + AgNO_3 \rightarrow NaNO_3 + AgCl\downarrow$

$LiBr + AgNO_3 \rightarrow LiNO_3 + AgBr\downarrow$

$KI + AgNO_3 \rightarrow KNO_3 + AgI\downarrow$

Exercises

a. Classic chains of chemical reactions.

$HCl \rightarrow Cl_2 \rightarrow FeCl_3 \rightarrow Fe(OH)Cl_2 \rightarrow Fe(OH)_2Cl$

$HClO \rightarrow Cl_2 \rightarrow HCl \rightarrow KCl \rightarrow AgCl$

b. Calculate the sum of molecular masses for aluminum containing compounds B and D from the chain of chemical reactions.

$$Al(OH)_3 \xrightarrow{+1HCl} A \xrightarrow{+1HCl} B \xrightarrow{+1HCl} C \xrightarrow{+3NaOH} D$$

c. Calculate the sum of chlorine containing compounds B and D from the chain of chemical reactions.

$$2NaCl(solid) \xrightarrow{+H_2SO_4\ (98\ \%)} A \xrightarrow{+Fe} B \xrightarrow{+Cl_2} C \xrightarrow{+3KOH} D$$

d. HCl has been produced in the reaction between 29.25 g of solid NaCl and an excess of concentrated H_2SO_4. Then HCl has been dissolved in 73 g of water. Determine the mass percentage of HCl in the hydrochloric acid solution.

e. Chlorine gas produced in the reaction between manganese oxide (IV) and 36 % hydrochloric acid (density is equal to 1.18 g/ml) oxidized iodide ions in potassium iodide. Determine the volume of hydrochloric acid solution if the mass of molecular iodine was equal to 25.4 g.

f. What is the volume (in normal conditions) of HCl produced in the reaction between 15 L of chlorine gas and 3.4 g of hydrogen?

LESSON 3

3.1 OXYGEN AND OZONE

Oxygen as a pure chemical element exists in two allotropic modifications: oxygen gas (O_2) and ozone (O_3).

The common allotrope of elemental oxygen on Earth is called dioxygen, O_2. This is the form that is used by complex forms of life, such as animals, in cellular respiration and is the form that is an important part of the Earth’s atmosphere.

Ozone (Trioxygen, O_3) is a very reactive allotrope of oxygen that is damaging to lung tissue. It demonstrates higher reactivity than oxygen and can even react with such inactive metals as gold and platinum.

Ozone is produced in the upper atmosphere when O_2 combines with atomic oxygen made by the splitting of O_2 by ultraviolet (UV) radiation. Since ozone absorbs strongly in the UV region of the spectrum, the ozone layer of the upper atmosphere functions as a protective radiation shield for the planet.

Exercise

Try to explain why the molecule of ozone is polar (use the structure of ozone molecule shown in figure 4).

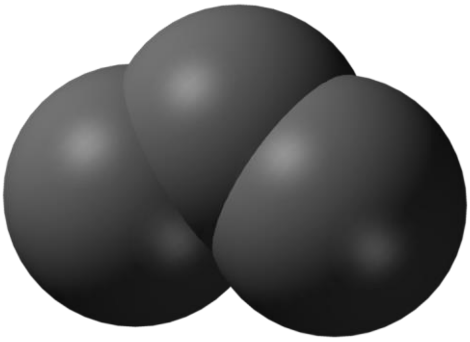


Figure 4. Structure of ozone

3.2 Oxygen compounds

Oxygen is able to form three types of compounds with alkali metals: oxides, peroxides and superoxides.

In oxides the oxidation state of oxygen is equal to –2, as well as in the most of oxygen compounds.

$4Na + O_2 \rightarrow 2Na_2O$

In peroxides oxygen atoms have the oxidation state of –1.

$2Na + O_2 \rightarrow Na_2O_2$

In superoxides oxygen demonstrates fractional oxidation state of $-^1/_2$. Actually, superoxide is a compound that contains the superoxide anion with the chemical formula O_2^-.

$K + O_2 \rightarrow KO_2$

In fact, a mixture of oxide and peroxide is formed after the reaction between sodium and oxygen. In the reaction between oxygen and potassium the mixture of peroxide and superoxide is formed.

Superoxides of alkali metals can react with those metals to produce peroxides.

$KO_2 + K \rightarrow K_2O_2$

Peroxides of alkali metals can react with those metals to produce oxides.

$Na_2O_2 + 2Na \rightarrow 2Na_2O$

Peroxides react with water. Oxygen is produced in that kind of reactions.

$2Na_2O_2 + 2H_2O \rightarrow 4NaOH + O_2\uparrow$

If chemical compounds are burned in the excess of oxygen, a mixture of oxides is produced.

$2H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$

$2CuS + 3O_2 \rightarrow 2CuO + 2SO_2$

$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$

If chemical compounds are burned in conditions with the limited amount of oxygen, some pure chemical elements may be produced.

$2H_2S + O_2 \rightarrow 2S + 2H_2O$

$4NH_3 + 3O_2 \rightarrow 6H_2O + 2N_2$

Oxygen can be produced in laboratory in several decomposition reactions.

$2KMnO_4 \rightarrow K_2MnO_4 + MnO_2 + O_2\uparrow$

$2KClO_3 \rightarrow 2KCl + 3O_2\uparrow$

$2KNO_3 \rightarrow 2KNO_2 + O_2\uparrow$

$2H_2O_2 \rightarrow 2H_2O + O_2\uparrow$

Exercises

a. Determine the oxidation state of oxygen in the following compounds: H_2O, H_2O_2, O_2, Na_2O, Na_2O_2, KO_2, F_2O_2, F_2O.

b. Classic chains of chemical reactions.

$O_2 \rightarrow O_3 \rightarrow O_2 \rightarrow Na_2O_2 \rightarrow NaOH$

$O_2 \rightarrow KO_2 \rightarrow K_2O \rightarrow K_2CO_3 \rightarrow CO_2$

c. Calculate the sum of molecular masses for potassium containing compounds B and D from the chain of chemical reactions.

$$K \xrightarrow{+1O_2} A \xrightarrow{+1K} B \xrightarrow{+2K} C \xrightarrow{+H_2O} D$$

d. Calculate the sum of molecular masses for oxygen containing compounds B and D from the chain of chemical reactions.

$$O_2 \xrightarrow{+H_2} A \xrightarrow{+Na} B \xrightarrow{+HCl} C \xrightarrow{+Cl_2} D$$

e. Determine the volume of oxygen produced in the decomposition reaction from 10 g of potassium permanganate ($KMnO_4$); 10 g of potassium chlorate ($KClO_3$); 10 g of potassium nitrate (KNO_3); 10 g of hydrogen peroxide (H_2O_2).

f. What is the mass percentage of CuS which was burned in the reaction with oxygen if the volume of sulfur (IV) oxide is equal to 12 L? In the beginning of the reaction there were 100 g of CuS.

g. Calculate the volume of ozone that can be produced from 100 L of oxygen.

h. What is the density of ozone per dry air?

LESSON 4

4.1 SULFUR

Sulfur is a solid substance in normal conditions. Sulfur forms polyatomic molecules with different chemical formulas, with the best-known allotrope being octasulfur, cyclo-S_8 (figure 5). Sulfur forms over 30 solid allotropes, more than any other element.

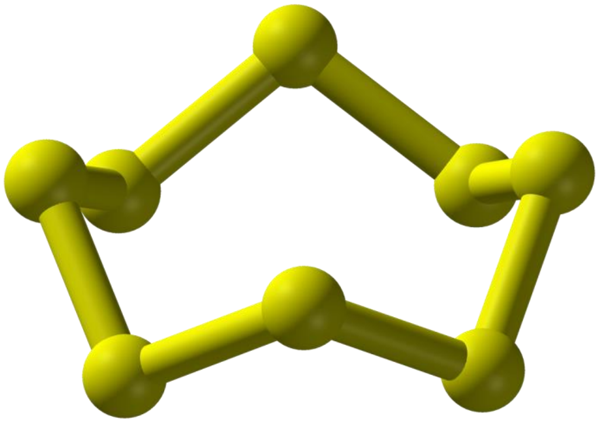


Figure 5. Structure of S_8 molecule

Sulfur can be produced in industry in the reaction between hydrogen sulfide and sulfur (IV) oxide.

$2H_2S + SO_2 \rightarrow 2H_2O + 3S$

In the laboratory sulfur can be produced in several ways.

$FeS_2 \rightarrow FeS + S$

$2H_2S + O_2 \rightarrow 2S + 2H_2O$

$SO_2 + C \rightarrow CO_2 + S\downarrow$

$H_2S + Cl_2 \rightarrow 2HCl + S\downarrow$

Diatomic compounds of sulfur and metals are known as sulfides. Sulfur demonstrates oxidation state of -2 in those salts.

$2K + S \rightarrow K_2S$

$Cu + S \rightarrow CuS$

However, in pyrite (FeS_2, also known as «fool's gold») sulfur demonstrates the oxidation state of –1.

Sulfur forms mostly SO_2 in the reaction with oxygen. Sulfuric acid anhydrate (SO_3) may be produced in the reaction between SO_2 and O_2 in the presence of catalyst.

$S + O_2 \rightarrow SO_2$

$2SO_2 + O_2 \rightleftarrows 2SO_3$

Sulfur can directly interact with alkali and certain acids.

$3S + 6KOH \rightarrow K_2SO_3 + 2K_2S + 3H_2O$

$S + 2H_2SO_4(\text{concentrated}) \rightarrow 3SO_2\uparrow + 2H_2O$

$S + 4HNO_3(\text{concentrated}) \rightarrow 4NO_2\uparrow + SO_2\uparrow + 2H_2O$

Exercise

a. What is the mass of sulfur in 10 kg of: a) FeS; b) Fe_2S_3; c) FeS_2?

b. What is the density of gaseous sulfur per dry air?

c. Calculate the volume (in normal conditions) of gas (gases) produced in the reaction between 10 g of sulfur and 100 g of: a) concentrated (98 %) sulfuric acid; b) concentrated (60 %) nitric acid?

4.2 COMPOUNDS OF SULFUR

Hydrogen sulfide in normal conditions is a colorless gas with the characteristic foul odor of rotten eggs. Water solution of H_2S demonstrates acidic properties. Best way to produce H_2S in laboratory is the reaction between sulfide and acid.

$Na_2S + 2HCl \rightarrow 2NaCl + H_2S\uparrow$

$FeS + 2HCl \rightarrow FeCl_2 + H_2S\uparrow$

It is also known that aluminum sulfide undergoes complete hydrolysis and produces aluminum hydroxide and hydrogen sulfide.

$Al_2S_3 + 6H_2O \rightarrow 2Al(OH)_3\downarrow + 3H_2S\uparrow$

Sulfides of metals are good reducers (just like hydrogen sulfide).

$2ZnS + 3O_2 \rightarrow 2ZnO + 2SO_2\uparrow$

$3CuS + 8HNO_3$(concentrated) $\rightarrow 3CuSO_4 + 8NO\uparrow + 4H_2O$

Soluble sulfides are partially hydrolyzed in water solutions.

$K_2S + H_2O \rightleftarrows KHS + KOH$

Sulfurous acid anhydrate (also known as sulfur (IV) oxide) demonstrates all the features of acidic oxide. Moreover, it can behave as oxidizer or reducer. Some specific reactions are listed below.

$SO_2 + Na_2CO_3$(concentrated) $\rightarrow Na_2SO_3 + CO_2\uparrow$

$SO_2 + 2CO \rightarrow S + 2CO_2\uparrow$

$SO_2 + Br_2 + 2H_2O \rightarrow H_2SO_4 + 2HBr$

$SO_2 + 2HNO_3$(concentrated) $\rightarrow H_2SO_4 + 2NO_2\uparrow$

Sulfurous acid produced in reactions between sulfites (salts of sulfurous acid) and other acids decomposes into SO_2 and H_2O.

$Na_2SO_3 + H_2SO_4 \rightarrow Na_2SO_4 + SO_2\uparrow + H_2O$

Sulfurous acid and its salts participate in some specific redox reactions. There are some examples.

$2H_2SO_3 + O_2 \rightarrow 2H_2SO_4$

$2Na_2SO_3 + O_2 \rightarrow 2Na_2SO_4$

$H_2SO_3 + Br_2 + H_2O \rightarrow H_2SO_4 + 2HBr$

$H_2SO_3 + 2H_2S \rightarrow 3S + 3H_2O$

$4K_2SO_3 \rightarrow K_2S + 3K_2SO_4$

Sulfuric acid anhydrate (sulfur (VI) oxide) demonstrates common properties of acidic oxide. SO_3 is also a strong oxidizer.

$5SO_3 + 2P \rightarrow 5SO_2\uparrow + P_2O_5$

$3SO_3 + H_2S \rightarrow 4SO_2 + H_2O$

Industrial method of sulfuric acid production includes four steps.

1. $4FeS_2 + 11O_2 \rightarrow 2Fe_2O_3 + 8SO_2$ (oxidation of pyrite)

2. $2SO_2 + O_2 \rightarrow 2SO_3$ (oxidation of sulfur (IV) oxide in the presence of catalyst)

3. $SO_3 + H_2SO_4$(concentrated) $\rightarrow H_2SO_4 \cdot SO_3 = H_2S_2O_7$ (concentrated sulfuric acid interacts with sulfur (VI) oxide and produces so-called oleum also known as «fuming sulfuric acid»)

4. $H_2S_2O_7 + H_2O \rightarrow 2H_2SO_4$ (oleum is then diluted by water to produce H_2SO_4 of the needed concentration)

Diluted sulfuric acid (mass percentage is lower than 20 %) demonstrates all the common features of acids. Remember than diluted (and not concentrated) sulfuric acid interacts with metals and produces hydrogen gas.

$Fe + H_2SO_4$(diluted) $\rightarrow FeSO_4 + H_2\uparrow$

Concentrated sulfuric acid (mass percentage is equal to 93–98 %) reacts with all metals (except aluminum, iron and chrome at low temperature, and gold and platinum at any temperature) and produces sulfur (IV) oxide. It is important to mention that concentrated sulfuric acid is a weak electrolyte and exists in form of molecules (figure 6). For this reason sulfur atoms themselves act as oxidizers when sulfuric acid is concentrated. In contrast, in diluted sulfuric acid hydrogen atoms act as oxidizers (just like in case with the most of other acids).

$Zn + 2H_2SO_4$(concentrated) $\rightarrow ZnSO_4 + SO_2\uparrow + 2H_2O$

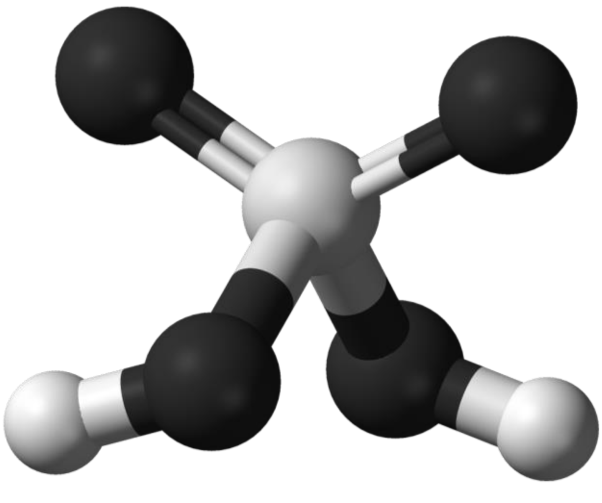


Figure 6. Structure of sulfuric acid molecule. Sulfur atom is in the middle, oxygen atoms are black, and hydrogen atoms are grey

Sulfuric acid of average concentrations can react with metals of an average activity and produce a variety of products.

$3Zn + 4H_2SO_4(50\ \%) \rightarrow 3ZnSO_4 + S\downarrow + 4H_2O$

$4Zn + 5H_2SO_4(30\ \%) \rightarrow 4ZnSO_4 + H_2S\uparrow + 4H_2O$

Concentrated sulfuric acid can oxidize not only metals but nonmetals as well.

$2P + 5H_2SO_4(\text{concentrated}) \rightarrow 2H_3PO_4 + 5SO_2\uparrow + 2H_2O$

$C + 2H_2SO_4(\text{concentrated}) \rightarrow CO_2\uparrow + 2SO_2\uparrow + 2H_2O$

Concentrated sulfuric acid is used to produce acids from their solid salts.

$2KNO_3(\text{solid}) + H_2SO_4(\text{concentrated}) \rightarrow K_2SO_4 + 2HNO_3\uparrow$

Sulfates (salts of sulfuric acid) can be decomposed into metal oxide and sulfur (VI) oxide, or into metal oxide, sulfur (IV) oxide and oxygen gas. The later reaction takes place at higher temperature than the first one: SO_3 decomposes into SO_2 and O_2.

$CuSO_4 \rightarrow CuO + SO_3\uparrow$

$2CuSO_4 \rightarrow 2CuO + 2SO_2\uparrow + O_2\uparrow$

Soluble sulfates are recognized in their solutions in the following way. Addition of barium chloride results in formation of white precipitate $BaSO_4$.

$Na_2SO_4 + BaCl_2 \rightarrow 2NaCl + BaSO_4\downarrow$

Exercises

a. Classic chains of chemical reactions.

$KClO_3 \rightarrow O_2 \rightarrow SO_2 \rightarrow CaSO_3 \rightarrow Ca(HSO_3)_2$

$Na_2S \rightarrow H_2S \rightarrow NaHS \rightarrow H_2S \rightarrow S$

$ZnS \rightarrow H_2S \rightarrow CuS \rightarrow SO_2 \rightarrow Na_2SO_3$

$H_2SO_4 \rightarrow SO_2 \rightarrow S \rightarrow FeS \rightarrow H_2S$

$KMnO_4 \rightarrow O_2 \rightarrow SO_3 \rightarrow NaHSO_4 \rightarrow Na_2SO_4$

$FeS_2 \rightarrow Fe_2O_3 \rightarrow Fe_2(SO_4)_3 \rightarrow FeCl_3 \rightarrow Fe(OH)_3$

$H_2SO_4 \rightarrow SO_2 \rightarrow NaHSO_3 \rightarrow Na_2SO_3 \rightarrow Na_2SO_4$

b. Calculate the sum of molecular masses for sulfur containing compounds B and D from the chain of chemical reactions.

$$SO_3 \xrightarrow{+H_2O} A \xrightarrow[-CuSO_4,\ -H_2O]{+Cu} B \xrightarrow{+1KOH} C \xrightarrow{+1KOH} D$$

c. There are 5 g of NaOH in the water solution. 10 g of H_2S have been dissolved in that solution. Determine what kind of salt is formed and find out its mass.

d. Calculate the mass of $Na_2SO_3 \cdot 7H_2O$ which is needed to produce 5 L of SO_2 in normal conditions.

e. What is the volume of gas (in normal conditions) produced in the reaction between 13 g of zinc and: a) 500 g of 10 % sulfuric acid solution; b) 500 g of 30 % sulfuric acid solution; c) 500 g of 95 % sulfuric acid solution?

f. There is a concentrated sulfuric acid solution (volume = 1 L; mass percentage = 96 %; density = 1.84 g/ml). Determine the volume of that solution which is needed to make 1 L of 1M H_2SO_4.

LESSON 5

5.1 NITROGEN AND ITS COMPOUNDS

Elemental nitrogen (N_2) is a colorless, odorless, tasteless, and mostly inert diatomic gas at normal conditions, constituting 78 % of the atmosphere by volume.

There are several reactions in which molecular nitrogen can be produced in laboratory.

$NH_4NO_2 \rightarrow 2H_2O + N_2\uparrow$

$(NH_4)_2Cr_2O_7 \rightarrow Cr_2O_3 + 4H_2O + N_2\uparrow$

$3CuO + 2NH_3 \rightarrow 3Cu + N_2\uparrow + 3H_2O$

$5Mg + 12HNO_3 \rightarrow 5Mg(NO_3)_2 + N_2\uparrow + 6H_2O$

$NH_4Cl + NaNO_2 \rightarrow N_2\uparrow + NaCl + 2H_2O$

Lithium is the only one known substance which reacts with nitrogen gas in normal conditions. Nitrides of other metals are formed at higher temperatures.

$6Li + N_2 \rightarrow 2Li_3N$

$2Al + N_2 \rightarrow 2AlN$

Nitrides of metals react with water and produce ammonia.

$Mg_3N_2 + 6H_2O \rightarrow 3Mg(OH)_2\downarrow + 2NH_3\uparrow$

Nitrides react with acids and produce ammonium salts.

$Ca_3N_2 + 8HCl \rightarrow 3CaCl_2 + 2NH_4Cl$

Ammonia behaves as a weak base in water solutions.

$NH_3 + H_2O \rightleftarrows NH_4OH \rightleftarrows NH_4^+ + OH^-$

However, equilibriums of both processes described above are shifted towards reactants (ammonia and water). For this reason water solution of ammonia may be described as $NH_3 \cdot H_2O$.

Ammonium cation (NH_4^+) is formed due to donor-acceptor bond formation between hydrogen atom (acceptor of the electron pair) and nitrogen from ammonia (donor of the electron pair). As a result, all the bonds in the NH_4^+ cation have the same length (figure 7).

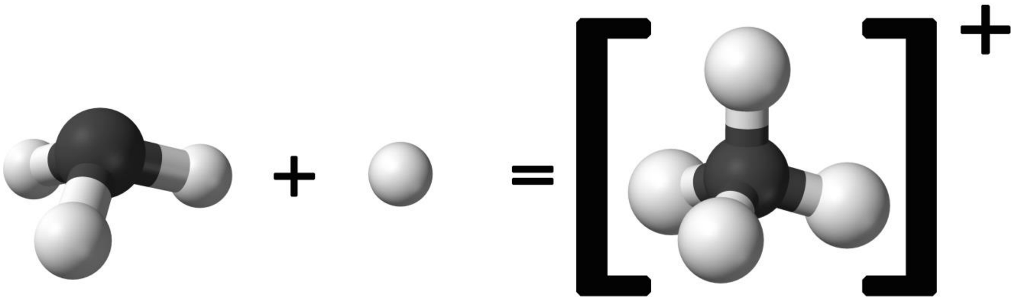


Figure 7. Ammonium cation formation. Nitrogen atom is black, hydrogen atoms are grey

Ammonium hydroxide (NH_4OH) demonstrates all the properties of a weak base. In the mixture of ammonium salt and alkali newly produced NH_4OH decomposes into ammonia and water.

$NH_4NO_3 + NaOH \rightarrow NaNO_3 + H_2O + NH_3\uparrow$

Ammonia can react with oxygen at high temperature only.

$4NH_3 + 3O_2 \rightarrow 2N_2 + 6H_2O$

In the presence of catalyst the products of that reaction are different.

$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$

Ammonium nitrate decomposes at high temperature into water and nitrogen (I) oxide.

$NH_4NO_3 \rightarrow 2H_2O + N_2O\uparrow$

At higher temperatures nitrogen (I) oxide decomposes as well.

$2NH_4NO_3 \rightarrow 4H_2O + 2N_2\uparrow + O_2\uparrow$

Nitrogen (III) oxide forms weak nitrous acid in the reaction with water.

$N_2O_3 + H_2O \rightarrow 2HNO_2$

Nitrogen (IV) oxide forms nitric acid in the reaction with water in the presence of oxygen.

$4NO_2 + O_2 + 2H_2O \rightarrow 4HNO_3$

In the absence of oxygen both nitrous and nitric acids are produced in the reaction between NO_2 and H_2O.

$2NO_2 + H_2O \rightarrow HNO_2 + HNO_3$

Nitrogen (V) oxide forms just nitric acid in the reaction with water.

$N_2O_5 + H_2O \rightarrow 2HNO_3$

Nitrogen (IV) oxide can produce ammonia in the reaction with hydrogen gas.

$2NO_2 + 7H_2 \rightarrow 2NH_3 + 4H_2O$

Exercises

a. Calculate the volume of nitrogen (in normal conditions) which can be produced from 100 g of: a) ammonium nitrate; b) ammonium dichromate.

b. Calculate the volume of oxygen gas (in normal conditions) which is required to burn down 20 L of ammonia: a) with; b) without catalyst.

c. What is the volume (in normal conditions) of ammonia (NH_3) released from 200 g of 5 % NH_4NO_3 water solution after addition of 2 g of 10 % NaOH solution?

5.2 PROPERTIES OF NITRIC ACID

Nitric acid (figure 8) demonstrates all the properties of strong acids: it reacts with bases, basic oxides and certain salts. Exceptional behavior of nitric acid is associated with the ability of its nitrogen atom to oxidize metals. However, cold concentrated nitric acid cannot react with such metals as iron, chrome and aluminum.

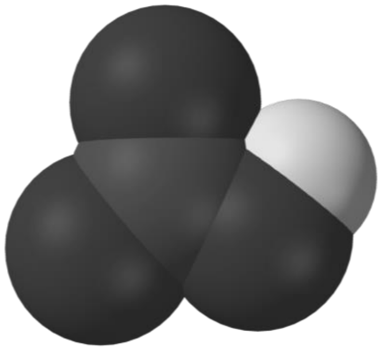


Figure 8. Structure of nitric acid molecule. Nitrogen atom is in the middle, oxygen atoms are black, and hydrogen atom is grey

It is important to remember that nitric acid never produces pure hydrogen gas in reactions with metals. There is always a mixture of products. Even so hydrogen may be produced in reaction between dilute nitric acid and metal, it immediately reacts with oxygen and forms water. As in case with sulfuric acid, concentration of nitric acid determines the main product in the reaction with metal. The lower is its concentration, the lower is the oxidation state of nitrogen atoms in the main product of that reaction.

$Mg + 4HNO_3$ (≥ 60 %) $\rightarrow Mg(NO_3)_2 + 2NO_2\uparrow + 4H_2O$

$3Mg + 8HNO_3$ (30 %) $\rightarrow 3Mg(NO_3)_2 + 2NO\uparrow + 4H_2O$

$3Mg + 10HNO_3$ (20 %) $\rightarrow 3Mg(NO_3)_2 + 2N_2O\uparrow + 5H_2O$

$5Mg + 12HNO_3$ (10 %) $\rightarrow 5Mg(NO_3)_2 + N_2\uparrow + 6H_2O$

$4Mg + 10HNO_3$ (3 %) $\rightarrow 4Mg(NO_3)_2 + NH_4NO_3 + 3H_2O$

Concentrated nitric acid is also able to oxidize some nonmetals.

$6HNO_3$(concentrated) $+ S \rightarrow H_2SO_4 + 6NO_2\uparrow + 2H_2O$

$5HNO_3$(concentrated) $+ P \rightarrow H_3PO_4 + 5NO_2\uparrow + H_2O$

$4HNO_3$(concentrated) $+ C \rightarrow CO_2\uparrow + 4NO_2\uparrow + 2H_2O$

Nitrates (salts of nitric acid) of alkali (except lithium) and alkali-earth metals can be decomposed into nitrites (salts of nitrous acid) and oxygen gas.

$2NaNO_3 \rightarrow 2NaNO_2 + O_2\uparrow$

Nitrates of metals situated between magnesium and copper in the reactivity series (including those two metals) decompose into corresponding metal oxides, nitric (IV) oxide and oxygen.

$4Al(NO_3)_3 \rightarrow 2Al_2O_3 + 12NO_2\uparrow + 3O_2\uparrow$

Nitrates of metals situated after the copper in the reactivity series produce pure metals, nitric (IV) oxide and oxygen in the decomposition reaction.

$2AgNO_3 \rightarrow 2Ag + 2NO_2 + O_2\uparrow$

Industrial method of nitric acid production includes three steps:

1. $4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$
2. $2NO + O_2 \rightarrow 2NO_2$
3. $4NO_2 + O_2 + 2H_2O \rightarrow 4HNO_3$

Exercises

a. Classic chains of chemical reactions.

$N_2 \rightarrow NH_3 \rightarrow NO \rightarrow NO_2 \rightarrow Cu(NO_3)_2$

$NH_4HCO_3 \rightarrow NH_3 \rightarrow NH_4Cl \rightarrow NH_4NO_3 \rightarrow N_2O$

$NH_4NO_2 \rightarrow N_2 \rightarrow NO_2 \rightarrow NaNO_3 \rightarrow NaNO_2$

$NH_3 \rightarrow (NH_4)_2SO_4 \rightarrow NH_4Cl \rightarrow NH_4NO_3 \rightarrow NH_3$

$NH_4NO_3 \rightarrow NH_3 \rightarrow NO_2 \rightarrow HNO_3 \rightarrow N_2O$

b. Calculate the sum of molar masses for nitrogen containing compounds C and D from the chain of chemical reactions.

$$Zn \xrightarrow[-NO_2-H_2O]{+HNO_3} A \xrightarrow{t^\circ} B \xrightarrow{+H_2O+O_2} C \xrightarrow[-NO-H_2O]{+Cu} D$$

c. A mixture of copper and copper (II) oxide had a mass of 50 g. In the reaction between that mixture and concentrated nitric acid 2.3 L of gas (in normal conditions) have been produced. What is the mass percentage of copper (II) oxide in the mixture?

d. 15 g of a mixture of silver and copper nitrates has been heated up. As a result, 0.96 L of oxygen (in normal conditions) have been produced. Determine the mass percentage of silver nitrate in that mixture.

e. 200 g of sodium nitrate have been heated. As a result, the mass of the salt decreased up to 188 g. What was the volume of oxygen released?

f. Determine the yield (in %) of the potassium nitrate thermal decomposition, if the decrease of the mass of the portion of that salt was equal to 20 %.

g. Determine the yield (in %) of the copper nitrate thermal decomposition, if the decrease of the mass of the portion of that salt was equal to 15 %.

h. Determine the yield (in %) of the silver nitrate thermal decomposition, if the decrease of the mass of the portion of that salt was equal to 10 %.

LESSON 6

6.1 PHOSPHORUS

Phosphorus exists as several forms that exhibit strikingly different properties. The two most common allotropes are white phosphorus and red phosphorus. Black phosphorus is obtained by heating white phosphorus under high pressures. White phosphorus is a molecular substance with P_4 molecule (figure 9). Red phosphorus is amorphous, while black phosphorus has an atomic crystal structure. The most reactive allotropic modification of phosphorus is white phosphorus, the most stable one is black phosphorus.

Industrial method to produce phosphorus is to heat up the mixture of calcium phosphate with sand and coal.

$Ca_3(PO_4)_2 + 5C + 3SiO_2 \rightarrow 3CaSiO_3 + 2P + 5CO$

Phosphorus can react with concentrated nitric and sulfuric acids. Phosphoric acid is one of the products of those reactions.

$5HNO_3$(concentrated) + P → $H_3PO_4 + 5NO_2$↑ + H_2O

2P + $5H_2SO_4$(concentrated) → $2H_3PO_4 + 5SO_2$↑ + $2H_2O$

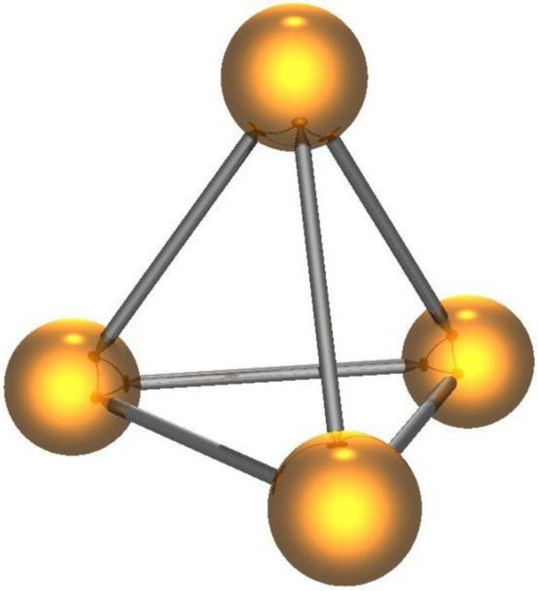


Figure 9. Structure of white phosphorus molecule (P_4)

Exercises

a. How much phosphorus can be produced from 1 kg of calcium phosphate?

b. What is the mass of coal required to produce 2 kg of phosphorus in the reaction between calcium phosphate and silicon dioxide?

c. Calculate the mass percentage of phosphorus in calcium phosphate ($Ca_3(PO_4)_2$).

d. The mass of phosphorus is equal to 2.5 g, the mass of sulfur is equal to 5 g. That mixture reacted with concentrated sulfuric acid. Calculate the volume of gas (in normal conditions) produced.

6.2 PHOSPHORUS COMPOUNDS

Phosphorus reacts with metals and produces phosphides of metals.

Al + P → AlP

Those phosphides of metals can react with water and acids to produce phosphine.

$Mg_3P_2 + 6H_2O \rightarrow 3Mg(OH)_2\downarrow + 2PH_3\uparrow$

$Ca_3P_2 + 6HCl \rightarrow 3CaCl_2 + 2PH_3\uparrow$

Phosphine combustion results in phosphorus (V) oxide formation.

$2PH_3 + 4O_2 \rightarrow P_2O_5 + 3H_2O$

Phosphorus (III) oxide forms phosphorous acid in the reaction with water.

$P_2O_3 + 3H_2O \rightarrow 2H_3PO_3$

Phosphorus (III) oxide can be easily oxidized and form phosphorous (V) oxide.

$P_2O_3 + O_2 \rightarrow P_2O_5$

Phosphorus (V) oxide forms phosphoric acid in the reaction with water.

$P_2O_5 + 3H_2O \rightarrow 2H_3PO_4$

Phosphoric acid demonstrates all the properties of weak acids. It is important to highlight that there are two types of acidic salts (dihydrogen phosphates and hydrogen phosphates) which can be produced from phosphoric acid (figure 10). The nature of the product of the phosphoric acid neutralization reaction depends on the molar ratio between the acid and the base.

$NaOH + H_3PO_4 \rightarrow NaH_2PO_4 + H_2O$

$2NaOH + H_3PO_4 \rightarrow Na_2HPO_4 + 2H_2O$

$3NaOH + H_3PO_4 \rightarrow Na_3PO_4 + 3H_2O$

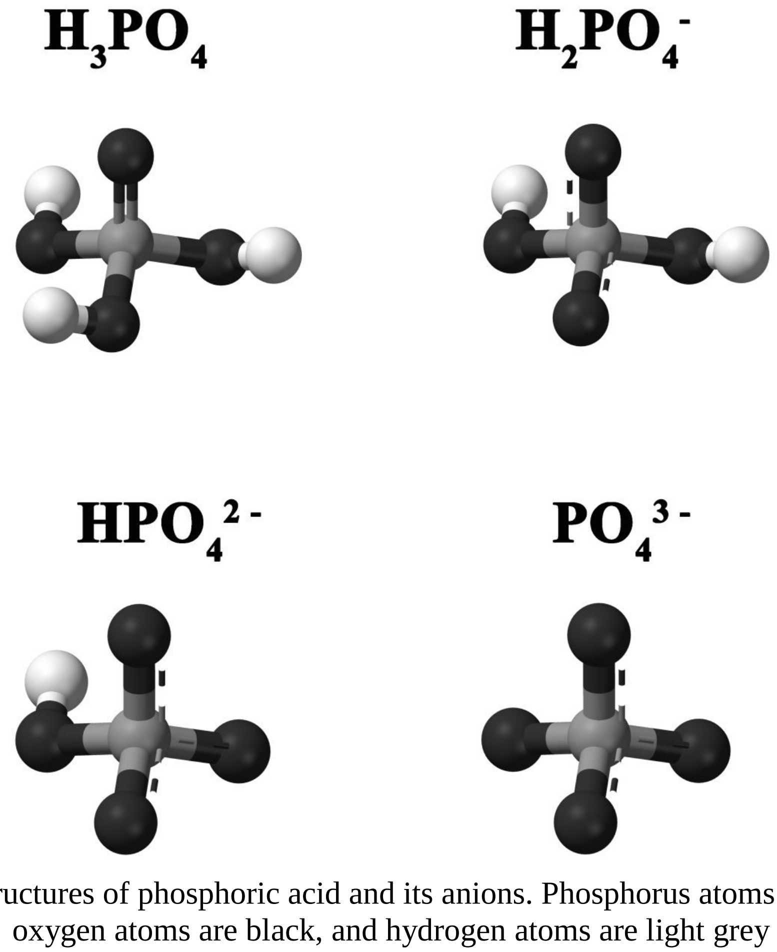


Figure 10. Structures of phosphoric acid and its anions. Phosphorus atoms are dark grey, oxygen atoms are black, and hydrogen atoms are light grey

Exercises

a. Classic chains of chemical reactions.

$Ca_3(PO_4)_2 \rightarrow CaHPO_4 \rightarrow Ca(H_2PO_4)_2 \rightarrow CaHPO_4 \rightarrow Ca_3(PO_4)_2$

$Ca_3(PO_4)_2 \rightarrow P \rightarrow H_3PO_4 \rightarrow (NH_4)_2HPO_4 \rightarrow Ca_3(PO_4)_2$

$P \rightarrow P_2O_3 \rightarrow P_2O_5 \rightarrow NH_4H_2PO_4 \rightarrow (NH_4)_2HPO_4$

$P \rightarrow Ca_3P_2 \rightarrow PH_3 \rightarrow P_2O_5 \rightarrow Ca_3(PO_4)_2$

b. Calculate the sum of molecular masses for phosphorus containing compounds C and D from the chain of chemical reactions.

$$Mg_3(PO_4)_2 \xrightarrow{+1H_3PO_4} A \xrightarrow{+1H_3PO_4} B \xrightarrow{+2Mg(OH)_2} C \xrightarrow{+AgNO_3} D$$

c. Calculate the sum of molar masses for phosphorus containing compounds C and D from the chain of chemical reactions.

$$P \xrightarrow{+\text{ the excess of } O_2} A \xrightarrow{+H_2O} B \xrightarrow{+\text{ the excess of NaOH}} C \xrightarrow{+3LiOH} D$$

d. What salt(s) will be formed in the reaction between 100 g of phosphoric acid and 100 g of potassium hydroxide? Calculate masses of salts produced.

e. What salt(s) will be formed in the reaction between 200 g of phosphoric acid and 200 g of calcium hydroxide? Calculate masses of salts produced.

f. Calculate the mass of phosphorus (V) oxide produced from phosphine oxidation. Phosphine has been released during hydrolysis of 450 g of magnesium phosphide.

g. 3.1 g of phosphorus have been burned. Phosphorus (V) oxide has been produced. That phosphorus (V) oxide has been dissolved in 70 ml of 14 % potassium hydroxide solution with density equal to 1.14 g/ml. Calculate the mass percentage of a salt in the final solution.

h. Calculate the mass percentage of phosphorus oxide (V) in calcium dihydrogen phosphate ($Ca(H_2PO_4)_2$), calcium hydrogen phosphate ($CaHPO_4$) and calcium phosphate ($Ca_3(PO_4)_2$). Which of those substances should be better fertilizer?

LESSON 7

7.1 CARBON

There are several allotropes of carbon of which the best known are graphite, diamond, and amorphous carbon. Diamond is the hardest naturally-occurring material known, while graphite is soft enough to form a streak on paper (that is why it is used in pencils).

As it is shown in figure 11, electron orbitals of carbon atoms in diamond are in the sp^3 hybridization state. Each carbon atom makes four bonds to other atoms. All of those bonds are of the same length.

In graphite electron orbitals of carbon atoms are in the sp^2 hybridization state. Each carbon atom makes three bonds to other atoms. Each layer of graphite is the combination of numerous planar hexagons. The bonds between those layers are much weaker than the bonds within layers. For this reason layers can be easily separated from each other. Thanks to this phenomenon we are able to write with the help of pencil (its rod is usually made from graphite).

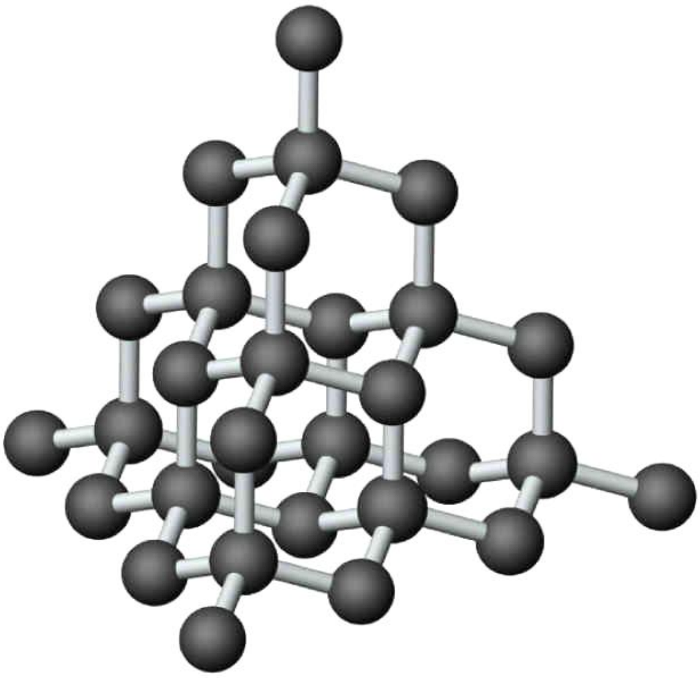


Figure 11. Structure of diamond

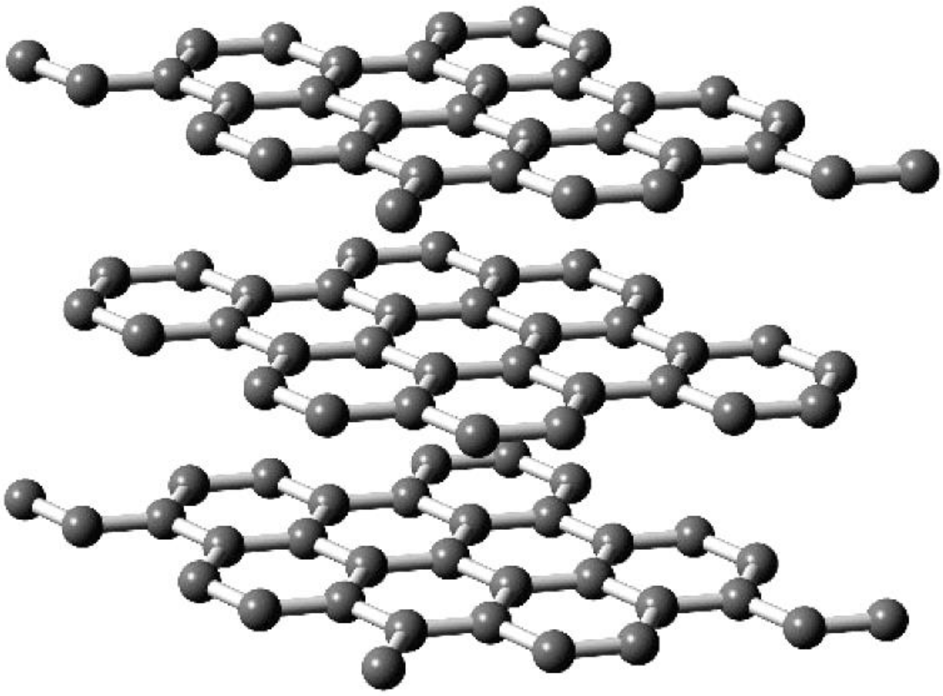


Figure 12. Structure of graphite

There are numerous artificial allotropic modifications of carbon. The most of them are based on carbon hexagons (graphite-like ones) arranged as football (soccer) balls, as tubes, spheres or ellipsoids. Their common name is fullerenes.

In carbyne (linear acetylenic carbon) there are alternating single and triple bonds $(-C\equiv C-C\equiv C-)_n$. So, electron orbitals in carbon atoms from carbyne are in sp^1 hybridization state.

Carbon is able to form very long chains of atoms connected by very strong and stable C–C, C=C or C≡C bonds. This property allows carbon to form an almost infinite number of compounds (there are more known carbon-containing compounds than all the compounds of the other chemical elements combined except those of hydrogen, because almost all organic compounds contain hydrogen too).

Carbon (in amorphous form of soot) reacts with an excess of oxygen and produces carbon dioxide.

$C + O_2 \rightarrow CO_2$

If there is a deficit of oxygen carbon dioxide can react with soot and form dangerous carbon monooxide which combines with hemoglobin to produce carboxyhemoglobin. Oxygen is unable to replace CO in the carboxyhemoglobin, so the transport of oxygen to body tissues fails.

$CO_2 + C \rightarrow 2CO$

Carbon in form of soot is used in metallurgy with the aim to produce metals from their oxides.

$Fe_2O_3 + 3C \rightarrow 2Fe + 3CO\uparrow$

$CuO + C \rightarrow Cu + CO\uparrow$

Soot also reacts with concentrated sulfuric and nitric acids.

$C + 2H_2SO_4\text{(concentrated)} \rightarrow CO_2\uparrow + 2SO_2\uparrow + 2H_2O$

$C + 4HNO_3\text{(concentrated)} \rightarrow CO_2\uparrow + 4NO_2\uparrow + 2H_2O$

Exercises

a. What is the mass of iron produced from 550 g of Fe_2O_3 in its reaction with soot if the yield of that reaction is 67.3 %?

b. Calculate the total volume of gases (in normal conditions) released in reaction between 300 g of soot and concentrated: a) sulfuric; b) nitric acid?

c. Calculate the mass of carbon in 10 L of carbon dioxide.

d. The coal has been burned in the excess of oxygen. The gas formed during that reaction has been passed through the excess of lime water and produced 313.3 g of precipitate. Calculate the mass percentage of impurities in the coal if the initial mass of a sample was equal to 40 g.

e. What is the volume of oxygen required to oxidize 2.6 L of carbon (II) oxide?

7.2 COMPOUNDS OF CARBON

Salt-like carbides are composed of highly electropositive elements and carbon. Those carbides can be further classified into methanides (with «C^{4-}» anion); acetylides (with two-atom anions «C_2^{2-}»; and sesquicarbides (with three-atom units «C_3^{4-}»).

Methanides, such as aluminum carbide, produce methane in the reaction with water.

$Al_4C_3 + 12H_2O \rightarrow 4Al(OH)_3\downarrow + 3CH_4\uparrow$

Acetylides produce acetylene in the reaction with water.

$CaC_2 + 2H_2O \rightarrow Ca(OH)_2 + C_2H_2\uparrow$

Sesquicarbides, such as Mg_2C_3, produce a variety of hydrocarbon products in the reaction with water.

Carbon dioxide (CO_2) demonstrates all the properties of acidic oxides. Carbonic acid (H_2CO_3) decomposes into CO_2 and H_2O in water solutions. That is why carbonates (salts of carbonic acid) produce CO_2 in reactions with acids.

$Na_2CO_3 + 2HCl \rightarrow 2NaCl + CO_2\uparrow + H_2O$

All the carbonates (except carbonates of all alkali metals but not a lithium carbonate) can be decomposed into oxides of corresponding metals and CO_2.

$CaCO_3 \rightarrow CaO + CO_2\uparrow$

Acidic salts of carbonic acid (hydrogen carbonates — figure 13) and alkali-earth metals demonstrate better solubility in water than carbonates. Hydrogen-carbonates (usually called bicarbonates) decompose into carbonates, CO_2 and H_2O in the boiling water.

$Ca(HCO_3)_2 \rightarrow CaCO_3\downarrow + CO_2\uparrow + H_2O$

$Mg(HCO_3)_2 \rightarrow MgCO_3\downarrow + CO_2\uparrow + H_2O$

So, some part of calcium and magnesium cations can be removed from water by the way of boiling.

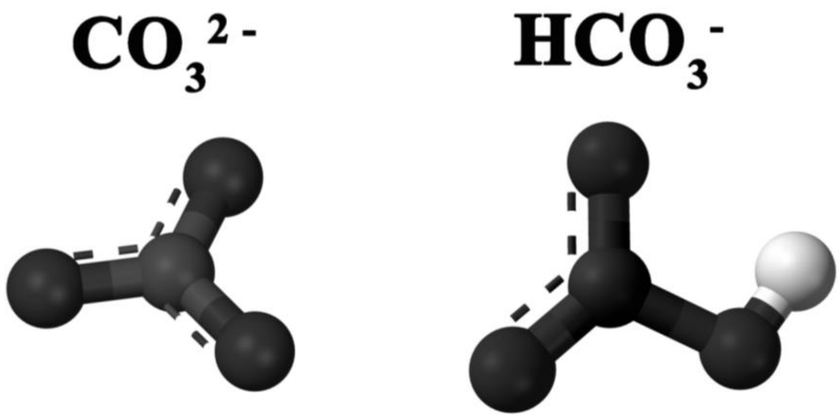


Figure 13. Structures of carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) anions. Carbon atom is in the middle, oxygen atoms are black, and hydrogen atom is light grey

Exercises

a. Classic chains of chemical reactions.

$C \rightarrow CO_2 \rightarrow NaHCO_3 \rightarrow Na_2CO_3 \rightarrow CaCO_3$

$C \rightarrow Al_4C_3 \rightarrow CH_4 \rightarrow CO_2 \rightarrow MgCO_3$

$Ca \rightarrow CaC_2 \rightarrow C_2H_2 \rightarrow CO_2 \rightarrow K_2CO_3$

$Ca(HCO_3)_2 \rightarrow CO_2 \rightarrow CO \rightarrow CO_2 \rightarrow Ca(HCO_3)_2$

b. Calculate the sum of molecular masses for carbon containing compounds C and D from the chain of chemical reactions.

$$C \xrightarrow{+\text{ the excess of } O_2} A \xrightarrow{+1NaOH} B \xrightarrow{+1NaOH} C \xrightarrow{+CaCl_2} D$$

c. Calculate the sum of molecular masses for carbon containing compounds B and D from the chain of chemical reactions.

$$C \xrightarrow{+O_2} A \xrightarrow{+C} B \xrightarrow{+O_2} C \xrightarrow{+1KOH} D$$

d. 20 g of $NaHCO_3$ have been decomposed and produced 2.24 L of CO_2 (in normal conditions). Determine the yield of that reaction.

e. 2.44 L of CO_2 (in normal conditions) have been dissolved in 200 g of 12 % KOH solution. Determine the mass of salt formed in that solution.

f. What is the mass of salt formed in the reaction between 4.5 L of carbon dioxide and 100 g of 5 % sodium hydroxide solution?

g. Determine the mass of $CaCO_3$ produced after the boiling of water contained 0.001 M of $Ca(HCO_3)_2$. The volume of water is equal to 3 L.

LESSON 8

8.1 SILICON

Silicon is solid at room temperature. Elemental silicon has a large impact on the modern world economy. Although the portion of very highly purified silicon that is used in semiconductor electronics (< 10 %) is relatively small, a great deal of modern technology depends on it. Silicon is used in integrated circuits which are essential for microprocessors of computers.

Numerous minerals found in the Earth crust contain silicon, while for living organisms silicon is just a microelement.

Chains of hydrosilicons (compounds made from silicon and hydrogen atoms) can incorporate up to 60 silicon atoms. Even though silicon is able to form numerous compounds with hydrogen (including branched ones), those compounds are not as stable as hydrocarbones.

Silicon can be produced from SiO_2 in reactions with carbon or metals.

$SiO_2 + 2C \rightarrow 2CO + Si$

$SiO_2 + 2Mg \rightarrow 2MgO + Si$

Metals can react with silicon and produce silicides.

$2Mg + Si \rightarrow Mg_2Si$

$2Ca + Si \rightarrow Ca_2Si$

Silicon directly reacts with alkali and produces silicates and hydrogen gas.

$Si + 2NaOH + H_2O \rightarrow Na_2SiO_3 + 2H_2\uparrow$

Exercises

a. Try to discuss why carbon and not silicon forms all the compounds found in living organisms (DNA, RNA, proteins, carbohydrates, fats, etc.). Compare such features of carbon and silicon, as: atomic radii, electron configurations, existence of empty electron orbitals, electronegativity, polarity of bonds with hydrogen.

b. Try to find an explanation why hydrosilicons are much less stable than hydrocarbons.

c. Calculate the oxidation state of silicon in silane (SiH_4) molecule and compare it with the oxidation state of carbon in methane (CH_4) molecule.

d. Try to speculate why SiO_2 is a solid substance in normal conditions, while CO_2 is a gas.

8.2 COMPOUNDS OF SILICON

Silicon (IV) oxide is known as sand. It cannot react with water, even though it demonstrates acidic properties.

$SiO_2 + CaO \rightarrow CaSiO_3$

That oxide also can replace other (more vaporous) oxides in salts.

$Ca_3(PO_4)_2 + 3SiO_2 \rightarrow 3CaSiO_3 + P_2O_5\uparrow$

$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2\uparrow$

Silicides are able to react with acids. Silane (SiH_4) is produced in those reactions.

$Mg_2Si + 4HCl \rightarrow 2MgCl_2 + SiH_4\uparrow$

Silane is easily oxidized by the air.

$SiH_4 + 2O_2 \rightarrow SiO_2 + 2H_2O$

Silane (unlike methane) is able to react with alkali.

$SiH_4 + 2NaOH + H_2O \rightarrow Na_2SiO_3\downarrow +4H_2\uparrow$

Silicates are salts of silicic acid (H_2SiO_3). That acid is insoluble in water solutions.

$Na_2SiO_3 + H_2O + CO_2 \rightarrow Na_2CO_3 + H_2SiO_3\downarrow$

Exercises

a. Classic chains of chemical reactions.

$SiO_2 \rightarrow Si \rightarrow Mg_2Si \rightarrow SiH_4 \rightarrow SiO_2$

$SiO_2 \rightarrow K_2SiO_3 \rightarrow H_2SiO_3 \rightarrow NaHSiO_3 \rightarrow Na_2SiO_3$

$Si \rightarrow Na_2SiO_3 \rightarrow H_2SiO_3 \rightarrow CaSiO_3 \rightarrow SiO_2$

$Si \rightarrow K_2SiO_3 \rightarrow K_2CO_3 \rightarrow KHCO_3 \rightarrow CaCO_3$

b. Calculate the sum of molecular masses for silicon containing compounds B and D from the chain of chemical reactions.

$Si \xrightarrow{+O_2} A \xrightarrow{+2KOH} B \xrightarrow{+HCl} C \xrightarrow{+NaOH} D$

c. Calculate the sum of molecular masses for silicon containing compounds B and D from the chain of chemical reactions.

$$Si \xrightarrow{+Mg} A \xrightarrow{+HCl} B \xrightarrow{+O_2} C \xrightarrow{+CaCO_3} D$$

d. 48.8 kg of sodium silicate has been produced in the reaction between sodium hydroxide and 25 kg of sand. What is the mass percentage of SiO_2 in the sand?

e. Determine the volume of CO_2 (in normal conditions) produced in the reaction between 80 g of SiO_2 and 260 g of $CaCO_3$.

f. 25 g of a mixture of magnesium and aluminum silicides reacted with an excess of hydrochloric acid. 8.2 L of silane (in normal conditions) have been produced. Determine the mass percentage of magnesium silicide in the mixture of silicides.

LESSON 9

9.1 ALKALI METALS

Alkali metals can be found in the first group of the Periodic table. Hydrogen, of course, is a single element from the first group which is not a metal. Alkali metals are soft enough to be cut with a knife. Alkali metals are highly reactive in normal conditions because they are ready to lose their single electron from the outer shell to form cations with charge +1.

Because of the ability of metals to lose their electrons, there are atoms and positively charged anions in their crystals (figure 14). Atoms lose their electrons much more frequently than cations gain them. We may say that in the piece of metal valence electrons are common for all the positively charged metal ions. That is why all those valence electrons form a so-called «sea of electrons» or «electron gas».

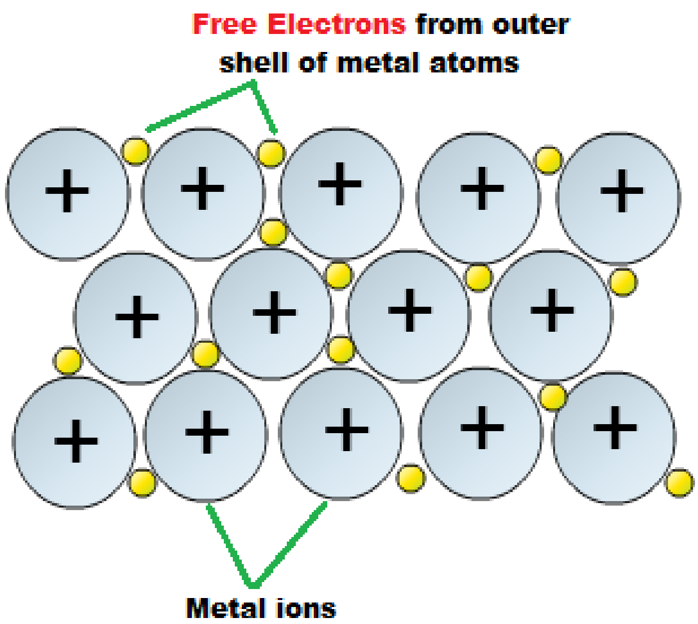


Figure 14. The scheme of metallic bonding

There are no negative ions in crystals of metals. That fact is true for alloys as well. In the alloy made from two metals there are positive ions and atoms of both metals connected together by the common electron gas.

All the alkali metals react with water in normal conditions and produce alkali and hydrogen gas.

$2Li + 2H_2O \rightarrow 2LiOH + H_2\uparrow$

$2Na + 2H_2O \rightarrow 2NaOH + H_2\uparrow$

$2K + 2H_2O \rightarrow 2KOH + H_2\uparrow$

Reaction between sodium and water produces more heat than reaction between lithium and water. Because of this, sodium melts during that reaction. Reaction between potassium and water produces so much heat that it is enough to make releasing hydrogen gas burn.

Alkali metals react with hydrogen gas at high temperatures and produce hydrides.

$2Na + H_2 \rightarrow 2NaH$

Exercises

a. How does the atomic radius of alkali metals change from the top to the bottom of the periodic table?

b. The charge density is the ratio between the charge of a particle and the area of its surface. How does the charge density of alkali metals' cations change from the top to the bottom of the periodic table?

c. The higher the charge density of ion the more water molecules make the solvate coat of that ion. How does the ionic radius of alkali metals in water solution change from the top to the bottom of the periodic table?

d. Calculate the volume of hydrogen produced in the reaction between water and 50 g of a) lithium, b) sodium, c) potassium.

e. Calculate the mass of lithium in 5 g of lithium carbonate.

f. Calculate the mass of cesium in 5 g of cesium chloride.

g. The alloy made from sodium and potassium has been dissolved in water. The volume of hydrogen released was equal to 3.77 L. Calculate the mass percentage of sodium in the alloy. The mass of the alloy was equal to 10 g.

9.2 COMPOUNDS OF ALKALI METALS

Alkali can be produced from hydrides of alkali metals.

$LiH + H_2O \rightarrow LiOH + H_2\uparrow$

$3NaH + Fe_2O_3 \rightarrow 2Fe + 3NaOH$

$2KH + O_2 \rightarrow 2KOH$

Oxides (i. e. Na_2O), peroxides (i. e. Na_2O_2) and superoxides (NaO_2) can be produced in reaction between an alkali metal and oxygen. All those compounds are ionic: they contain metal cations and certain anions. In crystals of oxides there are O^{2-} anions, in crystals of peroxides there are O_2^{2-} anions (figure 15), while in crystals of superoxides there are O_2^- anions.

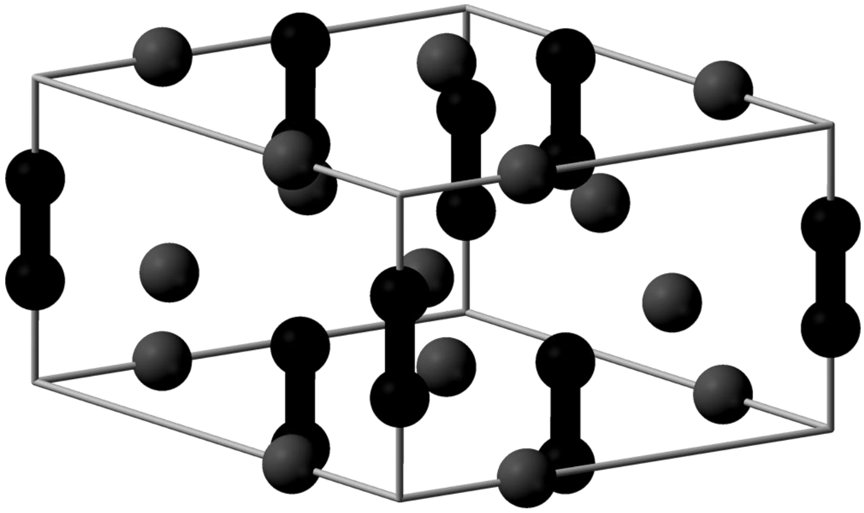


Figure 15. Structure of sodium peroxide. Sodium cations (Na^+) are grey, peroxide anions (O_2^{2-}) are black

Peroxides of alkali metals are used in H_2O_2 production.

$Na_2O_2 + 2HCl \rightarrow 2NaCl + H_2O_2$

Oxides can be produced from peroxides and superoxides. An excess of pure metal is needed for that purpose.

$Na_2O_2 + 2Na \rightarrow 2Na_2O$

$KO_2 + 3K \rightarrow 2K_2O$

Oxides (and so hydroxides) of alkali metals demonstrate strong basic properties: they react with acids, acidic oxides and hydroxides.

$Na_2O + 2HCl \rightarrow 2NaCl + H_2O$

$2KOH + CO_2 \rightarrow K_2CO_3 + H_2O$

$2LiOH + H_2SO_4 \rightarrow Li_2SO_4 + 2H_2O$

Hydroxides of alkali metals (except LiOH) cannot be decomposed into oxides and water.

$2LiOH$ (temperature) $\rightarrow Li_2O + H_2O$

NaOH (temperature) $\neq$

KOH (temperature) $\neq$

Nitrates of alkali metals are able to react with corresponding pure metals and produce oxides and nitrogen gas.

$10K + 2KNO_3 \rightarrow 6K_2O + N_2\uparrow$

Exercises

a. Classic chains of chemical reactions.

$Na \rightarrow NaOH \rightarrow NaHCO_3 \rightarrow Na_2CO_3 \rightarrow NaCl$

$K \rightarrow KOH \rightarrow K_2CO_3 \rightarrow KNO_3 \rightarrow KNO_2$

$KO_2 \rightarrow K_2O \rightarrow K_2CO_3 \rightarrow K_2SO_4 \rightarrow KNO_3$
$NaH \rightarrow NaOH \rightarrow NaCl \rightarrow NaNO_3 \rightarrow Na_2O$

b. Calculate the sum of molar masses for sodium containing compounds B and D from the chain of chemical reactions.

$$Na \xrightarrow{+H_2O} A \xrightarrow{+HCl} B \xrightarrow{+AgNO_3} C \xrightarrow{t^\circ} D$$

c. Calculate the sum of molar masses for potassium containing compounds B and D from the chain of chemical reactions.

$$K \xrightarrow{+H_2O} A \xrightarrow{+H_2SO_4} B \xrightarrow{+BCl_2} C \xrightarrow{+AgNO_3} D$$

d. Calculate the sum of molar masses for lithium containing compounds B and D from the chain of chemical reactions.

$$Li \xrightarrow{+O_2} A \xrightarrow{+H_2O} B \xrightarrow{+HCl} C \xrightarrow{+Na_3PO_4} D$$

e. Determine the mass of 10% NaOH solution required for complete neutralization of 196 g of 20% H_2SO_4 solution.

f. Determine the volume of hydrogen gas (in normal conditions) produced from: a) 100 g of Na; b) 100 g of NaH in the reaction with water.

g. What kind of salt is formed in the reaction between 8 g of KOH and 9.8 g of H_3PO_4? Calculate the mass of that salt.

LESSON 10

10.1 ALKALINE-EARTH METALS

Alkaline-earth metals occupy the second group of the Periodic table. However, alkali (soluble hydroxides) can be produced from Ca, Sr and Ba only, and not from Be and Mg. Moreover, Be demonstrates amphoteric features similar for those characteristic to Al.

For example, beryllium reacts with water solutions of alkali and forms complex salts.

$Be + 2NaOH + 2H_2O \rightarrow Na_2[Be(OH)_4] + H_2\uparrow$ (at high temperatures)

Magnesium reacts with water at high temperature and produces magnesium oxide.

$Mg + H_2O \rightarrow MgO + H_2\uparrow$

Very clean magnesium ribbon has a very slight reaction with cold water. After several minutes, some bubbles of hydrogen form on its surface. However, the reaction soon stops because the magnesium hydroxide formed is almost insoluble in water and becomes a barrier on the piece of magnesium preventing further reaction.

$Mg + 2H_2O \rightarrow Mg(OH)_2\downarrow + H_2\uparrow$

Just magnesium powder (in which the area of magnesium surface is very large) can react with water and produce magnesium hydroxide and hydrogen gas.

Calcium, strontium and barium react with water in a similar way as alkali metals.

$Ca + 2H_2O \rightarrow Ca(OH)_2 + H_2\uparrow$

$Sr + 2H_2O \rightarrow Sr(OH)_2 + H_2\uparrow$

$Ba + 2H_2O \rightarrow Ba(OH)_2 + H_2\uparrow$

Exercises

a. What volume of hydrogen will be released after mixing 10 g of calcium and strontium alloy in water? Mass percentage of calcium in the alloy is 85 %.

b. Calculate the mass percentage (in %) of calcium in the dolomite ($CaCO_3 \cdot MgCO_3$).

c. Calculate the mass percentage (in %) of calcium in calcined gypsum powder ($CaSO_4 \cdot ½H_2O$) and in solid gypsum ($CaSO_4 \cdot 2H_2O$).

10.2 Compounds of alkaline-earth metals

Hydroxides of alkaline-earth metals can be decomposed into oxides and water.

$Ca(OH)_2$ (temperature) $\rightarrow CaO + H_2O$

$Ba(OH)_2$ (temperature) $\rightarrow BaO + H_2O$

Sulfates of alkaline-earth metals decompose into oxides, sulfur (IV) oxide and oxygen.

$2SrSO_4 \rightarrow 2SrO + 2SO_2\uparrow + O_2\uparrow$

Oxides (and hydroxides) of Mg, Ca, Sr and Ba show basic properties: they react with acids and acidic oxides.

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3\downarrow + H_2O$

Water solution of calcium hydroxide (so-called «limewater») reacts with carbon dioxide. When the amount of carbon dioxide is lower than the amount of calcium hydroxide white precipitate of insoluble calcium carbonate begins to form. When the amount of carbon dioxide becomes higher $CaCO_3$ starts to react with it. As a result, white precipitate disappears because calcium bicarbonate is soluble, unlike calcium carbonate.

$CaCO_3\downarrow + CO_2 + H_2O \rightarrow Ca(HCO_3)_2$

Common equation for limewater reaction with two times (or more) excess of carbon dioxide is written below.

$Ca(OH)_2 + 2CO_2 \rightarrow Ca(HCO_3)_2$

Hard water can be defined as a water with high concentration of calcium and magnesium cations. Water hardness can be divided into temporary hardness and permanent hardness. Temporary hardness is due to bicarbonate anions presence. That kind of hardness can be removed by the way of boiling.

$Ca(HCO_3)_2 \rightarrow CaCO_3\downarrow + 2CO_2\uparrow + H_2O$

$Mg(HCO_3)_2 \rightarrow MgCO_3\downarrow + 2CO_2\uparrow + H_2O$

Permanent hardness is due to the presence of anions other than bicarbonate. To fight the permanent hardness one needs to add some reactants (like washing soda — Na_2CO_3 or limewater — $Ca(OH)_2$) or use special filters which can catch Ca^{2+} and Mg^{2+} ions.

$Ca(HCO_3)_2 + Na_2CO_3 \rightarrow CaCO_3\downarrow + 2NaHCO_3$

$Mg(HCO_3)_2 + Na_2CO_3 \rightarrow MgCO_3\downarrow + 2NaHCO_3$

$Ca(HCO_3)_2 + Ca(OH)_2 \rightarrow 2CaCO_3\downarrow + 2H_2O$

$Mg(HCO_3)_2 + Mg(OH)_2 \rightarrow 2MgCO_3\downarrow + 2H_2O$

Exercises

a. Classic chains of chemical reactions

$CaCO_3 \rightarrow CaO \rightarrow Ca(OH)_2 \rightarrow Ca(HCO_3)_2 \rightarrow CaCO_3$

$CaO \rightarrow Ca(OH)_2 \rightarrow CaCO_3 \rightarrow Ca(NO_3)_2 \rightarrow Ca(NO_2)_2$

$Mg \rightarrow MgO \rightarrow MgCO_3 \rightarrow MgCl_2 \rightarrow Mg(NO_3)_2$

$Ba(OH)_2 \rightarrow BaO \rightarrow Ba(NO_3)_2 \rightarrow BaCl_2 \rightarrow BaSO_4$

b. Calculate the sum of molecular masses for strontium containing compounds C and D from the chain of chemical reactions.

$$Sr_3(PO_4)_2 \xrightarrow{+1H_3PO_4} A \xrightarrow{+1H_3PO_4} B \xrightarrow{+1Sr(OH)_2} C \xrightarrow{+1Sr(OH)_2} D$$

c. Calculate the sum of molecular masses for calcium containing compounds B and D from the chain of chemical reactions.

$$Ca \xrightarrow{+O_2} A \xrightarrow{+CO_2} B \xrightarrow{t^\circ} C \xrightarrow{+H_2O} D$$

d. Calculate the sum of molecular masses for barium containing compounds B and D from the chain of chemical reactions.

$$Ba \xrightarrow{+H_2O} A \xrightarrow{+1CO_2} B \xrightarrow{+HCl} C \xrightarrow{+K_2SO_4} D$$

e. 0.336 L of carbon dioxide have been dissolved in 300 ml of 0.01 M $Ca(OH)_2$ solution. Determine the mass of salt produced in the reaction.

f. The mass of $BaSO_4$ produced in the reaction between $BaCl_2$ and 0.1 L of Na_2SO_4 is equal to 1.2 g. Determine the concentration of Na_2SO_4 solution.

LESSON 11

11.1 ALUMINUM AND ITS COMPOUNDS

Aluminum is the third most abundant element (after oxygen and silicon), and the most abundant metal, in the Earth's crust. Aluminum is easily oxidized by oxygen.

$4Al + 3O_2 \rightarrow 2Al_2O_3$

Aluminum oxide (alumina) is responsible for the resistance of metallic aluminum to weathering. A thin passivation layer of aluminum oxide (~ 4 nm) forms on any exposed aluminum surface. This layer protects the metal from further oxidation. However that passivation layer cannot protect aluminum from acids and bases.

$Al_2O_3 + 6HCl \rightarrow 2AlCl_3 + 3H_2O$

$2Al + 6HCl \rightarrow 2AlCl_3 + 3H_2\uparrow$

$Al_2O_3 + 2NaOH + 3H_2O \rightarrow 2Na[Al(OH)_4]$

$2Al + 2NaOH + 6H_2O \rightarrow 2Na[Al(OH)_4] + 3H_2\uparrow$

$2Al + 6NaOH + 6H_2O \rightarrow 2Na_3[Al(OH)_6] + 3H_2\uparrow$

Remember that aluminum is resistant to concentrated cold solutions of nitric and sulfuric acids, as well as to cold acetic and phosphoric acids.

Aluminum is able to reduce the most of metals from their oxides.

$8Al + 3Fe_3O_4 \rightarrow 4Al_2O_3 + 9Fe$

Aluminum hydroxide is insoluble. That compound demonstrates amphoteric properties, as well as aluminum oxide.

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

When solid aluminum and sodium hydroxides are heated together, sodium aluminate ($NaAlO_2$) and water are formed.

$Al(OH)_3(solid) + NaOH(solid) \rightarrow NaAlO_2 + 2H_2O$

When aluminum hydroxide is added to the water solution of alkali, a complex salt will be formed. If the ratio between $Al(OH)_3$ and NaOH is equal to 1:1, resulting complex salt will be $Na[Al(OH)_4]$ — sodium tetrahydroxoaluminate.

$Al(OH)_3 + NaOH \rightarrow Na[Al(OH)_4]$

If the ratio between $Al(OH)_3$ and NaOH is 1 : 3, then resulting complex salt will be $Na_3[Al(OH)_6]$ — sodium hexahydroxoaluminate.

$Al(OH)_3 + 3NaOH \rightarrow Na_3[Al(OH)_6]$

Complex salts (figure 16) are formed due to donor-acceptor bonds formation between empty electron orbitals of the central metal cation (Al^{3+} in our case) and electron pairs of ligands (oxygen atom from OH^- ions in our case).

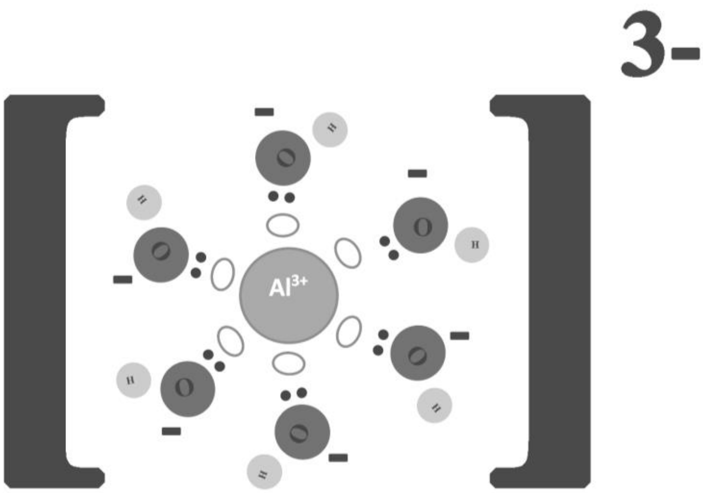


Figure 16. Scheme of hexahyroxoaluminate ($[Al(OH)_6]^{3-}$) anion. Aluminum cation is in the middle, oxygen atoms are dark grey, hydrogen atoms are light grey

Exercises

a. Classic chains of chemical reactions

$Al \rightarrow Na[Al(OH)_4] \rightarrow NaAlO_2 \rightarrow Na[Al(OH)_4] \rightarrow AlCl_3$

$Al_2O_3 \rightarrow Al(OH)_3 \rightarrow Al_2(SO_4)_3 \rightarrow Al_2O_3 \rightarrow Al$

$Al \rightarrow Al(NO_3)_3 \rightarrow K[Al(OH)_4] \rightarrow AlCl_3 \rightarrow Al(OH)_3$

b. Calculate the sum of molecular masses for aluminum containing compounds C and D from the chain of chemical reactions.

$$Al \xrightarrow{+HNO_3} A \xrightarrow{+4KOH} B \xrightarrow{+4HCl} C \xrightarrow{+3KOH} D$$

c. Calculate the sum of molecular masses for aluminum containing compounds C and D from the chain of chemical reactions.

$$Al \xrightarrow{+NaOH\,+\,H_2O} A \xrightarrow{+HCl_{in\ excess}} B \xrightarrow{+3NaOH} C \xrightarrow{+3NaOH} D$$

d. The mass of the mixture of copper and aluminum is equal to 20 g. That mixture reacted with hydrochloric acid. The volume of hydrogen gas was equal to 13.44 L. Determine the mass percentage of copper in the mixture.

e. The mass of the mixture of copper and aluminum is equal to 10 g. That mixture reacted with sodium hydroxide. The volume of hydrogen gas was equal to 6.72 L. Determine the mass percentage of copper in the mixture.

11.2 IRON AND ITS COMPOUNDS

Pure iron is soft (softer than aluminum), but is unobtainable by smelting. The material is significantly hardened and strengthened by impurities from the smelting process, such as carbon.

Elemental iron occurs in meteoroids and other low oxygen environments, but is reactive to oxygen and water. Fresh iron surfaces appear lustrous silvery-gray, but oxidize in normal air to give hydrated iron oxides (i. e. hydroxides), commonly known as rust ($Fe(OH)_3$). Unlike many other metals which form passivating oxide layers, iron oxides occupy more volume than iron metal, and thus iron oxides flake off and expose fresh surfaces for corrosion.

$4Fe + 6H_2O + 3O_2 \rightarrow 4Fe(OH)_3\downarrow$

At higher temperatures iron and water produce iron oxides $FeO{\cdot}Fe_2O_3$ ($=Fe_3O_4$).

$3Fe + 4H_2O$ (high temperature) $\rightarrow Fe_3O_4 + 4H_2\uparrow$

Iron forms iron (III) chloride in the reaction with chlorine gas.

$2Fe + 3Cl_2 \rightarrow 2FeCl_3$

In the reaction with hydrochloric acid, as well as with diluted sulfuric or nitric acid, salts of Fe^{2+} are formed.

$Fe + HCl \rightarrow FeCl_2 + H_2\uparrow$

$Fe + H_2SO_4 \rightarrow FeSO_4 + H_2\uparrow$

Concentrated sulfuric and nitric acids oxidize Fe^0 to Fe^{3+}.

$2Fe + 6H_2SO_4$(concentrated) $\rightarrow Fe_2(SO_4)_3 + 3SO_2\uparrow + 6H_2O$

$Fe + 6HNO_3$(concentrated) $\rightarrow Fe(NO_3)_3 + 3NO_2\uparrow + 3H_2O$

Iron (II) hydroxide (mostly basic hydroxide) is quite instable substance which is easily oxidized by the air.

$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3$

Iron (III) oxide and iron (III) hydroxide are amphoteric.

$Fe_2O_3 + 6HCl \rightarrow 2FeCl_3 + 3H_2O$

$Fe(OH)_3 + H_3PO_4 \rightarrow FePO_4 + 3H_2O$

If iron (III) oxide (or hydroxide) reacts with solid sodium hydroxide sodium ferrite and water are formed.

$Fe_2O_3(solid) + 2NaOH(solid) \rightarrow 2NaFeO_2 + H_2O$

$Fe(OH)_3(solid) + NaOH(solid) \rightarrow NaFeO_2 + 2H_2O$

If iron (III) oxide (or hydroxide) reacts with sodium hydroxide solution a complex salt (sodium hexahydroxoferrate) will be formed.

$Fe_2O_3 + 3H_2O + 6NaOH \rightarrow 2Na_3[Fe(OH)_6]$

$Fe(OH)_3 + 3NaOH \rightarrow Na_3[Fe(OH)_6]$

Concentrated alkali solutions are able to react with pure iron as well.

$2Fe + 2NaOH + 6H_2O \rightarrow 3H_2\uparrow + 2Na[Fe(OH)_4]\downarrow$

Exercises

a. Classic chains of chemical reactions

$FeS_2 \rightarrow FeO \rightarrow FeCl_2 \rightarrow Fe(NO_3)_2 \rightarrow Fe(OH)_3$

$Fe \rightarrow FeCl_2 \rightarrow FeCl_3 \rightarrow Fe(OH)_3 \rightarrow Fe_2O_3$

$Fe(OH)_3 \rightarrow Fe(OH)_2Cl \rightarrow Fe(OH)Cl_2 \rightarrow FeCl_3 \rightarrow Fe(OH)_3$

b. Calculate the sum of molecular masses for iron containing compounds B and D from the chain of chemical reactions.

$Fe(OH)_3 \xrightarrow{+1HCl} A \xrightarrow{+1HCl} B \xrightarrow{+1HCl} C \xrightarrow{+3KOH} D$

c. Determine the volume of chlorine gas reacted with 2.8 g of iron.

d. Hydrochloric acid reacted with 12 g of a mixture consisting of iron and silver. The volume of hydrogen gas produced was equal to 0.6 L. What is the mass percentage of silver in that mixture?

e. Diluted sulfuric acid reacted with 20 g of a mixture consisting of iron and aluminum. The volume of hydrogen gas produced was equal to 20.67 L. What is the mass percentage of iron in that mixture?

f. The mass of the mixture made from iron and aluminum was equal to 11.49 g. The volume of chlorine gas reacted with that mixture was equal to 10 L. Determine the mass percentage of aluminum chloride in the mixture of iron and aluminum chlorides formed after the completion of the reaction.

g. The mixture of iron (III) hydroxide and aluminum hydroxide has been heated. After the complete decomposition of hydroxides the mass of the solid remain was 31.5 % lower than the initial mass of the mixture of hydroxides. Calculate the mass percentage of aluminum hydroxide in the initial mixture and the mass percentage of iron (III) oxide in the final mixture.

LESSON 12

12.1 SAMPLE TICKET #1 FOR CONTROL TASK ON THE CHEMISTRY OF THE ELEMENTS

Tasks with calculations

1. Calculate the mass of water produced in the reaction between hydrogen gas and 20 g of copper oxide (II).

2. Determine the mass of NaOH required for complete neutralization of 400 g of 30 % H_2SO_4 solution.

3. Determine the volume of oxygen produced in the decomposition reaction from 10 g of potassium nitrate (KNO_3).

4. Determine the volume of chlorine gas reacted with 2.8 g of iron.

Classic chains of chemical reactions

$I_2 \rightarrow NaI \rightarrow NaBr \rightarrow NaCl \rightarrow NaF$

$C \rightarrow CO_2 \rightarrow NaHCO_3 \rightarrow Na_2CO_3 \rightarrow CaCO_3$

$Al \rightarrow Al(NO_3)_3 \rightarrow K[Al(OH)_4] \rightarrow AlCl_3 \rightarrow Al(OH)_3$

$Fe(OH)_3 \rightarrow Fe(OH)_2Cl \rightarrow Fe(OH)Cl_2 \rightarrow FeCl_3 \rightarrow Fe(OH)_3$

Modern chains of chemical reactions

Calculate the sum of molecular masses for nitrogen containing compounds A, B, C and D from the chain of chemical reactions.

$$NH_3 \xrightarrow{+5O_2} A \xrightarrow{+O_2} B \xrightarrow{+H_2O,\ +O_2} C \xrightarrow{+KOH} D$$

Calculate the sum of molecular masses for aluminum containing compounds A, B, C and D from the chain of chemical reactions.

$$Al \xrightarrow{+H_2SO_4} A \xrightarrow{+3KOH} B \xrightarrow{+2HCl} C \xrightarrow{+1HCl} D$$

12.2 SAMPLE TICKET #2 FOR CONTROL TASK ON THE CHEMISTRY OF THE ELEMENTS

Tasks with calculations

1. Calculate the mass of zinc oxide produced in the reaction between 88 g of zinc and the excess of oxygen.

1. What kind of salt(s) will be formed in the reaction between 300 g of 10 % $Ca(OH)_2$ solution and 2L of carbon dioxide? Calculate the mass of the salt(s).

2. Determine the volume of nitric (IV) oxide produced in the decomposition reaction from 120 g of copper nitrate ($Cu(NO_3)_2$).

3. Determine the mass of sulfur reacted with 8.8 g of zinc.

Classic chains of chemical reactions

$I_2 \rightarrow KI \rightarrow KBr \rightarrow KCl \rightarrow AgCl$

$CO \rightarrow CO_2 \rightarrow CaCO_3 \rightarrow CaHCO_3 \rightarrow CO_2$

$Al \rightarrow AlCl_3 \rightarrow Na[Al(OH)_6] \rightarrow AlCl_3 \rightarrow Al(NO_3)_3$

$Zn(OH)_2 \rightarrow ZnCl_2 \rightarrow Zn(OH)_2 \rightarrow K_2[Zn(OH)_4] \rightarrow Zn(OH)_2$

Modern chains of chemical reactions

Calculate the sum of molecular masses for nitrogen containing compounds A, B, C and D from the chain of chemical reactions.

$$N_2 \xrightarrow{+O_2} A \xrightarrow{+O_2} B \xrightarrow{+H_2O,\ +O_2} C \xrightarrow{+NaOH} D$$

Calculate the sum of molecular masses for aluminum containing compounds A, B, C and D from the chain of chemical reactions.

$$Al \xrightarrow{+HCl} A \xrightarrow{+3NaOH} B \xrightarrow{+3NaOH} C \xrightarrow{+6HCl} D$$

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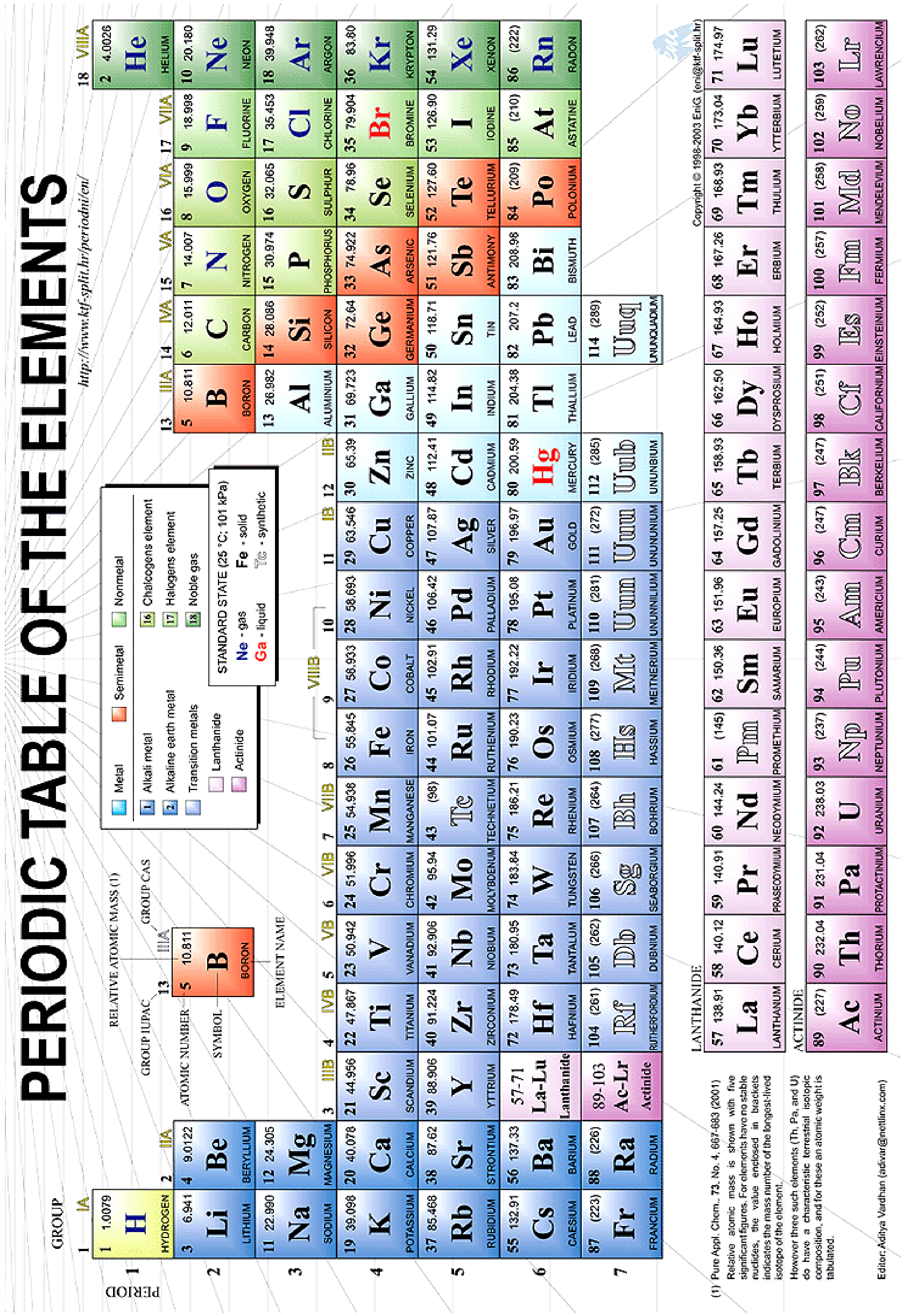
PERIODIC TABLE OF THE ELEMENTS
http://www.ktf-split.hr/periodni/en/
LANTHANIDE
ACTINIDE
STANDARD STATE (25 °C; 101 kPa)
Copyright © 1998-2003 EniG. (eni@ktf-split.hr)
Editor: Aditya Vardhan (adivar@netlinx.com)

THE SOLUBILITY CHART

S — soluble (more than 1 g per 100 g of water)	M — marginally soluble (0,1 g - 1 g per 100 g of water)	I — insoluble (less than 0,1 g per 100 g of water)	D — decomposes in water	U — compound doesn't exist or is unstable

cation / anion	H^+	Li^+	K^+	Na^+	NH_4^+	Ba^{2+}	Ca^{2+}	Mg^{2+}	Sr^{2+}	Al^{3+}	Cr^{3+}	Fe^{2+}	Fe^{3+}	Ni^{2+}	Co^{2+}	Mn^{2+}	Zn^{2+}	Ag^+	Hg^{2+}	Pb^{2+}	Sn^{2+}	Cu^{2+}
OH^-		S	S	S	S	S	M	I	M	I	I	I	I	I	I	I	I	D	D	I	I	I
F^-	S	S	S	S	S	M	I	I	M	S	I	I	I	S	S	M	S	S	M	I	S	S
Cl^-	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	I	S	M	S	S
Br^-	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	I	M	M	S	S
I^-	S	S	S	S	S	S	S	S	S	S	U	S	U	S	S	S	S	I	I	I	M	S
S^{2-}	S	S	S	S	S	S	D	D	S	D	D	I	D	I	I	I	I	I	I	I	I	I
HS^-	S	S	S	S	S	S	S	S	S	U	U	U	U	U	I	U	U	U	U	U	U	U
SO_3^{2-}	S	S	S	S	S	M	M	M	I	U	D	M	U	I	I	U	M	I	I	I	U	U
HSO_3^-	S	U	S	S	S	S	S	S	S	U	U	U	U	U	U	U	U	U	U	U	U	U
SO_4^{2-}	S	S	S	S	S	I	M	S	I	S	S	S	S	S	S	S	S	M	D	I	S	S
HSO_4^-	S	S	S	S	S	U	U	U	D	U	U	U	U	U	U	U	U	U	U	I	U	U
NO_3^-	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	S	D	S
NO_2^-	S	S	S	S	S	S	S	S	S	U	U	U	U	S	M	U	U	M	U	U	U	U
PO_4^{3-}	S	I	S	S	D	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I	I
HPO_4^{2-}	S	U	S	S	S	I	I	M	I	U	U	I	U	U	U	I	U	U	U	M	I	U
$H_2PO_4^-$	S	S	S	S	S	S	S	S	S	U	U	S	U	U	U	S	S	S	U	D	U	U
CO_3^{2-}	S	S	S	S	S	I	I	I	I	U	U	I	U	I	I	I	I	I	U	I	U	I
HCO_3^-	S	S	S	S	S	S	S	S	S	U	U	S	U	U	U	U	U	U	U	S	U	U
CH_3COO^-	S	S	S	S	S	S	S	S	S	D	S	S	D	S	S	S	S	S	S	S	D	S
SiO_3^{2-}	I	S	S	S	U	I	I	I	I	U	U	I	U	U	U	I	I	U	U	I	U	U

THE REACTIVITY SERIES OF METALS

Active metals — those which react with water and acids										
Cs	**Rb**	**K**	**Na**	**Li**	**Ba**	**Sr**	**Ca**			
Metals which react with acids and produce salts and H_2										
Mg	**Al**	**Mn**	**Zn**	**Cr**	**Fe**	**Cd**	**Co**	**Ni**	**Sn**	**Pb**
Metals which react with strong oxidizing acids only and don't produce H_2										
Sb	**Bi**	**Cu**	**Hg**	**Ag**	**Au**	**Pt**				

CONTENTS

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Хрусталёва Татьяна Александровна

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