# Inorganic Chemistry

From the Periodic Law to the atomic structure.

May 10, 2020

## 1 Do atoms have an internal structure?

As we have seen from the Periodic table, properties of atoms of different type (elements) are very diverse, and there is some strict periodic interconnection between this diversity and the atomic mass. How can that be explained? Two different explanations are conceivable.

Firstly, one may argue the properties of different elements are different because their atoms have an intrinsically different nature. This concept, which is the original Democritus's concept, assumes atoms (we remember the word "atom" literally means "indivisible") are impossible to separate onto smaller parts, which means atoms have no internal structure. Therefore, atoms are intrinsically inconceivable, and nothing can be said about the reasons why the atoms of different elements have different properties. Obviously, such a concept would be hardly acceptable for modern scientists who believe there is no limits to knowledge. Interestingly, even John Dalton already anticipated the possibility that future generations of scientists would be capable of having a look inside atoms. Remember, when he wrote that atoms cannot be destroyed, he made an insightful reservation: cannot be destroyed ***by chemical means***. In other words, he admitted peoples would eventually be able to study atoms by some other, non-chemical means.

Accordingly, the second explanation of the difference in the atomic properties was that all atoms are composed of a limited set of some smaller particles, which are arranged differently in different atoms.

## 2 Discovery of atom's composition.

The composition of atoms was determined mostly in late XIX - early XX century by British and German physicists. This discoveriy became possible due to the progress in study of electric discharge in vacuum tubes (actually, the tubes filled with rarified gases, similar to modern luminiscent lamps) and the radioactivity phenomenon.

## 2.1 Discovery of electron.

Intense studies of an electric discharge in vacuum tubes (which would later lead to the discovery of X-rays by Rudolph Roentgen) revealed that such discharges generate so called *cathode rays*, which are a stream of some light negatively charged particles, *electrons*. In 1896, the British physicist J. J. Thomson, along with his colleagues John S. Townsend and H. A. Wilson, established that electrons that form cathode rays are the result of decomposition of the atoms of the gas which was present in their apparatus in trace amount. Thompson proposed that electrons, which are two thousand times lighter that the lightest atom, hydrogen, and which have smallest possible electric charge, are essential components of all atoms. Based on that assumption, he proposed the first model of atom, which we can call a "muffin model": according to him, an atom (which, as we know is electrically neutral) is a loose positively charged sphere, where small compact electrons are uniformly distributed like raisins in a muffin.

Figure 1: Sir Joseph John Thomson (1856-1940)
a discoverer of electron

The significance of this model was that it was the first rational model of atom. By no means that model could explain any chemical properties of the elements. However, it was a good starting point for further experiments, which were done by Thompson's student, Ernts Rutherford.

## 2.2 Rutherford's experiment.

By the moment Rutherford conceived his groundbreaking experiment, the *radioactivity* phenomenon had already been discovered. Scientist already knew that some radioactive materials irradiate some rays, which are composed of some very small particles with high energy. Rutherford's idea was to use those high energy particles (people called them "alpha"-particles, although they didn't know yet what they are) to probe the atomic structure. His rationale was as follows: "if atoms are loose spheres, an alpha particle will easy fly through atoms, and their trajectory will not change significantly. However, if an alpha-particle hits an electron, its trajectory will change more significantly. Therefore, by monitoring the average dispersion of an alpha particles passing through some material[1] it is possible to see how concretely the electrons are distributed within atoms."

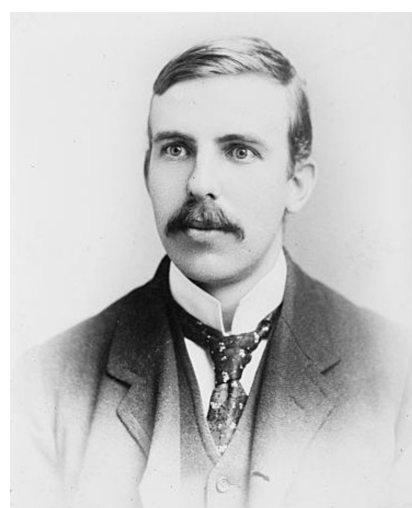

Figure 2: "We haven't money, so we've got to think"
Ernst Rutherford (1871-1937), a discoverer of atomic structure.

In other words, Rutherford expected that a narrow

[1]Rutherford used thin gold foil as a target.

alpha-particles beam passing through thin gold foil would undergo slight dispersion: according to Thomson's model, almost every alpha-particle would deviate slightly from its original trajectory, so instead of seeing a small bright spot in the screen Rutherford expected to see a larger and diffuse spot.

However, what he observed was totally unexpected. **During Rutherford's experiment, overwhelming majority of alpha-particles passed through the foil as if there was no foil at all. Only a tiny fraction of alpha-particles deviated from its original trajectory, however, this deviation was very significant: some of them even bounced back.** The only possible explanation for such observation was that Thompson's model is absolutely wrong. Rutherford concluded that some very compact object exists in atoms where virtually all atom's mass in concentrated. Based on the ratio between the number of alpha-particles that had not been deflected by the foil, and the number of particles that were strongly deflected, Rutherford was able to estimate the size of this small object (which he dubbed "a nucleus"). The size of a nucleus appeared to be astonishingly small: *atomic nucleus is one hundred thousand times smaller than the atom itself.*

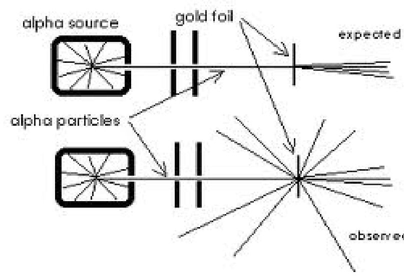


Figure 3: Rutherford's experiment

However, if all material atoms are composed of are concentrated in the tiny atom's nucleus, which force prevents electrons from falling on the nucleus? Rutherford proposed that force is a centrifugal force. According to him, atoms resemble our Sun system: light electrons, like planets, are rotating around a massive nucleus, which plays a role the Sun. Accordingly, this model was called a **planetary model of atom.**

# 3 Which material atomic nucleus is composed of?

Thomson's and Rutherford's studies allowed them to identify one type of particles (i.e. electrons) atoms are composed of, and to establish overall architecture of atoms. However, according to the planetary model, the lion's share of the material atoms are composed of was concentrated in the nucleus, a strange object situated in the center of each atom, whose size was unbelievably small ($10^{-15}$ m, a hundred thousand times smaller than the size of the atom itself), and, accordingly, whose density was incredibly high. The first step to understanding of the composition of atomic nuclei was made by Rutherford in his experiments with *anode rays.*

## 3.1 Anode rays, and discovery of a proton.

During the previous class, we learned about cathode rays, i.e. accelerated electrons that form when the atoms of rarefied gas are being torn apart in a strong electric field. Obviously, when atoms break apart, their electrons fly from the cathode (which is negatively charged) towards the anode (which is charged positively), hence the name *cathode rays.* However, what happens to the nuclei of the atoms when the electrons fly away? Isn't it logical to suggest they will fly in the opposite direction, i.e. from the anode to the cathode? And if that is the case, is it possible to detect them?

Detection of nuclei (especially, the nuclei of the lightest element, hydrogen) was done in the apparatus named *anode tube*. This tube represents a modification of the cathode tube. The anode tube had a perforated anode, which made observation of positively charged particles possible. The holes in the anode allowed accelerated positive particles, which were falling onto the anode, to continue its flight further after they reached the anode. As a result, they were seen as a glowing beams behind the anode (Fig. 1, the right part of the tube.) Since they anode rays particles are charged, their were deflected in magnetic field. The deflection angle allowed Rutherford to calculate the mass of such particles.

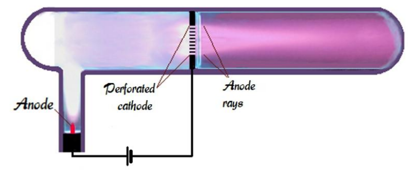

Figure 4: Anode tube. Anode rays are seen in the right part of the tube, behind the anode.

Rutherford found that, when the anode tube was filled with hydrogen, the mass of anode rays particles generated in such a tube was almost equal to the mass of a hydrogen atom. In a series of elegant experiments, Rutherford demonstrated this type particles are not possible to break apart further. He called this particle a **proton**, after the Greek word for "first", or "primary"[2]

## 3.2 Hydrogen atom

Based on his findings, Rutherford proposed the hydrogen atom is composed of two particles, a proton and an electron. A heavy proton, whose mass is almost exactly equal to 1 Da (the mass of the hydrogen atom) is situated in the center of the atom, whereas the electron is rotating around it in the same manner the Moon is rotating around our Earth. The $p^+$ and $e^-$ are currently the standard symbols for protons and electrons, accordingly.

## 3.3 Other atoms. Moseley's law

Unfortunately, discovery of the proton did not fully clarified the composition of other atoms. Indeed, whereas the mass of hydrogen is 1 Da, the mass of the next element, helium, is 4 Da. Does it mean helium is composed of four protons and four electrons? If yes, why there are no elements between hydrogen and helium? To answer this question, it was absolutely necessary to measure the charge of nuclei of various elements. This had been done in early XX century by Henry Moseley, a brilliant British physicist. In a series of X-ray spectroscopy experiments

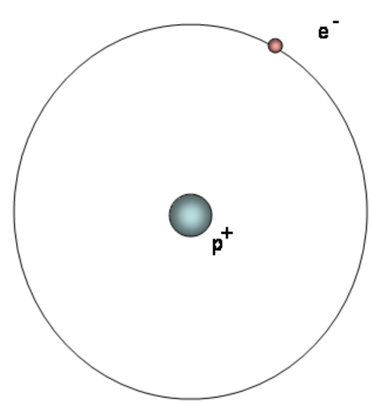

Figure 5: Rutherford's model of a hydrogen atom.

[2]Compare with "proteins" (a "first" or "primary" biological molecule), "prototype" (or a first representative of some class), etc.

(we cannot go into the details of those experiments yet)
Moseley demonstrated the profound linkage between the element's position number in the Periodic table and the charge of its nucleus. Concretely,

**Moseley's law says: "The charge of the element's nucleus is equal to the proton charge times the element's number in the Periodic table."**

A discovery of this law by Moseley was a major breakthrough towards understanding of the structure of atoms bigger than a hydrogen atom. Interestingly, Moseley made this groundbreaking discovery on the eve of his scientific career. He could have become one of the greatest XX century physicists, however, outbreak of the First World War changed everything.

> *When the World War I broke out in August 1914, Moseley enlisted in the Royal Engineers of the British Army and was killed in action 10 August 1915 during the Battle of Gallipoli in Turkey. Isaac Asimov once wrote, "In view of what he [Moseley] might still have accomplished ... his death might well have been the most costly single death of the War to mankind generally."*

Figure 6: Henry Moseley (1887-1915), a British physicist who measured the charge of atomic nuclei.

Since the atomic number is equal to the charge of the nucleus, it is also equal to the number of electrons in each element (this is so because atoms are electrically neutral, so the positive charge of the nucleus must be fully compensated by electrons around it). In other words, there is one electron in a hydrogen atom, two electrons in a helium atom, three electron in a lithium atom, and so on.

However, the next conclusion one has to draw from the Moseley's law is the following: the nuclei of elements other than hydrogen are composed of protons and some other heavy and electrically neutral particles. Indeed, the electric charge of the nucleus of helium is 2 (two times bigger than the charge of hydrogen's nucleus) , but its mass is 4 (four times heavier than hydrogen's nucleus). What material is responsible for that mass difference?

## 3.4 "Beryllium rays" and discovery of a neutron.

This missing particle was discovered only in 1932 by James Chadwick, who studied so called "beryllium rays", strange rays that were observed earlier by German physicists Bothe and Becker during the bombardment of beryllium targets by alpha-particles (particles similar to those used by Rutherford). Chadwick demonstrated those "rays" consisted of uncharged particles of the mass roughly equal to the mass of proton. These particles were called neutrons, from the Latin root for "neutral" and the Greek ending -on (to preserve the same naming style as for electron and proton). Soon after that, it was demonstrated neutrons, along with protons are the only components of atomic nuclei. Based on this, the proton-neutron model of atomic nucleus had been proposed by Chadwick. The combined electron-proton-neutron concept of atom says:

**Atoms are composed of a nucleus and electrons orbiting around it (see Fig. 5). A nucleus is composed of protons and neutrons. The number of protons is equal to the nucleic charge (i.e. the atomic number). The number of neutrons and protons is roughly equal to the atom's mass (in Daltons).**

# 4 Atomic number and atomic mass. Isotopes.

Although the electron-proton-neutron model of atom is elegant and beautiful, there is something that it seems to fail to explain. Indeed, when you look at the Periodic table, you can see the masses of most elements are not multiple of the mass hydrogen. For example, mass of chlorine is 35.45, mass of magnesium is 24.31. How can that be possible if every atom is composed of the integer number of **nucleons** (i.e. protons and neutrons) and electrons? To explain that, scientists proposed the hypothesis that for each element, different types of atoms are possible. These atoms have the same number of protons and electrons, but the amount of neutrons can be different. For example, three different variants of hydrogen atom exist in nature. The most abundant type of hydrogen atom whose nucleus is composed of just one proton. Its atomic weight is almost equal to 1 Da. The second atom variant contains one proton and one neutron in its nucleus. Its weight is ca 2 Da. The third variant has two neutrons and one proton. Its mass is 3 Da. Since all of them have identical chemical properties and identical atomic charge, all of them occupy the same cell in the Periodic table. Accordingly, such variants of the same elements are called **"isotopes"**.

**"Isotopes" (from Greek words "isos" (equal) and "topos" (place, position)) are the different variants of the certain element. Different isotopes of some elements have the same amount of protons and electrons, but different amount of neutrons (hence the difference in their masses).**
**Isotopes of the same elements are denoted by the same symbol. To discriminate between different isotopes, their mass is added left to the element symbol as a superscript number, e.g. $^{16}$O, $^{23}$Na, $^{2}$H.**

Different isotopes of the same element have identical (or almost identical) chemical properties, but their physical properties (boiling point, density, etc) may be slightly different. Due to the difference in physical properties, they can be separated from each other (although it is a very laborious process).

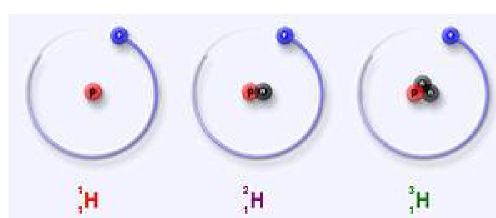

Figure 7: Three different isotopes of hydrogen. Protons are depicted as red balls, neutrons as blue balls.

The existence of isotopes explains the non-integer masses of some elements. Thus, the observed mass of chlorine (35.45 Da) is due to the fact that natural chlorine exists in a form of two isotopes, $^{35}$Cl (76%) and $^{37}$Cl (24%).

In contrast, some elements, such as oxygen or carbon, exist in nature mostly in a form of one isotope ($^{12}$C and $^{16}$O, accordingly.) Such elements are called **monoisotopic**.

## Homework

Read the CW materials and answer the following question. Imagine Rutherford, during his experiment, observed that alpha-particles passed through the foil were distributed as follows: 95% of all particles were not deflected at all, and 5% of particles were deflected very strongly. The density of gold is 19.30 g $/cm^3$, foil thickness is 100 nm[3], the atomic weight of gold is 197, which means 197 grams of gold contain $6 \times 10^{23}$ gold atoms. What can you say about the structure of the atoms that foil was composed of? Concretely, what is the ratio between the atom's size and the nucleus's size, according to those data?

As far as I know, most of you attend Physics in SchoolNova. During our next classes we will need to use physics for understanding atomic structure and the nature of chemical bond. Therefore, I would like you to refresh your physics knowledge, and to pay special attention to such concepts as Coulomb law, magnetism, energy, force. During the next class we will probably have a short quiz where I'll ask you some physics related questions. I need to know the state of your physics knowledge to decide how fast can we move further during this spring. Please, answer the following questions.

1. What does Coulomb law says?
2. How many fundamental forces (besides the electrostatic force) do you know?
3. How do you understand the term "energy"?
4. What is light?
5. Look at the Periodic table and name 20 elements that are essentially monoisotopic.
6. Find five elements that exist in nature as a mixture of roughly comparably abundant isotopes (in the same manner as chlorine). On the internet, find which isotopes they are.
7. As you know, the elements in the Periodic table are arranged lightest to heaviest. However, this order is broken for tellurium and iodine. Why did Mendeleev decide to swap tellurium and iodine? How can that be explained based on the electron-proton-neutron theory?

# 5 Why don't nuclei break apart?

Although the electron-proton-neutron model of atoms answered many questions, two new questions emerged, which this model failed to explain. Those questions are:

1. Why doesn't a nucleus break apart?
2. Why don't electrons fall onto an atomic nuclei?

[3] 1 nm = $10^{-9}$ m.

By no means these two questions were idle, because they could not be answered in terms of XIX century physics. Let's forget for a while about the second question, and focus on the question number 1. Indeed, as we all know, the interaction between two charged particles obeys Coulomb law. In other words, its strength is inversely proportional to the square of the distance between two charges. Now imagine two protons separated by a distance which is 100,000 (one hundred thousand) times smaller than the size of an atom. Do you realize, how strong the repulsion between those protons will be? (please, calculate this repulsion force at home).

Obviously, such a tremendous repulsion force needs to be compensated for by some other, equally powerful force. However, only two forces exist in our world (i.e. in our big, *macroscopic* world), gravity and Coulomb forces, and none of them is capable of holding protons in the nucleus. That is why physicists hypothesized some new force exists in nature that holds protons and neutrons in atomic nuclei. They called it a "strong force". It is really strong, but it acts only at very short distance, the distance comparable with the size of atomic nuclei. That is why we cannot feel it, and cannot detect it using our conventional instruments. This force acts only upon protons and neutrons[4]. Electrons are not affected by this force at all. In nuclei, strong forces act both on protons and on neutrons, and Coulomb repulsion occurs only between protons. As a result, strong forces are capable of compensating repulsion between protons.

# 6 Decay of a neutron

Although neutrons, like protons and electrons, can be considered fundamental building blocks all matter is composed of, they are not stable in free from. A freely flying neutron undergoes a fast decay onto a proton, an electron and a *neutrono*, a massless and neutral particle, which is very hard to detect.

$$\mathrm{n} \longrightarrow \mathrm{p}^+ + \mathrm{e}^- + \nu \qquad (1)$$

From this equation, one may conclude neutron is composed of a proton, electron and neutrino. However, protons also may undergo a decay when they are inside some nuclei. The equation of this decay is astonishing:

$$\mathrm{p}^+ \longrightarrow \mathrm{n} + \mathrm{e}^+ + \nu \qquad (2)$$

In other wards, when proton falls apart, it generate a neutron, a neutrino, and a new particle called *positron*, a particle totally identical to electron, except its charge is positive. We cannot devote much time to this apparent paradox, however these two equations demonstrate the elementary particles world differs from our "big" world.

[4]...and other particles called hadrons. Several hadrons exist in nature, but only neutrons and protons are stabe. Other hadrons have a very short life time, they form in high energy collisions of accelerated particles. We do not discuss them.

# 7 Three types of radioactive rays

When scientists discovered the radioactivity phenomenon, they observed radioactive rays can be separated onto three different fractions. Two of them were deflected by magnetic field in opposite directions, which meant those rays actually were some accelerated particles with opposite charges. The positive particles were heavy[5], its charge was equal to the charge of two protons, and its mass was equal to the mass of four protons. In other words, those particles (alpha-particles) were the nuclei of helium atoms.

The second type particles (bets-particles) were negatively charged, their charge and mass were equal to the charge of electron (and physicists concluded they are electrons).

The third type rays were not affected by magnetic field. They were true rays of light, although it was a very high energy light.

# 8 Nuclear reactions

Which processes lead to generation of radioactive rays? Obviously, the easiest question was the question about the origin of beta-particles. If you look at the equation 1, you will see, that electrons (beta-particles) are generated as a result of neutron decay. That means one neutron in some nucleus became a proton, so the atomic number of that atom increased by one, but its mass remained the same. Indeed, physicists established that the radioactive decay that generates beta-particles leads to conversion of a radioactive element into an element in the next cell of the Periodic table. For example, radioactive decay of $^3$H leads to formation of a helium isotope with atomic mass of 3.

$$^3\mathrm{H} \longrightarrow {}^3\mathrm{He} + \mathrm{e}^- + \nu \tag{3}$$

In contrast, when an alpha-particle is generated during the decay, the atomic number of the atom decreases by 2, and its atomic mass decreases by 4. For example, alpha-decay of uranium (atomic number 92) leads to formation of thorium (atomic number 90):

$$^{238}\mathrm{U} \longrightarrow {}^{234}\mathrm{Th} + \alpha \tag{4}$$

# Homework

1. Calculate the repulsion force (in newtons) between two individual protons in a helium nucleus. The values of Coulomb constant, proton charge and nucleus diameter can be found on Internet.

2. Three different isotopes of oxygen and three different isotopes of hydrogen exist in nature (although some of them are much less abundant). How many different water molecules can be found in a glass of water?

3. Natural copper exists as a mixture of two isotopes, $^{63}$Cu and $^{65}$Cu. Based on the atomic mass of the natural copper, calculate a relative abundance of its isotopes.

[5] Scientists realized that because their deflection angle was comparatively small

4. Radon, the heaviest know noble gas, was named after radium (Ra), a metal that produces a radon gas as a result of radioactive decay. Which type of nuclear reactions this process belongs to?

5. Tritium ($^3$H) is a radioactive isotope of hydrogen. During its undergoes radioactive decay beta-particle is being emitted. Which element is a product of that reaction?

# 9 Few simple concepts

Today we introduce several concepts that explain the rules that govenrn Periodic table's structure, the atomic structure, chemical bond and valence. We introduce these concepts without explanation. We will study them in details later.

These concepts are as follows.

## 9.1 Electron shell

Simply put, an electron shell is the same as Bohr's orbit. An electron cannot have some arbitrary energy in an atom: its energy can have only some discrete values. The electrons that have roughly the same value form an electron shell. The first shell corresponds to the lowest possible value, the second shell corresponds to the second lowest energy, etc.

Each electron shell has some concrete capacity: thus, the first shell can accommodate up to two electrons, the second shell - eight electrons, the thids shell - 18 electrons, the fourth shell - 32 electrons, etc.

## 9.2 Orbitals

Orbital is a state of an electron within an electron shell. An orbital can be understood as electron's orbit inside an atom. The word "orbital" is used instead of the word "orbit", because the latter implies some concrete trajectory, whereas it is impossible to speak about electron's trajectory in an atom (we will talk about that later in more details). An orbital can be occupied by zero, one, or two electrons. It cannot be occupied by more than two electrons. Both electrons at the same orbital have exactly the same energy, and they are identical in all aspects[6].

Orbitals can be considered as "bulding blocks" an electron shell is composed of. It is easy to see that the first shell is compposed of just one orbital, the second shell is composed of four orbitals, etc.

## 9.3 Open shell

When some orbital in an electron shell are partially occupied by electrons, such a shell is called an *open shell*. As a rule, an open is the outer shell. All other shell are closed. For example, the second shell in a lithium atom is open, because it contains one electron, whereas the first shell is full, or closed.

[6]Except one; we will talk about that later.

It is easy to see that the elements from groups 1 to 7 have open shells, whereas in noble gases all shells are closed. From that, we can hypothecise that there is some intrinsic connection between the number of electrons on the outer shell and chemical reactivity. This hypothesis is absolutely correct: noble gases are chemically inert because their outer shell is full.

With regard to the atoms with an open shell (i.e. the atoms of 1st to 7th group elements), they are prone to transform to a state where all shells are full, and this explains their chemical reactivity. A transformation from the open shell state to the closed shell state can be achieved in two ways, and these ways are as follows.

## 9.4 Ionisation

An atom can lose one or several electrons from its outer shell, and this shell becomes empty. Since the next shell is closed, the new particle that forms in that process is chemically stable. Let's consider a sodium atom as an example. It has one electron at the outer shell, and it can lose it easily. The new particle that forms in that process is similar to a neon atom, except it is positively charged. This particle is called an *ion*. It is denoted as $Na^+$.

This process can be formally described with an equation:

$$Na - e^- \longrightarrow Na^+$$

Sometimes, to convert from the open shell to a closed shell state atoms do not donate electrons but take them. That usually occurs in the elements that have an outer shell that is almost full. Thus, a chlorine atom has an open shell where just one electron is missing. It can take one electron, thereby converting into a negative ion ($Cl^-$).

This process can be formally described with an equation:

$$Cl + e^- \longrightarrow Cl^-$$

This new particle, $Cl^-$ has an electronic structure that is identical to the structure of the argon atom, except it is not neutral. This particle is also an ion. Do discriminate between negative and positive ions, scientists use speciall names for them: Positive ions are called *cations*, and negative ions - *anions*[7].

The processes of ion formation is called *ioniisation*.

Obviously, formation of cations and anions cannot go independently from each other: if some atom loses its electron, it actually *donates* it to some other atom or molecule. Accordingly, an atom that gets an electron obtains it from some other atom. For example, the two above processes can occur in parallel when chlorine (an element) reacts with sodium, and sodium chloride forms as a result. In sodium chloride, chlorine atoms exist in a form of chlorine ions ($Cl^-$), and sodium atoms are sodium ions ($Na^+$), and they from a new compound, NaCl, where sodium and chloruine ions are held together due to electrostatic attraction force (Coulomb force). This type interaction is called an *ionic bond*.

***An ionic bond froms between two atoms when first atom donates one or several electrons to other atoms. As a result, electron shells in all***

[7] We will learn later why

***atoms become more stable (they become closed), and the atoms are held together due to electrostatic interaction.***

## 9.5 Oxidation and reduction

As we can see, when chlorine reacts with sodium, it takes an electron from sodium. That means sodium is being *oxidized* in this reaction. Chlorine, which accepts an electron, is being *reduced.*

***Oxidation is a process of donation of electron(s). This process always occurs in parallel with reduction. An atom or molecule that takes electrons from another atom or molecule is called an "oxidizer", and it is being reduced in this process. Accordingly, an atom or a molecule that donates electron(s) is called a "reducer", and it is being oxidized in that process. The whole process is called "reduction-oxidation", or redox reaction.***

As a rule, the atoms that have one or few electrons on its outer shell have a tendency to donate electrons. Most metals fit this category. In contrast, the elements that have almost full outer shell (halogens, halkogens) prefer to accept electrons. Accordingly, these elements are strong oxidizerd, whereas metals are reducers.

## 9.6 Octet rule

This is a popular rule that tells any atom prefers to come to a state where exactly eight electrons are on its outer shell. This rule works mostly for elements of the second and third period of the Periodic table, but it is convenient for understanding of many chemical processes. Thus, it works perfectly for the above reaction: a sodium atom loses one electron, and there are exactly eight electrons at the outer shell of the sodium ion that froms as a result. The same works fro chlorine: it gets one electron, and there are exactly 8 electrons at its outer shell now.

The octet rule is just a consequaence of the fact that atoms prefer to form a state where the outer shell of closed. Obviously, this rule does not work for hydrogen or helium, because the capacity of the first shell is 2. The reason why the octer rule works for heavier elements will be discussed later.

The octet rule perfectly explains why alkali metals are always monivalent: they can donate just one electron, so they form just one ionic bond. The same works for halogens: they accept just one electron (and the outer shell becomes full), so they form just one ionic bond.

Calcium and other alkaline earth metals can donate *two* electrons, so they form two bonds with halogen atoms, hence they are divalent.

We will discull more complex cases later.

## 9.7 Covalent bond

In a situation when the atoms cannot donate or accept electrons, for example for two identical atoms, another possibility exists for observing the octet rule. They can *share* a pair of electrons. For example, one chlorine atom can meet another chlorine atom, and they can share a pair of electrons. What happens as a result of that?

Each chlorine atom has 7 electrons[8], or three electron pair at three orbitals and one electron at the fourth orbital. If each of two chlorine atoms donates their seventh electron, these electrons form a common orbital, which has two electrons now. One can say each chlorine atom has *four* orbitals each of which has two electrons, so the octet rule is satisfied now, and the electronic shells in both atoms becomes stable.

That explains why all halogens from a diatomic molecules:

$$\mathrm{Cl} + \mathrm{Cl} \longrightarrow \mathrm{Cl_2}$$

In chemistry, this situation described as "formation of a covalent bond between two chlorine atoms".

> ***An covalent bond is a bond between two atoms that forms as a result of sharing of two electrons among them.***

Oxygen has only six electrons, which means two oxygen atom need to share *two* electron pairs to meet the octet rule: each atom has two *their own electron pairs* and they share two electron pairs. Importantly, that does not mean the oxygens are connected with a "four electron" covalent bond. Actually they form *two* separate covalent bonds, or with a double bond.

# Homework

1. Using the Periodic table and the octet rule, explain why the valence of aluminium is three, and the valence of sulfur can be 2 and 6.

2. Read the Bottle Imp story `https://en.wikisource.org/wiki/Island_Nights%27_Entertainments/The_Bottle_Imp` (the link is clickable). We will need it during the next class.

Now we are ready to discuss the effects that prevent electrons from falling on nuclei, and the effects explain atomic structure. Before we started, it is useful to remind you a wisdom that was discovered nearly two thousands years ago. These words belong to ancient alchemist and pholosopher Hermes Trismegistus ("thrice-greatest Hermes"), who is believed to be one of prototypes of Jesus Christ. His *Emerald Tablet* contains a very interesting statement:

> ***Whatever is below is similar to that which is above. Through this the marvels of the work of one thing are procured and perfected.***

Thranslated to our modern language, these words mean that the same laws of nature governs the processes on the Earth and the Heaven, or, more generally speaking, that the

[8]We chemists usually discuss only the electrons at the outer shell, because other electrons play almost no role in chemical interactions. That is why I say chlorine has 7 electrons, despite the fact that it has more.

laws of nature are universal. This idea seems obvious to most Western thinkers, however, it is absoilutely non-trivial. Thus, in most Eastern cultures this idea is absent.

It would be correct to say that this short statement is one of the starting points all scientific knowlege originated from.

Why are we talking about that? Because the idea that the laws of Nature are universal means that no specific effects exists inside atoms that are responsible for existence of electron shells, orbitals, chemical bonds, etc., and all of that can be deduced from general laws of Physics. However, as we already demonstrated during previous lessons, these laws are unable to explain atomic structure. The reason why that happens is in one physical effect that is very hard to detect in our “big” world (the world where the average size of objects is more than 1 millimeter and the mass is more than 1 milligram). this effect become detectable when we are dealing with very small objects or when we are trying too measure very small distances. We will talk about that soon.

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