3.2: Chemistry of Minerals

Rocks are composed of minerals that have a specific chemical composition. To understand mineral chemistry, it is essential to examine the fundamental unit of all matter, the atom.

The Atom

Matter is made of atoms. Atoms consist of subatomic particles—protons, neutrons, and electrons. A simple model of the atom has a central nucleus composed of protons, which have positive charges, and neutrons which have no charge. A cloud of negatively charged electrons surrounds the nucleus, the number of electrons equaling the number of protons thus balancing the positive charge of the protons for a neutral atom. Protons and neutrons each have a mass number of 1. The mass of an electron is less than \(1/1000\)th that of a proton or neutron, meaning most of the atom’s mass is in the nucleus.
Matter is composed of elements which are atoms that have a specific number of protons in the nucleus. This number of protons is called the **Atomic Number** for the element. For example, an oxygen atom has 8 protons and an iron atom has 26 protons. An element cannot be broken down chemically into a simpler form and retains unique chemical and physical properties. Each element behaves in a unique manner in nature. This uniqueness led scientists to develop a periodic table of the elements, a tabular arrangement of all known elements listed in order of their atomic number.

The first arrangement of elements into a periodic table was done by Dmitri Mendeleev in 1869 using the elements known at the time [1]. In the periodic table, each element has a chemical symbol, name, atomic number, and atomic mass. The chemical symbol is an abbreviation for the element, often derived from a Latin or Greek name for the substance [2]. The atomic number is the number of protons in the nucleus. The atomic mass is the number of protons and neutrons in the nucleus, each with a mass number of one. Since the mass of electrons is so much less than the protons and neutrons, the atomic mass is effectively the number of protons plus neutrons.
The atomic mass of natural elements represents an average mass of the atoms comprising that substance in nature and is usually not a whole number as seen on the periodic table, meaning that an element exists in nature with atoms having different numbers of neutrons. The differing number of neutrons affects the mass of an element in nature and the atomic mass number represents this average. This gives rise to the concept of ‘isotope’. **Isotopes** are forms of an element with the same number of protons but different numbers of neutrons. There are usually several isotopes for a particular element. For example, 98.9% of carbon atoms have 6 protons and 6 neutrons. This isotope of carbon is called carbon-12 ($^{12}\text{C}$). A few carbon atoms, carbon-13 ($^{13}\text{C}$), have 6 protons and 7 neutrons. A trace amount of carbon atoms, carbon-14 ($^{14}\text{C}$), has 6 protons and 8 neutrons. Among the 118 known elements, the heaviest are fleeting human creations known only in high energy particle accelerators, and they decay rapidly. The heaviest naturally occurring element is uranium, atomic number 92. The eight most abundant elements in Earth’s continental crust are shown in Table ([PageIndex{1}]): [3; 4]. These elements are found in the most common rock-forming minerals.

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Abundance %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>O</td>
<td>47%</td>
</tr>
<tr>
<td>Silicon</td>
<td>Si</td>
<td>28%</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Al</td>
<td>8%</td>
</tr>
<tr>
<td>Iron</td>
<td>Fe</td>
<td>5%</td>
</tr>
<tr>
<td>Calcium</td>
<td>Ca</td>
<td>4%</td>
</tr>
<tr>
<td>Sodium</td>
<td>Na</td>
<td>3%</td>
</tr>
<tr>
<td>Potassium</td>
<td>K</td>
<td>3%</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Mg</td>
<td>2%</td>
</tr>
</tbody>
</table>

Figure ([PageIndex{3}]): Formation of Carbon 14 from Nitrogen 14
Chemical Bonding

Most substances on Earth are compounds containing multiple elements. Chemical bonding describes how these atoms attach with each other to form compounds, such as sodium and chlorine combining to form NaCl, common table salt. Compounds that are held together by chemical bonds are called molecules. Water is a compound of hydrogen and oxygen in which two hydrogen atoms are covalently bonded with one oxygen making the water molecule. The oxygen we breathe is formed when one oxygen atom covalently bonds with another oxygen atom to make the molecule O$_2$. The subscript 2 in the chemical formula indicates the molecule contains two atoms of oxygen.

![Figure 4](PageIndex(4)) A model of a water molecule, showing the bonds between the hydrogen and oxygen.

Most minerals are also compounds of more than one element. The common mineral calcite has the chemical formula \(\text{CaCO}_3\) indicating the molecule consists of one calcium, one carbon, and three oxygen atoms. In calcite, one carbon and three oxygen atoms are held together by covalent bonds to form a molecular ion, called carbonate, which has a negative charge. Calcium as an ion has a positive charge of plus two. The two oppositely charged ions attract each other and combine to form the mineral calcite, \(\text{CaCO}_3\). The name of the chemical compound is calcium carbonate, where calcium is \(\text{Ca}\) and carbonate refers to the molecular ion \(\text{CO}_3^{2-}\).

The mineral olivine has the chemical formula \((\text{Mg,Fe})_2\text{SiO}_4\), in which one silicon and four oxygen atoms are bonded with two atoms of either magnesium or iron. The comma between iron (Fe) and magnesium (Mg) indicates the two elements can occupy the same location in the crystal structure and substitute for one another.

Valence and Charge

The electrons around the atom’s nucleus are located in shells representing different energy levels. The outermost shell is called the valence shell. Electrons in the valence shell are involved in chemical bonding. In 1913, Niels Bohr proposed a simple model of the atom that states atoms are more stable when their outermost shell is full [5; 6]. Atoms of most elements thus tend to gain or lose electrons so the outermost or valence shell is full. In Bohr’s model, the innermost shell can have a maximum of two electrons and the second and third shells can have a maximum of eight electrons. When the innermost shell is the valence shell, as in the case of hydrogen and helium, it obeys the octet rule when it is full with two electrons. For elements in higher rows, the octet rule of eight electrons in the valence shell applies.
The rows in the periodic table present the elements in order of atomic number and the columns organize elements with similar characteristics, such as the same number of electrons in their valence shells. Columns are often labeled from left to right with Roman numerals I to VIII, and Arabic numerals 1 through 18. The elements in columns I and II have 1 and 2 electrons in their respective valence shells and the elements in columns VI and VII have 6 and 7 electrons in their respective valence shells.

In row 3 and column I, sodium (Na) has 11 protons in the nucleus and 11 electrons in three shells—2 electrons in the inner shell, 8 electrons in the second shell, and 1 electron in the valence shell. To maintain a full outer shell of 8 electrons per the octet rule, sodium readily gives up that 1 electron so there are 10 total electrons. With 11 positively charged protons in the nucleus and 10 negatively charged electrons in two shells, sodium when forming chemical bonds is an ion with an overall net charge of +1.

All elements in column I have a single electron in their valence shell and a valence of 1. These other columns I elements also readily give up this single valence electron and thus become ions with a +1 charge. Elements in column II readily give up 2 electrons and end up as ions with a charge of +2. Note that elements in columns I and II which readily give up their valence electrons, often form bonds with elements in columns VI and VII which readily take up these electrons. Elements in columns 3 through 15 are usually involved in covalent bonding. The last column 18 (VIII) contains the noble gases. These elements are chemically inert because the valence shell is already full with 8 electrons, so they do not gain or lose electrons. An example is the noble gas helium which has 2 valence electrons in the first shell. Its valence shell is therefore full. All elements in column VIII possess full valence shells and do not form bonds with other elements.

As seen above, an atom with a net positive or negative charge as a result of gaining or losing electrons is called an ion. In general, the elements on the left side of the table lose electrons and become positive ions, called cations because they are attracted to the cathode in an electrical device. The elements on the right side tend to gain electrons. These are called anions because they are attracted to the anode in an electrical device. The elements in the center of the periodic table, columns 3 through 15, do not consistently follow the octet rule. These are called transition elements. A common example is iron, which has a +2 or +3 charge depending on the oxidation state of the element. Oxidized Fe$^{+3}$ carries a +3 charge and reduced Fe$^{+2}$ is +2. These two different oxidation states of iron often impart dramatic colors to rocks containing their minerals—the oxidized form producing red colors and the reduced form producing green.

### Ionic Bonding

Ionic bonds, also called electron-transfer bonds, are formed by the electrostatic attraction between atoms having opposite charges. Atoms of two opposite charges attract each other electrostatically and form an ionic bond in which the positive ion
transfers its electron (or electrons) to the negative ion which takes them up. Through this transfer both atoms thus achieve a full valence shell. For example, one atom of sodium (Na\(^{+1}\)) and one atom of chlorine (Cl\(^{-1}\)) form an ionic bond to make the compound sodium chloride (NaCl). This is also known as the mineral halite or common table salt. Another example is calcium (Ca\(^{+2}\)) and chlorine (Cl\(^{-1}\)) combining to make the compound calcium chloride (CaCl\(_2\)). The subscript 2 indicates two atoms of chlorine are ionically bonded to one atom of calcium.

![Cubic arrangement of Na and Cl ions in Halite](image)

**Figure \(\PageIndex{6}\):** Cubic arrangement of Na and Cl ions in Halite

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**Covalent Bonding**

Ionic bonds are usually formed between a [metal](https://www.chemwiki.ucdavis.edu/) and a [nonmetal](https://www.chemwiki.ucdavis.edu/). Another type, called a covalent or electron-sharing bond, commonly occurs between nonmetals. Covalent bonds share electrons between ions to complete their valence shells. For example, oxygen (atomic number 8) has 8 electrons—2 in the inner shell and 6 in the valence shell. Gases like oxygen often form diatomic molecules by sharing valence electrons. In the case of oxygen, two atoms attach to each other and share 2 electrons to fill their valence shells to become the common oxygen molecule we breathe (O\(_2\)). Methane (CH\(_4\)) is another covalently bonded gas. The carbon atom needs 4 electrons and each hydrogen needs 1. Each hydrogen shares its electron with the carbon to form a molecule as shown in the figure.

![Electron sharing in methane](image)

- **Electron from hydrogen**
- **Electron from carbon**
Figure \PageIndex{7}): Methane molecule

References


