3.1: Elements, Atoms, and Atomic Theory

Chemistry is the science of matter. The fundamental building blocks of matter are the atoms of the various elements, which are composed of **subatomic particles**, the positively charged **proton** (+), the negatively charged **electron** (-), and the electrically neutral **neutron** (n). It is the properties of these atoms that determine matter's chemical behavior. More specifically, it is the arrangement and energy levels of electrons in atoms that direct how they interact with each other, thus dictating all chemical behavior. One of the most fundamental aspects of chemistry is that elemental behavior varies periodically with increasing atomic number. This has enabled placement of elements in an orderly arrangement with increasing atomic number known as the **periodic table**. The periodic behavior of elements' chemical properties is due to the fact that, as atomic number increases, electrons are added incrementally to atoms and occupy so-called shells, each filled with a specific number of electrons. After each shell is filled, a new shell is started, thus beginning a new period (row) of the periodic table. This sounds complicated, and indeed may be so, occupying the full-time computational activities of banks of computers to explain the behavior of electrons in matter. However, this behavior can be viewed in simplified models and is most easily understood for the first 20 elements using dots to represent electrons, enabling construction of an abbreviated 20-element periodic table. Although simple, this table helps understand and explain most of the chemical phenomena discussed in this book.

The chapter also emphasizes some of the green aspects of the first 20 elements and how they relate to sustainability. Included among these elements are the nitrogen, oxygen, carbon (contained in carbon dioxide), and hydrogen and oxygen (in water vapor) that make up most of the air in the "green" atmosphere; the hydrogen and oxygen in water, arguably the greenest compound of all; the sodium and chlorine in common table salt; the silicon, calcium, and oxygen that compose most mineral matter, including the soil that grows plants supplying food to most organisms; and the hydrogen, oxygen, carbon, nitrogen, phosphorus, and sulfur that are the predominant elements in all living material.

Long Before Subatomic Particles Were Known, There Was Dalton's Atomic Theory

Atomic theory describes the atoms in relation to chemical behavior. With the sophisticated tools now available to chemists, the nature of atoms, largely based upon the subatomic particles of which they are composed, especially the negatively charged electrons, is well known. But long before these sophisticated tools were even dreamed about, more than two centuries ago in 1808, an English schoolteacher named John Dalton came up with the atomic theory that bears his name. To a large extent, this theory is the conceptual basis of modern chemistry. Key aspects of Dalton's atomic theory are the following:

- The matter in each element is composed of extremely small particles called atoms. (Dalton regarded atoms as indivisible, unchanging bodies. We now know that they exchange and share electrons, which is the basis of chemical bonding.)
- Atoms of different elements have different chemical properties. (These differences may range from very slight, such as those between the noble gases neon and argon, to vastly different, such as those between highly metallic sodium and strongly nonmetallic chlorine.)
- Atoms cannot be created, destroyed, or changed to atoms of other elements. (In modern times, the provision is added that these things do not happen in ordinary chemical processes, since atoms can be changed to atoms of other elements by nuclear reactions, such as those that occur in nuclear reactors.)
- Chemical compounds are formed by the combination of atoms of different elements in definite, constant ratios that usually can be expressed as integers or simple fractions.
- Chemical reactions involve the separation and combination of atoms. (This phenomenon was surmised before anything was known about the nature of chemical bonds that are broken and formed as part of the process of chemical reactions.)

Three Important Laws

Dalton's atomic theory explains the three important laws listed below. Evidence for these laws had been found prior to the publishing of Dalton's atomic theory, and the atomic theory is largely based upon them.

1. **Law of Conservation of Mass**: *There is no detectable change in mass in an ordinary chemical reaction*. (This law, which was first stated in 1798 by "the father of chemistry," the Frenchman Antoine Lavoisier, follows from the fact that in ordinary chemical reactions no atoms are lost, gained, or changed; in chemical reactions, mass is conserved.)
2. **Law of Constant** Composition: *A specific chemical compound always contains the same elements in the same proportions by mass*.
3. **Law of Multiple Proportions**: *When two elements combine to form two or more compounds, the masses of one combining with a fixed mass of the other are in ratios of small whole numbers*. A common illustration of this law is provided by the simple

hydrocarbon compounds of carbon and hydrogen, which include CH_4, C_2H_2, C_2H_4, and C_2H_6. In these compounds the relative masses of C and H are in ratios of small whole numbers.

The Nature of Atoms

At this point it is useful to note several characteristics of atoms, which were introduced in Section 2.11. Atoms are extremely small and extremely light. Their individual masses are expressed by the minuscule atomic mass unit, u. The sizes of atoms are commonly expressed in picometers, where a picometer is 0.000 000 001 millimeters (a millimeter is the smallest division on the metric side of a ruler). Atoms may be regarded as spheres with diameters between 100 and 300 picometers.

As noted at the beginning of this chapter, atoms are composed of three basic *subatomic particles*, the positively charged *proton*, the electrically neutral *neutron*, and the much lighter negatively charged *electron*. Each proton and neutron has a mass of essentially 1 atomic mass unit, whereas the mass of the electron is only about 1/2000 as much The protons and neutrons are located in the *nucleus* at the center of the atom and the electrons compose a “fuzzy cloud” of negative charge around the nucleus. Essentially all the mass of an atom is in the nucleus and virtually all the volume is in the cloud of electrons. Each atom of a specific element has the same number of protons in its nucleus. This is the *atomic number* of the element. Each element has a name and is represented by a **chemical symbol** consisting of one or two letters. Atoms of the same element that have different numbers of neutrons and, therefore, different masses, are called **isotopes**. Isotopes may be represented by symbols such as $^{12}_{6}C$ where the subscript is the atomic number and the superscript is the **mass number**, which is the sum of the numbers of protons and neutrons in an atom.

The average mass of all the atoms of an element is the **atomic mass**. Atomic masses are expressed relative to the carbon $^{12}_{6}C$ the isotope, which contains 6 protons and 6 neutrons in its nucleus. The mass of this isotope is taken as exactly 12 u. Atomic masses normally are not integers, in part because atoms of most elements consist of two or more isotopes with different masses.

Electrons in Atoms

The behavior of electrons in the cloud of negative charge making up most of the volume of atoms, particularly their energy levels and orientations in space, are what determine chemical behavior. Arrangements of electrons are described by *electron configuration*. A detailed description of electron configuration is highly mathematical and sophisticated, but is represented in a very simplified fashion in this chapter. Because of their opposite charges, electrons are strongly attracted to positively charged nuclei, but they do not come to rest on it.

The placement of electrons in atoms determines the configuration of the periodic table, a complete version of which is printed at the end of this chapter. Elements are listed across this table in *periods* such that elements located in the same vertical *groups* have generally similar chemical behavior. The derivation of the complete periodic table showing more than 100 elements is too complicated for this book. So, in the remainder of this chapter, the first 20 elements will be discussed in order and the placement of electrons in the atoms of these elements will illustrate how these elements can be placed in the periodic table. From this information a brief 20-element periodic table will be constructed that should be very useful in explaining chemical behavior.