ATOMIC AND NUCLEAR THEORY AND THE PERIODIC TABLE

Atoms and other subatomic particles make up all matter in the universe. Atoms have a nucleus containing protons and neutrons surrounded by a larger region containing electrons. The number of protons in the nucleus of the atom defines the characteristics of each atom and is known as the "atomic number." Protons and neutrons have relatively the same mass, while electrons have approximately 1,837 times less mass than protons and neutrons. The "atomic mass" of an atom is equivalent to the number of protons and neutrons in the nucleus of the atom. Not all atoms of a particular element contain the same number of neutrons in the nucleus. Atoms with different numbers of neutrons but with the same number of protons in their nuclei are called isotopes. Despite the great number of substances in the universe, there are only about 100 different stable elements.

Through the years, scientists have developed models to organize the elements according to their properties. The result of this work is the periodic table. The periodic table is a model in which elements are organized horizontally by increasing atomic number and vertically by families of elements with related chemical properties. Today, scientists recognize that patterns in chemical properties, such as in chemical reactivity and bond formation, are related to the patterns in atoms' outermost electrons.

The nucleus of an atom is an active space. Understanding of the processes that take place in the nucleus is important to explain the formation and abundance of the elements, radioactivity, the generation of nuclear energy, and the release of energy from stars. Two important forces, the strong and weak nuclear forces, play a fundamental role in the type of processes that take place in the nucleus. Without the strong nuclear force, the electromagnetic forces between protons would make all nuclei other than hydrogen unstable. Nuclear fission is a process in which a heavy nucleus splits into two or more smaller nuclei. These processes release radiation in the form of alpha particles and beta particles and/or the emission of gamma rays. Nuclear fusion is a process in which a collision of two small nuclei results in the formation of a single heavy nucleus and the release of energy.

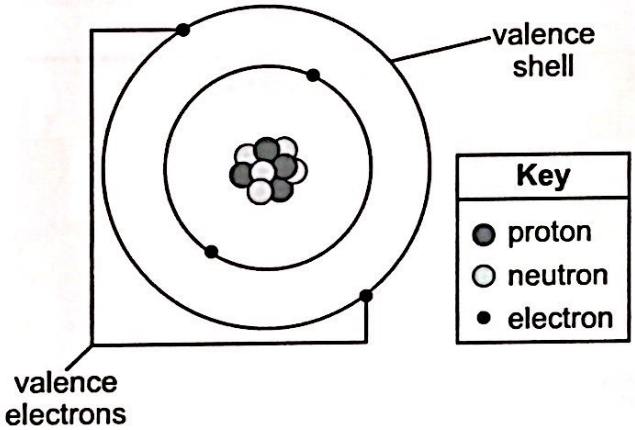
CORE IDEAS

- The characteristics of an atom are determined by its structure. (SPS1a)
- A change in the nuclear structure or electron configuration, or both, results in the emission of radiation. (SPS4a)
- Valence electrons determine the chemical properties of atoms. (SPS1b)
- The rate of radioactive decay for an isotope is constant and is measured by its half-life. (SPS4b)
- The number of protons determines the type of element. (SPS1a)
- The elements, arranged by increasing atomic number, exhibit periodic trends in properties. (SPS1c)
- Non-stable nuclei are radioactive and emit ionizing radiation in the form of alpha particles, beta particles, or gamma radiation. (SPS4a)
- Properties such as valence electrons, ion formation, metallic or nonmetallic properties, and phase at room temperature can be predicted for representative elements by using the periodic table. (SPS1b)
- Chemical reactions are the result of changes in electron configuration. (SPS1a, b)
- Nuclear reactions convert matter into energy through the processes of radioactive decay, fission, and fusion. (SPS4a, b)
- Bonds between atoms are formed when electrons are transferred or shared. (SPS2a)
- The International Union for Pure and Applied Chemistry (IUPAC) conventions provide a standard system for naming compounds and writing formulas. (SPS2c)

KEY CONCEPTS

All the things that we observe in the universe are made up of atoms. Atoms contain subatomic particles called protons, neutrons, and electrons. These particles are composed of smaller particles named quarks.

Protons and **neutrons** are located in the **nucleus**, or center, of the atom. The proton has a single positive (+) charge, while the neutron has a zero (0), or neutral, charge. The proton and neutron have approximately the same mass. The electron has a single negative (–) charge, and its mass is about 1,837 times less than the proton or neutron. Electrons, unlike protons and neutrons, are found outside the nucleus in a region called the **electron cloud**. The electron cloud is divided into **energy levels**, which are sometimes referred to as **electron shells.** Electrons in the outermost energy level, or **valence shell**, are called **valence electrons.** The outermost electrons determine how the element will react chemically with other elements.



There are many ways to describe an atom. One way is to use the **atomic number.** It tells how many protons reside in the nucleus and identifies the element. For example, an element with an atomic number of 6 (an atom with six protons) is a carbon (C) atom. All atoms with the same number of protons are of the same element, no matter how many electrons or neutrons they might have.

Look It Up

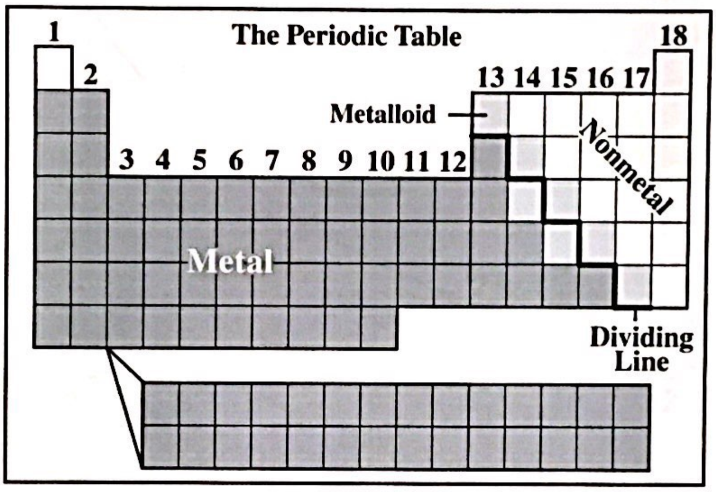
Use the periodic table to locate the following information about the first 20 elements:

- Element name
- Symbol
- Atomic number
- Atomic mass

Isotopes are atoms that have the same number of protons but different numbers of neutrons. For example, there are several isotopes of carbon. Most carbon on Earth is in the form of carbon-12, which has 6 protons and 6 neutrons. However, carbon also exists naturally with 7 neutrons, called carbon-13, and 8 neutrons, called carbon-14. Similarly, hydrogen normally has a single proton and no neutrons but also can exist with 1 neutron, as hydrogen-2, which is sometimes called deuterium, and as hydrogen-3 with 2 neutrons, sometimes called tritium. As a result, a sample of a single element may contain atoms that have different masses. The **atomic mass** is the average mass of all the different isotopes that make up the element in the proportions found in nature.

In the nineteenth century, chemists discovered that certain elements had similar properties. They found that when elements were arranged according to reactivity, a periodic pattern in the properties of the elements could be observed. The **periodic table** was then developed to organize and classify these elements and even predict the existence of elements that had not yet been discovered.

There are three major classifications for the elements. These can be seen in the periodic table below.



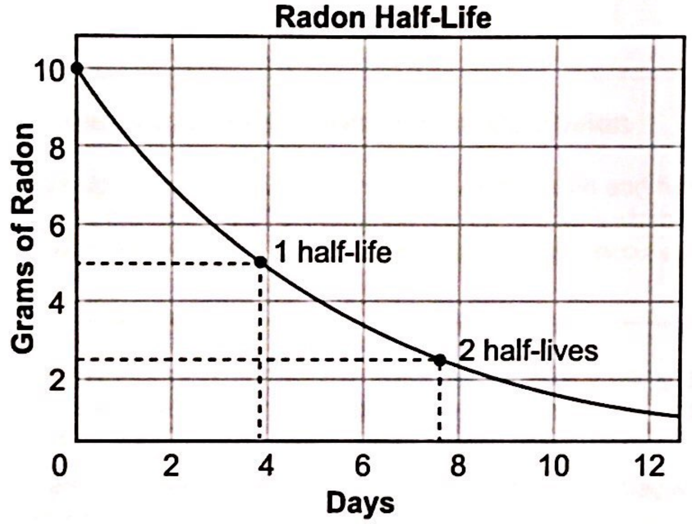
- The **metal** elements are located to the left of the dividing line. These elements are all solids at room temperature with the exception of mercury (Hg). Metals are notable for their shiny luster and ability to conduct electricity.
- The **nonmetal** elements are located to the right of the dividing line. Nitrogen (N), oxygen (O), fluorine (F), chlorine (Cl), and the noble gases (in the last column) are gases at room temperature. Bromine (Br) is a liquid, while all other nonmetals are solid. Nonmetals do not conduct electricity.
- **Metalloids** have both metallic and nonmetallic properties. These are solid at room temperature. They are located between the metals and nonmetals and straddle the diagonal dividing line. Metalloids are useful as part of electronic circuits.

Elements that have similar chemical properties are arranged in vertical columns called **families.** Each column is identified by a number seen at the top of each column as in the periodic table above. The **representative elements** are those elements located in columns 1 and 2 and 13–18. Elements in columns 1 and 2 have the same number of valence electrons as their column number. The number of valence electrons for elements in columns 13–18 can be found by subtracting 10 from the column number. Valence electrons for non-representative elements (columns 3–12) will not be covered on the test. It is important to note that elements within the same column have the same number of valence electrons. Elements with the same number of valence electrons react with other elements in a very similar way. Elements in column 1, the **alkali metals**, column 2, the **alkaline earth metals**, and column 17, the

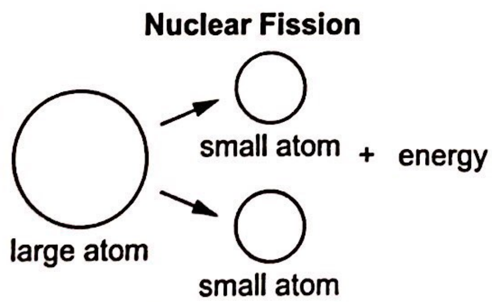
halogens, are the most reactive representative elements, while the **noble gases** (column 18) are the most nonreactive elements.

When a metal and a nonmetal react with each other, the metal forms a positive ion (cation) and the nonmetal forms a negative ion (anion). Metals in column 1 lose one electron to form an ion with a charge or valence number of $^{+}1$. Column 2 metals lose two electrons to form ions with a $^{+}2$ charge. Nonmetallic elements in columns 15, 16, and 17 gain electrons, forming ions with a negative charge. Column 15 elements gain three electrons to form ions with a $^{-}3$ charge. Column 16 elements gain two electrons and form ions with a $^{-}2$ charge. Column 17 elements gain one electron and form ions with a $^{-}1$ charge.

Every radioactive element has a distinctive rate of decay. This rate is measured by the **half-life** ($t_{1/2}$). The half-life is the time required for one-half of the atoms to undergo decay to isotopes of other atoms. Radon, a radioactive gas, has a half-life of 3.8 days. That means after 3.8 days, only one-half of the original radon atoms are left. After 7.6 days, only one-fourth are left, and so on.

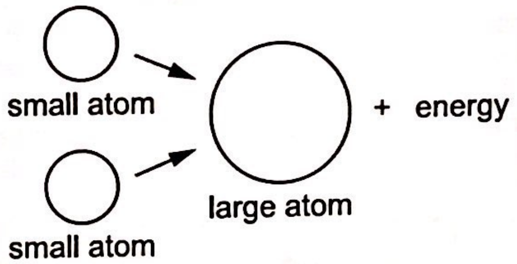


Fission occurs when some atomic nuclei decay spontaneously or when they are bombarded by neutrons. This results in the production of elements with less mass and radiation. One benefit of fission is that it provides a significant amount of electrical energy for the United States and other developed nations. Compared to coal or oil, fission provides about a million times more energy per pound of fuel. It also eliminates air pollutants. However, nuclear waste from fission creates disposal problems. Improper disposal of radioactive wastes underground can lead to radioactive contamination of water supplies.



Fusion as a future energy source might provide all the benefits of fission with few of its problems. Fusion occurs when two low mass nuclei, such as hydrogen, collide and combine to form nuclei with greater mass. Fusion occurs in the sun and is one of the most energetic processes in the universe.

Nuclear Fusion



> **Memory Aid—Fission/Fusion Confusion**
>
> Here is a way to help remember the difference between fission and fusion. *Fission* is similar to *fissure*, the process of splitting. So fission happens when the nucleus splits in two. *Fusion* is like *fuse*, to unite two things. So fusion occurs when two nuclei join.

Radiation is the emission of energy as electromagnetic waves or as moving particles. Sometimes, very massive elements have unstable nuclei, causing them to decay into less massive elements. This process, called radioactive decay, could result in three main types of radiation:

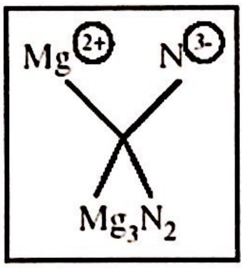
- **Alpha** (α) radiation or particles: These particles consist of helium (He) nuclei, which are very large. Usually, a sheet of paper can stop them.
- **Beta** (β) radiation or particles: These particles consist of electrons (e^-), which are much smaller and have less mass than alpha particles. They have much more penetrating power, and a thick wooden board is required to stop them.
- **Gamma** (γ) rays: These rays are an extremely energetic form of light. Usually, several inches of lead or a few feet of concrete are required to shield people from the damaging effects of gamma radiation.

Covalent bonds form when atoms share valence electrons. The names of **binary covalent compounds** must include prefixes to show the number of atoms of each element in the compound. The first atom is named after the element it represents. If there are two or more atoms of that element, the prefixes *di-*, *tri-*, or *tetra-* or a higher numeral prefix are used. The prefix *mono-* (one) is never used for the first element. All numerical prefixes, however, are used to indicate the number of atoms of the second element. This prefix is placed before the first syllable of the element name. The suffix *-ide* is then added to the end. For example, the covalent compound CO_2 is named carbon dioxide. Notice the *di-* prefix for the second element and the lack of a prefix for the first element. Another example is P_2S_5. It is named diphosphorus pentasulfide. Notice that the *di-* prefix is used for the two phosphorus atoms and that the *penta-* prefix is used for the five sulfur atoms in the compound.

Numerical Prefixes

mono-	1
di-	2
tri-	3
tetra-	4
penta-	5
hexa-	6
hepta-	7
octa-	8
nona-	9
deca-	10

Binary ionic compounds contain only two different elements. Ionic bonds form between metals and nonmetals because of a complete transfer of electrons from the metal to the nonmetal. The resulting oppositely charged ions attract. Sodium chloride, NaCl, is an example of a binary ionic compound. In binary ionic compounds with more than one atom of each element, the correct formula can be found by making a cross, as in the example below.



Notice that the charge on the nitride ion (N^{3-}) becomes the number of magnesium ions in the formula. Likewise, the charge on the magnesium ion (Mg^{2+}) becomes the number of nitride ions in the formula. In this way, the net charges are balanced (+6 and −6), making magnesium nitride neutral. This method usually works, except when the charges on the ions are exact opposites, such as $^{+}2$ and $^{-}2$. In that case, the ions should be combined in a 1:1 ratio to balance the charges.

A **cation** is an ion that results from atoms or molecules that have lost one or more valence electrons, giving them a positive charge. An **anion** is an ion that results from atoms or molecules that have gained one or more valence electrons, giving them a negative charge. In the cross above, Mg^{2+} is the cation and N^{3-} is the anion.

Any combination of cations and anions can form a binary ionic compound. To name this type of compound, simply write the name of the element that forms the cation first. Then follow with the name of the anion. The name of the anion will usually contain the first syllable of the element name and end with the suffix *-ide*. For example, the formula unit $AlCl_3$ would be named aluminum chloride. Notice that the cation has the element name and that the first syllable of chlorine, *chlor-*, has taken the *-ide* ending.