2.1 Atoms and Their Composition

Section Preview/ Specific Expectations

In this section, you will

- **define** and **describe** the relationships among atomic number, mass number, atomic mass, isotope, and radioisotope
- **communicate** your understanding of the following terms: *atom, atomic mass unit (u), atomic number (Z), mass number (A), atomic symbol, isotopes, radioactivity, radioisotopes*

Technology LINK

How scientists visualize the atom has changed greatly since Dalton proposed his atomic theory in the early nineteenth century. Technology has played an essential role in these changes. At a library or on the Internet, research the key modifications to the model of the atom. Create a summary chart to show your findings. Include the scientists involved, the technologies they used, the discoveries they made, and the impact of their discoveries on the model of the atom. If you wish, use a suitable graphics program to set up your chart.

Elements are the basic substances that make up all matter. About 90 elements exist naturally in the universe. The two smallest and least dense of these elements are hydrogen and helium. Yet hydrogen and helium account for nearly 98% of the mass of the entire universe!

Here on Earth, there is very little hydrogen in its pure elemental form. There is even less helium. In fact, there is such a small amount of helium on Earth that it escaped scientists' notice until 1895.

Regardless of abundance, any two samples of hydrogen—from anywhere on Earth or far beyond in outer space—are identical to each other. For example, a sample of hydrogen from Earth's atmosphere is identical to a sample of hydrogen from the Sun. The same is true for helium. This is because *each element is made up of only a single kind of atom*. For example, the element hydrogen contains only hydrogen atoms. The element helium contains only helium atoms. What, however, is an atom?

The Atomic Theory of Matter

John Dalton was a British teacher and self-taught scientist. In 1809, he described atoms as solid, indestructible particles that make up all matter. (See Figure 2.1.) Dalton's concept of the atom is one of several ideas in his atomic theory of matter, which is outlined on the next page. Keep in mind that scientists have modified several of Dalton's ideas, based on later discoveries. You will learn about these modifications at the end of this section. See if you can infer what some of them are as you study the structure of the atom on the next few pages.

Figure 2.1 **This illustration shows an atom as John Dalton (1766–1844) imagined it. Many reference materials refer to Dalton's concept of the atom as the "billiard ball model." Dalton, however, was an avid lawn bowler. His concept of the atom was almost certainly influenced by the smooth, solid bowling balls used in the game.**

Dalton's Atomic Theory (1809)

- All matter is made up of tiny particles called atoms. An atom cannot be created, destroyed, or divided into smaller particles.
- The atoms of one element cannot be converted into the atoms of any another element.
- All the atoms of one element have the same properties, such as mass and size. These properties are different from the properties of the atoms of any other element.
- Atoms of different elements combine in specific proportions to form compounds.

CHECKPOINT

The atomic theory was a convincing explanation of the behaviour of matter. It explained two established scientific laws: the law of conservation of mass and the law of definite composition.

- *Law of conservation of mass*: During a chemical reaction, the total mass of the substances involved does not change.
- *Law of definite proportion*: Elements always combine to form compounds in fixed proportions by mass. (For example, pure water always contains the elements hydrogen and oxygen, combined in the following proportions: 11% hydrogen and 89% oxygen.)

How does the atomic theory explain these two laws?

The Modern View of the Atom

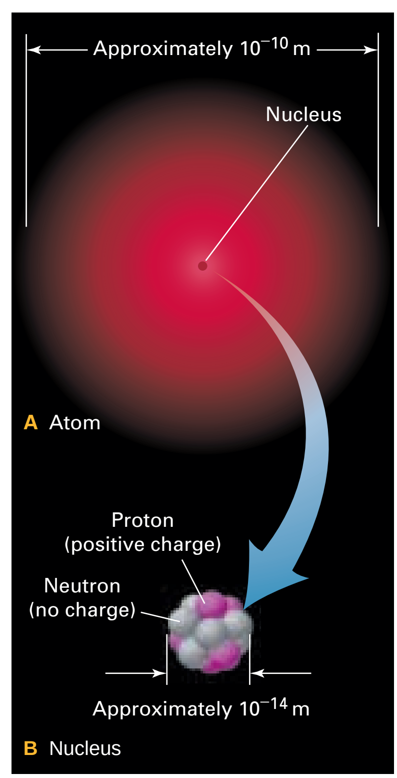
An **atom** is the smallest particle of an element that still retains the identity and properties of the element. For example, the smallest particle of the writing material in your pencil is a carbon atom. (Pencil "lead" is actually a substance called graphite. Graphite is a form of the element carbon.)

An average atom is about 10^{-10} m in diameter. Such a tiny size is difficult to visualize. If an average atom were the size of a grain of sand, a strand of your hair would be about 60 m in diameter!

Atoms themselves are made up of even smaller particles. These *subatomic particles* are protons, neutrons, and electrons. Protons and neutrons cluster together to form the central core, or *nucleus*, of an atom. Fast-moving electrons occupy the space that surrounds the nucleus of the atom. As their names imply, subatomic particles are associated with electrical charges. Table 2.1 and Figure 2.2 summarize the general features and properties of an atom and its three subatomic particles.

Table 2.1 Properties of Protons, Neutrons, and Electrons

Subatomic particle	Charge	Symbol	Mass (in g)	Radius (in m)
electron	1–	e^-	9.02×10^{-28}	smaller than 10^{-18}
proton	1+	p^+	1.67×10^{-24}	10^{-15}
neutron	0	n^0	1.67×10^{-24}	10^{-15}



Expressing the Mass of Subatomic Particles

As you can see in Table 2.1, subatomic particles are incredibly small. Suppose that you could count out protons or neutrons equal to

602 000 000 000 000 000 000 000 (or 6.02×10^{23})

and put them on a scale. They would have a mass of about 1 g. This means that one proton or neutron has a mass of

$$\frac{1 \text{ g}}{6.02 \times 10^{23}} = 0.000\,000\,000\,000\,000\,000\,000\,001\,66 \text{ g}$$
$$= 1.66 \times 10^{-24} \text{ g}$$

It is inconvenient to measure the mass of subatomic particles using units such as grams. Instead, chemists use a unit called an **atomic mass unit** (symbol **u**). A proton has a mass of about 1 u, which is equal to 1.66×10^{-24} g.

Figure 2.2 This illustration shows the modern view of an atom. Notice that a fuzzy, cloud-like region surrounds the atomic nucleus. Electrons move rapidly throughout this region, which represents most of the atom's volume.

CHEM FACT

The number 6.02×10^{23} is called the Avogadro constant. In Chapter 5, you will learn more about the Avogadro constant.

CHEM FACT

A proton is about 1837 times more massive than an electron. According to Table 2.1, the mass of an electron is 9.02×10^{-28} g. This value is so small that scientists consider the mass of an electron to be approximately equal to zero. Thus, electrons are not taken into account when calculating the mass of an atom.

The Nucleus of an Atom

All the atoms of a particular element have the same number of protons in their nucleus. For example, all hydrogen atoms—anywhere in the universe—have one proton. All helium atoms have two protons. All oxygen atoms have eight protons. Chemists use the term **atomic number** (symbol ***Z***) to refer to the number of protons in the nucleus of each atom of an element.

As you know, the nucleus of an atom also contains neutrons. In fact, the mass of an atom is due to the combined masses of its protons and neutrons. Therefore, an element's **mass number** (symbol ***A***) is the total number of protons and neutrons in the nucleus of one of its atoms. Each proton or neutron is counted as one unit of the mass number. For example, an oxygen atom, which has 8 protons and 8 neutrons in its nucleus, has a mass number of 16. A uranium atom, which has 92 protons and 146 neutrons, has a mass number of 238.

Information about an element's protons and neutrons is often summarized using the chemical notation shown in Figure 2.3. The letter X represents the **atomic symbol** for an element. (The atomic symbol is also called the *element symbol*.) Each element has a different atomic symbol. All chemists, throughout the world, use the same atomic symbols. Over the coming months, you will probably learn to recognize many of these symbols instantly. Appendix G, at the back of this book, lists the elements in alphabetical order, along with their symbols. You can also find the elements and their symbols in the periodic table on the inside back cover of this textbook, and in Appendix C. (You will review and extend your understanding of the periodic table, in section 2.2.)

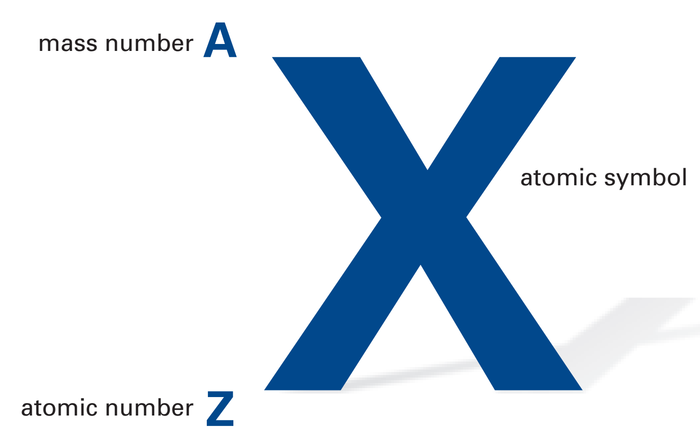


Figure 2.3

Notice what the chemical notation in Figure 2.3 does, and does not, tell you about the structure of an element's atoms. For example, consider the element fluorine: ${}^{19}_{9}F$. The mass number (the superscript 19) indicates that fluorine has a total of 19 protons and neutrons. The atomic number (subscript 9) indicates that fluorine has 9 protons. Neither the mass number nor the atomic number tells you how many neutrons fluorine has. You can calculate this value, however, by subtracting the atomic number from the mass number.

$$\text{Number of neutrons} = \text{Mass number} - \text{Atomic number}$$
$$= A - Z$$

Thus, for fluorine,

$$\begin{aligned}\text{Number of neutrons} &= A - Z \\ &= 19 - 9 \\ &= 10\end{aligned}$$

Now try a few similar calculations in the Practice Problem below.

Practice Problems

1. Copy the table below into your notebook. Fill in the missing information. Use a periodic table, if you need help identifying the atomic symbol.

Chemical notation	Element	Number of protons	Number of neutrons
$^{11}_{5}B$	(a)	(b)	(c)
$^{208}_{82}Pb$	(d)	(e)	(f)
(g)	tungsten	(h)	110
(i)	helium	(j)	2
$^{239}_{94}Pu$	(k)	(l)	(m)
$^{56}_{26}$(n)	(o)	26	(p)
(q)	bismuth	(r)	126
(s)	(t)	47	60
$^{20}_{10}$(u)	(v)	(w)	(x)

Using the Atomic Number to Infer the Number of Electrons

As just mentioned, the atomic number and mass number do not give you direct information about the number of neutrons in an element. They do not give you the number of electrons, either. You can infer the number of electrons, however, from the atomic number. The atoms of each element are electrically neutral. This means that their positive charges (protons) and negative charges (electrons) must balance one another. In other words, *in the neutral atom of any element, the number of protons is equal to the number of electrons*. For example, a neutral hydrogen atom contains one proton, so it must also contain one electron. A neutral oxygen atom contains eight protons, so it must contain eight electrons.

Isotopes and Atomic Mass

All neutral atoms of the same element contain the same number of protons and, therefore, the same number of electrons. The number of neutrons can vary, however. For example, most of the oxygen atoms in nature have eight neutrons in their atomic nuclei. In other words, most oxygen atoms have a mass number of 16 (8 protons + 8 neutrons). As you can see in Figure 2.4 on the next page, there are also two other naturally occurring forms of oxygen. One of these has nine neutrons, so $A = 17$. The other has ten neutrons, so $A = 18$. These three forms of oxygen are called isotopes. **Isotopes** are atoms of an element that have the same number of protons but different numbers of neutrons.

Math LINK

Expressing numerical data about atoms in units such as metres is like using a bulldozer to move a grain of sand. Atoms and subatomic particles are so small that they are not measured using familiar units. Instead, chemists often measure atoms in nanometres ($1 \text{ nm} = 1 \times 10^{-9}$ m) and picometres ($1 \text{ pm} = 1 \times 10^{-12}$ m).

- Convert the diameter of a proton and a neutron into nanometres and then picometres.
- Atomic and subatomic sizes are hard to imagine. Create an analogy to help people visualize the size of an atom and its subatomic particles. (The first sentence of this feature is an example of an analogy.)

Web LINK

www.school.mcgrawhill.ca/resources/
The atomic symbols are linked to the names of the elements. The links are not always obvious, however. Many atomic symbols are derived from the names of the elements in a language other than English, such as Latin, Greek, German, or Arabic. With your classmates, research the origin and significance of the name of each element. Go to the web site above. Go to **Science Resources**, then to **Chemistry 11** to find out where to go next. See if you can infer the rules that are used to create the atomic symbols from the names of the elements.

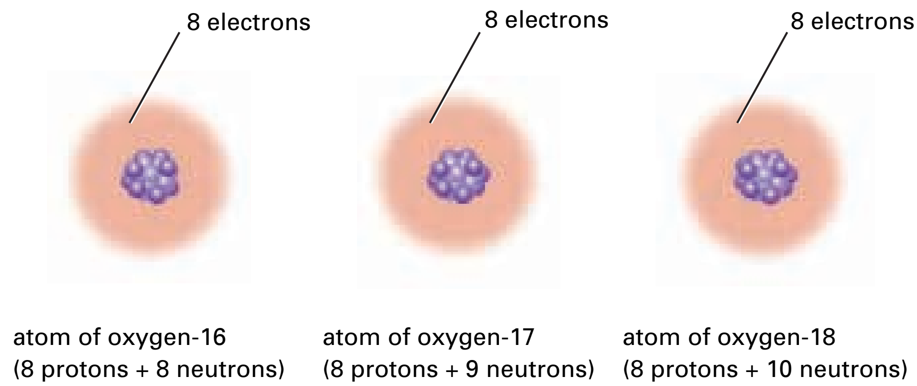


Figure 2.4 **Oxygen has three naturally occurring isotopes. Notice that oxygen-16 has the same meaning as $^{16}_{8}O$. Similarly, oxygen-17 has the same meaning as $^{17}_{8}O$ and oxygen-18 has the same meaning as $^{18}_{8}O$.**

The isotopes of an element have very similar chemical properties because they have the same number of protons and electrons. They differ in mass, however, because they have different numbers of neutrons.

Some isotopes are more unstable than others. Their *nuclei* (plural of *nucleus*) are more likely to decay, releasing energy and subatomic particles. This process, called **radioactivity**, happens spontaneously. All uranium isotopes, for example, have unstable nuclei. They are called radioactive isotopes, or **radioisotopes** for short. Many isotopes are not radioisotopes. Oxygen's three naturally occurring isotopes, for example, are stable. In contrast, chemists have successfully synthesized ten other isotopes of oxygen, all of which are unstable radioisotopes. (What products result when radioisotopes decay? You will find out in Chapter 4.)

CHEM FACT

Radioisotopes decay because their nuclei are unstable. The time it takes for nuclei to decay varies greatly. For example, it takes billions of years for only half of the nucleus of naturally occurring uranium-238 to decay. The nuclei of other radioisotopes — mainly those that scientists have synthesized — decay much more rapidly. The nuclei of some isotopes, such as sodium-22, take about 20 years to decay. For calcium-47, this decay occurs in a matter of days. The nuclei of most synthetic radioisotopes decay so quickly, however, that the radioisotopes exist for mere fractions of a second.

Electrons in Atoms

So far, much of the discussion about the atom has concentrated on the nucleus and its protons and neutrons. What about electrons? What is their importance to the atom? Recall that electrons occupy the space surrounding the nucleus. Therefore, they are the first subatomic particles that are likely to interact when atoms come near one another. In a way, electrons are on the "front lines" of atomic interactions. The number and arrangement of the electrons in an atom determine how the atom will react, if at all, with other atoms. As you will learn in section 2.2, and throughout the rest of this unit, electrons are responsible for the chemical properties of the elements.

CHECKPOINT

When chemists refer symbolically to oxgyen-16 atoms, they often leave out the atomic number. They write ^{16}O. You can write other isotopes of oxygen, and all other elements, the same way. Why is it acceptable to leave out the atomic number?

Revisiting the Atomic Theory

John Dalton did not know about subatomic particles when he developed his atomic theory. Even so, the modern atomic theory (shown on the next page) retains many of Dalton's ideas, with only a few modifications. Examine the comments to the right of each point. They explain how the modern theory differs from Dalton's.

The atomic theory is a landmark achievement in the history of chemistry. It has shaped the way that all scientists, especially chemists, think about matter. In the next section, you will investigate another landmark achievement in chemistry: the periodic table.

The Modern Atomic Theory

- All matter is made up of tiny particles called atoms. Each atom is made up of smaller subatomic particles: protons, neutrons, and electrons.

  Although an atom is divisible, it is still the smallest particle of an element that has the properties and identity of the element.

- The atoms of one element cannot be converted into the atoms of any another element by a chemical reaction.

  Nuclear reactions (changes that alter the composition of the atomic nucleus) may, in fact, convert atoms of one element into atoms of another.

- Atoms of one element have the same properties, such as average mass and size. These properties are different from the properties of the atoms of any other element.

  Different isotopes of an element have different numbers of neutrons and thus different masses. As you will learn in Chapter 5, scientists treat elements as if their atoms have an average mass.

- Atoms of different elements combine in specific proportions to form compounds.

  This idea has remained basically unchanged.

Section Review

1 **C** Copy the table below into your notebook. Use a graphic organizer to show the relationship among the titles of each column. Then fill in the blanks with the appropriate information. (Assume that the atoms of each element are neutral.)

Element	Atomic number	Mass number	Number of protons	Number of electrons	Number of neutrons
(a)	(b)	108	(c)	47	(d)
(e)	(f)	(g)	33	(h)	42
(i)	35	(j)	(k)	(l)	45
(m)	79	179	(n)	(o)	(p)
(q)	(r)	(s)	(t)	50	69

2 **K/U** Explain the difference between a stable isotope and a radioisotope. Provide an example other than oxygen to support your answer.

3 **K/U** Examine the information represented by the following pairs: $^{3}_{1}H$ and $^{3}_{2}He$; $^{14}_{6}C$ and $^{16}_{7}N$; $^{19}_{9}F$ and $^{18}_{9}F$.

(a) For each pair, do both members have the same number of protons? electrons? neutrons?

(b) Which pair or pairs consist of atoms that have the same value for Z? Which consists of atoms that have the same value for A?

4 **C** Compare Dalton's atomic theory with the modern atomic theory. Explain why scientists modified Dalton's theory.

5 **C** In your opinion, should chemistry students learn about Dalton's theory if scientists no longer agree with it completely? Justify your answer.

CHEM FACT

Not all chemists believed that Dalton's atoms existed. In 1877, one skeptical scientist called Dalton's atoms "stupid hallucinations." Other scientists considered atoms to be a valuable *idea* for understanding matter and its behaviour. They did not, however, believe that atoms had any physical reality. The discovery of electrons (and, later, the other subatomic particles) finally convinced scientists that atoms are more than simply an idea. Atoms, they realized, must be matter.