Chapter 12

Atoms and the Periodic Table

There is something more to wintergreen-flavored candy (the kind with a hole in the middle) than its refreshing taste. When you crush one of these candies with your teeth, blue sparks jump out of your mouth! You can only see the sparks if you hold a mirror up to your mouth in a very dark place, like a closet. You will be able to see the sparks even better if you crush one of the candies with a pair of pliers (no mirror required). In order to understand why the blue sparks appear, you must know what an atom is and what it is made of. After reading this chapter on atoms, you can do an Internet search on the term *triboluminescence* to find out why this candy sparks when you crush it.

Key Questions

- ✔ *What are atoms and what are they made of?*
- ✔ *What does light have to do with atoms?*
- ✔ *What is the periodic table and why does it have a specific shape?*
- ✔ *What do electrons have to do with the chemical properties of atoms?*

12.1 The Structure of the Atom

Scientists once believed atoms were the smallest particles of matter. With the advancement of technology, it became clear that atoms themselves are made of even smaller particles. Today, we believe atoms are made of three basic particles: the proton, electron, and neutron. It's amazing that the incredible variety of matter around us can all be built from just three subatomic particles!

VOCABULARY

electric charge - a fundamental property of matter that can be either positive or negative.

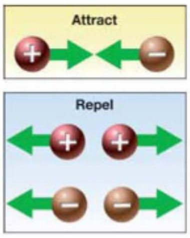
elementary charge - the smallest unit of electric charge that is possible in ordinary matter; represented by the lowercase letter *e*.

Electric charge

Electric charge is a property of matter In order to understand atoms, we need to understand the idea of electric charge. **Electric charge** is a fundamental property of matter that can be either positive or negative. One of the two forces that holds atoms together comes from electric charge.

Positive and negative There are two different kinds of electric charge—*positive* and *negative*. Because there are two kinds of charge, the force between electric charges can be either *attractive* or *repulsive*.

- A positive and a negative charge will attract each other.
- Two positive charges will repel each other.
- Two negative charges will also repel each other.



The elementary charge Scientists use the letter *e* to represent the **elementary charge**. At the size of atoms, electric charge always comes in units of +*e* or –*e*. It is only possible to have charges that are multiples of *e*, such as +e, +2*e*, –*e*, –2*e*, –3*e*, and so on. Scientists believe it is impossible for ordinary matter to have charges that are fractions of *e*. For example, a charge of +0.5*e* is impossible in ordinary matter. Electric charge appears only in whole units of the elementary charge (Figure 12.1).

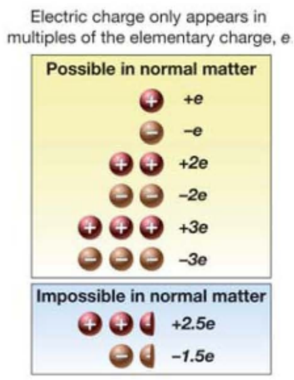
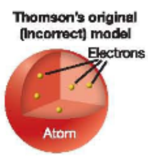


Figure 12.1: *Just as normal matter is divided into atoms, electric charge appears only in whole units of the elementary charge,* e.

Inside an atom: Solving the puzzle

The electron identified The first strong evidence that something smaller than an atom existed was found in 1897. English physicist J. J. Thomson discovered that electricity passing through a gas caused the gas to give off particles that were too small to be atoms. The new particles had negative electric charge. Complete atoms have zero charge. Thomson's particles are now known as **electrons**. Electrons were the first particles discovered that are smaller than atoms.

An early model of an atom



Thomson proposed that negative electrons were sprinkled inside atoms like raisins in a loaf of raisin bread. The "bread" was positively charged and the electrons were negatively charged. This was the first real model for the inside of an atom. As it soon turned out, it was not the *right* model, but it was a good place to start.

Testing the model with an experiment In 1911, Ernest Rutherford, Hans Geiger, and Ernest Marsden did an experiment to test Thomson's model of the atom. They launched positively charged helium ions (a charged atom is an *ion*) at a very thin gold foil (Figure 12.2). They expected most of the helium ions to be deflected a little as they plowed through the gold atoms.

An unexpected result! They found something quite unexpected. Most of the helium ions passed right through the foil with no deflection at all. Even more surprising—a few bounced back in the direction they came! This unexpected result prompted Rutherford to remark, "It was as if you fired a fifteen-inch (artillery) shell at a piece of tissue paper and it came back and hit you!"

The nuclear model of the atom The best way to explain the pass-through result was if a gold atom was mostly empty space. If most of the helium ions hit nothing, they wouldn't be deflected. The best way to explain the bounce-back result was if nearly all the mass of a gold atom were concentrated in a tiny, dense core at the center. Remember, two positive charges will repel each other. This causes the deflection. Further experiments confirmed Rutherford's idea about this dense core. We now know that every atom has a tiny **nucleus**, which contains more than 99 percent of the atom's mass.

VOCABULARY

electron - a particle with an electric charge (–*e*) found inside of atoms but outside the nucleus.

nucleus - the tiny core at the center of an atom containing most of the atom's mass and all of its positive charge.

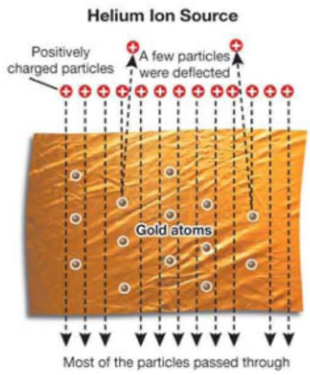


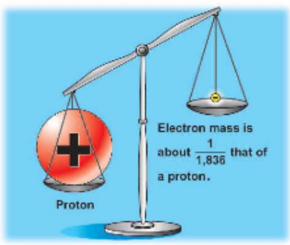
Figure 12.2: *Rutherford's famous experiment led to the discovery of the nucleus.*

Three particles make up all atoms

Protons and neutrons

Today, we know that the nucleus of an atom contains protons and neutrons. **Protons** have positive charge, opposite of electrons. The charge on a proton (+*e*) and an electron (–*e*) are exactly equal and opposite. **Neutrons** have zero electric charge.

The nucleus contains most of the mass



Protons and neutrons are *much* more massive than electrons. A proton has 1,836 times as much mass as an electron. A neutron has about the same mass as a proton. The table below compares electrons, protons, and neutrons in terms of charge and mass. Because protons and neutrons have so much more mass, more than 99 percent of an atom's mass is in the nucleus.

	Occurrence	Charge	Mass (g)	Relative Mass
Electron	Found outside of nuclei	-1	9.109×10^{-28}	1
Proton	Found in all nuclei	+1	1.673×10^{-24}	1,836
Neutron	Found in almost all nuclei (exception: most H nuclei)	0	1.675×10^{-24}	1,839

Electrons define the volume of an atom

Electrons occupy the space *outside* the nucleus in a region called the *electron cloud*. The diameter of an atom is really the diameter of the electron cloud (Figure 12.3). Compared to the tiny nucleus, the electron cloud is enormous, more than 10,000 times larger than the nucleus. As a comparison, if an atom were the size of a football stadium, the nucleus would be the size of a pea, and the electrons would be equivalent to a small swarm of gnats buzzing around the stadium at an extremely high speed. Can you imagine how much empty space there would be in the stadium? An atom is mostly empty space!

VOCABULARY

proton - a particle found in the nucleus with a positive charge exactly equal and opposite to the electron.

neutron - a particle found in the nucleus with mass similar to the proton but with zero electric charge.

Size and Structure of the Atom

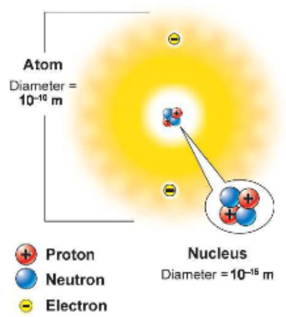


Figure 12.3: *The overall size of an atom is the size of its electron cloud. The nucleus is much, much smaller.*

Forces inside atoms

Electromagnetic force Electrons are bound to the nucleus by the attractive force between electrons (–) and protons (+). The electrons don't fall into the nucleus because they have kinetic energy, or momentum. The energy of an electron causes it to move around the nucleus instead of falling in (Figure 12.4). A good analogy is Earth orbiting the Sun. Gravity creates a force that pulls Earth toward the Sun. Earth's kinetic energy causes it to orbit the Sun rather than fall straight in. While electrons don't really move in orbits, the energy analogy is approximately right.

Strong nuclear force Because of electric force, all the positively charged protons in the nucleus repel each other. So, what holds the nucleus together? There is another force that is even stronger than the electric force. We call it the *strong nuclear force*. The strong nuclear force is the strongest force known to science (Figure 12.5). This force attracts neutrons and protons to each other and works only at the extremely small distances inside the nucleus. If there are enough neutrons, the attraction from the strong nuclear force wins out over repulsion from the electromagnetic force and the nucleus stays together. In every atom heavier than helium, there is at least one neutron for every proton in the nucleus.

Weak force There is another nuclear force called the *weak force*. The weak force is weaker than both the electric force and the strong nuclear force. If you leave a single neutron outside the nucleus, the weak force eventually causes it to break down into a proton and an electron. The weak force does not play an important role in a stable atom, but it comes into action in certain special cases when atoms break apart.

Gravity The force of gravity inside the atom is much weaker than even the weak force. It takes a relatively large mass to create enough gravity to make a significant force. We know that particles inside an atom do not have enough mass for gravity to be an important force on the scale of atoms. But there are many unanswered questions. Understanding how gravity works inside atoms is an unsolved scientific mystery.

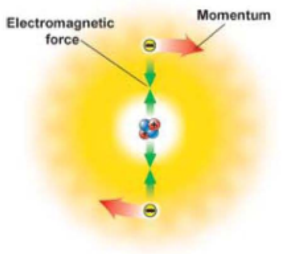


Figure 12.4: *The negative electrons are attracted to the positive protons in the nucleus, but their momentum keeps them from falling in.*

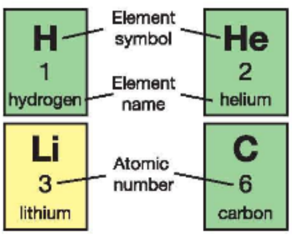
Figure 12.5: *When enough neutrons are present, the strong nuclear force wins out over the repulsion between positively charged protons and pulls the nucleus together tightly. The strong nuclear force is the strongest known force in the universe.*

How atoms of various elements are different

The atomic number is the number of protons

How is an atom of one element different from an atom of another element? The atoms of different elements contain varying numbers of protons in the nucleus. For example, all atoms of carbon have six protons in the nucleus and all atoms of hydrogen have one proton in the nucleus (Figure 12.6). Because the number of protons is so important, it is called the **atomic number**. The atomic number of an element is the number of protons in the nucleus of every atom of that element.

Elements have unique atomic numbers



Each element has a unique atomic number. On a periodic table of elements, the atomic number is usually written above or below the atomic symbol. An atom with only one proton in its nucleus is the element hydrogen, atomic number 1. An atom with six protons is the element carbon, atomic number 6. Atoms with seven protons are nitrogen, atoms with eight protons are oxygen, and so on.

Complete atoms are electrically neutral

Because protons and electrons attract each other with very large forces, the number of protons and electrons in a *complete* atom is always equal. For example, hydrogen has one proton in its nucleus and one electron outside the nucleus. The net electric charge of a hydrogen atom is zero because the negative charge of the electron cancels the positive charge of the proton. Each carbon atom has six electrons, one for each of carbon's six protons. Like hydrogen, a complete carbon atom is electrically neutral.

Ions

Complete atoms have a net zero charge. *Ions* are atoms that have a different number of protons than electrons and so have a net electric charge. Positively charged ions have more protons than electrons. Negatively charged ions have more electrons than protons.

VOCABULARY

atomic number - the number of protons in the nucleus of an atom. The atomic number determines what element the atom represents.

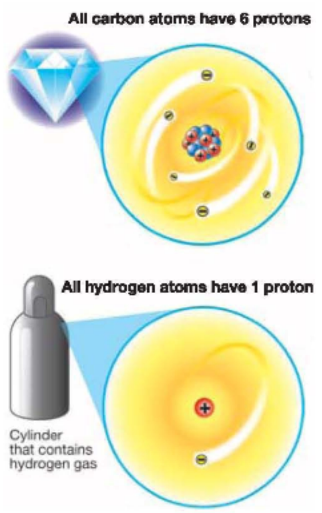


Figure 12.6: *Atoms of the same element always have the same number of protons in the nucleus.*

Isotopes

Isotopes All atoms of the same element have the same number of protons in the nucleus. However, atoms of the same element might have different numbers of neutrons in the nucleus. **Isotopes** are atoms of the *same* element that have different numbers of neutrons.

The isotopes of carbon Figure 12.7 shows three isotopes of carbon that exist in nature. Most carbon atoms have six protons and six neutrons in the nucleus. However, some carbon atoms have seven or eight neutrons. They are all carbon atoms because they all contain six protons, but they are different *isotopes* of carbon. The isotopes of carbon are called carbon-12, carbon-13, and carbon-14. The number after the name is called the mass number. The **mass number** of an isotope tells you the number of protons plus the number of neutrons.

VOCABULARY

isotopes - atoms of the same element that have different numbers of neutrons in the nucleus.

mass number - the number of protons plus the number of neutrons in the nucleus.

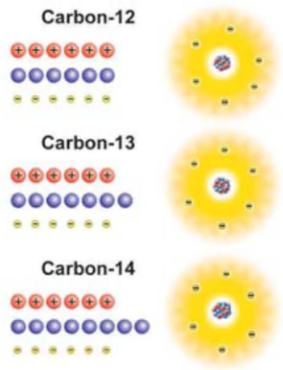


Figure 12.7: *The isotopes of carbon.*

Solving Problems: Isotopes

How many neutrons are present in an aluminum atom that has an atomic number of 13 and a mass number of 27?

1. Looking for: You are asked to find the number of neutrons.

2. Given: You are given the atomic number and the mass number.

3. Relationships: Use the relationship: protons + neutrons = mass number.

4. Solution: Plug in and solve: $13 + x = 27$; $x = 14$
The aluminum atom has 14 neutrons.

Your turn...

a. How many neutrons are present in a magnesium atom with a mass number of 24?

b. Find the number of neutrons in a calcium atom that has a mass number of 40.

SOLVE FIRST LOOK LATER

a. 12

b. 20

Section 12.1 Review

1. Which of the following statements regarding electric charge is TRUE?
   a. A positive charge repels a negative charge and attracts other positive charges.
   b. A positive charge attracts a negative charge and repels other positive charges.
2. Is electric charge a property of just electricity or is charge a property of all atoms?
3. Which of the drawings in Figure 12.8 is the most accurate model of the interior of an atom?
4. There are four forces in nature. Name the four forces and rank them from strongest to weakest.
5. There are three particles inside an atom. One of them has zero electric charge. Which one is it?
6. All atoms of the same element have (choose one):
   a. the same number of neutrons
   b. the same number of protons
   c. the same mass
7. The atomic number is:
   a. the number of protons in the nucleus
   b. the number of neutrons in the nucleus
   c. the number of neutrons plus protons
8. Use the diagram in Figure 12.9 to answer the following questions.
   a. Which atoms are isotopes of the same element?
   b. Give the mass number for each atom.
9. An atom has a mass number of 31 and 16 neutrons in its nucleus. What is its atomic number? What is the element?

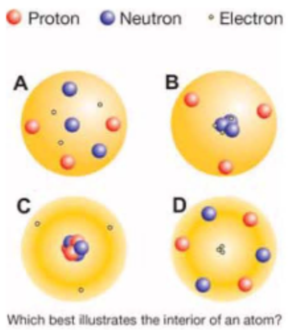


Figure 12.8: *Question 3.*

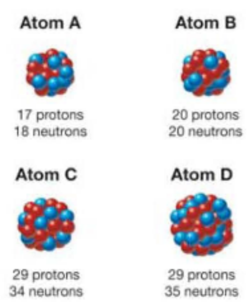


Figure 12.9: *Question 8.*