



18.2 Comparing Atoms

As you know, some substances are made up of only one kind of atom and these substances are called elements. You already know something about a number of elements—you've heard of hydrogen, helium, silver, gold, aluminum, copper, lead, and carbon, for example.

Exactly how does one element differ from another? This information is important. Over the centuries chemists, physicians, technologists, and inventors have used this knowledge to create everything from better medicines to beautiful jewelry.

How people figured out *why* the elements are different from each other is one of the most fascinating stories in science. It brings together the work of physicists, who studied the structure of the atom, and chemists, who studied how elements react and combine.



Figure 18.8: How does one kind of atom differ from another?

Atomic number

The number of protons determines an element Remember that atoms are themselves composed of protons, electrons, and neutrons. Through intense study of the structure of the atom, people discovered that it is the *number of protons* that distinguishes an atom of one element from the atom of another element.

Can you change the number of protons? All atoms of the same element will have the same number of protons, and atoms of different elements will have different numbers of protons. Adding or removing a proton from an atom usually takes (or releases) huge amounts of energy. Therefore, most atoms are very stable. Even if atoms bond or break apart during chemical reactions, the number of protons in each atom always remains the same. The atoms themselves are only rearranged in different combinations.

What is the atomic number? Because the number of protons in an atom remains the same during physical and chemical changes, we can refer to each element by the number of protons its atoms contain. This unique number is called the **atomic number**.

Atomic numbers start at 1, with the element hydrogen, and go up by ones until 111, the element ununium. The heaviest elements have been created in a laboratory and have not been seen in nature.

Atomic number
The number of protons

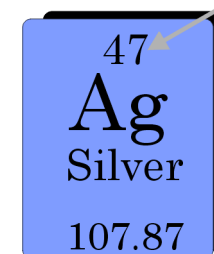


Figure 18.9: Look at the periodic table in the back cover of this book. The atomic number tells you the number of protons in an atom.

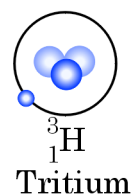
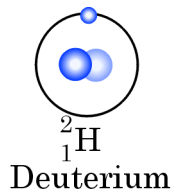
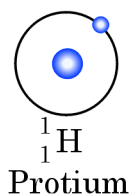
Atomic mass, mass number, and isotopes

In addition to the atomic number, every atomic nucleus can be described by its **mass number**. The mass number is equal to the total number of protons plus neutrons in the nucleus of an atom. Recall that atoms of the same element have the same number of protons. Atoms of the same element *can* have different numbers of neutrons.

What does the atomic mass tell you? Chemists arrange the elements in a table called the **periodic table of elements**. If you look at the periodic table in the back cover of this book, you will notice that the atomic number increases by one whole number at a time. This is because you add one proton at a time for each element. The atomic masses however, increase by amounts greater than one (figure 18.10). This difference is due to the neutrons in the nucleus. Neutrons add mass to the atom, but do not change its charge.

Mass number and neutrons The total number of protons and neutrons in the nucleus of an atom is called the mass number. Sometimes, the mass number of an element is included in the symbol. By convention, the mass number is written as a superscript above the symbol and the atomic number as a subscript below the symbol (figure 18.11). You can find the number of neutrons by subtracting the atomic number from the mass number. How many neutrons does the carbon atom in figure 18.11 have?

What are isotopes? Many elements have atoms with different numbers of neutrons. These different forms of the same element are called **isotopes**. Isotopes are atoms of the same element that have different numbers of neutrons. Because of this, the notation shown in figure 18.11 is called *isotope notation*.



The three isotopes of hydrogen are shown here.

Atomic mass
increases by amounts
greater than one



Figure 18.10: The difference between the atomic number and atomic mass is due to the number of neutrons.

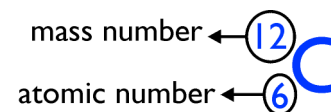


Figure 18.11: The isotope notation for carbon-12.

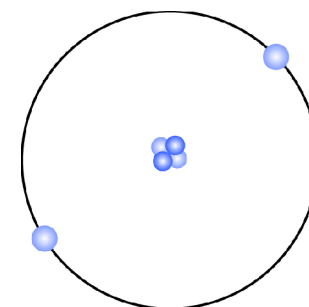


Figure 18.12: This atom has 2 protons and 2 neutrons. What is the element? What is its mass number?



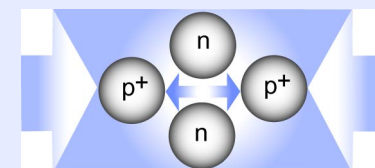
Example: finding the number of neutrons

Example: How many neutrons are present in an atom of carbon that has a mass number of 14?

Solution: The mass number is the number of protons plus the number of neutrons.

- (1) You are asked for the number of neutrons.
- (2) You are given that it is carbon-14. Carbon has 6 protons.
- (3) The relationship is $n + p = \text{mass number}$
- (4) Solve for n
 $n = \text{mass number} - p$
- (5) Plug in numbers and get answer
 $n = 14 - 6 = 8$
 There are 8 neutrons in a carbon-14 nucleus.

What holds the nucleus together?



Protons in the nucleus both repel and attract each other. The repulsions are due to electromagnetic force and the attractions are due to the strong nuclear force. The strong nuclear force only acts over very short distances, about the size of an atomic nucleus. Neutrons and protons also attract each other because of the strong nuclear force.

How many different elements are possible?

Why aren't there infinite numbers of elements? Why aren't there infinite numbers of elements, each with an atomic number greater than the one before it? The answer may lie in the forces that keep a nucleus together. Remember that positive charges repel each other. In the nucleus, however, positive protons and neutral neutrons sit side by side. Because the protons are repelling each other, they (and the nucleus) should fly apart!

What holds the nucleus of an atom together? The nucleus stays together because there is another force acting that is stronger than the repulsion of the protons for each other. Because it is stronger than the electromagnetic force, scientists call it the **strong nuclear force**. Unlike gravity, which can reach millions of miles, the strong force only acts on very short distances. The effective distance for the strong force is so short, we do not feel it outside the nucleus of an atom.

How are electrons arranged in atoms?

Neutral atoms have the same number of electrons as protons Atoms are electrically neutral. An atom of helium has an atomic number of 2 and two protons in its nucleus. A neutral atom of helium would therefore have two electrons, which stay close to the nucleus because the positive protons and the negative electrons attract each other. An atom of silver has an atomic number of 47 and 47 protons in its nucleus. A neutral atom of silver would therefore have 47 electrons. Are these electrons randomly placed or are they organized in some way?

Electrons are found in the electron cloud Electrons are never all in one place at the same time. Instead, they literally buzz around the nucleus at a very fast rate, or frequency. Because of this behavior, we can refer to the entire space that electrons occupy as the *electron cloud* (figure 18.13).

The electron cloud is divided into energy levels The current model of the atom describes the area of the electron cloud that each electron occupies as an *energy state*. The farther away from the nucleus the electron is found, the higher its energy state. Therefore, the electron cloud is divided into *energy levels*. The first energy level is closest to the nucleus and has the lowest energy. Electrons that occupy this level are at a lower energy state than electrons that occupy the second energy level, which is farther from the nucleus. Each energy level can hold up to a specific number of electrons (figure 18.14). Sometimes, when energy is added to an atom, electrons can absorb enough energy to “jump” to a higher energy level. When they fall back to their normal energy level, they release light in a characteristic frequency.

Like the layers of an onion, as the energy levels extend farther from the nucleus, they get larger in diameter and can hold more electrons. The maximum number each level can hold is shown in figure 18.14.

Energy levels can overlap It is important to note that some energy levels can overlap. In fact, each energy level is subdivided into smaller regions called *orbitals*. Some orbitals in the third energy level may have higher energy than some in the fourth and so on. Scientists have found out exactly which orbitals are occupied, and by how many electrons, in all 111 elements. You will explore this concept in greater detail in future chemistry courses.

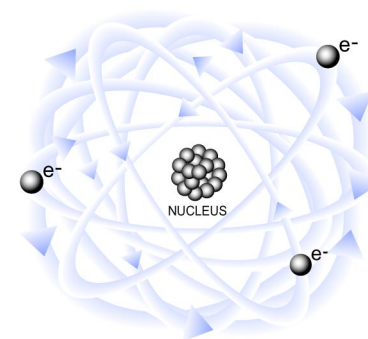


Figure 18.13: Electrons buzz around the nucleus at a very fast rate.

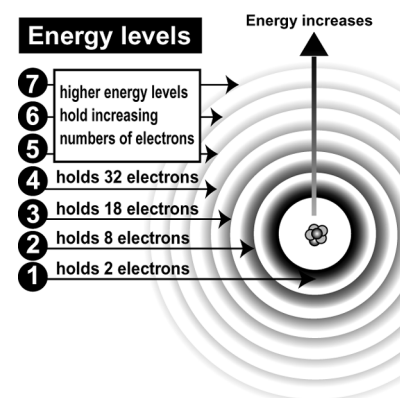


Figure 18.14: Electrons occupy energy levels around the nucleus. The farther away an electron is, the higher the energy it possesses.



Fireworks and electron energy levels

Almost everyone enjoys the bright colors, noise, and drama of fireworks. The loud noises are caused by a black powder that explodes when burned. What causes the colors? The answer to this question is directly related to energy levels and the strict rules that govern how electrons act around a nucleus.

Electrons will fill up the lowest energy level first, because they are attracted to the nucleus. But just as we can lift a marble to the top of a hill, energy can be used to move an electron farther away from the nucleus. When fireworks burn at a high heat, the energy provided by the heat moves electrons into higher energy levels farther from the nucleus. This process is called *electron excitation*.

When an electron falls back down to its original position, the energy it gained from the heat is released in the form of electromagnetic radiation. The release of electromagnetic energy that occurs when the electrons fall down into a lower-energy position is called *emission*.

Because electromagnetic radiation is a wave, it comes in different frequencies. Some frequencies we can see with our eyes and we call those frequencies light. As you remember from the last unit, light of different frequencies we see as different colors.

Because of the arrangement of the energy levels surrounding an atom, excited electrons can release electromagnetic radiation in a range of frequencies. The trick in building fireworks is to find materials that release radiation at the right frequency for us to see. These materials are metal salts, which are combinations of metal ions with other ions. With energy input, these metal ions release electromagnetic radiation at wavelengths that we see as colors. The colors we see from different elements are listed in figure 18.16.

The fact that different elements, when heated, can release different colors of light tells us that electrons have specific amounts of energy. For example, the wavelengths for different colors are approximately: 610 nanometers for red; 579 for yellow; 546 for green; 436 for blue; and 405 for purple.

The discovery around 1900 that electrons exist at set energy levels changed the way people looked at the physical world. Before then, people believed that objects could have any amount of energy.

The idea that electrons exist at set energy levels has redefined the field of physics and led us to a much deeper understanding of the way the physical universe works. This idea is known as *quantum theory*.



Figure 18.15: What causes all the different colors in fireworks? Electrons!

Metal	Color
copper	green
barium	yellow-green
sodium	yellow
calcium	red-orange
strontium	bright red

Figure 18.16: Metals used in fireworks.