6.7

Explaining the Periodic Table

In Investigation 6.5, you observed differences in the reactivity of the alkali metals with water (Figure 1). Why do the elements become more reactive as you descend a family in the periodic table? You will learn that the Bohr–Rutherford model of the atom explains this trend, as well as other trends on the periodic table. First, let's take a more detailed look at the contents of the atom.

Figure 1 Lithium (a), sodium (b), and potassium (c) react at different rates with water to produce flammable hydrogen gas. The reactions release so much thermal energy that the hydrogen gas ignites.

Atomic Number

You learned in Section 6.1 that elements are the building blocks of substances. You also learned that pure substances differ because they consist of different elements. You know from Dalton's atomic theory that the atoms of each element are different from the atoms of all other elements.

atomic number the number of protons in an atom's nucleus

What makes atoms unique is the number of protons they contain. The number of protons in the nucleus is called the **atomic number**. A hydrogen atom has one proton, so its atomic number is 1. Any atom that has a single proton in its nucleus can only be hydrogen. Any atom that does not have a single proton in its nucleus cannot be hydrogen. The periodic table lists the atomic number for each element in the top left-hand corner of each cell (box) (Figure 2). Chemists have found that when elements are arranged according to increasing atomic number on the periodic table, the elements within each column have similar properties.

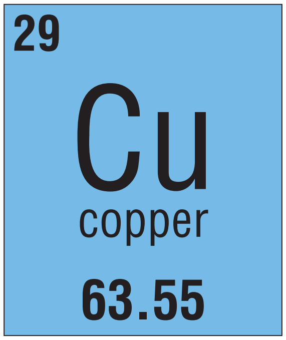


Figure 2 The atomic number is given in the top left-hand corner of each element on the periodic table.

The atomic number for gold, Au, is 79. This number tells us that there are 79 protons in every atom of gold. Can we take copper and turn it into gold? The atomic number of copper, Cu, is 29. A copper atom has 29 protons and is 50 protons short of being a gold atom. Where can we find a spare 50 protons? A tin atom, Sn, with an atomic number of 50, contains exactly 50 protons. If we could combine the nucleus of a copper atom with the nucleus of a tin atom, we would get an atom containing exactly 79 protons—a gold atom (Figure 3)!

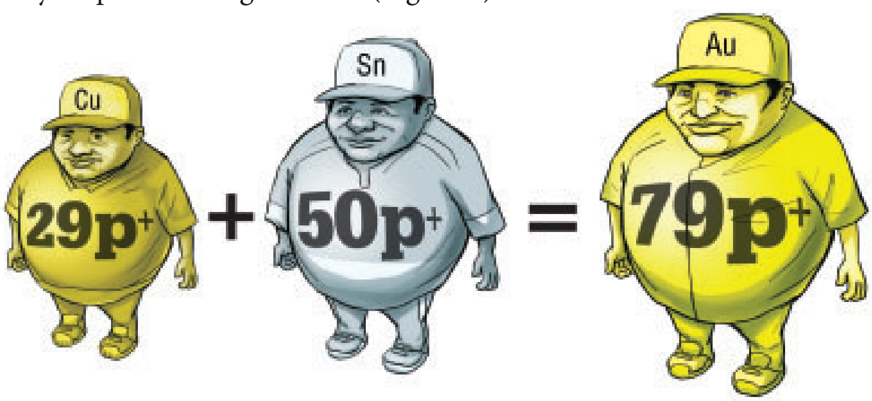


Figure 3 To make a gold atom, we need 79 protons.

This idea is theoretically brilliant, but practically, it is very difficult to accomplish. Protons are tightly held in the nucleus of an atom. It would take a nuclear reaction (such as that inside an atomic bomb or a nuclear reactor) to combine two nuclei into one. This is not an efficient way to turn copper and tin into gold.

Mass Number and Atomic Mass

In Rutherford's atomic model, the atom is described as mostly empty space. Since electrons have a relatively insignificant mass, the mass of an atom consists of the contents of its nucleus—protons and neutrons. This value is called the **mass number**. Consider the element lithium, Li. The atomic number of lithium is 3, so all lithium atoms contain three protons. Most lithium atoms also contain 4 neutrons. The sum of three and four is seven. Therefore, these lithium atoms have a mass number of 7 (Figure 4).

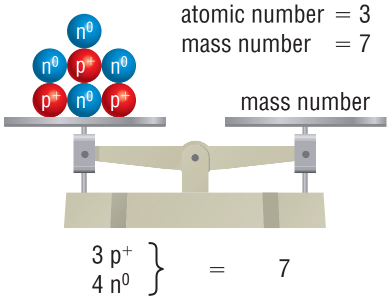


Figure 4 A lithium atom contains 3 protons and 4 neutrons, giving it a mass number of 7.

A small number of naturally occurring lithium atoms contain only three neutrons. These lithium atoms have a mass number of 6. Atoms with the same number of protons but different numbers of neutrons are called **isotopes**. Scientists use mass number to distinguish between the isotopes of an element. For example, the lithium isotope with a mass number of 6 is called lithium-6 or Li-6. The lithium isotope that has a mass number of 7 is called lithium-7 or Li-7. Since Li-7 has one more neutron, it is heavier than Li-6 (Figure 5).

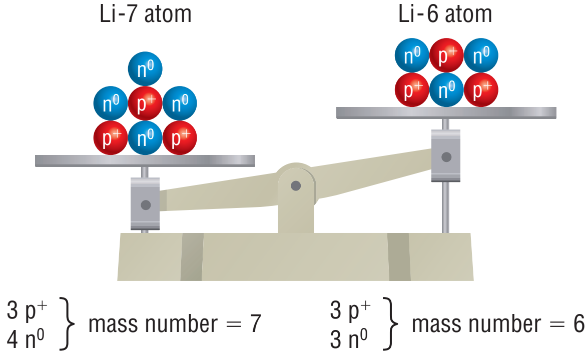


Figure 5 One lithium isotope contains 3 protons and 4 neutrons, giving it a mass number of 7. The other lithium isotope contains 3 protons and 3 neutrons, giving it a mass number of 6.

The mass of an atom is called the **atomic mass** and is measured in atomic mass units (u). The atomic mass of each element is given below the element symbol on the periodic table. The atomic masses given on the periodic table are not whole numbers. For example, the atomic mass of lithium is 6.94 u (Figure 6). Naturally occurring lithium is a mixture of two isotopes, Li-6 and Li-7. The atomic mass of an element is the weighted average of the masses of its isotopes. Since Li-7 is far more common than Li-6, the average atomic mass for lithium is closer to 7 u than to 6 u. In many cases, you can determine the most common isotope of an element by rounding the atomic mass to the nearest whole number. For example, boron (B) has an atomic mass of 10.81 u. Therefore, the most common isotope of boron is B-11. Once you know the mass number, you can also determine the number of neutrons.

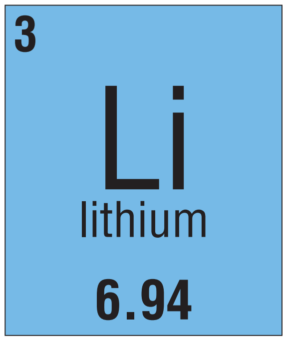


Figure 6 The element lithium has an atomic number of 3 and an atomic mass of 6.94 u.

SAMPLE PROBLEM 1 Finding the Number of Neutrons

Find the number of neutrons in the most common isotope of aluminum.

Given: atomic mass of Al = 26.98 u
atomic number = 13

Required: number of neutrons

Analysis: Round the atomic mass of the element to the nearest whole number to get the mass number of the most common isotope.

mass number of Al = 27 u (rounded up)
mass number – atomic number = number of neutrons

Solution: 27 – 13 = 14

Statement: The most common isotope of aluminum contains 14 neutrons.

mass number the number of protons and neutrons in an atom's nucleus

isotope an atom with the same number of protons but a different number of neutrons

atomic mass the mass of an atom in atomic mass units (u)

Bohr–Rutherford Diagrams of an Atom

Bohr–Rutherford diagram a simple drawing that shows the numbers and locations of protons, neutrons, and electrons in an atom

A picture is worth a thousand words. This holds true for atoms as well. The Bohr–Rutherford model of an atom can be depicted by a few simple strokes—a kind of stick drawing of an atom. Stick drawings show only the essential components of objects and are not drawn to scale. Since these diagrams of atoms represent both Bohr's and Rutherford's atomic models, they are called Bohr–Rutherford diagrams.

A **Bohr–Rutherford diagram** shows the numbers and locations of protons, neutrons, and electrons in an atom. We can deduce these numbers from the atomic number and mass number:

- the number of protons equals the atomic number
- the number of neutrons equals the difference between the mass number and the atomic number
- the number of electrons equals the number of protons in a neutral atom

SAMPLE PROBLEM 2 Drawing a Bohr–Rutherford Diagram

Draw a Bohr–Rutherford diagram of N-14.

Step 1. Determine the number of protons and the number of neutrons from the atomic number and mass number. Draw a small circle for the nucleus. Write the numbers of protons and neutrons inside the nucleus (Figure 7). Because atoms are neutral in charge, the number of negatively charged electrons must equal the number of positively charged protons.

For N-14, the atomic number is 7 and the mass number is 14.

$$\text{number of protons} = \text{atomic number} = 7p^+$$
$$\text{number of neutrons} = \text{mass number} - \text{atomic number}$$
$$= 14 - 7$$
$$= 7n^0$$
$$\text{number of electrons} = \text{number of protons} = 7e^-$$

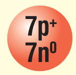


Figure 7

Step 2. Draw one to four concentric circles outside the nucleus to represent electron orbits. The number of circles depends on the size of the atom.

The nitrogen atom has seven electrons. The first orbit can hold a maximum of two electrons, so draw two circles (Figure 8).

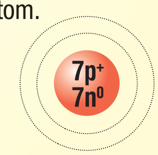


Figure 8

Step 3. Draw dots on these circles, starting from the circle immediately surrounding the nucleus, to represent the electrons in their orbits. There is a maximum number of electrons that can occupy each orbit. Current scientific evidence indicates that for the first 20 elements, the maximum number of electrons in the first, second, and third orbits is 2, 8, and 8, respectively. So, draw a pair of dots on the first circle. Then draw no more than 8 dots on the second circle. The first four electrons are usually drawn equally spaced. The next four are paired with the first four. Each orbit must be completely filled before dots can be drawn in higher orbits.

For the nitrogen atom, draw one pair of dots to fill the first orbit. Then draw five dots in the second orbit (Figure 9).

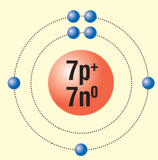
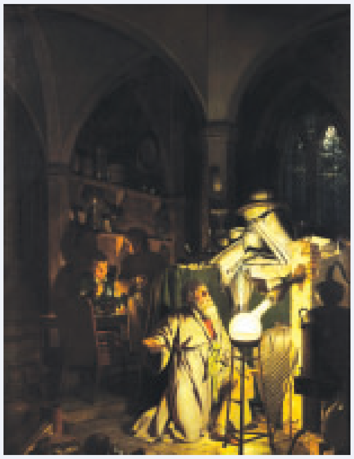


Figure 9 Note that the fifth electron in the second orbit is paired.

DID YOU KNOW?

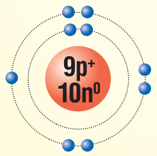
Phosphorus, the Light Bearer

Phosphorus was discovered by accident, like many other marvellous substances. In 1669, Hennig Brand, an alchemist in Hamburg, was trying to make gold from urine. He boiled urine down to a paste and heated the paste to high temperatures. To his great amazement, what he got was not gold, but a white waxy substance that glowed in the dark. This substance was named phosphorus, meaning "light bearer."



COMMUNICATION EXAMPLE 1 Drawing a Bohr–Rutherford Diagram

Draw a Bohr–Rutherford diagram for the fluorine atom.



There is an easy way to remember how many electrons each orbit can hold. Just look at the periodic table. The first row has 2 elements, and the first orbit holds 2 electrons. The second row has 8 elements, and the second orbit holds 8 electrons. The third row has 8 elements, and the third orbit holds 8 electrons. For elements 19 and 20, place additional electrons in the fourth orbit.

The Periodic Table Meets Bohr–Rutherford

Can the Bohr–Rutherford atomic model explain the patterns in the families of elements in the periodic table? A simple way to test whether the model can explain the evidence is to sketch a "portrait" of each element and then to arrange the elements in their assigned spots on the periodic table. The next step is to examine whether any pattern or "family resemblance" emerges.

TRY THIS FAMILY RESEMBLANCES IN THE PERIODIC TABLE

SKILLS: Performing, Analyzing, Communicating

Draw a "portrait" of each element in the family for the first 20 elements to see if there are any patterns of similarities in elemental families.

Equipment and Materials: periodic table; paper; pen or pencil

1. Make a blank periodic table for the first 20 elements (Figure 10).

1	2	13	14	15	16	17	18
H							He
Li	Be	B	C	N	O	F	Ne
Na	Mg	Al	Si	P	S	Cl	Ar
K	Ca						

Figure 10 Draw a Bohr–Rutherford diagram for each of these elements.

2. In each square of the table, draw a Bohr–Rutherford diagram of the element indicated. Use a periodic table to find the atomic number and mass number of the most common isotope of each element. Recall that the first 3 electron orbits can hold a maximum of 2, 8, and 8 electrons, respectively. The lower orbits (closest to the nucleus) must be completely filled before filling the higher orbits. T/I

A. What similarities and differences, if any, do you see in the Bohr–Rutherford diagrams for elements within the family of
   (i) the noble gases?
   (ii) the alkali metals?
   (iii) the alkaline earth metals?
   (iv) the halogens? T/I

B. How do the electron arrangements differ
   (i) between the alkali metals and the noble gases?
   (ii) between the halogens and the noble gases?
   (iii) between the alkaline earth metals and the alkali metals? T/I

DID YOU KNOW?

Poisoning of a Spy

In 2006, 43-year-old Russian spy Alexander Litvinenko was poisoned with a radioactive substance called polonium-210. Extraordinarily high levels of radiation were found in his urine, in his apartment, and at a restaurant where he ate his last lunch. Marie Curie discovered polonium in 1898 and named it after her native land, Poland. Polonium-210 is an element that contains 84 protons and 126 neutrons. Such a high number of protons and neutrons makes its nucleus very crowded and therefore unstable. Litvinenko ate polonium nuclei, which released energy and particles that were absorbed into his tissues. This polonium radiation caused extensive tissue damage that killed Litvinenko.

Patterns in the Periodic Table

Did you notice any pattern emerging from the periodic table of Bohr–Rutherford diagrams? Mendeleev would have been fascinated to see such a startling pattern from these "family portraits" of the elements.

- As you go down each family, the number of electron orbits increases—a new orbit is added with each new row. For example, in the alkaline earth metal family, Be has two orbits, Mg has three orbits, and so on.
- Within each family, all atoms have the same number of electrons in their outermost orbits. From the alkali metal family, Li has one outer electron, as do Na, K, and so on. This electron arrangement explains why the reaction of the alkali metals with water becomes more vigorous as you go down the group from lithium to potassium. Evidence suggests that when an alkali metal reacts with water, the alkali metal atoms lose one electron. The most likely electron to be lost is the single electron in the outermost orbit (Figure 11). This electron is farthest from the nucleus, so it has the weakest attraction to the nucleus. Furthermore, since the outermost electron of the sodium atom is farther from the nucleus than the outermost electron of the lithium atom, sodium reacts faster with water than lithium does. So, the reactivity of the alkali metals increases as you go down Group 1.
- The alkali metals undergo similar reactions because they all have one electron in their outermost orbits.

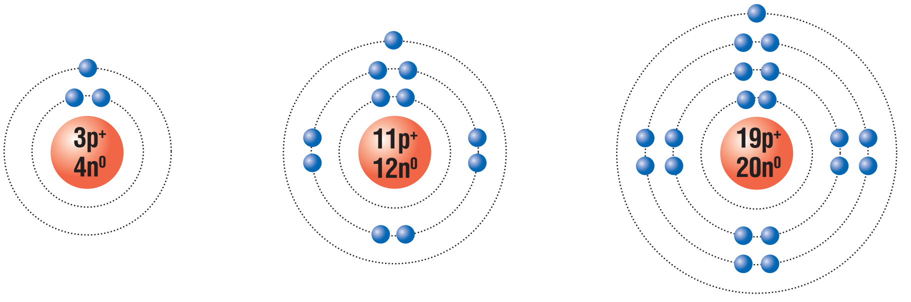


Figure 11 These elements have similar properties because they each have one outer electron.

READING TIP

Use Prior Knowledge

Think about what you already know about an example or description to help you make inferences. For example, you know how bulky a sweatshirt can be, so you can visualize how big a student wearing several sweatshirts would appear. The analogy can help you understand a pattern in the periodic table.

This pattern is similar to a classroom of students who are all wearing sweatshirts with pockets filled with apples. As you go down the column, each student is wearing one additional sweatshirt, so students at the end of the column appear larger than students at the front. Since you can only see their outermost sweatshirts, students in the same column all appear to have the same number of apples in their pockets. The next question is: Does having the same number of electrons in the outermost orbit explain why other groups of elements also have similar properties? You will explore this question in the next chapter.

The Bohr–Rutherford model of the atom is a useful tool to explain the properties of the elements on the periodic table. Table 1 on the next page summarizes some of the evidence you have learned about atomic structure and how the Bohr–Rutherford model explains this evidence.

Table 1 Theory Meets Evidence

Evidence	Theory
Elements have unique properties.	• Each element is made of different atoms.
Some objects can attract each other.	• All atoms contain three subatomic particles: protons, neutrons, and electrons. • Atoms are electrically neutral because they have an equal number of protons and electrons. • Matter is positively charged if it contains more protons than electrons. • Matter is negatively charged if it contains more electrons than protons. • Objects that attract each other are oppositely charged.
In Rutherford's gold foil experiment, positively charged particles were fired at a sample of gold atoms. • Most particles passed through the foil.	• Most of the volume of the atom is empty space.
• Some particles were deflected at large angles.	• The centre of the atom is a very small, dense, positively charged core called the nucleus.
Elements of the same chemical family have similar properties.	• Electrons exist in specific orbits around the nucleus. • The number of electrons in the outermost orbit determines many elemental properties. • Elements of the same chemical family have the same number of electrons in their outermost orbits.
Each element gives off a unique pattern of coloured lines when it is excited by energy.	• Each electron orbit has a definite amount of energy. • Electrons that absorb energy jump to higher orbits. • Electrons emit energy when they return to lower orbits. • The colour of light observed corresponds to the energy difference between the two electron orbits.

IN SUMMARY

- Atomic number represents the number of protons in an atom. This number is unique to each element.
- In a neutral atom, the number of electrons equals the number of protons.
- Atomic mass is the mass of an atom measured in atomic mass units, u.
- Mass number represents the total number of protons and neutrons in an atom.
- The maximum number of electrons in the first, second, and third orbits is 2, 8, and 8, respectively. Electrons fill lower orbits before filling higher orbits.
- Bohr–Rutherford diagrams of atoms show the number and location of protons, neutrons, and electrons in the atom.
- All atoms within each family of elements have the same number of electrons in their outermost orbits.

CHECK YOUR LEARNING

1. Do all atoms of the same element contain the same number of protons? Explain. K/U
2. Do all atoms of the same element contain the same number of neutrons? Explain. K/U
3. Which of the following statements are correct? Rewrite incorrect statements to correct them. K/U
   (a) The atomic number always equals the number of protons.
   (b) The atomic mass can be smaller than the atomic number.
   (c) The mass number of an atom can be equal to the atomic number.
   (d) The number of protons always equals the number of neutrons in an atom.
   (e) The number of protons always equals the number of electrons in an atom.
   (f) If the number of protons in an atom were changed, it would be a different element.
4. Determine the number of neutrons in the most common isotope of nickel. T/I
5. What is the maximum number of electrons that each of the first three electron orbits can hold, starting from the nucleus? K/U
6. Use a periodic table to complete Table 2 with the correct information about each atom. Round atomic mass to the nearest whole number to obtain the mass number. T/I
7. Draw Bohr–Rutherford diagrams for each of the following atoms. T/I
   (a) sulfur-32
   (b) argon-40
   (c) potassium-39
   (d) oxygen-16
8. Which of the following statements are true? Rewrite false statements to make them true. K/U
   (a) The first four elements in the alkali metal family have the same number of electron orbits.
   (b) The first three elements in the noble gas family have full outermost electron orbits.
   (c) All elements in the second row of the periodic table have the same number of electron orbits.
   (d) The first three elements in the alkaline earth metal family have the same number of electrons in their outer orbits.
9. What evidence is there that chemical properties of elements are related to the number of electrons in the outermost orbit? Choose one chemical family to support your answer. A
10. In Section 6.1, you learned that an element is a pure substance that cannot be broken down into a simpler chemical substance by any physical or chemical means. Write a new definition of an element based on what you have learned in this section. K/U C

Table 2

Element name	Element symbol	Atomic number	Mass number	Number of protons	Number of neutrons	Number of electrons
magnesium						
	Al					
		15				
				50		
						47