7.4 Using the Bohr Theory

LEARNING TIP

Models such as Figures 1 to 4, on pages 218 and 219, help you visualize scientific explanations. As you examine Figures 1 to 4, look back and forth between the diagrams and the related information in the text to ensure you understand the information in the figures.

For many years, chemists determined through experiments the amounts of substances that go into reactions and the amounts of substances that are produced. They learned, for example, that the compound zinc iodide always contained two atoms of iodine for every one atom of zinc. Through experiments chemists also determined the ion charges of the elements.

The Periodic Table gave scientists a tool to model the behaviour of elements during reactions and to make predictions about the compounds that can be formed from specific elements. This is because the Periodic Table is arranged according to properties, and elements with similar chemical properties are grouped vertically. The way that one member of a chemical group reacts with other substances will likely be repeated for any other member of this group. For example, iodine and chlorine are in the same group. How many atoms of each element would you expect the compound zinc chloride (the compound formed from zinc and chlorine) to have? Zinc chloride has two atoms of chlorine for every one atom of zinc.

The arrangement of elements in the Periodic Table agreed with Dalton's, Thomson's, and Rutherford's theories of the atom, and it also works for Bohr's theory.

Did You KNOW

A Prize-Winning Theory

Niels Bohr received the Nobel Prize in Physics in 1922 for his work on atomic theory. His son Aage Bohr also won the Nobel Prize in Physics in 1975 for his work on the structure of the nucleus.

Using the Bohr Theory to Describe Atoms and Ions

Recall that Bohr's theory of the atom places protons and neutrons in the nucleus of the atom, and electrons around the nucleus in specific shells. There is a maximum number of electrons that can occupy each shell. The first shell can contain a maximum of two electrons, and the second and third shells can contain a maximum of eight electrons. (This is true only for the first 20 elements.) The outermost shell is involved in chemical reactions. What happens in chemical reactions can be shown using a model of Bohr's atoms.

Bohr Diagrams

You can draw models called **Bohr diagrams** to help you to visualize the arrangement of electrons in different atoms. Bohr diagrams help to explain the mechanism by which elements combine to form compounds. Bohr diagrams are a series of concentric rings (the shells) around a nucleus, with electrons shown as dots on the rings. Figure 1 shows the Bohr diagram for phosphorus. Inside the nucleus is the chemical symbol for phosphorus, P. The number of protons and neutrons is often written in the centre, but this is not strictly necessary for a Bohr diagram.

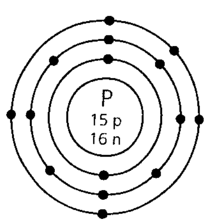

Figure 1 The Bohr diagram for phosphorus

Phosphorus has a full first shell (two electrons), a full second shell (eight electrons), and five electrons occupying the third shell. When an atom forms an ion, it either acquires extra electrons and becomes negatively charged, or gives up electrons and becomes positively charged. Phosphorus contains five electrons in its outer shell, so there is room for up to three more. Therefore, for phosphorus to form an ion, it has to acquire three extra electrons (Figure 2).

Experimentation has determined that phosphorus has an ion charge of 3−, which corresponds to the 3 "vacancies" available in its outer shell, as shown in the Bohr diagram.

You can use Bohr diagrams to show ions as well. The phosphorus ion is shown in Figure 3. The outer shell is now fully occupied with the three extra electrons. Metal elements tend to give up electrons when they form ions, as shown in the Bohr diagrams for the magnesium atom and ion (Figure 4).

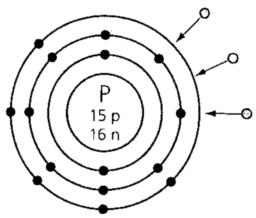

Figure 2 This phosphorus atom is acquiring three electrons to fill its outer shell and form an ion.

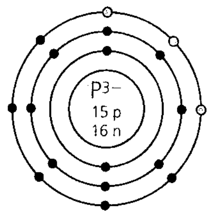

Figure 3 The Bohr diagram for the phosphorus ion, showing the full outer shell. Can you determine the charge of this ion from the diagram?

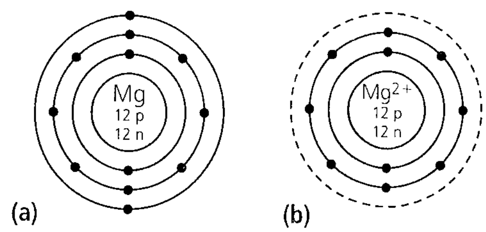

Figure 4 The Bohr diagrams for the magnesium atom (a) and the magnesium ion (b). The magnesium ion has lost two electrons, and now has a full outer shell. The third shell is empty. Higher, empty shells are ignored when drawing Bohr diagrams.

TRY THIS: Drawing Bohr Diagrams

Skills Focus: creating models, inferring, interpreting data

Materials: blank paper or prepared Bohr diagram templates; Periodic Table

In this activity, you will draw the Bohr diagrams for the atoms of the first 20 elements using information from the Periodic Table.

1. Draw a Bohr diagram for each of the first 20 elements, hydrogen through calcium.
2. Below each diagram, write the number of electrons in the outer shell.
3. Write the ion charge of the element above each diagram. Figure 5 shows a sample for magnesium.

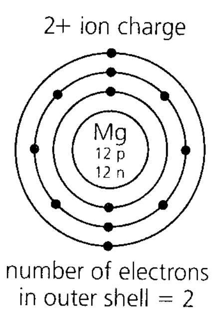

Figure 5

A. For the metal elements, what is the relationship between the ion charge and the number of electrons in the outer shell?

B. For the non-metal elements, what is the relationship between the ion charge and the number of electrons in the outer shell?

C. Compare the number of vacancies, or empty spaces, in the outer shell of the non-metals with the ion charges. What is the relationship?

D. How many electrons are in the outer shell of the elements Li and Na in Group 1?

E. How many vacancies are in the outer shell of the elements F and Cl in Group 17?

F. Is there a pattern between the number of electrons in the outer shell of an element and its position along the row in the Periodic Table? If so, what is the pattern?

G. How many shells are needed for the elements in each of the first four rows of the Periodic Table?

When ions are formed, they will have a full outer shell. Consider one of the Group 18 elements, like neon. It has 10 protons, and therefore its atom has 10 electrons. Two of these occupy the first shell, and the remaining eight electrons fully occupy the second shell. With a fully occupied outer shell as an atom, neon cannot acquire or give up electrons and retain a full outer shell. Do you think this explains why elements in Group 18 have an ion charge of 0 in the Periodic Table?

To see Bohr diagrams for more elements and ions, go to www.science.nelson.com

The Bohr Theory and Reactivity

The two most reactive chemical groups are Group 1 (1st column of the Periodic Table) and Group 17 (17th column). The least reactive chemical group is Group 18. The Bohr diagrams for these groups show that the Group 1 metals have only a single outer electron, the Group 17 non-metals have only a single vacancy in their outer shells, and the Group 18 non-metals have a full outer shell (Figure 6). The Group 1 elements are the most reactive metals because their single outer electron is easily given up. The Group 17 elements are the most reactive non-metals because they easily acquire one more electron to fill their outer shells completely. The Group 18 elements are non-reactive because their outer shells are full.

LEARNING TIP
Check your understanding. How does Bohr's theory help to explain the placement of the elements in the Periodic Table?

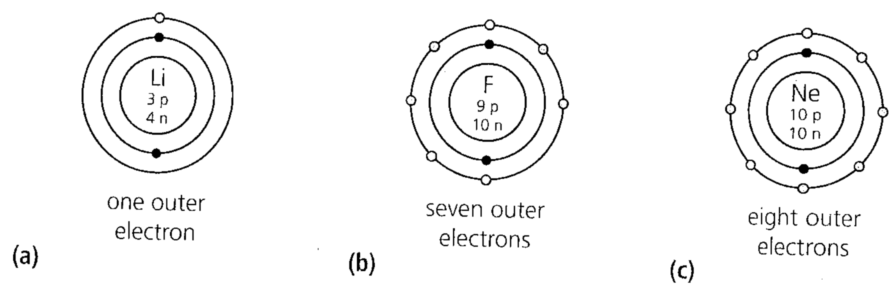

Figure 6 The reactivity of elements is determined by the number of electrons in their outer shells. Both (a) lithium (Li) and (b) fluorine (F) are very reactive, but (c) neon (Ne) has very low reactivity.

Using the Bohr Theory to Predict the Composition of Compounds

In the Try This activity, you saw that the outer shells of all the elements in a chemical group are similar. For example, lithium and sodium have a different number of electrons and a different number of shells. Both, however, have a single electron in the outer shell of their atoms. Similarly, fluorine and chlorine both have seven electrons in their outer shells (and, therefore, only one vacancy each). For most of the chemical groups, all the elements have the same number of electrons in their outer shells (Figure 7). For the first 20 elements in the Periodic Table, the number of electrons in the outer shell of an atom determines in which column (and group) the element appears in.

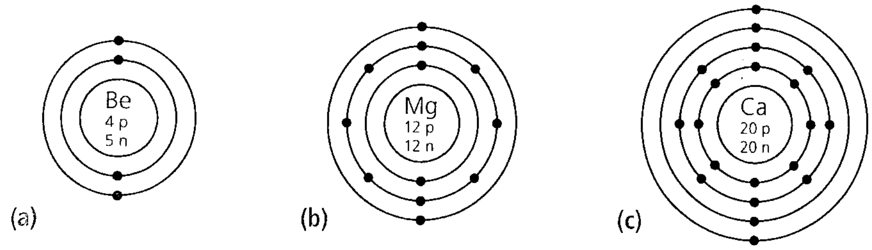

Figure 7 The Bohr diagrams for three of the Group 2 elements—(a) beryllium (Be), (b) magnesium (Mg), and (c) calcium (Ca). Note that there are two outer electrons for each atom.

All members of a chemical group react with other substances in a similar manner. It would seem that the number of electrons in the outer shell is important to the way that an element reacts. It is this interaction between the outer electrons of elements that drives all chemical reactions.

Ionic Compounds

When a metal atom reacts with a non-metal atom, they form an **ionic compound**. Consider the collision of an atom of fluorine with an atom of lithium. Lithium has a single electron in its outer shell. Fluorine has a single vacancy in its outer shell. During the collision, the lithium atom gives up its outer electron (to empty its outer shell), and the fluorine atom captures this electron (to fill its outer shell). Lithium, having lost an electron, becomes a positive ion, and fluorine, having gained an electron, becomes a negative ion. The pair of oppositely charged ions are held together by the electrostatic force that exists between charged objects. This process of **electron transfer** between metals and non-metals is what creates an **ionic bond**—metal ions joined to non-metal ions. The bonded lithium and fluorine ions form the compound lithium fluoride (LiF). Figure 8 illustrates the process of electron transfer between the metal and non-metal. 7B *Investigation*

Ionic Compounds and Molecular Compounds

Compounds can be classified as either ionic compounds or molecular compounds. Molecular compounds are composed of **molecules**; two or more atoms joined together to form the smallest particle that has the same properties as the compound. Molecular compounds are usually formed from a collection of non-metal atoms, such as hydrogen and oxygen (water) and nitrogen and oxygen (nitrogen dioxide). The bond between atoms in molecules is not due to electron transfer, but to the sharing of electrons in the outer shells of the atoms. This is called a covalent bond.

Strictly speaking, ionic compounds do not have discrete molecules. The description of electron transfer above is a simplified version of the process that leads to the formation of positive and negative ions. In a real chemical reaction, an extremely large number of both positive and negative ions are formed at once. The ionic compound formed is, in reality, a collection of positive and negative ions that occupy the same space. When in solid form,

LEARNING TIP

Try to work out your own explanation of how lithium fluoride is formed. Read the paragraph a few sentences at a time, translate the meaning of the sentences into your own words, and create a picture in your head.

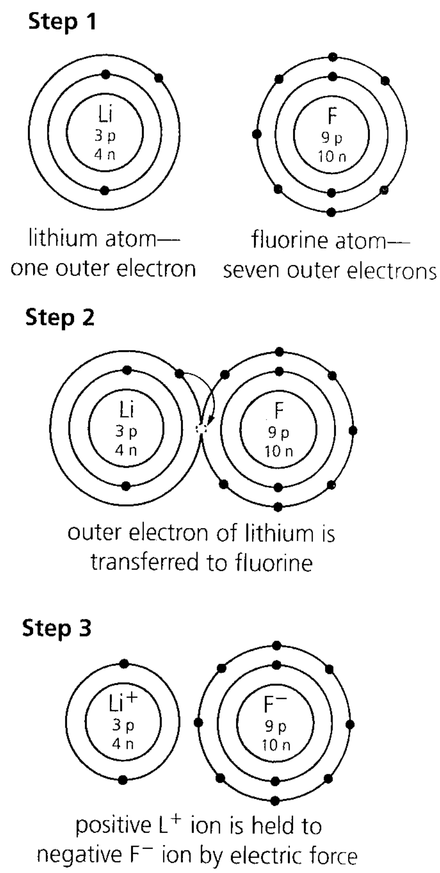

Figure 8 The formation of the ions of lithium and fluorine, and the compound LiF

7B *Investigation*

Ions and Atoms

To perform this investigation, turn to page 226.

In this investigation, you will explore the differences in the properties of an atom and its ion.

the negative and positive ions collect and arrange themselves in a specific structure, forming a crystal. Each positive ion is attracted to several negative ions and repels the other positive ions. Each negative ion is attracted to positive ions, and repels the other negative ions. You can see a similar behaviour when several small compasses are placed near each other (Figure 9).

When dissolved in a solution, or in the liquid or gaseous state, the individual ions move about freely, independent of other ions. There is no definite grouping of atoms that could be considered molecules of the compound. In contrast, in liquid water for example, the three atoms of H_2O move around together as a unit. The water molecules may move past each other, but the three atoms stay together.

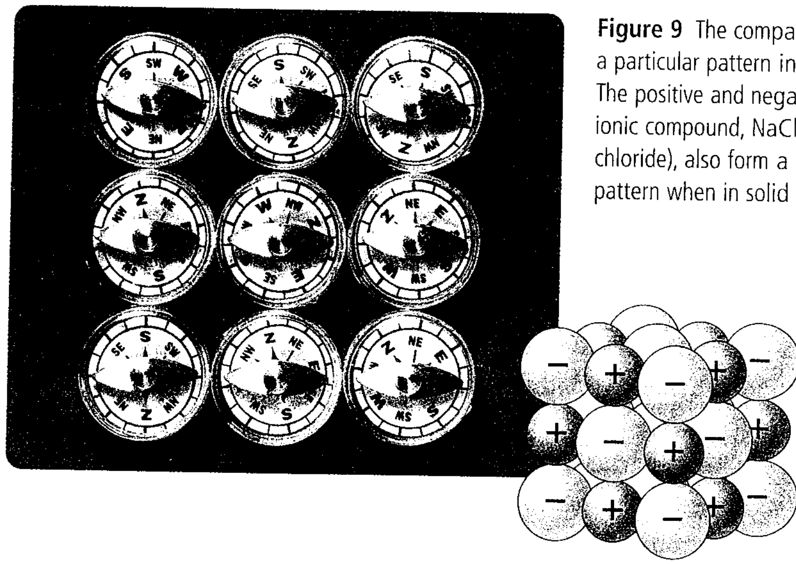

Figure 9 The compass needles show a particular pattern in how they align. The positive and negative ions in the ionic compound, NaCl (sodium chloride), also form a particular pattern when in solid form.

The Ionic Bond and Ion Charge

As you have seen, for elements to form an ionic compound, they must first form ions. Recall that the ion charge is the number of electrons that must be given up or acquired to form an ion. Lithium has an ion charge of 1+, meaning it gives up one electron to form an ionic bond. Fluorine has an ion charge of 1−, meaning it acquires one electron to form an ionic bond. You can see this in Figure 8 on the previous page.

If oxygen atoms (ion charge 2−) contact aluminum atoms (ion charge 3+), each aluminum atom must give up its three outer electrons to form an ion. Each oxygen atom must acquire two electrons to form an ion. Therefore, two aluminum atoms must transfer six electrons to three oxygen atoms to form the ions that make up aluminum oxide, as shown in Figure 10. The metal atoms lose electrons and become positive ions, and the non-metal atoms gain electrons and become negative ions. The total number of electrons given up by the metal ions must equal the total number of electrons accepted by the non-metal ions. The total positive charge of the metal ions must be the same as the total negative charge of the non-metal ions. In the next chapter, you will learn how this balancing of ion charge determines the proportions of the elements in an ionic compound.

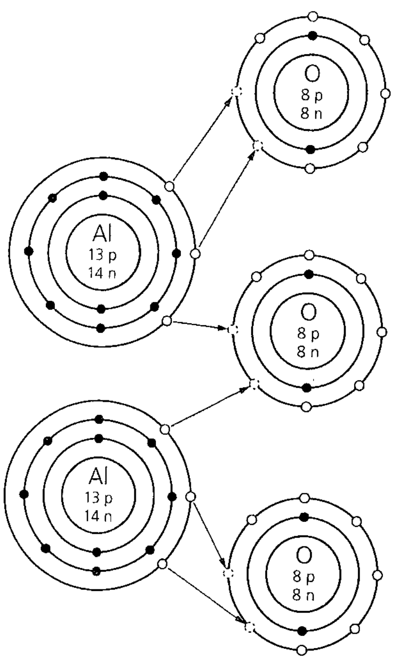

Figure 10 For aluminum and oxygen to form a compound, the atoms must form ions. Each aluminum atom must give up three electrons to become an ion, and each oxygen atom must accept two electrons to become an ion. Two aluminum atoms must transfer six electrons to three oxygen atoms for all the outer shells to be full.

7.4 CHECK YOUR Understanding

1. What is an electron shell?
2. In the first three rows of the Periodic Table, what is the maximum number of electrons that can occupy the first shell? What is the maximum number of electrons that can occupy the second shell and third shell?
3. Consider an atom of oxygen.
   (a) How many electrons are in the first shell?
   (b) How many electrons are in the second shell?
   (c) How many electrons are in the third shell?
4. Consider an atom of nitrogen.
   (a) How many electrons are in the first shell?
   (b) How many electrons are in the second shell?
   (c) How many electrons are in the third shell?
5. When an atom forms an ion, describe the outer shell of the ion.
6. Draw a Bohr diagram for each of the following atoms:
   (a) nitrogen
   (b) boron
   (c) neon
   (d) potassium
7. Draw a Bohr diagram for each of the following ions:
   (a) sodium
   (b) sulfur
   (c) carbon
8. Do noble gases such as helium and neon normally form ions? Explain.
9. Consider the first three rows of the Periodic Table. State the column (or group) that has an element with
   (a) one outer electron
   (b) two outer electrons
   (c) three outer electrons
   (d) four outer electrons
   (e) five outer electrons
   (f) six outer electrons
   (g) seven outer electrons
   (h) eight outer electrons
10. Draw a Bohr diagram for the ions of the compound sodium chloride.
11. Refer to the two Bohr diagrams (Figures 11 and 12) below.
   (a) What is the number of protons in each atom or ion?
   (b) What is the number of electrons in each atom or ion?
   (c) Which element does each diagram represent?
   (d) Is each diagram an atom or an ion?

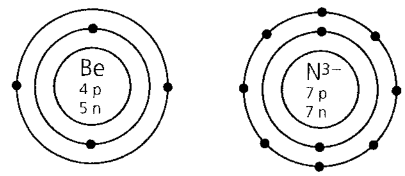

Figure 11 Figure 12

12. If a new element that has seven outer electrons is discovered, in which column or group do you think it should be placed?
13. If a new element that has two outer electrons is discovered, in which column or group do you think it should be placed?
14. Describe the process by which aluminum sulfide is formed from atoms of aluminum and sulfur. How many atoms of each element are required? How many electrons are transferred? Which atoms give up electrons, and which atoms accept electrons?
15. Sodium is stored in oil to keep it away from water. Magnesium has fewer special storage requirements. Explain why sodium is so much more reactive than magnesium.
16. Describe a situation that could be used as an analogy to explain the formation of ions in ionic compounds.
17. Does sodium chloride (an ionic compound) exist as molecules? Explain why or why not.