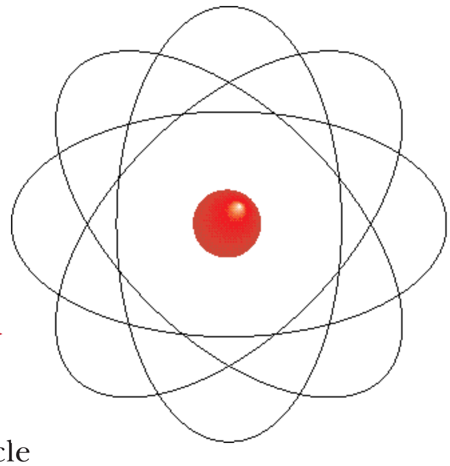
CHAPTER

3 Models for Atoms

Getting Started



1 The better our model of matter, the more we can understand about matter itself, and the more uses we can make of that understanding. Models of matter help us understand the chemical processes that affect every aspect of modern life, from nourishing our bodies to fuelling space shuttles.

You are already familiar with one model, the particle theory, which states that all matter is made of tiny particles. Like all models, this model is a mental picture, a diagram, or a three-dimensional means of representing something. For instance, the particle theory can be used to help understand physical behaviour of substances, such as changes of state. It can also be applied to explain the formation of various molecules from different combinations of atoms. But what makes atoms different from each other? Look at the illustrated model. What is "inside" the particle we call an atom?

2 Over time, it became more and more clear to scientists that the particle theory could not explain all observable behaviours of matter. New evidence required that new models be created. For instance, the particle theory is not useful for understanding static electricity. Why do we sometimes get electric shocks when we touch metal doorknobs? Why is dust more attracted to your television screen than to your television cabinet? How can a different model of matter be used to answer these questions?

3 How do fireworks produce dazzling displays of light, colour, and sound? The answer lies in the nuclear model of the atom. What are some other practical applications of this model?

Reflecting

Think about the questions in 1, 2, 3. What ideas do you already have? What other questions do you have about atoms? Think about your answers and questions as you read the chapter.

Try This: What You Know About Atoms

Make a table similar to **Table 1**. In the first column, write the answers to the following questions:

1. What do you know for certain about the structure of the atom?
2. What do you think you know about the structure of the atom?
3. What do you think you might learn about the structure of the atom? (Include any questions you might have about the structure of the atom.)

In the second column, jot down new ideas, details, examples, or even diagrams about the structure of the atom that occur to you as you read this chapter. After you have finished the chapter, put a check in the first column beside the ideas that your reading has confirmed, and a question mark beside the ideas left unconfirmed by your reading.

Table 1

Ideas and questions	What I learned
?	?
?	?
?	?
?	?

3.1 Investigation

SKILLS MENU

- ○ Questioning
- ○ Hypothesizing
- ○ Planning
- ● Conducting
- ● Recording
- ● Analyzing
- ● Communicating

Making a Logical Model

Imagine that you are standing in front of a pop vending machine (**Figure 1**). You put in a coin, press a button, and a can falls down into the tray at the bottom. How does the machine work? You can't see inside it, so you have to create a model that could explain the workings of the machine.

One possibility is that there is a very small person working inside. When the coin appears, the person checks to see which button was pushed, searches for the right can, and puts it in the tray.

A second possibility might involve a mechanical system with various electronic sensors, levers, motors, and slots that operate when the coin is inserted to release the can.

How could you test these hypotheses? You could pull out the electric plug in the back. If no can appears when the power is off, perhaps the second hypothesis is correct. Or maybe the person inside refuses to work in the dark—the first hypothesis is still a possibility!

The best model you can create is the one that allows you to predict how the vending machine will behave in as many situations as you can imagine. You may come up with a model that works perfectly for all of the evidence that you have. But someone else might try using the vending machine in a completely new situation. If the can doesn't fall and the model can't explain it, then the model needs to be adjusted.

Like a scientist exploring models of matter, all of your testing, thinking, and experimenting is based on the fact that you can't see what's going on inside the vending machine. Atoms can't be seen—we can only see how matter behaves in certain circumstances. The model of matter changes when that model is tested in new circumstances that produce new and unpredictable results. In this investigation, you will follow a similar process, by trying to guess what is inside a sealed box. You will use some basic scientific skills:

- gathering and organizing observations,
- inventing a model to explain these observations, and
- communicating your findings to others.

Figure 1
What model could explain how a vending machine works?

Materials

- a sealed box (e.g., a shoe box) containing an object or objects
- ruler
- magnet

Question

What is inside a sealed box?

Hypothesis

Simple experiments can be designed to make a model of the contents of a sealed box.

Procedure

1 Obtain a sealed box that contains an object. Measure the outside dimensions of the box. (6B)

(a) Record your observations.

2 Without breaking the seal, make all the observations you can by carefully shaking, tilting, or otherwise moving the box.

(a) Record each movement that you chose to use, and the observations you made each time.

(b) Write a description, or model, of what you think the object is. For example, describing it as "a 15-cm-long metal object, branched into four small projections at one end" is better than describing it as "a fork."

3 Examine your observations and invent new movements of the box that will help you determine the size, shape, and other physical properties of the object. In particular, try to make some quantitative observations.

(a) Record each movement that you chose to use, and the observations made each time.

4 With your group, discuss a model for the object in the box.

(a) Make a labelled drawing of your model, including measurements if possible.

(b) Write a short description of the main characteristics of your model.

5 After completing the drawing and description, open the box and look at the object.

(a) Describe the object.

Analysis and Communication

6 Analyze your observations by answering the following questions:

(a) Write a two-paragraph summary of the similarities and differences between the real object and your model. In the first paragraph, list the characteristics that you were successful in determining. In the second paragraph, list those characteristics that you were unable to determine. (7E)

(b) Speculate on why this "black box" experiment is similar to the process that scientists followed when they produced their models for matter.

Making Connections

1. Think about the original example of the vending machine.

(a) What experiments could you do to find out how the vending machine operates?

(b) Draw a model of how you think the machine operates.

2. Choose an everyday appliance. Draw and label a model to explain how it works. Suggest ways that your model could be tested.

Exploring

3. Obtain a polystyrene sphere in which your teacher has embedded an object. Take a thin metal probe or knitting needle and carefully insert it into the sphere. Make a systematic series of probings. Record your observations and make a model drawing to describe what is inside the polystyrene "atom."

Reflecting

4. Think about your group's success with determining the identity of the object in the box. Is there any reason why you successfully determined some characteristics but not others?

SKILLS HANDBOOK: (6B) Obtaining Quantitative Data (7E) Reflecting on Ideas

Developing Models of Matter

Have you ever taken something apart to figure out how it works? Have you ever watched the sand wash away from around your feet as you stand at the edge of the ocean? Like scientists and philosophers through the ages, you are curious about the world around you. You want to know how things will behave in certain circumstances. Perhaps you will develop an idea about something and test it. In just the same way, scientists have observed, questioned, and theorized for centuries about the "stuff" that makes up the world: matter. They looked at the evidence around them and, in an attempt to explain it, developed many models of matter. These have been modified, combined, or rejected as new evidence was discovered.

Did You Know

Empedocles had a theory for the combination and separation of elements, based on the human emotions of love and hate. Love made elements combine and hate made them break apart.

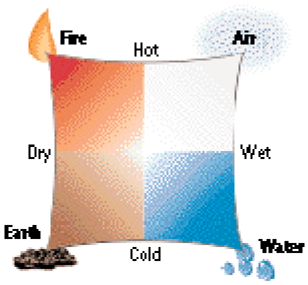


Figure 1
According to the four-element model, each element is a mixture of two properties. For example, fire is a mixture of hotness and dryness.

Figure 2
In the atomic model, atoms were conceived to be of different sizes, to have regular geometric shapes, and to be in constant motion.

Figure 3
The Greek philosopher Aristotle also believed that matter was made of four elements: earth, air, fire, and water.

About 450 B.C.

A Greek scholar named Empedocles proposed that matter was composed of four "elements": earth, air, fire, and water (**Figure 1**). These elements mixed together in different proportions to yield different substances. Rust might be one part fire and two parts earth. Volcanic rock might be two parts fire and one part air. Unlike most philosophers of his time, Empedocles checked some of his theories experimentally. He demonstrated that, even though air is invisible, it is not just "nothing." Because it takes up space, it must be a form of matter.

About 400 B.C.

Another Greek, Democritus, suggested that matter was made of tiny particles that could not be broken down further (**Figure 2**). He called the particles atoms, after the Greek word *atomos*, which means "indivisible." Thus, different elements were composed of different kinds of atoms, a revolutionary concept at the time. However, Democritus' ideas were never widely accepted because Socrates, a very influential figure at the time, did not accept them.

About 350 B.C.

The philosopher Aristotle believed in Empedocles' "four element" model despite the more recent "atomic" model (**Figure 3**). Aristotle's influence was so great, and his writings read by so many people, that the "four-element" model was accepted for almost 2000 years.

450 B.C. 400 B.C. 350 B.C.

A.D. 500–1600

Do metals grow like plants, ripening into gold? Many **alchemists** (combination of philosopher, mystic, magician, and chemist) believed that they did. For centuries they performed numerous experiments attempting to make gold from cheap metals such as iron and lead. They devised chemical symbols for substances that we now recognize as elements and compounds. They also invented many laboratory tools that we still use today: beakers, filters, stirring rods, and distillation apparatus. However, despite finding many new substances, they still accepted the four-element model. And no one ever turned lead into gold!

Figure 4

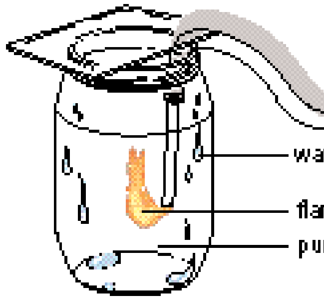
Antoine Lavoisier is often considered the father of modern chemistry. His involvement in a state organization that collected taxes led to his execution by guillotine in 1791 during the French Revolution.

1650

An English scientist, Robert Boyle, did not believe in the four-element model. He devised a new definition for the word *element:* "I mean by element, simple unmitigated bodies." This became the modern definition of an element: a pure substance that cannot be chemically broken down into simpler substances. Boyle also believed that air was not an element, but rather a mixture.

Figure 5

When Cavendish burned hydrogen in oxygen, he produced water.



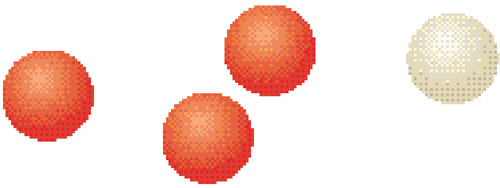
Late 1700s

Joseph Priestley was the first person to isolate oxygen scientifically, but he did not know that oxygen is an element. This fact was soon recognized by Antoine Lavoisier (**Figure 4**). Experimenting with Priestley's oxygen, Lavoisier concluded that air must be a mixture of at least two gases, one of which was oxygen.

Meanwhile, Henry Cavendish experimented by mixing a metal with acid, which resulted in a flammable gas that was lighter than air. He did not know that the gas he had prepared was hydrogen, but discovered that his gas would burn in some of Priestley's oxygen, producing water (**Figure 5**). Until that time, scholars had believed that water was an element.

A.D. 500–1600 **1650** **Late 1700s**

Figure 6
In Dalton's atomic model, an atom is a solid sphere. This model is still useful for explaining chemical charges: atoms combine and molecules come apart as chemical reactions occur.



1808

By this time it was generally accepted that matter was made of elements: the two models had come together. English chemist John Dalton published a theory of why elements differ from each other and from non-elements (**Figure 6**). Dalton's **atomic model** for matter stated that:

- All matter is made of atoms, which are particles too small to see.
- Each element has its own kind of atom, with its own particular mass.
- Compounds are created when atoms of different elements link to form molecules.
- Atoms cannot be created, destroyed, or subdivided in chemical changes.

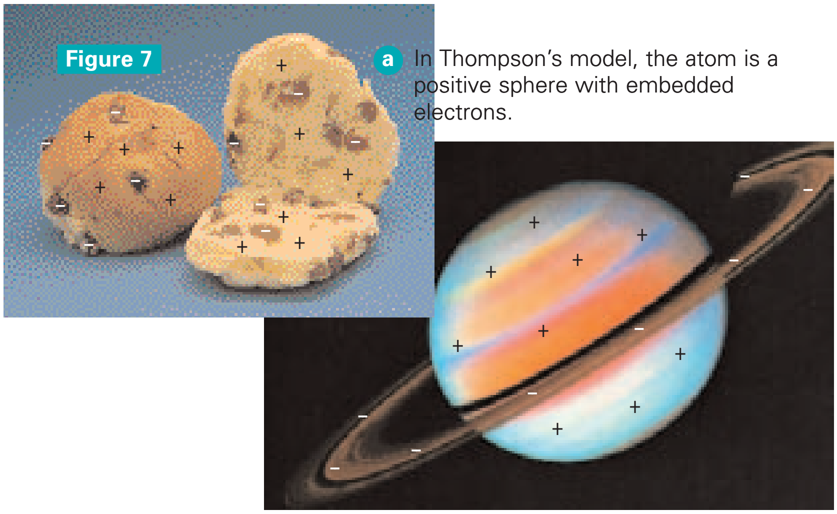
1800s

However, Dalton's atomic model cannot explain why, on a dry winter day, you get a spark when you touch a metal doorknob. Obviously, matter is able to develop positive and negative **charges**—quantities of electricity that may build up on an object. A new model was developed, introducing tiny negatively charged particles that could be separated from their atoms and moved to other atoms.

In 1831, Michael Faraday found that electric current could cause chemic changes in some compounds in solution. The atoms could gain electric charges and form charged atoms, called **ions**. In this modified version of Dalton's model:

- Matter must contain positive and negative charges.
- Opposite charges attract and like charges repel.
- Atoms combine to form molecules because of electrical attractions between atoms.

Figure 7



a In Thompson's model, the atom is a positive sphere with embedded electrons.

b In Nagaoka's model, the atom is compared with the planet Saturn, where the planet represents the positively charged part of the atom, and the rings represent the negatively charged electrons.

1904

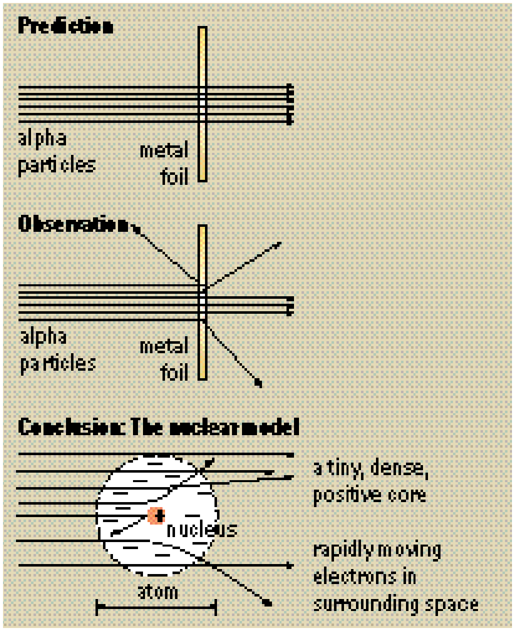
J. J. Thomson revised the atomic model further, to explain his discovery of very light negative particles, called electrons. He also did experiments with beams of much heavier positive particles (later identified as protons). The new model became known as the "raisin-bun" model (**Figure 7a**).

- Atoms contain particles called electrons.
- Electrons have a small mass and a negative charge.
- The rest of the atom is a sphere of positive charge.
- The electrons are embedded in this sphere, so that the resulting atoms are neutral or uncharged.

The Japanese scientist H. Nagaoka, working at about the same time, modelled the atom as a large positive sphere surrounded by a ring of negative electrons (**Figure 7b**).

1808 **1800s** **1904**

Figure 8
Rutherford's experiment



1911

Ernest Rutherford, working at McGill University in Montreal, designed an experiment to test Thomson's and Nagaoka's models. He aimed a type of radiation called alpha particles (positively charged particles smaller than most atoms) at a thin sheet of gold foil. He predicted, based on Thomson's raisin-bun model, that the particles would pass straight through the gold foil, as indeed most of them did. However, a very small number of the alpha particles bounced almost straight back from the gold foil (**Figure 8**). Rutherford was amazed and described the result as being similar to firing bullets at a piece of tissue paper and having one of them bounce back! To explain how the positive alpha particles had been repelled, Rutherford had to come up with another new model—the **nuclear model**:

- An atom has a tiny, dense, positive core called the nucleus (which deflected the alpha particles and contains protons).
- The nucleus is surrounded mostly by empty space, containing rapidly moving negative electrons (through which the alpha particles passed unhindered).

Understanding Concepts

1. How were alchemists similar to and different from modern scientists?
2. Describe the changing definitions of an element.
3. Describe the changing definitions of an atom.
4. What were the four main points in Dalton's theory?
5. Whose work led to a model that suggested that
   - (a) the atom contains a dense positive core?
   - (b) atoms can form charged particles called ions?
   - (c) atoms contain electrons and protons?
   - (d) atoms cannot be divided further?
   - (e) electrons surround a central positive core?
6. In Rutherford's gold foil experiment,
   - (a) what kind of electrical charge did the alpha particles have?
   - (b) what might Rutherford have expected to observe, based on Thomson's model?
   - (c) what is the relative size of the heaviest part of the atom compared with the whole atom?

Exploring

7. Design an experiment to demonstrate that fire and earth are not elements.
8. Design and build a model to represent one of the early models of the atom.

Reflecting

9. Why do scientists continue to make models of matter if the models keep changing? Write a few sentences to suggest why models might be useful.

Challenge

Draw a series of diagrams to represent the various models of the atom. How would you build and display these? How would you use these in your presentation to Mendeleev?

1911

Career Profile

Biochemistry and Ethics

As a child growing up in India, Shree Mulay was fascinated by biographies of famous scientists. When she was eight years old she read about Marie Curie, the Nobel prize-winner whose work in the chemistry of radioactive materials revolutionized our understanding of the structure of atoms. She was so excited by Curie's work that she decided to pursue a career in chemistry. After obtaining her B.Sc. in Delhi, she came to McGill University to obtain a Master's and then a Doctorate in chemistry.

> "I found it exciting—the possibility of knowing that you can relate the chemical structure of a molecule to its function in the body."

Today Dr. Mulay is assistant director of the Clinical Laboratory at the Royal Victoria Hospital in Montreal, as well as director of the McGill Centre for Research and Teaching on Women. She teaches endocrinology to students at McGill, and in her laboratory work she examines the roles of hormones as they affect reproduction and pregnancy.

Dr. Mulay believes that scientists have an obligation to take an active part in their society. She has criticized governments and pharmaceutical companies that develop contraceptives for women, for not adequately safeguarding the health of women, especially in Third World countries. "Women were reporting problems and they were not being recorded by the investigators," she says. After discovering in 1999 that some clinical drug trials were not meeting ethical guidelines, Dr. Mulay was featured on David Suzuki's *The Nature of Things*.

Dr. Mulay highly recommends a career in chemistry. A basic knowledge of chemistry, she says, can lead to many, many different areas of medical and scientific research.

Exploring

1. There are very strict guidelines controlling how pharmaceutical companies can test, and then report on, their products. Research these guidelines and make a brief presentation to your class.
2. Why do you think so many areas of medical and scientific research depend on a knowledge of chemistry?

Inside the Atom

What does "splitting the atom" mean? And if the atom is split, what do the pieces look like? Rutherford's experiment was a breakthrough in how people thought about matter. As you have learned, in the nuclear model, most of the atom is empty space, filled with quickly moving electrons. The positive nucleus is so small that it takes up only a tiny fraction of the size of the atom. Yet almost all of the atom's mass is concentrated in this nucleus, which contains protons.

Did You Know

If an atom were the size of a football field, its nucleus would be the size of a grain of sand in the centre.

Types of Subatomic Particles

The "pieces" of an atom—the particles of which an atom is composed—are called **subatomic particles**. Electrons and protons are subatomic particles. Experiments conducted by the English scientist James Chadwick, in 1932, led to the discovery of a third subatomic particle with no charge: the neutron. These subatomic particles are described in terms of their mass relative to each other, their electrical charge, and their location.

- **Protons** are positively charged particles with a relative mass of 1, located in the nucleus.
- **Neutrons** are neutral particles with a relative mass of 1, also located in the nucleus.
- **Electrons** are negatively charged particles with a relative mass of approximately 1/2000 of the mass of a proton or neutron, travelling in regions of space around the nucleus.

Protons are especially significant, because the number of protons in an atom determines what the atom is. For example, any atom with one proton is a hydrogen atom (H), and any atom whose nucleus contains 12 protons is magnesium (Mg).

Counting Subatomic Particles

How many electrons, protons, and neutrons are there in an atom? An atom itself has no electric charge, and the negative charge of one electron is as strong as the positive charge of one proton. The number of protons and electrons in an atom is the same, so the charges cancel each other out. Some examples are given in **Table 1**.

Table 1

Element	Number of Protons	Total Positive Charge	Number of Electrons	Total Negative Charge	Net Charge of Atom
hydrogen	1	1+	1	1–	0
oxygen	8	8+	8	8–	0
magnesium	12	12+	12	12–	0
copper	29	29+	29	29–	0
uranium	92	92+	92	92–	0

The number of protons in an atom is called the **atomic number**. If you know the atomic number of an atom, you know how many protons—and how many electrons—that atom contains.

Another significant number is the mass number. The **mass number** represents the sum of protons and neutrons in an atom. (The mass of the electrons, relative to the mass of the protons and neutrons, is insignificant.) Therefore, if you know the atomic number (the number of protons) and the mass number (the sum of protons and neutrons), you can easily calculate the number of neutrons:

number of neutrons = mass number – atomic number

We can represent the numbers of subatomic particles by using **standard atomic notation**, an internationally recognized system that allows anyone to communicate information about any atom. In this notation, we write the chemical symbol of the atom and place the atomic number to the lower left and the mass number to the upper left.

For example, the atomic notation of chlorine is

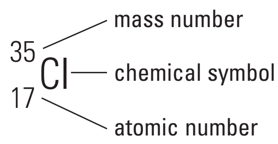
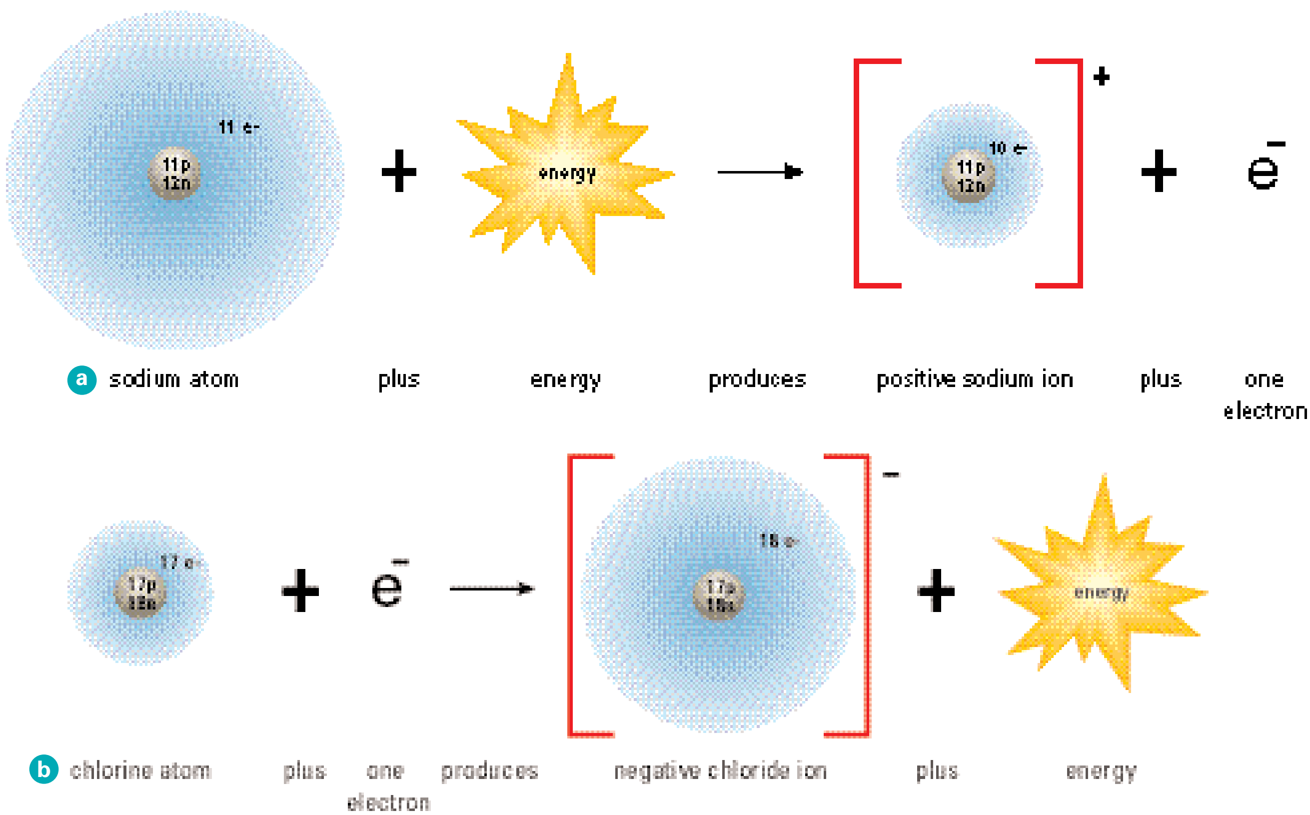


Figure 1

Atoms can gain or lose electrons to form charged atoms or ions. The elements are still the same because the number of protons has not changed.



Similarly, the atomic notation for an atom of sodium is

$$^{23}_{11}\text{Na}$$

This notation tells us that sodium has 11 protons and 23 – 11 = 12 neutrons. Since the atom is neutral, it also tells us that the number of electrons is 11. This sodium atom could also be represented as sodium -23.

Charged Atoms

Why is it dangerous to work with electrical appliances around water? Tap water and rain water can conduct electricity because they are not pure water: they contain charged atoms that can move in the solution and carry electric current. These charged atoms are called ions—they have a charge because the number of electrons is not equal to the number of protons. For example, salt water contains sodium ions, which have 11 protons and 10 electrons—the sodium ions have a charge of +1. Salt water also contains chloride ions, which have 17 protons and 18 electrons —the chloride ions have a charge of –1.

Ions are formed when negatively charged electrons move from one atom to another. If an atom loses an electron, there are more protons in the nucleus than electrons in the space around it. Atoms such as sodium and calcium lose electrons to form such ions with net positive charges (**Figure 1a**). If atoms gain electrons, there are more electrons than protons. Atoms such as chlorine and oxygen gain electrons to form ions with net negative charges (**Figure 1b**). These charged particles, now described as ions rather than atoms, can move in solutions and conduct electricity.

Understanding Concepts

1. Draw and complete a table with three rows and four columns to summarize what you know about the nuclear model of the atom. The column headings should be "particle, proton, neutron, electron." The row headings should be "mass, charge, location in atom."
2. Write standard atomic notation for the following:
   - **(a)** an atom of nitrogen with 7 protons and 8 neutrons
   - **(b)** an atom of bromine with 35 protons and 36 neutrons
   - **(c)** an atom of sulfur with 16 protons and 16 neutrons

   (You may want to look at the table of chemical symbols on page 58.)
3. Assuming that each atom is neutral, copy and complete **Table 2** by filling in the blanks.

Table 2

atomic number	mass number	no. of protons	no. of neutrons	no. of electrons
8	16	?	?	?
11	?	?	12	?
?	?	14	16	?
?	29	?	?	14

4. An ion is an atom that has gained an electrical charge.
   - **(a)** A magnesium atom has 12 protons. How many electrons does a magnesium ion, with a charge of +2, contain?
   - **(b)** A fluorine atom has an atomic number of 9. How many electrons does a fluorine ion, with a charge of –1, have?

Reflecting

5. If the atom is almost entirely empty space, why do atoms not just collapse into each other and into a much smaller volume? (Hint: think about what you know about attraction and repulsion of charges.)

Challenge

If it is useful to build a model of an atom for your challenge, what materials would you use to represent protons, neutrons, and electrons?

A "Planetary" Model of the Atom

Why do some elements and not others combine to form compounds? What part of an atom is involved when chemical reactions occur? Rutherford's nuclear model did not answer these questions. Also, the nuclear model itself had problems. Since electrons are negative and protons in the nucleus are positive, why didn't the atom collapse as the electrons were attracted to the nucleus? To answer these questions, another model was required.

Look at the planetary model in **Figure 1**. How does this model resemble Rutherford's nuclear atom? Further experiments suggested that, as an improvement to Rutherford's model, electrons orbited around the nucleus like planets around the Sun.

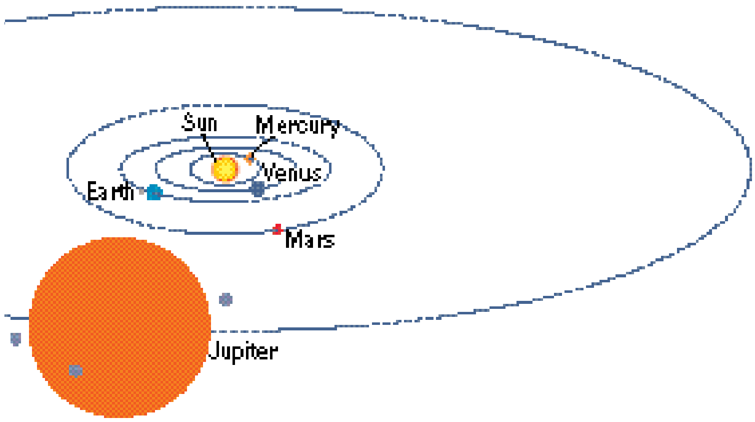


Figure 1
Planetary model of the atom

Atoms and Rainbows

What do atoms and rainbows have in common? Their behaviour can be explained in terms of energy. When white light passes through raindrops or a prism, it is split into a **spectrum**—a rainbow of the many colours that combine to make white light (**Figure 2**). Different colours of light have different energies. For example, blue light has more energy than red light. When elements are heated in a flame, they show a few specific colours (**Figure 3**). These specific colours, seen through a spectroscope, are called a line spectrum. How could these definite energies of light be explained?

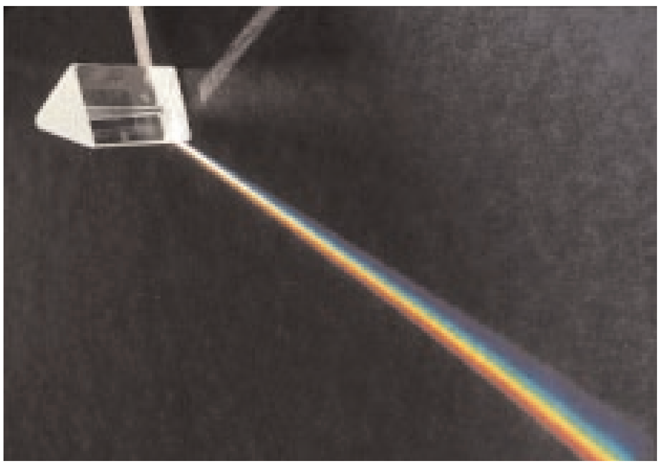


Figure 2
A narrow beam of white light is split by a prism into a continuous rainbow of colours.

a cesium
b sodium
c lithium

Figure 3
When an element is heated in a flame, it produces only certain colours or energies of light. Each element has its own unique line spectrum.

A Danish physicist, Niels Bohr, proposed a "planetary" model of the atom to explain line spectra. Bohr suggested that:

- Electrons move around the nucleus in nearly circular paths called **orbits**, like planets around the Sun (**Figure 4**).
- Each electron in an orbit has a definite amount of energy.
- The farther away the electron is from the nucleus, the greater its energy is.
- Electrons cannot exist between these orbits, but can move up or down from one orbit to another.
- The order of filling of electrons in the first three orbits is 2, 8, and 8.
- Electrons are more stable when they are at lower energy, closer to the nucleus.

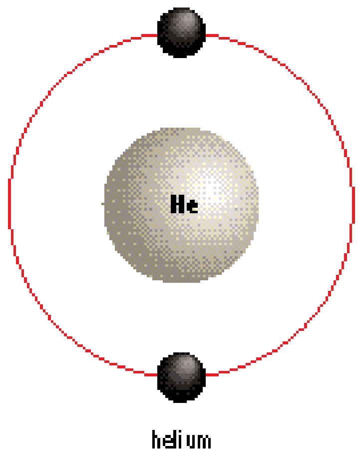


Figure 4
In Bohr's model of the atom, electrons travelled around the nucleus in nearly circular orbits, much like planets around the Sun.

Bohr's model explains the spectra of elements in terms of the "jumps" that electrons make from one orbit or **energy level** to another (**Figure 5**). In his model, electrons are arranged in orbits that surround the nucleus like layers of an onion. Space in the orbits is limited, and the electrons are arranged in a definite pattern. Within the orbits, electrons move quickly. When electrons are energized by heat, electricity, or light, they use this extra energy to jump out to a higher orbit (**Figure 6**). We say they are in an **excited state**.

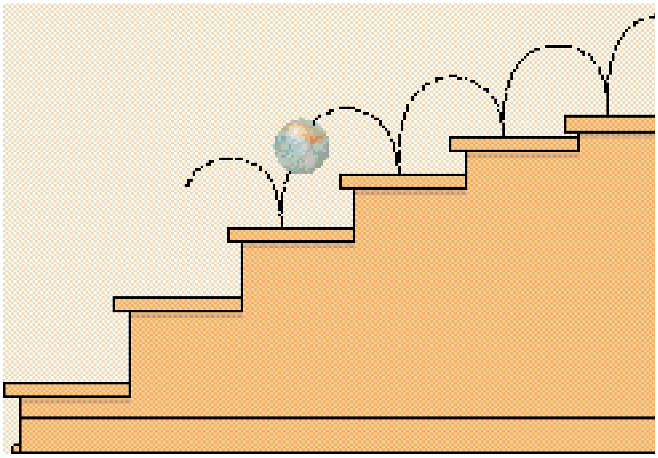


Figure 5
Imagine an electron in Bohr's model as being like a marble on a staircase. The marble can only be at certain definite levels. It can jump up or fall down by only very specific amounts.

The excited electrons are very unstable and tend to fall back into their normal, more stable orbits. This low-energy state is called the **ground state**. When the electrons drop back to their normal orbits, their extra energy is given off in the form of light. The amount of energy given off is equal to the difference in energy between the higher and lower energy levels. This very specific energy amount corresponds to a very specific colour.

Bohr's model of electrons in energy levels also explains why each element has a different spectrum. For example, hydrogen has only a single proton and a single electron. Sodium has 11 protons and 11 electrons. The orbits in these two atoms are at different distances from the nucleus. Therefore, the energies of the electrons in the two atoms are slightly different. An electron jumping from the third level to the second level in a hydrogen atom may produce a red colour. The colour is evidence of the difference in energy between the two levels. An electron jumping from the third level to the second in a sodium atom may produce a yellow colour, because the orbits are at different distances from the nucleus.

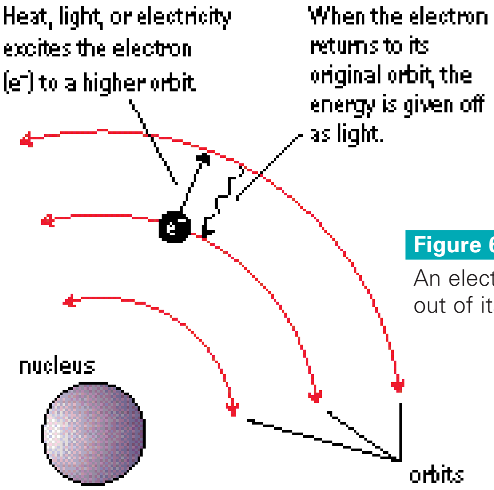


Figure 6
An electron "jumping" out of its regular orbit

The Bohr Model of Electron Arrangement

Bohr developed his model of the atom to explain the line spectrum of hydrogen, but it was soon extended to other elements. Scientists drew **Bohr diagrams** to represent the electronic structure of elements. In these diagrams, the symbol of the element is written in the centre to represent the nucleus of the atom. A series of concentric circles is drawn around the nucleus to represent the orbits, and electrons are shown in these orbits.

The element hydrogen, which has an atomic number of 1, has 1 electron in its first orbit. The element nitrogen (symbol N), which has an atomic number of 7, has 7 electrons. Two electrons are in the atom's first orbit, and the remaining 5 electrons are in its second orbit. Phosphorus (symbol P), with an atomic number of 15, has 15 electrons. Two electrons are in the first orbit, 8 are in the second orbit, and 5 are in the third orbit (**Figure 7**).

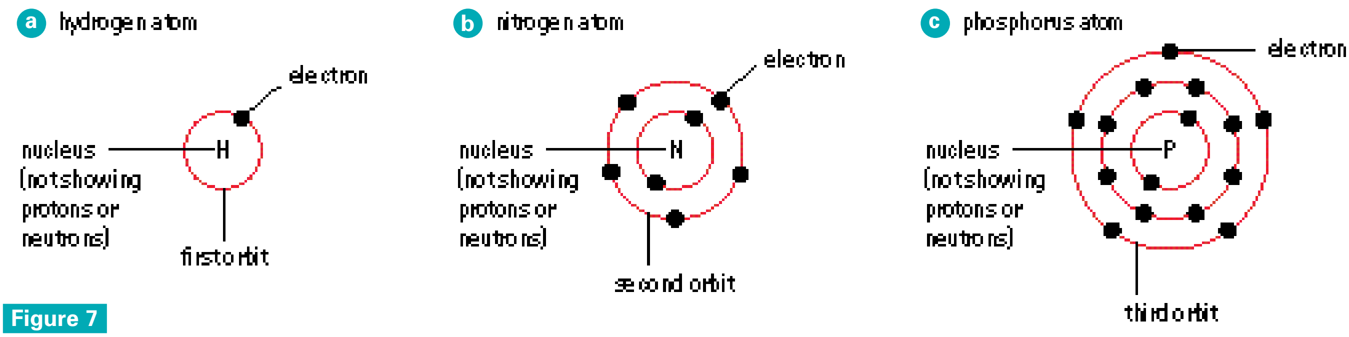


Figure 7
Bohr models of electron arrangement for hydrogen, nitrogen, and phosphorus

Bohr-Rutherford Diagrams

We can combine Rutherford's nuclear model with Bohr's planetary model in diagrams that summarize the numbers and positions of all three subatomic particles in an atom. In these **Bohr-Rutherford diagrams**, a circle is drawn in the centre to represent the nucleus of the atom. The numbers of protons and neutrons are written in this circle. Electrons are again shown in circular orbits about the nucleus. For example, consider a Bohr-Rutherford diagram for magnesium, Mg-24. The atomic number of magnesium is 12 and its mass number is 24. Therefore, there are 12 protons and 12 neutrons in the nucleus. Mg-24 has 12 electrons, 2 in the first orbit, 8 in the second orbit, and 2 in the third orbit. Similarly, Cl-35 has 17 protons and 18 neutrons in the nucleus, 2 electrons in the first orbit, 8 electrons in the second orbit, and 7 electrons in the third orbit. The Bohr-Rutherford diagrams for these atoms are shown in **Figure 8**.

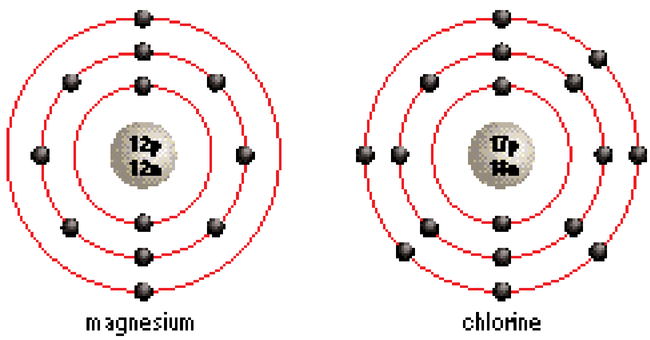


Figure 8
Bohr-Rutherford diagrams for Mg-24 and Cl-35. The electron arrangements can be described as 2, 8, 2 for magnesium and 2, 8, 7 for chlorine.

Electron Arrangements in Ions

Recall that atoms can lose or gain electrons to form charged atoms (ions). But which ions do atoms form? In Bohr diagrams for the first 20 elements from the Periodic Table, there is something special or "stable" about the numbers 2, 8, and 8. Many elements tend to form ions by losing or gaining enough electrons to have 2 or 8 electrons in their orbits. For example, look at the atoms in **Figure 9** and compare them with **Figure 8**. A magnesium atom becomes an ion by losing the two electrons in its outermost orbit. The ion has 2 electrons in the first orbit and 8 in the second. It also has a +2 charge because it has two more protons than electrons. Chlorine forms an ion by gaining one electron. The ion has 2 electrons in the first orbit, 8 in the second, and 8 in the third. It has a –1 charge because it has gained an extra electron.

Did You Know

The Bohr-Rutherford model is useful because it explains how most chemical reactions occur. But, like all models, it can change with further experiments. There is a very complicated model called the quantum-mechanical model that you might learn about in senior chemistry.

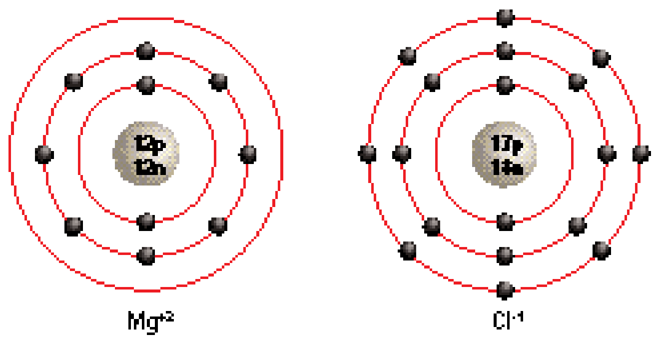


Figure 9

Bohr-Rutherford diagrams for Mg-24 and Cl-35 ions. The atoms gain or lose electrons to have a "stable" arrangement of electrons. The ions are described as Mg^{+2} and Cl^{-1} ions.

Understanding Concepts

1. (a) What is meant by the term "spectrum"?
   (b) How is the spectrum seen in a rainbow different from the spectrum of an element?
2. (a) In words, describe the structure of the atom using the Bohr-Rutherford model.
   (b) What paths do electrons follow in the Bohr model?
   (c) Why are orbits also called energy levels?
   (d) How do the energies of electrons in different orbits compare?
3. (a) How does the Bohr model of the atom explain light given off in line spectra?
   (b) Why do different elements produce different line spectra?
4. Draw Bohr diagrams for
   (a) oxygen (symbol O), atomic number 8
   (b) aluminum (symbol Al), atomic number 13
   (c) calcium (symbol Ca), atomic number 20
5. Draw Bohr-Rutherford diagrams for
   (a) fluorine-20 (symbol F), atomic number 9
   (b) boron-11 (symbol B), atomic number 5
   (c) potassium-40 (symbol K), atomic number 19
6. (a) Draw Bohr-Rutherford diagrams for the stable ions formed by gain or loss of electrons in each of the atoms in the previous two questions.
   (b) Write the symbol and charge for the stable ion formed by each atom.
7. For atoms to interact, they must collide with each other. Which subatomic particle do you think has the most important role in chemical change? Explain why.
8. Look at the tables of combining capacities on pages 64–65 and your answers to question 6.
   (a) Which elements are named in both the table and the question?
   (b) Compare the combining capacity and the charge on the ion for each of these elements. What pattern do you notice?

Reflecting

9. Draw a chart to help you organize and remember what you need to know to draw Bohr-Rutherford diagrams.

3.5 Investigation

SKILLS MENU
- ○ Questioning
- ● Hypothesizing
- ○ Planning
- ● Conducting
- ● Recording
- ● Analyzing
- ● Communicating

Using Electrons to Identify Elements

According to the Bohr model of the atom, when the atoms in an element are provided with energy, some of the electrons may "jump" up to higher levels. This energy can be in the form of heat, light, or electricity. The electrons are said to be in an excited state because they are in higher energy orbits than normal.

The electrons then tend to fall back down to their normal, lower energy level or ground state. When this happens, the atoms give out energy in the form of light. Since different elements have slightly different energy levels, different energies or colours of light are given out (**Figure 1**). These colours are like the "fingerprints" of elements, especially metals, even when they are combined with other elements in chemical compounds.

In this investigation, you will use an experimental technique called a **flame test**. You will heat samples of compounds and determine the identity of the metal in each. **Figure 2** shows an alternative method for conducting flame tests.

Some of these solutions are poisonous. Any spills of these solutions on the skin, in the eyes, or on clothing should be washed immediately with cold water. Inform your teacher of any spills.

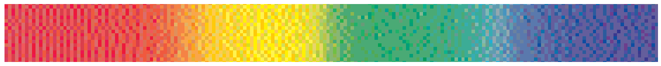
Materials

- safety goggles
- apron
- Bunsen burner
- flint lighter
- eight 250-mL beakers, each containing one splint for each student group
- each splint soaked in 0.5 mol/L solutions of one of the following: lithium nitrate, sodium nitrate, potassium nitrate, barium nitrate, calcium nitrate, copper nitrate, and two unknown metal nitrates
- beaker containing water for extinguishing splints

Question

What can be observed when various compounds are heated in a flame?

Figure 1



(a) Sunlight produces a continuous spectrum of light corresponding to many different energies.

(b) An element like hydrogen produces only certain energies of light that correspond to electrons dropping to lower energy orbits.

Hypothesis

1 Write your own hypothesis about what you might observe. (4A)

Procedure

2 Design an observation table in which to record what you see.

3 Review the safety procedures for using a Bunsen burner. Put on your apron and safety goggles.

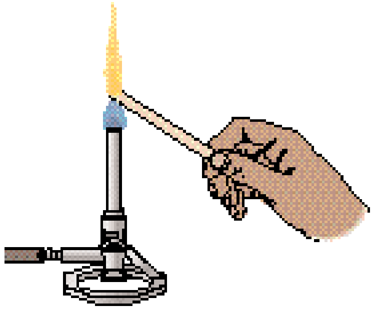
4 Obtain from your teacher 8 wooden splints that have been soaked for 2–4 h in solutions of 6 known and 2 unknown compounds.

Only the bottom halves of the splints have been soaked. Handle the splints by the "dry" ends only.

5 Use the flint lighter to ignite the Bunsen burner. Adjust the burner to produce the hottest flame possible.

6 Hold the soaked end of the lithium nitrate splint in the flame for a short time. As soon as the flame is no longer strongly coloured extinguish the splint by placing it in the beaker of water.

SKILLS HANDBOOK: (4A) Asking Questions and Hypothesizing



(a) Record your observations of the flame colour for lithium in your data table.

Do not burn the splints.

7 Repeat step 6 for each of the other 5 known solutions.

(a) Record your observations of the flame colours for the other metals in your table.

8 Repeat step 6 for the 2 unknown solutions. What do you think is the identity of the unknown solutions?

(a) Record your observations of the flame colours for the unknown metals in your table.

9 Return the splints as directed by your teacher. Clean up your work station and return your apparatus. Wash your hands.

Analysis and Communication

10 Analyze your observations by answering the following questions:

(a) What was the identity of each of the unknown solutions? How did you decide?

(b) Which metals were easy to identify? Explain.

(c) Which metals were difficult to identify? Explain.

(d) Why were all of the compounds you tested nitrates?

8A **11** Write a lab report for this investigation.

Figure 2
Another way to do flame tests is to dip a loop of platinum wire into a solution and then into the flame.

Understanding Concepts

1. What is the significance of conducting flame tests?

2. Explain how you might test a sample of an unknown white solid to determine if it was table salt, sodium chloride. Remember that a taste test is never recommended.

Exploring

3. Design an investigation to answer the question: "What chemicals are used to make the flame colours of burning fire logs?" Conduct the investigation and report on your findings, if your design is approved by your teacher. 2A

4. Your teacher may have cardboard spectroscopes available to view the spectrum of each element. Describe the so-called "line spectrum" that you observe. How would this line spectrum be more useful than a simple flame test?

3.6

Isotopes and Radioisotopes

The discovery of isotopes and radioisotopes has changed our lives in many ways: we now have sophisticated medical equipment, nuclear waste, and an ongoing debate about nuclear power.

An **isotope** is any of two or more forms of an element, each having the same number of protons but having a different mass due to a different number of neutrons. For example, chlorine has two common isotopes. Each has 17 protons, but some atoms contain 18 neutrons and others contain 20 neutrons. Thus, one isotope of chlorine is called Cl-35, having an atomic number of 17 and a mass number of 35 (17 protons plus 18 neutrons). The other isotope of chlorine, Cl-37, has an atomic number of 17 and a mass number of 37 (17 plus 20). Hydrogen has three isotopes (**Figure 1**).

Isotopes of the same element have the same physical properties and the same chemical properties—they undergo the same reactions. However, some isotopes are unstable, or **radioactive**, which means that the nucleus has a tendency to break apart and eject very-high-energy particles into its surroundings (**Figure 2**). The huge amount of energy these particles have can be both dangerous and useful. Atoms that have unstable nuclei are called **radioisotopes**.

Did You Know

Marie Sklodowska Curie (1867–1934) won the Nobel Prize in Physics in 1903 for her research into radioactivity, and the Nobel Prize in Chemistry in 1911 for her discovery of the elements radium and polonium. Marie Curie died of leukemia, likely caused by her exposure to radiation during her experiments.

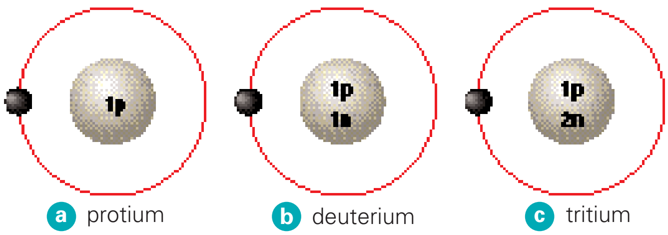


Figure 1
The three isotopes of hydrogen have the same number of protons but different numbers of neutrons. The one with no neutrons is the most common.

Figure 2
This symbol indicates that a radioactive substance is present and should be handled with care.

Types of Radioactivity

Radioactivity was discovered accidentally in 1896 by a French scientist, Henri Becquerel, when he was studying a sample of uranium. He found that the uranium could produce an image on photographic film even when the film remained sealed inside its package. Some of the unstable uranium nuclei split apart or **decayed**, producing particles that went right through the packaging and reacted with the film. Over the next seven years, three different kinds of radioactivity were identified (**Figure 3**). They were

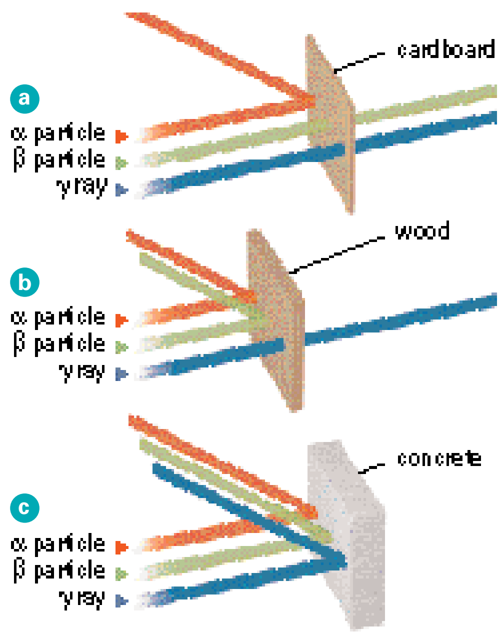


Figure 3
The three types of radioactivity have different penetrating power. Gamma rays are the most dangerous and can only be blocked by thick sheets of concrete or lead.

named alpha (α) and beta (β) particles and gamma (γ) rays. Alpha particles were later found to be helium nuclei, containing two protons and two neutrons. Beta particles are high-energy electrons, and gamma radiation is high-energy electromagnetic radiation with no mass.

Applications of Radioisotopes

Radioisotopes must be treated with caution because they can damage living tissue. They may alter the DNA, which affects how cells divide. This can cause serious diseases, including cancer and birth defects. However, radioisotopes are very useful when used carefully by qualified doctors, scientists, and technicians. A few of the many applications of radioisotopes are shown in **Figures 4** to **6**.

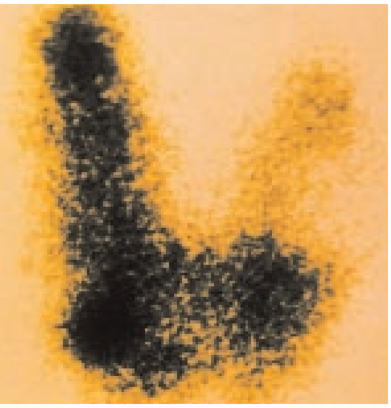


Figure 4

Radioisotopes are often used to diagnose medical problems such as thyroid disease. Doctors inject the radioactive isotope iodine-131 into the body, and the blood carries most of it to the thyroid gland in the neck. Technicians can then take a "photo" of the neck to see the size, shape, and activity of the gland.

Figure 5

Archaeologists use a technique called "carbon-14 dating" when they want to know the age of ancient humans and their artifacts. Carbon dioxide in the atmosphere naturally contains a measurable amount of carbon-14, which is absorbed by plants in the process of photosynthesis. It is then incorporated into the bodies of animals that eat the plants. This reindeer bone was discovered in a glacier. During the years since the animal's death, the bone's carbon-14 steadily "decayed." When scientists test the bone, they measure the amount of carbon-14 left. They then calculate the length of time since the animal died.

Figure 6

You probably have a radioisotope in your home. Some smoke detectors contain a tiny amount of the radioisotope americium-241. The radioactive particles charge air molecules so that a small electric current flows. When smoke enters the detector, it interferes with this current and the alarm sounds.

Understanding Concepts

1. What is an isotope?

2. What is meant by the term "radioactivity"? Give an example of a radioisotope.

3. Represent the following radioisotopes using standard atomic notation. How many neutrons does each have?

- **(a)** technetium-99 (atomic number 43)
- **(b)** cobalt-60 (atomic number 27)
- **(c)** carbon-14 (atomic number 6)
- **(d)** iodine-131 (atomic number 53)
- **(e)** americium-241 (atomic number 95)
- **(f)** uranium-235 (atomic number 92)

Making Connections

4. Describe four useful applications of radioisotopes. What are their risks, if any?

Exploring

5. Visit your local medical centre or dentist to find out how X rays are produced. Find out what steps medical professionals take to protect themselves and their patients from radiation.

Fireworks: Electron Jumps in Action

What creates the colours in fireworks?

A modern firework shell contains black powder that burns to propel the firework up into the air. The shell also contains separate packages of chemicals that produce special effects, such as bursts of colour, flashes, and sound. Some of these materials are described in **Table 1**.

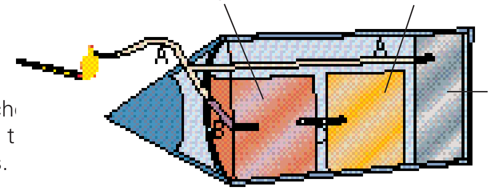
Each firework explosion is a carefully controlled series of chemical changes that occur at just the right times. These chemical changes produce large amounts of heat which make electrons in metal atoms jump up to higher energy levels or orbits. When the electrons drop back to their normal ground state in orbits nearer the nucleus, they give off energy including bursts of coloured light.

Making fireworks is hazardous and should be attempted only by well-trained professionals.

Table 1 Some Chemicals Used for Special Effects

Material	Special Effect
magnesium metal	white flame
sodium oxalate	yellow flame
barium chlorate	green flame
cesium(II) sulfate	blue flame
strontium carbonate	red flame
iron filings and charcoal	gold sparks
potassium benzoate	whistle effect
potassium nitrate and sulfur	white smoke
potassium perchlorate, sulfur, and aluminum	flash and bang

Figure 1 A fireworks shell



1. The technician lights the first fast-burning fuse (A), which causes an explosion that launch[es] the shell into the air as t[he] black powder explodes.
2. Fuse A also lights a slow-burning fuse (B) which ignites a mixture that produces a red burst, when the shell is high in the air.
3. The red explosion lights another slow-burning fuse (C) which ignites a mixture that produces a final flash and loud bang.

Inside a Firework Shell

Suppose a pyrotechnics technician had the job of making a firework shell that would rise 50 m and then produce a red burst of fire followed by a loud bang and a flash. The technician would have to make three different explosive mixtures: one to lift the shell into the air and one for each of the two special effects (**Figure 1**).

The first and most dangerous step is mixing the ingredients. As in other combustion reactions, the ingredients needed in fireworks include a fuel, a source of oxygen (called an oxidizer), and a source of heat to start the reaction (a burning fuse). Typical

Did You Know

The history of fireworks (pyrotechnics) began in China 1000 years ago with the discovery of black powder (gunpowder), a mixture of potassium nitrate (saltpetre), charcoal, and sulfur. At the time, people used saltpetre to preserve meat. They may have found by chance that a mixture of charcoal, iron, and saltpetre produced sparks when sprinkled into a fire. When this mixture burns, it produces large amounts of gases and energy in the form of heat and light.

oxidizers are potassium nitrate, potassium chlorate, potassium perchlorate, and ammonium perchlorate. Each mixture also contains binders like red gum, paraffin oil, or dextrin. The binders act as fuel and hold the mixture together. The technician then wraps each mixture in a cardboard package and links the packages with fuses.

Issue: Should Fireworks Be Banned?

Imagine that your local council has received complaints about fireworks displays in your area. Some people have given the council a proposal.

The council decides to discuss this issue in a private meeting. They invite interested groups of citizens to write position papers, in which they state their opinions and back them up with evidence.

(a) Read the points listed below.

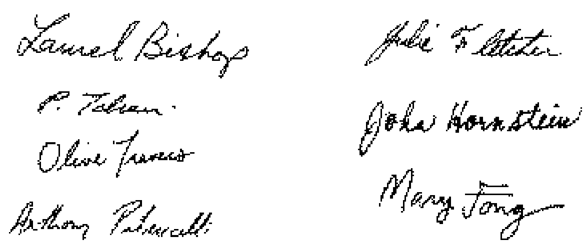
(b) Choose one of the two opinions. (Your teacher may assign these points of view to groups of students.)

(c) 3A Research the issue further, expand upon the points provided, and develop or reflect upon your position.

(d) 3B Write a one-page position paper, clearly stating your opinion and the reasons for it.

THE PROPOSAL

No one should be allowed to buy or use fireworks at any time within city boundaries.



Opinion A

- Fireworks are dangerous mixtures of chemicals. When ignited, they can explode in unpredictable ways. People have been terribly injured through the unsafe use of fireworks.
- Fireworks displays pollute the environment. The reactants involved can produce nitrogen dioxide and sulfur dioxide, both of which are poisonous gases and produce acid rain. Noise pollution is also created.
- Fireworks are very expensive, and they last for only a few seconds. We would be better off using the money to celebrate special occasions in other ways.

Opinion B

- Fireworks are a traditional way of celebrating for some cultures. The move to prevent fireworks could be seen as discriminating against those groups.
- People who want to use fireworks will continue to do so outside the city. In wooded areas or farmlands far from emergency services, the risk of fire or accident would be greater.
- Fireworks displays that mark special events promote tourism and bring economic benefits to the community.

Chapter 3 Review

Key Expectations

Throughout the chapter, you have had opportunities to do the following things:

- Explain the usefulness of scientific models, and describe the evolution of models of the atom. (3.1, 3.2, 3.4)
- Describe the Bohr-Rutherford model of the atom, and draw diagrams for atoms and ions of the first 20 elements. (3.2, 3.4)
- Write standard atomic notation, and state numbers of subatomic particles in a given atom or isotope. (3.3, 3.6)
- Demonstrate knowledge of laboratory safety procedures while conducting investigations. (3.1, 3.5)
- Investigate the relationship between atomic models and properties of substances, and organize, record, analyze, and communicate results. (3.1, 3.5)
- Formulate and research questions related to the properties of elements and compounds and communicate results. (3.2, 3.6, 3.7)
- Describe technologies that have depended on understanding atomic and molecular structure. (3.6, 3.7)
- Explore careers requiring an understanding of the properties of matter. (Career Profile)

KEY TERMS

alchemist	isotope
atomic model	mass number
atomic number	neutron
Bohr diagram	nuclear model
Bohr-Rutherford diagram	orbit
charge	proton
decay	radioactive
electron	radioisotope
energy level	spectrum
excited state	standard atomic notation
flame test	subatomic particle
ground state	
ion	

Reflecting

- "The ultimate building block of matter is the atom. Scientists try to understand the behaviour of matter by developing models of the atom." Reflect on this idea. How does it connect with what you've done in this chapter?
- Revise your answers to the questions raised in Getting Started. How has your thinking changed?
- What new questions do you have? How will you answer them?

Understanding Concepts

1. Make a concept map to summarize the material that you have studied in this chapter. Start with the word "atoms."

2. The sentences in the list below contain errors or are incomplete. In your notebook, write your complete, correct version of each sentence.

(a) Protons are negative particles in orbits around the nucleus.
(b) The mass number is the number of neutrons.
(c) Isotopes have different numbers of protons.
(d) A Bohr diagram shows protons in orbits.
(e) When an electron jumps to a higher level, the atom is in ground state.
(f) A chemical reaction results in new elements.

3. Who

(a) proposed an atomic model thousands of years ago?
(b) tried to change lead into gold in the Middle Ages?
(c) recognized oxygen as an element?
(d) proposed an atomic model in which compounds were made by combinations of atoms?
(e) discovered the nucleus?
(f) proposed that electrons existed in definite orbits?

4. (a) In Thomson's raisin-bun model, what were the electrical charges on the
(i) raisins? (ii) bun?
(b) How was Bohr's model different from Thomson's model of the atom?

5. With respect to the Bohr-Rutherford model of the atom,
(a) where are the protons, neutrons, and electrons found?
(b) which particles make up most of the mass of the atom?
(c) which particles take up most of the space in the atom?

6. When any of the first 20 elements form ions, what are the numbers of electrons in the first three energy levels?

7. Describe how you can use the mass number and atomic number to find the numbers of protons, electrons, and neutrons in an atom.

8. (a) What is meant by the term "isotope"?
(b) How many isotopes of the element hydrogen are there?
(c) What are the numbers of protons and neutrons in these isotopes?

Applying Skills

9. Copy **Table 1** into your notebook. Fill in the blanks with the missing numbers.

Table 1

Finding the Atomic Number, Mass Number, and Numbers of Subatomic Particles in an Element

Element	Symbol	Atomic No.	Mass No.	No. of Protons	No. of Electrons	No. of Neutrons
helium	He	2	4	?	?	?
oxygen	O	?	16	8	?	?
sodium	Na	11	23	?	?	?
chlorine	Cl	?	37	?	17	?
calcium	Ca	?	?	?	20	22

10. Write standard atomic notation for each of the atoms in the previous question.

11. Draw Bohr-Rutherford diagrams for each of the atoms in the previous question.

12. Match the description on the left with one term on the right. Use each term only once.

Description	Term
A atom with same atomic number but different mass number	1 atomic number
B atom with unstable nucleus	2 mass number
C charged atom	3 proton
D number of protons	4 neutron
E positive subatomic particle	5 isotope
F sum of protons and neutrons	6 ion
G uncharged subatomic particle	7 radioisotope

13. Describe how each of the following atoms gains or loses electrons to have a stable number of electrons in each energy level:
(a) beryllium, atomic number 4
(b) nitrogen, atomic number 7
(c) sulfur, atomic number 16

14. Write the charge for each of the ions in the previous question.

15. Identify the numbers of protons and neutrons in each of the following atoms by interpreting their standard atomic notation:
(a) $^{40}_{19}K$ (b) $^{28}_{13}Al$ (c) $^{14}_{6}C$

Making Connections

16. You have learned that models are modified as scientists gather new evidence. Has this happened with the atomic model? Explain your answer.

17. For centuries people believed Aristotle's model for matter was true.
(a) How did Aristotle's model differ from Dalton's model?
(b) Why did it take so long for the model to evolve?

18. Design and draw a diagram of a firework you think would be suitable for Canada Day. Explain why you chose your design. Include safety and environmental considerations.
Do not test your design. Fireworks are extremely hazardous.

19. Find out more about radioisotopes. How are they used in medicine to diagnose diseases? How are they used to kill cancerous cells? What radioactive elements are used for various medical purposes?