

Atoms and Isotopes

The history of atomic discovery begins with the ancient Greeks, when, around 400 BCE, philosopher Democritus asserted that all material things are composed of extremely small irreducible particles called atoms. His theory was rejected and ignored for almost 2000 years. John Dalton resurrected the atomic theory of matter in the early nineteenth century by characterizing elements by their atomic structure and weight. Over the next hundred years or so, scientists continued to refine their understanding of the atom, until the advances of Niels Bohr and Ernest Rutherford.

Bohr–Rutherford Model of the Atom

Niels Bohr, a Danish scientist, and Ernest Rutherford, a New Zealand scientist, are credited with a number of discoveries that led to the development of the Bohr–Rutherford atomic model. Rutherford found that when a beam of positively charged particles was fired at a thin gold foil, most particles passed through the foil, as expected, but some were scattered in all directions. To explain this, it was proposed that the atom consists of a dense, positively charged nucleus surrounded by tiny negatively charged electrons and a relatively vast region of empty space. Bohr also discovered that the electrons could only occupy certain energy levels. When these discoveries were combined, the Bohr–Rutherford model of the atom was created.

This model has the following key features:

- The dense nucleus contains the atom's protons and neutrons.
- The relatively tiny electrons orbit the nucleus.
- The electrons only occupy certain energy levels.
- Most of the atom consists of empty space.

The model provides a visual method for describing the atomic structure of an element. The atomic structure refers to the number of protons, neutrons, and electrons in an atom and their organization within the atom. Simplified Bohr–Rutherford diagrams for helium and fluorine are shown in **Figure 1**.

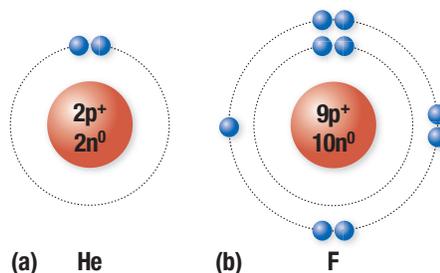


Figure 1 Bohr–Rutherford diagrams for (a) helium and (b) fluorine. Notice that a helium atom has two protons, two neutrons, and two electrons. A fluorine atom has nine protons, ten neutrons, and nine electrons.

The nucleus is the centre of the atom and consists of protons and neutrons. A **proton** is a positively charged particle, and a **neutron** is an uncharged particle. In nuclear physics, neutrons and protons are often referred to collectively as **nucleons**. Protons and neutrons have approximately the same mass. An **electron** is a negatively charged particle that moves in the space surrounding the nucleus and is extremely small compared to nucleons. In general, an atom in its normal state has the same number of electrons as protons.

In a Bohr–Rutherford diagram, electrons are placed in the lower energy levels, or shells, first, until these shells are filled. Atoms that have electrons placed in this way are said to be in their **ground state**: the electrons are all at the lowest possible energy levels. An atom is said to be in an **excited state** if it absorbs energy that causes an electron to have more energy and move to a higher energy level. An excited atom returns

proton a positively charged particle in the nucleus of an atom

neutron an uncharged particle in the nucleus of an atom

nucleons particles in the nucleus of an atom; protons and neutrons

electron a negatively charged particle found in the space surrounding the nucleus of an atom

ground state state in which all electrons are at their lowest possible energy levels

excited state state in which one or more electrons are at higher energy levels than in the ground state

to its ground state by releasing energy as the electron drops back to its lowest available energy level. **Figure 2** shows a hydrogen atom in the ground state and in an excited state. The first energy level is the innermost shell in the Bohr–Rutherford diagram.

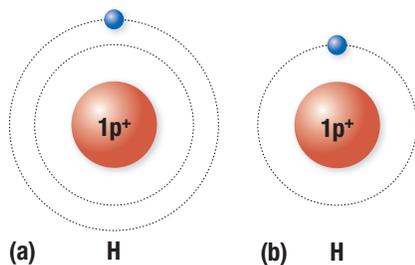


Figure 2 Hydrogen in (a) an excited state and (b) its ground state

According to the Bohr–Rutherford model, each energy level or shell can hold a certain number of electrons. **Table 1** gives the maximum number of electrons for each shell.

Atomic Number, Mass Number, and the Periodic Table

The periodic table of elements lists all the elements known today. It can be used to determine the atomic structure of an element (**Figure 3**).

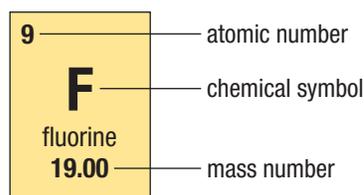


Figure 3 Identifying mass number and atomic number for the element fluorine on the periodic table

The **atomic number** is the number of protons in an atom of an element. Each element has a different number of protons. The **mass number** is equal to the number of nucleons in an atom. The periodic table entry shown in **Figure 3** indicates that fluorine has nine protons and nine electrons. The number of neutrons is determined by subtracting the atomic number from the mass number:

$$19 \text{ nucleons (mass number)} - 9 \text{ protons (atomic number)} = 10 \text{ neutrons}$$

Isotopes

Carbon-12 consists of six protons and six neutrons (**Figure 4**). Most naturally occurring carbon has this atomic structure. There is, however, another form of carbon called carbon-14. Carbon-14 has six protons and eight neutrons. Carbon-14 is a different **isotope** than carbon-12. Different isotopes of an element have the same number of protons, but different numbers of neutrons (**Figure 5**). The mass number of 14 indicates that an atom of carbon-14 has two more neutrons than an atom of carbon-12.

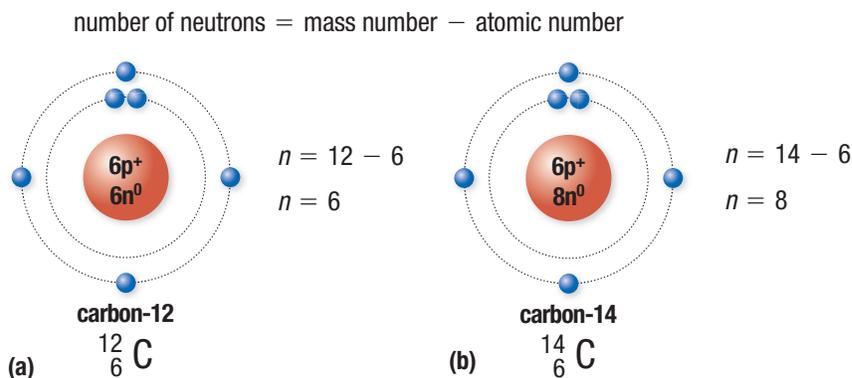


Figure 5 Bohr–Rutherford models for (a) carbon-12 and (b) carbon-14

Table 1 Electron Distribution in a Bohr–Rutherford Model

Shell number	Maximum number of electrons
1	2
2	8
3	18
4	32

atomic number the number of protons in the nucleus

mass number the number of protons and neutrons in the nucleus

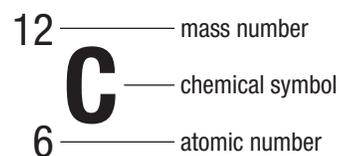


Figure 4 The standard notation for carbon-12

isotope a form of an element that has the same atomic number, but a different mass number than all other forms of that element

Carbon-14 has some interesting properties that are useful to archaeologists and scientists. A process called carbon dating provides a reasonably accurate method to determine the age of fossils and objects made of things that were once alive. You will learn more about carbon dating in Section 7.3.

Most samples of elements consist of a number of different isotopes, some occurring naturally and others produced in laboratories. The most common isotope of hydrogen has a nucleus consisting of only one proton. There are, however, two other isotopes of hydrogen. These isotopes are important in nuclear science, so they have been given their own names: deuterium and tritium. Deuterium, which has one proton and one neutron, is a naturally occurring substance. Tritium, which has one proton and two neutrons, is only produced as a by-product of human-made nuclear reactions.

The periodic table identifies the most commonly occurring isotopes for each element. A more general table that lists atomic information for all known isotopes is called a chart of the nuclides. In the following Tutorial, you will draw Bohr–Rutherford diagrams for various isotopes.

LEARNING TIP

Mass Numbers

The mass numbers of most elements have decimal values associated with them. Carbon-12 has a mass of exactly 12 atomic units because it is the substance to which all other elements are compared by atomic mass. The mass number that appears in the periodic table for carbon is slightly higher than 12 because of the small amounts of carbon-14 that exist in nature.

Tutorial 1 Constructing a Bohr–Rutherford Diagram

Sample Problem 1

Draw the Bohr–Rutherford diagram for silicon-31.

Step 1. Locate silicon on the periodic table. The chemical symbol for silicon is Si.

Step 2. The mass of this isotope is given: 31. Use a periodic table to identify the atomic number. The atomic number is 14.

Step 3. Since the atomic number is 14, there are 14 protons and 14 electrons. The number of neutrons is found by subtracting the atomic number from the mass number: $31 - 14 = 17$

There are 17 neutrons in an atom of silicon.

Use this information to draw a Bohr–Rutherford diagram for silicon (**Figure 6**).

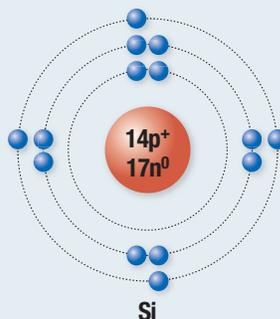


Figure 6

Practice

- Sketch a Bohr–Rutherford diagram for each element. T/A C
 - aluminum, Al (mass number 28)
 - silver, Ag (mass number 110)
 - two other elements of your choice from the periodic table or Appendix B (page 662)

radioisotope an unstable isotope that spontaneously changes its nuclear structure and releases energy in the form of radiation

radiation energy released when the nucleus of an unstable isotope undergoes a change in structure

Some isotopes, called **radioisotopes**, are unstable; that is, they spontaneously change their nuclear structure. **Radiation** is energy released in the form of waves when a radioisotope undergoes a structural change. This radiation can be harmful if not properly controlled. In some cases, however, these radioisotopes are beneficial. You will examine the process by which isotopes spontaneously change later in this chapter.

Medical Applications of Radioisotopes

Nuclear medical imaging is a diagnostic technique that involves injecting a patient with a small dose of a radioisotope, such as technetium-99m. These materials, sometimes called radioactive tracers, emit radiation that can be detected and converted into an image. By comparing radiation patterns of an unhealthy organ to those of a healthy one, doctors are better able to pinpoint a malignancy, or tumour (Figure 7). One of the advantages of nuclear imaging over traditional X-rays is that it provides a detailed account of both hard tissues like bone and softer tissues like the liver and kidneys. X-rays are primarily useful for detecting bone fractures.

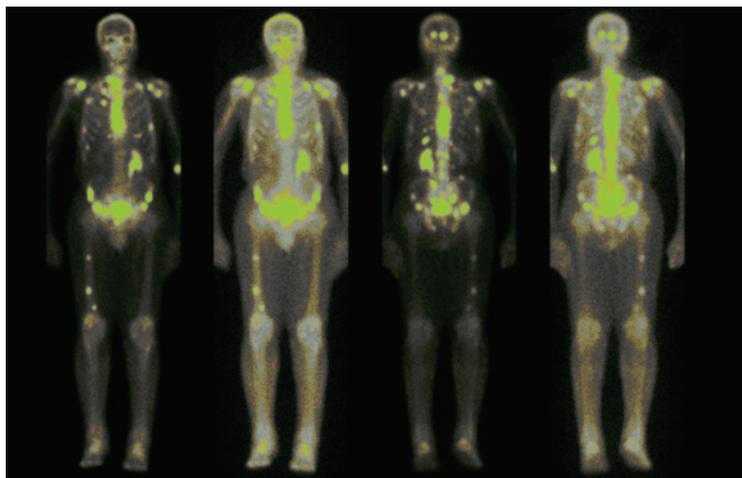


Figure 7 A radioactive tracer provides a detailed image of a diseased organ. This image is detecting the spread of lung cancer to the skeleton.

Research This

Technetium-99m

Skills: Researching, Analyzing, Communicating

SKILLS
HANDBOOK  A5.1

Technetium-99m is an unusual isotope for which medical scientists have discovered several important uses. The “m” in its name identifies it as a meta-stable isotope.

1. Research Technetium-99m (Tc-99m) on the Internet or at the library. Write a brief report of your findings that includes answers to the following questions:

- What is a meta-stable isotope? T/I
- How is Tc-99m obtained? T/I

- What is it about Tc-99m that makes it particularly useful in medicine? T/I
- Discuss some of the applications of Tc-99m in the medical field. A
- Are there any drawbacks to using nuclear imaging, such as health risks, costs, or wait times? A



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Medical Treatments

One of the earliest medical applications of radioisotopes began in the 1950s, when iodine-131 was used to diagnose and treat thyroid disease. Sufferers of hyperthyroidism have an overactive thyroid gland: it releases more thyroid hormone than the body requires. Iodine-131 can be used to both identify a diseased thyroid gland and halt production of the hormone.

Radionuclide therapy (RNT) is a rapidly growing medical field in which the properties of certain radioactive substances are used to treat various ailments. RNT is currently used to treat certain types of tumours, bone pain, and other conditions. In cancer treatments, the fundamental idea behind RNT is to bombard rapidly dividing harmful cells with radiation. These cells tend to absorb the radiation, which prevents them from dividing further. 

CAREER LINK

A radiation therapist works with doctors, other medical staff, and patients to design and administer radiation health treatment plans. To learn more about careers in radiation therapy and related fields,



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7.1 Summary

- The Bohr–Rutherford model of the atom illustrates the atomic structure of an element.
- You can identify the number of protons, neutrons, and electrons of an element from its Bohr–Rutherford model.
- You can identify the mass number and atomic number of an element from the periodic table.
- Isotopes of an element have the same number of protons but different numbers of neutrons.
- Radioactive isotopes are unstable and will spontaneously undergo a change in their nuclear structure.
- Some radioactive isotopes have useful applications, such as medical diagnosis and therapy.

7.1 Questions

1. Draw a Bohr–Rutherford diagram for each isotope. K/U C
 - (a) oxygen-16
 - (b) potassium-40
2. (a) Draw Bohr–Rutherford diagrams for hydrogen, deuterium, and tritium.
 - (b) Identify their similarities and differences. K/U C
3. For each Bohr–Rutherford model shown in **Figure 8**,
 - (a) determine the atomic number and the mass number
 - (b) write the chemical name of the isotope K/U

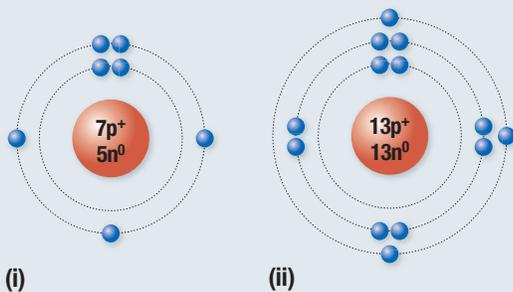


Figure 8

4. (a) Draw a Bohr–Rutherford diagram for each isotope of beryllium.
 - (i) ${}^7_4\text{Be}$
 - (ii) ${}^9_4\text{Be}$
 - (iii) ${}^{11}_4\text{Be}$
 - (b) Explain the similarities and differences between these models.
 - (c) Which isotope of beryllium is the most common in nature? Explain how you know. K/U C
5. (a) Draw a Bohr–Rutherford model for each isotope.
 - (i) lithium-5, ${}^5_3\text{Li}$
 - (ii) oxygen-20, ${}^{20}_8\text{O}$

- (b) Describe how each isotope compares with its most commonly occurring isotope. K/U C
6. Identify each isotope shown in **Figure 9** given its Bohr–Rutherford diagram. K/U

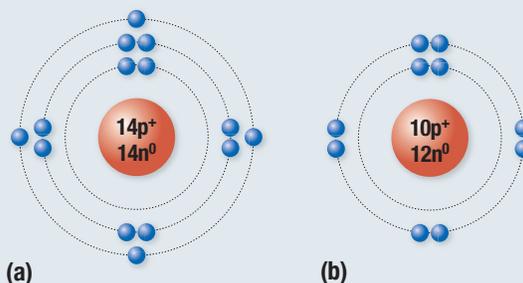


Figure 9

7. An isotope has 16 protons and 22 neutrons. Identify the element. K/U
8. (a) Draw a Bohr–Rutherford model for each isotope of argon.
 - (i) Ar-40
 - (ii) Ar-44
 - (iii) Ar-47
 - (b) Explain how these isotopes are
 - (i) alike
 - (ii) different K/U C
9. Neon has three stable isotopes: Ne-20, Ne-21, and Ne-22. K/U C
 - (a) Draw a Bohr–Rutherford model for each isotope.
 - (b) How are these models alike? How are they different?
10. (a) Draw Bohr–Rutherford models for lithium-10, beryllium-10, and boron-10.
 - (b) How are these models alike? How are they different? K/U C