Learning Objectives

• To become familiar with the components and structure of the atom.

Dissecting the Atom

Once scientists concluded that all matter contains negatively charged electrons, it became clear that atoms, which are electrically neutral, must also contain positive charges to balance the negative ones. Thomson proposed that the electrons were embedded in a uniform sphere that contained both the positive charge and most of the mass of the atom, much like raisins in plum pudding or chocolate chips in a cookie (Figure \(\PageIndex{1}\)).

In a single famous experiment, however, Rutherford showed unambiguously that Thomson’s model of the atom was incorrect. Rutherford aimed a stream of α particles at a very thin gold foil target (part (a) in Figure \(\PageIndex{2}\)) and examined how the α particles were scattered by the foil. Gold was chosen because it could be easily hammered into extremely thin sheets, minimizing the number of atoms in the target. If Thomson’s model of the atom were correct, the positively-charged α particles should crash through the uniformly distributed mass of the gold target like cannonballs through the side of a wooden house. They might be moving a little slower when they emerged, but they should pass essentially straight through the target (part (b) in Figure \(\PageIndex{2}\)). To Rutherford’s amazement, a small fraction of the α particles were deflected at large angles, and some were reflected directly back at the source (part (c) in Figure \(\PageIndex{2}\)). According to Rutherford, “It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”
Figure \(\PageIndex{2}\): A Summary of Rutherford’s Experiments. (a) A representation of the apparatus Rutherford used to detect deflections in a stream of α particles aimed at a thin gold foil target. The particles were produced by a sample of radium. (b) If Thomson’s model of the atom were correct, the α particles should have passed straight through the gold foil. (c) However, a small number of α particles were deflected in various directions, including right back at the source. This could be true only if the positive charge were much more massive than the α particle. It suggested that the mass of the gold atom is concentrated in a very small region of space, which he called the nucleus.

Rutherford’s results were not consistent with a model in which the mass and positive charge are distributed uniformly throughout the volume of an atom. Instead, they strongly suggested that both the mass and positive charge are concentrated in a tiny fraction of the volume of an atom, which Rutherford called the nucleus. It made sense that a small fraction of the α particles collided with the dense, positively charged nuclei in either a glancing fashion, resulting in large deflections, or almost head-on, causing them to be reflected straight back at the source.

Although Rutherford could not explain why repulsions between the positive charges in nuclei that contained more than one positive charge did not cause the nucleus to disintegrate, he reasoned that repulsions between negatively charged electrons would cause the electrons to be uniformly distributed throughout the atom’s volume. Today it is known that strong nuclear forces, which are much stronger than electrostatic interactions, hold the protons and the neutrons together in the nucleus. For this and other insights, Rutherford was awarded the Nobel Prize in Chemistry in 1908. Unfortunately, Rutherford would have preferred to receive the Nobel Prize in Physics because he considered physics superior to chemistry. In his opinion, “All science is either physics or stamp collecting.”
Figure 3: A Summary of the Historical Development of Models of the Components and Structure of the Atom. The dates in parentheses are the years in which the key experiments were performed.

The historical development of the different models of the atom’s structure is summarized in Figure 3. Rutherford established that the nucleus of the hydrogen atom was a positively charged particle, for which he coined the name proton in 1920. He also suggested that the nuclei of elements other than hydrogen must contain electrically neutral particles with approximately the same mass as the proton. The neutron, however, was not discovered until 1932, when James Chadwick (1891–1974, a student of Rutherford; Nobel Prize in Physics, 1935) discovered it. As a result of Rutherford’s work, it became clear that an α particle contains two protons and neutrons, and is therefore the nucleus of a helium atom.
Rutherford’s model of the atom is essentially the same as the modern model, except that it is now known that electrons are not uniformly distributed throughout an atom’s volume. Instead, they are distributed according to a set of principles described by Quantum Mechanics. Figure \(\PageIndex{4}\) shows how the model of the atom has evolved over time from the indivisible unit of Dalton to the modern view taught today.

### The Nuclear Atom

The precise physical nature of atoms finally emerged from a series of elegant experiments carried out between 1895 and 1915. The most notable of these achievements was Ernest Rutherford’s famous 1911 alpha-ray scattering experiment, which established that

- Almost all of the *mass* of an atom is contained within a tiny (and therefore extremely dense) *nucleus* which carries a positive electric charge whose value identifies each element and is known as the *atomic number* of the element.

- Almost all of the *volume* of an atom consists of empty space in which electrons, the fundamental carriers of negative electric charge, reside. The extremely small mass of the electron (1/1840 the mass of the hydrogen nucleus) causes it to behave as a quantum particle, which means that its location at any moment cannot be specified; the best we can do is describe its behavior in terms of the probability of its manifesting itself at any point in space. It is common (but somewhat misleading) to describe the volume of space in which the electrons of an atom have a significant probability of being found as the *electron cloud*. The latter has no definite outer boundary, so neither does the atom. The radius of an atom must be defined arbitrarily, such as the boundary in which the electron can be found with 95% probability. Atomic radii are typically 30-300 pm.

![Figure \(\PageIndex{5}\): The structure of the nuclear atom with a central nucleus and surrounding electrons.](image)

The nucleus is itself composed of two kinds of particles. *Protons* are the carriers of positive electric charge in the nucleus; the proton charge is exactly the same as the electron charge, but of opposite sign. This means that in any [electrically neutral] atom, the number of protons in the nucleus (often referred to as the *nuclear charge*) is balanced by the *same* number of electrons outside the nucleus.

The other nuclear particle is the *neutron*. As its name implies, this particle carries no electrical charge. Its mass is almost the same as that of the proton. Most nuclei contain roughly equal numbers of neutrons and protons, so we can say that these two particles together account for almost all the mass of the atom.
Because the electrons of an atom are in contact with the outside world, it is possible for one or more electrons to be lost, or some new ones to be added. The resulting electrically-charged atom is called an ion.

Atoms consist of electrons, protons, and neutrons. This is an oversimplification that ignores the other subatomic particles that have been discovered, but it is sufficient for discussion of chemical principles. Some properties of these subatomic particles are summarized in Table 1 which illustrates three important points:

1. Electrons and protons have electrical charges that are identical in magnitude but opposite in sign. Relative charges of −1 and +1 are assigned to the electron and proton, respectively.
2. Neutrons have approximately the same mass as protons but no charge. They are electrically neutral.
3. The mass of a proton or a neutron is about 1836 times greater than the mass of an electron. Protons and neutrons constitute the bulk of the mass of atoms.

The discovery of the electron and the proton was crucial to the development of the modern model of the atom and provides an excellent case study in the application of the scientific method. In fact, the elucidation of the atom’s structure is one of the greatest detective stories in the history of science.

<table>
<thead>
<tr>
<th>Particle</th>
<th>Mass (g)</th>
<th>Atomic Mass (amu)</th>
<th>Electrical Charge (coulombs)</th>
<th>Relative Charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>(9.109 \times 10^{-28})</td>
<td>0.0005486</td>
<td>(-1.602 \times 10^{-19})</td>
<td>−1</td>
</tr>
<tr>
<td>neutron</td>
<td>(1.675 \times 10^{-24})</td>
<td>1.008665</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>proton</td>
<td>(1.673 \times 10^{-24})</td>
<td>1.007276</td>
<td>(+1.602 \times 10^{-19})</td>
<td>+1</td>
</tr>
</tbody>
</table>

* For a review of using scientific notation and units of measurement, see Essential Skills 1 (Section 1.9 "Essential Skills 1").

Summary

- The atom consists of discrete particles that govern its chemical and physical behavior.

Atoms, the smallest particles of an element that exhibit the properties of that element, consist of negatively charged electrons around a central nucleus composed of more massive positively charged protons and electrically neutral neutrons. Radioactivity is the emission of energetic particles and rays (radiation) by some substances. Three important kinds of radiation are α particles (helium nuclei), β particles (electrons traveling at high speed), and γ rays (similar to x-rays but higher in energy).

Conceptual Problems

1. Describe the experiment that provided evidence that the proton is positively charged.
2. What observation led Rutherford to propose the existence of the neutron?
3. What is the difference between Rutherford’s model of the atom and the model chemists use today?
4. If cathode rays are not deflected when they pass through a region of space, what does this imply about the presence or absence of a magnetic field perpendicular to the path of the rays in that region?

5. Describe the outcome that would be expected from Rutherford’s experiment if the charge on α particles had remained the same but the nucleus were negatively charged. If the nucleus were neutral, what would have been the outcome?

6. Describe the differences between an α particle, a β particle, and a γ ray. Which has the greatest ability to penetrate matter?

Problems

Please be sure you are familiar with the topics discussed in Essential Skills 1 (Section 1.9 "Essential Skills 1") before proceeding to the Numerical Problems.

1. Using the data in Table 1.3 "Properties of Subatomic Particles*" and the periodic table (see Chapter 32 "Appendix H: Periodic Table of Elements"), calculate the percentage of the mass of a silicon atom that is due to
   a. electrons.
   b. protons.

2. Using the data in Table 1.3 "Properties of Subatomic Particles*" and the periodic table (see Chapter 32 "Appendix H: Periodic Table of Elements"), calculate the percentage of the mass of a helium atom that is due to
   a. electrons.
   b. protons.

3. The radius of an atom is approximately $10^4$ times larger than the radius of its nucleus. If the radius of the nucleus were 1.0 cm, what would be the radius of the atom in centimeters? in miles?

4. The total charge on an oil drop was found to be $3.84 \times 10^{-18}$ coulombs. What is the total number of electrons contained in the drop?