Further Understanding of the Atom

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Concept 1 Further Understanding of the Atom

Lesson Objectives

The student will:

- explain the observations that led to Thomson's discovery of the electron.
- describe Thomson's plum-pudding model of the atom.
- draw a diagram of Thomson's plum-pudding model of the atom and explain why it has this name.
- describe Rutherford's gold foil experiment and explain how this experiment disproved the plum-pudding model.
- draw a diagram of the Rutherford model of the atom and label the nucleus and the electron cloud.

Vocabulary

- cathode ray tube
- electron
- nucleus
- proton
- subatomic particle

Introduction

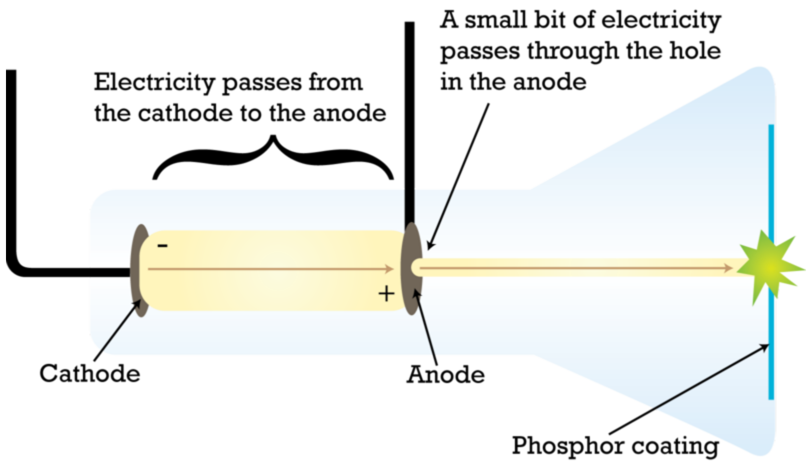
Dalton's atomic theory held up well in a lot of the different chemical experiments that scientists performed to test it. For almost 100 years, it seemed as if Dalton's atomic theory was the whole truth. It wasn't until 1897 when a scientist named J. J. Thomson conducted some research that suggested Dalton's atomic theory wasn't the entire story. Dalton had gotten a lot right - he was right in saying matter is made up of atoms; he was right in saying there are different kinds of atoms with different mass and other properties; he was *almost* right in saying atoms of a given element are identical; he was right in saying that atoms are merely rearranged during a chemical reaction; and he was right in saying a given compound always has atoms present in the same relative numbers. But he was *wrong* in saying atoms were indivisible or indestructible. As it turns out, atoms are divisible. In fact, atoms are composed of even smaller, more fundamental particles. These particles, called **subatomic particles**, are particles that are smaller than the atom. The discoveries of these subatomic particles are the focus of this chapter.

Thomson's Plum-Pudding Model

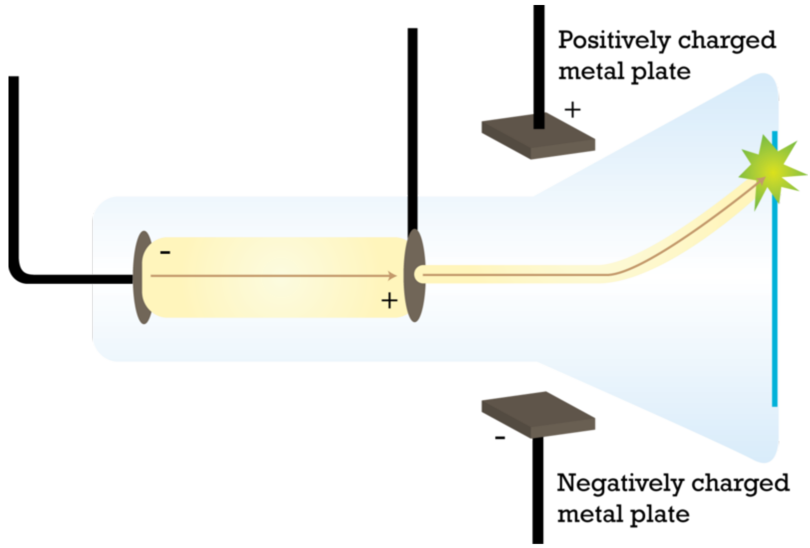
In the mid-1800s, scientists were beginning to realize that the study of chemistry and the study of electricity were actually related. First, a man named Michael Faraday showed how passing electricity through mixtures of different chemicals could cause chemical reactions. Shortly after that, scientists found that by forcing electricity through a tube filled with gas, the electricity made the gas glow. Scientists didn't, however, understand the relationship between chemicals and electricity until a British physicist named J. J. Thomson began experimenting with what is known as a cathode ray tube (**Figure** 1.1).

FIGURE 1.1
A portrait of J. J. Thomson.

The figure below shows a basic diagram of a cathode ray tube like the one Thomson would have used. A **cathode ray tube** is a small glass tube with a cathode (a negatively charged metal plate) and an anode (a positively charged metal plate) at opposite ends. By separating the cathode and anode a short distance, the cathode ray tube can generate what are known as cathode rays – rays of electricity that flow from the cathode to the anode. Thomson wanted to know what cathode rays were, where cathode rays came from, and whether cathode rays had any mass or charge. The techniques that he used to answer these questions were very clever and earned him a Nobel Prize in physics. First, by cutting a small hole in the anode, Thomson found that he could get some of the cathode rays to flow through the hole in the anode and into the other end of the glass cathode ray tube. Next, he figured out that if he painted a substance known as phosphor onto the far end of the cathode ray tube, he could see exactly where the cathode rays hit because the cathode rays made the phosphor glow.



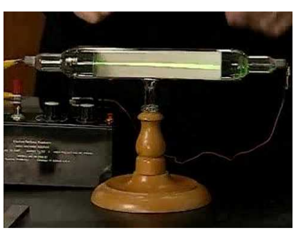
Thomson must have suspected that cathode rays were charged, because his next step was to place a positively charged metal plate on one side of the cathode ray tube and a negatively charged metal plate on the other side, as shown below. The metal plates didn't actually touch the cathode ray tube, but they were close enough that a remarkable thing happened. The flow of the cathode rays passing through the hole in the anode was bent upwards towards the positive metal plate and away from the negative metal plate. In other words, instead of glowing directly across from the hole in the anode, the phosphor now glowed at a spot quite a bit higher in the tube.



Thomson thought about his results for a long time. It was almost as if the cathode rays were attracted to the positively charged metal plate and repelled from the negatively charged metal plate. Thomson knew that charged objects are attracted to and repelled from other charged objects according to the rule: opposite charges attract, like charges repel. This means that a positive charge is attracted to a negative charge but repelled from another positive charge. Similarly, a negative charge is attracted to a positive charge but repelled from another negative charge. Using the "opposite charges attract, like charges repel" rule, Thomson argued that if the cathode rays were attracted to the positively charged metal plate and repelled from the negatively charged metal plate, the rays themselves must have a negative charge.

Thomson then did some rather complex experiments with magnets and used the results to prove that cathode rays not only were negatively charged, but they also had mass. Remember that anything with mass is part of what we call matter. In other words, these cathode rays must be the result of negatively charged matter flowing from the cathode to the anode. It was here that Thomson encountered a problem. According to his measurements, these cathode rays either had a ridiculously high charge or very, very little mass – much less mass than the smallest known atom. How was this possible? How could the matter making up cathode rays be smaller than an atom if atoms were indivisible? Thomson made a radical proposal: maybe atoms are divisible. He suggested that the small, negatively charged particles making up the cathode ray were actually pieces of atoms. He called these pieces "corpuscles," although today we know them as **electrons**. Thanks to his clever experiments and careful reasoning, Thomson is credited with the discovery of the electron.

For a demonstration of cathode ray tubes **(1h)**, see http://www.youtube.com/watch?v=XU8nMKkzbT8 (1:09).



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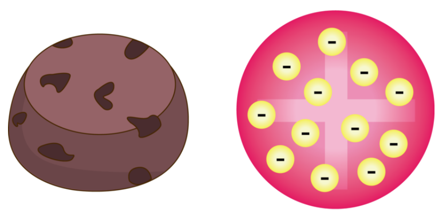
Now imagine what would happen if atoms were made entirely of electrons. First of all, electrons are very, very small; in fact, electrons are about 2,000 times smaller than the smallest known atom, so every atom would have to contain a lot of electrons. But there's another, bigger problem: electrons are negatively charged. Therefore, if atoms were made entirely out of electrons, the atoms themselves would be negatively charged, which would mean all matter was negatively charged as well.

Of course, matter isn't negatively charged. Most matter is what we call neutral – it has no charge at all. How can matter be neutral if matter is composed of atoms and atoms are composed of negative electrons? The only possible explanation is that atoms must consist of more than just electrons. Atoms must also contain some type of positively charged material that balances the negative charge of the electrons. Negative and positive charges of equal size cancel each other out, just like negative and positive numbers of equal size. If an atom contains an electron with a -1 charge and some form of material with a $+1$ charge, overall the atom must have a $(+1)+(-1)=0$ charge. In other words, the atom would be neutral, or have no overall charge.

Based on the fact that atoms are neutral and based on Thomson's discovery that atoms contain negative subatomic particles called electrons, scientists assumed that atoms must also contain a positive substance. It turned out that this positive substance was another kind of subatomic particle known as the **proton**. Although scientists knew that atoms had to contain positive material, protons weren't actually discovered, or understood, until quite a bit later.

When Thomson discovered the negative electron, he also realized that atoms had to contain positive material as well. As a result, Thomson formulated what's known as the plum-pudding model for the atom. According to the plum-pudding model, the negative electrons were like pieces of fruit and the positive material was like the batter or the pudding. In the figure below, an illustration of a plum pudding is on the left and an illustration of Thomson's plum-pudding model is on the right. (Instead of a plum pudding, you can also think of a chocolate chip cookie. In that case, the positive material in the atom would be the batter in the chocolate chip cookie, while the negative electrons would be scattered through the batter like chocolate chips.)



This made a lot of sense given Thomson's experiments and observations. Thomson had been able to isolate electrons using a cathode ray tube; however, he had never managed to isolate positive particles. Notice in the image above how easy it would be to pick the pieces of fruit out of a plum pudding. On the other hand, it would be a lot harder to pick the batter out of the plum pudding because the batter is everywhere. If an atom were similar to a plum pudding in which the electrons are scattered throughout the "batter" of positive material, then you would expect it to be easy to pick out the electrons and a lot harder to pick out the positive material.

Everything about Thomson's experiments suggested the plum-pudding model was correct. According to the scientific method, however, any new theory or model should be tested by further experimentation and observation. In the case of the plum-pudding model, it would take a man named Ernest Rutherford to prove it wrong. Rutherford and his experiments will be the topic of the next section.

There was one thing that Thomson was unable to determine. He had measured the charge-to-mass ratio of the electron, but he had been unable to measure accurately the charge on the electron. Instead, a different scientist named Robert Millikan would determine the charge of the electron with his oil drop experiment. When combined with Thomson's charge-to-mass ratio, Millikan was able to calculate the mass of the electron. Millikan's experiment involved putting charges on tiny droplets of oil suspended between charged metal plates and measuring their rate of descent. By varying the charge on different drops, he noticed that the electric charges on the drops were all multiples of 1.6×10^{-19} C (coulomb), the charge of a single electron.

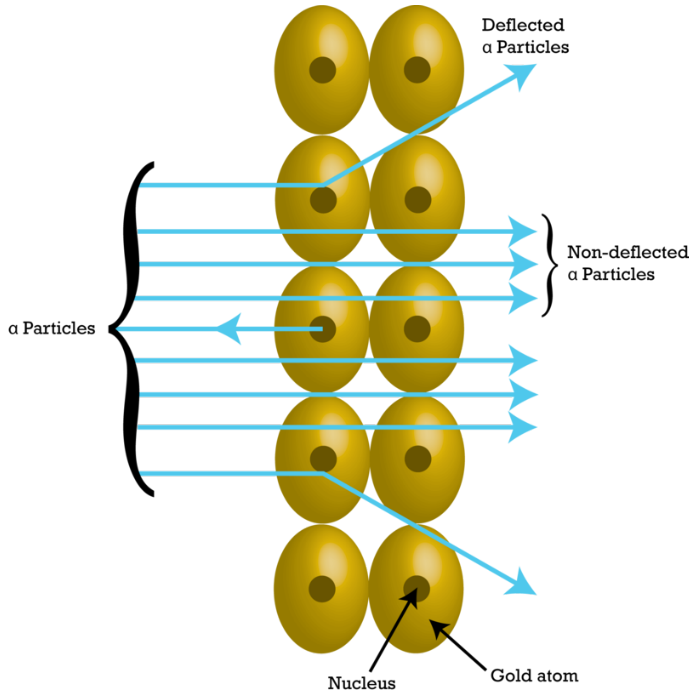
Rutherford's Nuclear Model

Disproving Thomson's plum-pudding model began with the discovery that an element known as uranium emits positively charged particles called alpha particles as it undergoes radioactive decay. Radioactive decay occurs when one element decomposes into another element. It only happens with a few very unstable elements. Alpha particles themselves didn't prove anything about the structure of the atom, but they were used to conduct some very interesting experiments.

FIGURE 1.2
A portrait of Ernest Rutherford.

Ernest Rutherford (pictured in **Figure** 1.2) was fascinated by all aspects of alpha particles and used them as tiny bullets that could be fired at all kinds of different materials. The results of one experiment in particular surprised Rutherford and everyone else.

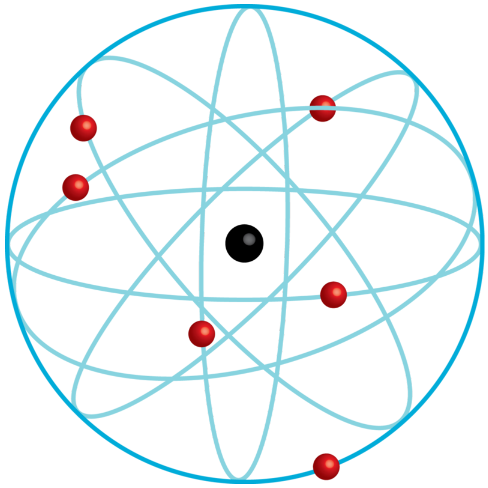
Rutherford found that when he fired alpha particles at a very thin piece of gold foil, an interesting phenomenon happened. The diagram below helps illustrate Rutherford's findings. Almost all of the alpha particles went straight through the foil as if they had hit nothing at all. Every so often, though, one of the alpha particles would be deflected slightly as if it had bounced off something hard. Even less often, Rutherford observed alpha particles bouncing straight back at the "gun" from which they had been fired. It was as if these alpha particles had hit a wall head-on and had ricocheted right back in the direction that they had come from.



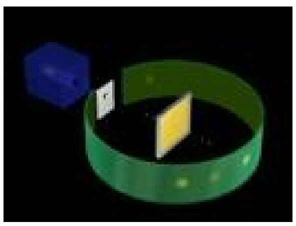
Rutherford thought that these experimental results were rather odd. He expected firing alpha particles at gold foil to be like shooting a high-powered rifle at tissue paper. The bullets would break through the tissue paper and keep on going, almost as if they had hit nothing at all. That was what Rutherford had expected to see when he fired alpha particles at the gold foil. The fact that most alpha particles passed through did not shock him, but how could he explain the alpha particles that were deflected? Furthermore, how could he explain the alpha particles that bounced right back as if they had hit a wall?

Rutherford decided that the only way to explain his results was to assume that the positive matter forming the gold atoms was not distributed like the batter in plum pudding. Instead, he proposed that the positive matter was concentrated in one spot, forming a small, positively charged particle somewhere in the center of the gold atom. We now call this clump of positively charged mass the **nucleus**. According to Rutherford, the presence of a nucleus explained his experiments because it implied that most of the positively charged alpha particles would pass through the gold foil without hitting anything at all. Occasionally, though, the alpha particles would actually collide with a gold nucleus, causing the alpha particles to be deflected or even bounced back in the direction they came from.

While Rutherford's discovery of the positively charged atomic nucleus offered insight into the structure of the atom, it also led to some questions. According to the plum-pudding model, electrons were like plums embedded in the positive batter of the atom. Rutherford's model, though, suggested that the positive charge was concentrated into a tiny particle at the center of the atom, while most of the rest of the atom was empty space. What did that mean for the electrons? If they weren't embedded in the positive material, exactly what were they doing? How were they held in the atom? Rutherford suggested that the electrons might be circling or orbiting the positively charged nucleus as some type of negatively charged cloud, like in the image below. At the time, however, there wasn't much evidence to suggest exactly how the electrons were held in the atom.



A short animation of Rutherford's experiment **(1h)** can be found at http://www.youtube.com/watch?v=5pZj0u_XMbc (0:47).



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For another video discussing J.J. Thomson's use of a cathode ray tube in his discovery of the electron **(1h)**, see http://www.youtube.com/watch?v=IdTxGJjA4Jw (2:54).

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Despite the problems and questions associated with Rutherford's experiments, his work with alpha particles seemed to point to the existence of an atomic nucleus. Between Thomson, who discovered the electron, and Rutherford, who suggested that the positive charges were concentrated at the atom's center, the 1890s and early 1900s saw huge steps in understanding the atom at the subatomic (smaller than the size of an atom) level. Although there was still some uncertainty with respect to exactly how subatomic particles were organized in the atom, it was becoming more and more obvious that atoms were indeed divisible. Moreover, it was clear that an atom contained negatively charged electrons and a positively charged nucleus. In the next lesson, we'll look more carefully at the structure of the nucleus. We'll learn that while the atom is made up of positive and negative particles, it also contains neutral particles that neither Thomson nor Rutherford were able to detect with their experiments.

Lesson Summary

- Dalton's atomic theory wasn't entirely correct, as it was found that atoms can be divided into smaller subatomic particles.

- According to Thomson's plum-pudding model, the negatively charged electrons in an atom are like the pieces of fruit in a plum pudding, while the positively charged material is like the batter.
- When Ernest Rutherford fired alpha particles at a thin gold foil, most alpha particles went straight through; however, a few were scattered at different angles, and some even bounced straight back.
- In order to explain the results of his gold foil experiment, Rutherford suggested that the positive matter in the gold atoms was concentrated at the center of the gold atom in what we now call the nucleus of the atom.

Further Reading / Supplemental Links

The *learner.org* website allows users to view the Annenberg series of chemistry videos. You are required to register before you can watch the videos, but there is no charge to register. The video called "The Atom" explores the structure of the atom.

- http://learner.org/resources/series61.html

Review Questions

1. Decide whether each of the following statements is true or false.
    a. Cathode rays are positively charged.
    b. Cathode rays are rays of light, thus they have no mass.
    c. Cathode rays can be repelled by a negatively charged metal plate.
    d. J.J. Thomson is credited with the discovery of the electron.
    e. Phosphor is a material that glows when struck by cathode rays.
2. Match each observation with the correct conclusion.
    a. Cathode rays are attracted to a positively charged metal plate.
        a. Cathode rays are positively charged.
        b. Cathode rays are negatively charged.
        c. Cathode rays have no charge.
    b. Electrons have a negative charge.
        a. Atoms must be negatively charged.
        b. Atoms must be positively charged.
        c. Atoms must also contain positive subatomic material.
    c. Alpha particles fired at a thin gold foil are occasionally scattered back in the direction that they came from.
        a. The positive material in an atom is spread throughout like the batter in pudding.
        b. Atoms contain neutrons.
        c. The positive charge in an atom is concentrated in a small area at the center of the atom.
3. What is the name given to the tiny clump of positive material at the center of an atom?
4. Choose the correct statement.
    a. Ernest Rutherford discovered the atomic nucleus by performing experiments with aluminum foil.
    b. Ernest Rutherford discovered the atomic nucleus using a cathode ray tube.
    c. When alpha particles are fired at a thin gold foil, they never go through.
    d. Ernest Rutherford proved that the plum-pudding model was incorrect.
    e. Ernest Rutherford experimented by firing cathode rays at gold foil.

5. Answer the following questions:
    a. Will the charges +2 and −2 cancel each other out?
    b. Will the charges +2 and −1 cancel each other out?
    c. Will the charges +1 and +1 cancel each other out?
    d. Will the charges −1 and +3 cancel each other out?
    e. Will the charges +9 and −9 cancel each other out?
6. Electrons are ______ negatively charged metals plates and ______ positively charged metal plates.
7. What was J. J. Thomson's name for electrons?
8. A "sodium cation" is a sodium atom that has lost one of its electrons. Would the charge on a sodium cation be positive, negative, or neutral? Would sodium cations be attracted to a negative metal plate or a positive metal plate? Would electrons be attracted to or repelled from sodium cations?
9. Suppose you have a cathode ray tube coated with phosphor so that you can see where on the tube the cathode ray hits by looking for the glowing spot. What will happen to the position of this glowing spot if:
    a. a negatively charged metal plate is placed above the cathode ray tube?
    b. a negatively charged metal plate is placed to the right of the cathode ray tube?
    c. a positively charged metal plate is placed to the right of the cathode ray tube?
    d. a negatively charged metal plate is placed above the cathode ray tube, and a positively charged metal plate is placed to the left of the cathode ray tube?
    e. a positively charged metal plate is placed below the cathode ray tube, and a positively charged metal plate is also placed to the left of the cathode ray tube?

References

1. . A portrait of J.J. Thomson. Public domain
2. . Ernest Rutherford. Public domain