Lesson 9: The History of the Atom, Part 2

Introduction

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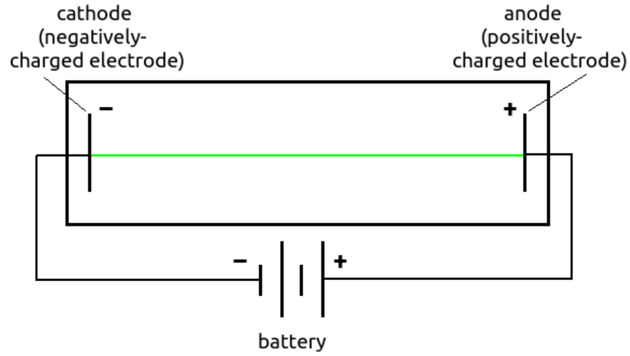
Lesson 9: The History of the Atom – Part 2

When last we left our investigation of the atom in Lesson 8, we learned about Dalton's theory of the atom, which states that atoms are small and indestructible, that atoms of the same element have the same properties and atoms of different elements have different properties, that atoms follow the law of conservation of mass, that atoms combine in whole number ratios, and that the recombination of atoms causes chemical reactions. If you haven't yet read about this, you really should go over to Lesson 8 before continuing reading.

Of course, there's more to the atom than Dalton's 1803 model which portrayed it as basically a very small billiard ball. Let's read about how this development transformed into what we understand today.

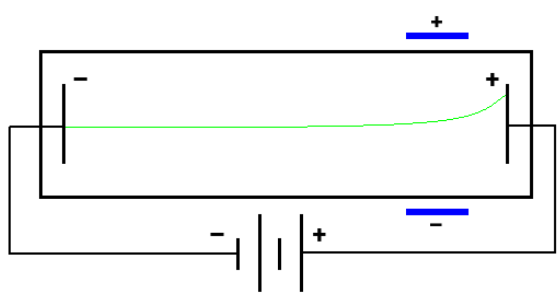
Thomson's Plum Pudding Model of the Atom (1904)

In 1904, J.J. Thomson was performing experiments with something known as a cathode ray tube. In a cathode ray tube, an empty glass tube was hooked up to a power source, which caused particles to move from the cathode (one of the electrodes in the tube) to the anode (the other electrode):



cathode ray tube experiment
(cathode ray shown as green line)

In and of itself, this wasn't particularly exciting. After all, batteries have electricity and the electricity has to show up in some form or another. What *was* exciting, however, was what happened when Thomson placed a positive charge on one side of the tube and a negative charge on the other: The cathode rays were bent away from the negative charge and toward the positive charge.

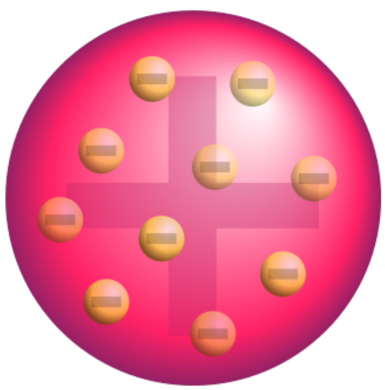


From this and from other information, Thomson was able to deduce the following about the particles in a cathode ray:

- **These particles have negative charge**. This explains why they move away from the applied negative charge (like charges repel) and toward the applied positive charge (opposite charges attract).
- **These particles are atomic particles**. Because the tube itself had no gas in it, the only place these particles could have come from is the atoms of the cathode itself.
- **These particles are very tiny**. When this experiment is conducted, there is no noticeable degradation of the cathode. This would not be the case if big hunks of stuff were flying off of it.
- **The positive charges in an atom must be big and heavy**. Because no significant anode rays (i.e. positively-charged rays) were observed going in the other direction, it stands to reason that whatever positive charge is contained in an atom must be much heavier than the cathode rays.[1]

We now refer to cathode rays as electrons.[2]

With the information above, Thomson was able to come up with what he called the **plum pudding model** of the atom:[3]



This model has the following features:

- **The atom is a solid ball of positive charge**. If you think of a chocolate chip cookie, the positive charge is the doughy part. This big blob of positive charge explains why positively-charged "anode rays" weren't observed in his experiment.
- **The negative particles in an atom (electrons) are small particles embedded in the big ball of positive charge**. The reason they can be knocked off of an atom so easily is that they're small and light.

Though incorrect, this model was the first to describe atoms as having internal structure – something we now take for granted.

1 *As it turns out, anode rays have been known since 1886, and their creation is the basis for mass spectrometry, which we'll learn about later. However, these anode rays are much fainter than cathode rays, so the idea that they must contain larger particles than cathode rays is both reasonable and correct.*

2 *The term "electron" is shorthand for "electric ion." Though electrons aren't, in fact, ions, the name has stuck.*

3 *Image public domain by fastfission, via Wikimedia Commons.*

Why Call It Plum Pudding?

Plum pudding is a traditional English Christmas dessert where raisins are suspended in a dough made from egg, lard, sugar, and alcohol. This pudding is then boiled in a sack and left to age for a month or so. In the plum pudding model, the raisins represent electrons and the dough represents the positive charge in an atom. In a more modern sense, you can think of an atom as being a chocolate chip brownie, with the chocolate electron chips embedded in the dough of positive charge.

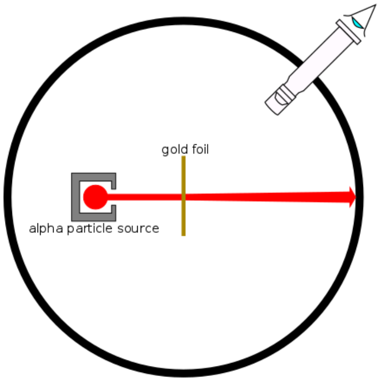
By the way, raisins were referred to as "plums" in the Victorian era, which explains why plum pudding didn't actually contain plums.

The flour "skin" around plum pudding is traditional for some reason or another.[4]

Rutherford and the Gold Foil Experiment (1911)

Ernest Rutherford was, by all accounts, an amazing scientist. By the age of 23 he had three degrees from the University of New Zealand. After this he started research at Cambridge under J.J. Thomson, where he started investigating radiation and radioactive particles – work for which he would shortly thereafter win a Nobel Prize. Along the way, he discovered radon and proposed the idea of radioisotope dating. It was at this point that he found himself in Manchester researching the behavior of alpha particles.

Rutherford, through his earlier work, had learned a lot about alpha particles. One form of radiation, **alpha particles** consist of positively-charged helium nuclei. Interested in how they interacted with matter, he set his students Geiger[5] and Marsden[6] to work on the subject. Their experimental setup was straightforward enough. Basically, all they did was to aim a beam of positively-charged alpha particles at a very thin piece of gold foil. It was thought that the interaction of the alpha particles with atoms would give some insight into the nature of atomic structure.[7]



4 *Celcom at the English language Wikipedia [GFDL (http://www.gnu.org/copyleft/fdl.html) or CC-BY-SA-3.0 (http://creativecommons.org/licenses/by-sa/3.0/)], via Wikimedia Commons.*

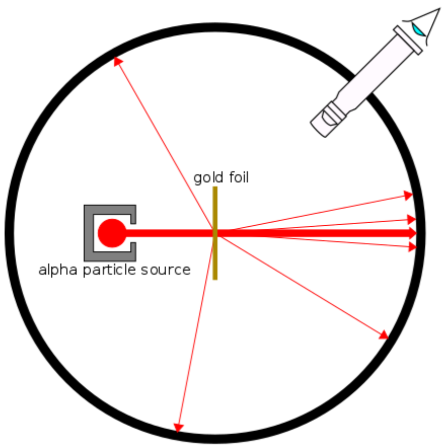
5 *Inventor of the Geiger counter, which is used to measure radioactivity.*

6 *First director of New Zealand's Department of Scientific and Industrial Research.*

7 *This diagram, as well as the two that follow it regarding the gold foil experiment, are from Kurzon (Own work) [CC BY-SA 3.0 (https://creativecommons.org/licenses/by-sa/3.0)], via Wikimedia Commons.*

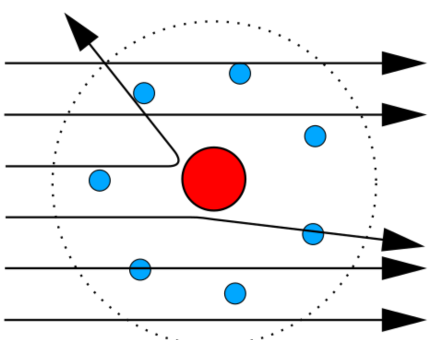
As this figure shows, it was expected that the alpha particles would just pass straight through the gold foil. After all, if atoms were essentially just uniform mixtures of positive and negative charge, there's no reason they shouldn't just pass through.

However, this isn't what this experiment found. Instead of the particles passing straight through, they found that the alpha particles behaved strangely. *Most* of the particles passed straight through, but a few of them would go flying off at different angles – some of them even flew back at the original source of alpha particles:



These odd observations led Rutherford to devise a new model of the atom that would explain these results. In Rutherford's **nuclear model** of the atom, all of the positive charge and most of the mass of the atom exists in a central nucleus, with electrons arrayed around the nucleus.

Rutherford believed this model did a good job of explaining the data. When most of the alpha particles came into contact with the gold foil, they passed straight through because atoms consist of mostly empty space. However, once in a very long while these positive alpha particles would pass close to the positively-charged nucleus, causing them to be deflected at different angles. It was this deflection that was the source for the stray alpha particles detected in the experiment.

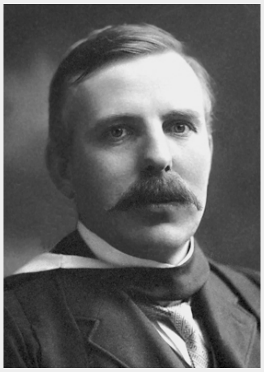


Most alpha particles passed through the atom away from the nucleus without changing direction. Occasionally an alpha particle would pass near the nucleus and be slightly deflected, and sometimes an alpha particle would pass close enough to the nucleus to return in the direction from which it came.

Once again, it was demonstrated that atoms were more complex than earlier imagined.

More Rutherford Awesomeness

After the gold foil experiment, Rutherford continued his amazing career. During World War I he invented the directional hydrophone for tracking submarines, was the first person to split the atom, advised the government of New Zealand on farming research, assisted in the discovery of the neutron, and co-discovered tritium with an early particle accelerator.[8]



He was also a handsome guy.

The Main Ideas In This Lesson:

- Thomson discovered electrons while experimenting with a cathode ray tube.
- The plum pudding model of the atom states that atoms consist of large balls of positive charge into which are embedded small negatively-charged particles. The negatively-charged particles are what we now know as electrons.
- Rutherford's gold foil experiment used alpha particles and thin foil to discover atomic nuclei.
- Rutherford's nuclear model of the atom states that all of the positive charge and most of the mass of an atom is found in a central nucleus. Electrons are found outside of the nucleus.

8 http://www.rutherford.org.nz/biography.htm

Lesson 9 – Glossary:

alpha particle: A helium nucleus which has been stripped of its electrons, which gives it positive charge. Rutherford used a beam of alpha particles to probe the atomic structure of gold atoms in his gold foil experiment.

anode: A positively-charged electrode.

cathode: A negatively-charged electrode.

cathode ray: A beam of electrons.

cathode ray tube: A glass tube from which most of the air has been evacuated. When an electric potential is applied to it, a cathode ray (i.e. beam of electrons) travels from the cathode to the anode. This cathode ray appears to be a glowing beam of light.

electron: A small, negatively-charged atomic particle.

gold foil experiment: An experiment in which Rutherford's research team fired positively-charged alpha particles at a very thin sheet of gold foil. Though most particles passed straight through, some were deflected, indicating that the positive charge of the atom is concentrated in a central nucleus.

nucleus: The central part of an atom. It contains protons which have positive charge and neutrons which have no charge.

plum pudding model: This is a model stating that atoms are large balls of positive charge with tiny negatively-charged electrons embedded in it.

Lesson 9: Practice Sheet

1) Sketch the cathode ray experiment apparatus and explain how it was able to identify the electron.

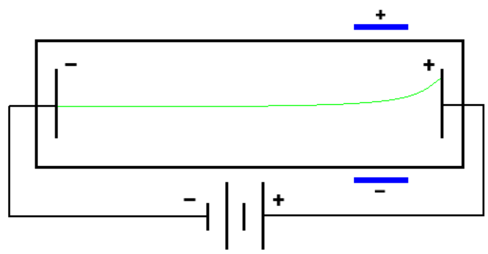
2) If the plum pudding model of the atom were correct, what do you believe the results of the gold foil experiment would have been? Explain your answer.

3) Explain why neither the cathode ray experiment nor the gold foil experiment were able to discover the neutrally-charged neutrons in the nucleus of the atom.

4) The gold foil experiment used a very thin sheet of gold foil – about 1,000 atoms thick. What would the result of this experiment have been if the foil were either much thinner (10 atoms thick) or much thicker (100,000 atoms thick)? Explain.

Lesson 9: Practice Sheet Answers

1) Sketch the cathode ray experiment apparatus and explain how it was able to identify the electron.



When an electric potential was applied, a beam of particles (the "cathode ray") traveled across the tube. When an additional set of charged plates (shown in blue) were added, the beam moved away from the negative plate and toward the positive one. This indicates that the beam of particles had negative charge. Furthermore, the fact that the cathode did not degrade shows that these negatively-charged particles are very small.

2) If the plum pudding model of the atom were correct, what do you believe the results of the gold foil experiment would have been? Explain your answer.

Either the positively-charged alpha particles would all have been repelled by the atoms in the gold foil and bounced backwards the way they came, or they would have blown a hole in the gold foil in the same way a bullet blows a hole through plywood. In neither case would the actual results have been observed.

3) Explain why neither the cathode ray experiment nor the gold foil experiment were able to discover the neutrally-charged neutrons in the nucleus of the atom.

Both experiments were designed to find charged particles. The cathode ray experiment was able to find electrons through the repulsion of these particles by charged electrodes. The gold foil experiment was able to find nuclei through the repulsion of positive alpha particles from the positive nucleus. Because neutrons have no charge, the application of charge would have had no effect on them.

4) The gold foil experiment used a very thin sheet of gold foil – about 1,000 atoms thick. What would the result of this experiment have been if the foil were either much thinner (10 atoms thick) or much thicker (100,000 atoms thick)? Explain.

If it had been much thinner, the number of deflected particles would be much smaller because there would be fewer nuclei for the alpha particles to interact with. If it were much thicker, there would have been more deflected particles, and at some point the alpha particles would stop penetrating the gold foil at all.

Lesson 9: Lab Activity – The Mystery Box

Parent Instructions

Equipment needed: A cardboard box (30 cm on a side or bigger), additional objects to be decided by you before doing the lab.

Safety: No safety issues are anticipated

Room destruction factor: None

What can go wrong: Nothing foreseeable

How the lab works:

In this lab, your child will be given a sealed cardboard box with an object inside. This object will be selected by you prior to the lab, and should be a personal possession that would be instantly identifiable to your child upon inspection. Good choices might be a favorite stuffed animal, a reasonably durable souvenir from a trip, or an item related to your child's favorite hobby. A good rule of thumb is this: If this item can be identified by your child by touch alone, it is probably a good choice.

When the item is selected and sealed in the box, your child will be given the task of identifying it. Initially, your child will have to guess the item based only on the clue that it is an item they are familiar with and that it fits in the box. After they have made their guess, they will be allowed to make one experimental observation to try and find out more about what is in the box.

Here's how it worked with my son when he did this lab:

- Presented with a box and the information that something he owns is inside of it, he guessed that it was a book. His reasoning was that a book will fit in the box and that he has lots of books. It was not a book.
- Given one experiment to perform, he decided to lift the box and see how much it weighed. Upon doing this he determined that the weight of the item is about that of a book and was able to narrow down the list of possibilities. He guessed that it was a school folder. It was not a school folder.
- His second choice for an experiment was to shake the box. He found that the object bounced around inside the box without making any clunking noises. He guessed that it was a stuffed animal. It was a stuffed animal, but he was given the task of determining *which* of his stuffed animals it was.
- His third experiment was to poke a tiny stick into the box to see if he could determine the stuffed animal's shape. Using this information as well as the weight and bounciness from earlier experiments, he correctly determined that it was his favorite teddy bear.

What this lab teaches:
The point of this lab is to show kids how hard it is to determine what something is when you have only limited information. It's easy for our modern minds with our modern data to get a pretty good idea about what atoms are. However, for people who were inventing the idea of the atom, things were not so obvious. The goal of this lab is to have kids realize that the process of learning about something already known is far more challenging than figuring out the information for the first time.

As opposed to learning about what is already known, real discovery tends to follow this pattern:

- Realization that there's something to discover: Before a phenomenon can be understood, it needs to be realized that it exists in the first place.
- Rough experimentation: Without information about what something is, experiments will tend to be fairly unfocused at first.
- Increasingly targeted experimentation: As more information is obtained, experiments will be targeted at increasing the fragmentary information to gain a better understanding of the phenomenon.

In this example, the conclusion of the experiment comes when the object is correctly identified. In the real world, our guesses about how something works may remain incomplete, necessitating new theories.

Grading:
This is pretty free form. Obviously, your child should have written a pretty clear idea of what their experiments are and how they interpreted the results. However, the number of guesses that led to the final answer isn't really the point of this lab. If your child finishes this lab understanding that science is an interactive and gradual process, they've gotten the point.

Postlab questions:

1) Your child should give a reasonable explanation about why their experimental path was either logical or could how it could be improved. There is no right answer, provided that they show that they have been logically contemplating this question.

2) Just like the early atomic investigators, your child was studying something about which he/she had no context from which to work. Developing the necessary background information, in this case, was the biggest challenge to the work.

3) Though there's no particular correct answer, it seems reasonable to assume that the discovery of the atom would be far simpler if undertaken in the modern day. This is because our experimental capabilities are greater.

Lesson 9: Lab Activity – The Mystery Box

You have been given a sealed cardboard box that contains an item you are familiar with it. The goal of this lab is to identify this item. However, you cannot simply open the box and determine what it contains.

Instead, like the scientists who determined what atoms are, you're going to have to do gradual experiments to figure out what this mystery item is. With each experiment, you'll be allowed to make one guess as to what this item is. When you have successfully identified it, you're finished!

The experiments you perform are up to you, provided that you do only one experiment at a time and that you don't look inside. You may pick up the box, weigh the box, shake the box, poke the box, yell at the box, send the box an email, or put food out and see if the box responds to it. The only criteria are that you cannot open the box, and that you get to perform only one experiment at a time before making a new guess.

Good luck!

Prelab guess:

- Before you do any experiments at all, what do you believe is in the box? What evidence do you have that is consistent with this guess?

Experiment 1:

- What experiment did you do to gain more insight as to the contents of this box?
- What do you believe is in the box?
- What evidence do you have that is consistent with this guess?

Experiment 2:

- What experiment did you do to gain more insight as to the contents of this box?
- What do you believe is in the box?
- What evidence do you have that is consistent with this guess?

Experiment 3:

- What experiment did you do to gain more insight as to the contents of this box?
- What do you believe is in the box?
- What evidence do you have that is consistent with this guess?

Experiment 4:

- What experiment did you do to gain more insight as to the contents of this box?
- What do you believe is in the box?
- What evidence do you have that is consistent with this guess?

Experiment 5:

- What experiment did you do to gain more insight as to the contents of this box?
- What do you believe is in the box?
- What evidence do you have that is consistent with this guess?

If you need to perform additional experiments, include them on a separate sheet of paper.

Postlab questions:

1) Looking back, do you believe that the experiments you performed to identify the object in the box were reasonable? Is there a different methodology you would follow if you had to do it again?

2) How are the things you did for this lab similar to the experimental processes followed by early atomic investigators?

3) If the atom were being discovered today, explain whether or not you believe that the process would go more smoothly than it did in our current history.

Lesson 9 Assessment

1) In Thomson's cathode ray experiment, he deduced that electrons were much smaller and lighter than the positively-charged particles in the nucleus. Explain how this is reasonable, based on his experimental evidence.

2) Sketch Rutherford's gold foil experimental apparatus and explain how the data collected from this experiment led to the discovery of the nucleus.

3) How would Rutherford's experimental results have been different if he had fired a beam of neutrally-charged particles at the sheet of gold foil in his experiment?

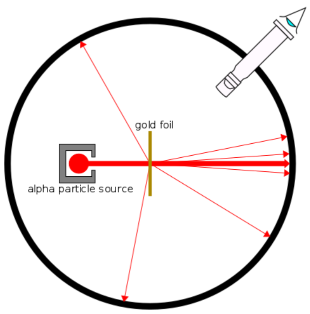
4) Atomic nuclei were discovered by Rutherford in 1911. However, protons were not discovered until 1919. Why do you believe it may have taken Rutherford an additional eight years to discover protons?

Lesson 9 Assessment – Answers

1) In Thomson's cathode ray experiment, he deduced that electrons were much smaller and lighter than the positively-charged particles in the nucleus. Explain how this is reasonable, based on his experimental evidence.

The fact that only negative particles moved from one electrode to the other suggests that they're much lighter than the positive particles in an atom. Additionally, the fact that there was no degradation of the cathode (i.e. it didn't get smaller as the particles were launched away from it) suggested to him that these particles were also very small.

2) Sketch Rutherford's gold foil experimental apparatus and explain how the data collected from this experiment led to the discovery of the nucleus.



The positively-charged alpha particles mostly went through undisturbed, but occasionally were deflected at strange angles. This is consistent with the idea of the atom being mostly empty space (which explains why most of the particles passed through) with only a very small nucleus in the center (which would deflect the very few alpha particles that came near it).

3) How would Rutherford's experimental results have been different if he had fired a beam of neutrally-charged particles at the sheet of gold foil in his experiment?

Nothing would have happened if he did this. The reason that the alpha particles were deflected was that they were being repelled from the positively-charged nucleus. If neutral particles had been shot at the gold foil, there would have been no reason for them to be deflected and they would have passed through undisturbed.

4) Atomic nuclei were discovered by Rutherford in 1911. However, protons were not discovered until 1919. Why do you believe it may have taken Rutherford an additional eight years to discover protons?

The gold foil experiment could detect a positively-charged body at the center of the atom in the nucleus. However, if there were many positive particles concentrated in this nucleus, this experiment would not be able to distinguish one from the other. It wasn't until 1919 that Rutherford, in an experiment different than the gold foil experiment, was able to discover the nucleus.

Lesson 9 – References for further study

How was the proton discovered?

- Find out here: http://www.physlink.com/education/askexperts/ae46.cfm

How was the neutron discovered?

- You undoubtedly already know that the nucleus contains a neutral particle called the neutron. However, given the fact that it has no charge, it couldn't be discovered in the same way as protons and electrons. Find out how this was done here: http://chemistry.bd.psu.edu/jircitano/neutron.html

Cathode ray tubes and TV sets

- Old TV sets used to be huge, heavy devices. Though to the casual observer these were just ways of showing bad sitcoms, these devices actually consisted of cathode ray tubes which worked in the same fundamental way that Thomson's tube did. Read more about it here: http://electronics.howstuffworks.com/tv3.htm