Lesson 37: Thomson's Plum Pudding Model

Remember back in Lesson 18 when we looked at trapping moving particles in a circular path using a magnetic field?
- In this lesson we look at how using this type of set up eventually helped physicists start to figure out the nature of the atom.

Early Theories about Atoms

In 1803 John Dalton presented his theory that the elements of the periodic table were made of atoms.
- The main reason he was proposing this idea was to be able to explain the chemistry that he was studying.
- Dalton believed that atoms were solid pieces of matter that could not be broken down any further.
  - This is why his model is often referred to as the **Solid Sphere Model**.
- Although Dalton's model was able to explain the way he saw chemical reactions working, he was unable to really prove that matter was made up of these atoms, or how chemical bonding could happen between them.

During the late 1800's experiments with cathode ray tubes (CRTs) were starting to give the first glimpses into what an atom might be.
- A cathode ray tube is just a vacuum tube with two electrodes at the ends.
  - When a really high voltage is applied, *mysterious* "cathode rays" moved from the negative electrode to the positive electrode.
  - Sometimes you could see a glow at the opposite end of the tube when the tube was turned on.
- William Crookes used a really high quality cathode ray tube in 1885.
  - In his tubes he usually placed a **mask**, an object that would block some of the cathode rays from getting to the other side of the tube. This resulted in a **shadow**.
  - He believed that the the results of his experiment suggested that the particles coming off the cathode were negatively charged.
- In 1895 Jean Baptiste Perrin was able to verify this by showing that cathode rays shot into a metal tube caused the metal tube to gain a negative charge.

The negative electrode is referred to as the **cathode**. That's the reason this is called a cathode ray tube.
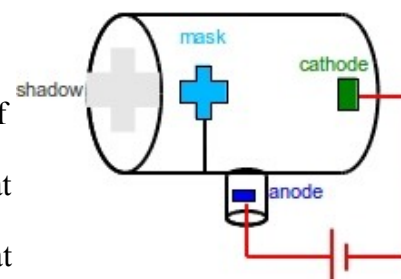

Illustration 1: A classic Crookes tube.

Video Killed the Radio Star!
You can watch a couple of videos demonstrating a Crookes tube by clicking here and here. You can also scan the following QR codes.

J.J. Thomson's Cathode Ray Tube

The real breakthroughs started when J.J. Thomson began his research. He performed a series of three experiments.

First Experiment

His first experiment was to see if the negative charges could be separated from the cathode rays using a magnetic field.
- At the time, it was not known that the cathode rays *were* the negative charges.
- When Thomson failed to separate them, he figured out that the negative charges were what the cathode rays were made up from.

Second Experiment

His second experiment was to see if he could cause the cathode rays to be deflected in an electric field.
- Before this, stray air molecules in the tube kept getting ionized and screwed up the results.
- Thomson built a nearly perfect vacuum tube for his CRT and showed that the electric field did bend the cathode rays in the direction to be expected for negative charges.

Third Experiment: Charge-to-Mass Ratio

Thomson's third experiment was the most important, and the one that he is most remember for.
- It allowed him to measure properties of the cathode rays, specifically the charge-to-mass ratio.
  - This value is really just a measurement of how much charge in Coulombs you get per kilogram of the substance.
  - You can guess that this number is pretty big... one kilogram of just electrons would have a huge amount of charge.
    Combined with later work, the charge-to-mass ratio was the first look into the atom that physicists really had.

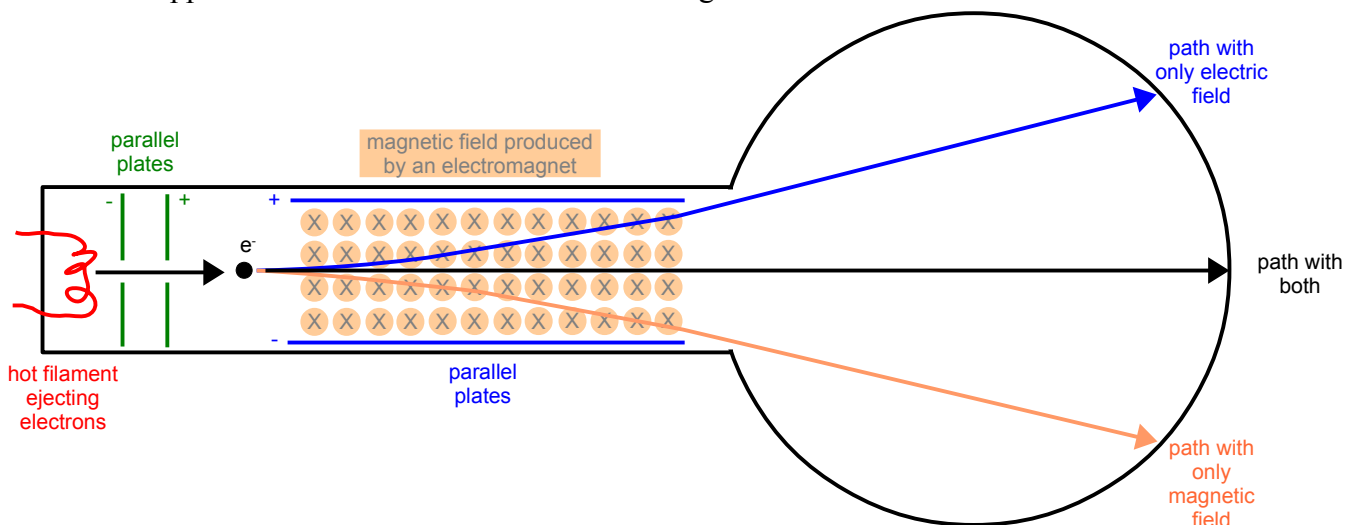Thomson's apparatus was a modified version of the regular CRT.

Illustration 2: Thomson's CRT for his charge-to-mass ratio experiment.

- At the start we have a **hot filament**. If this metal is hot enough it will start to eject electrons.
- The first set of **parallel plates** are arranged to accelerate the electrons towards the right.
- The electron now enters a part of the CRT that will change its path in one of several ways.
    - If just the second set of **parallel plates** are turned on, the **electric field** will cause the electrons to move up a bit as they travel to the right. When they hit the globe at the end of the tube, this results in a glow near the top.
    - If just the **magnetic field** being created by an electromagnet is on, then the electrons will be forced downwards by the **magnetic field** as they travel to the right (use your third hand rule). When they hit the globe at the end of the tube, this results in a glow near the bottom.
    - Here's the tricky one! If *both* the **electric** and **magnetic** fields are turned on at the same time, and everything has been set up just right, the electron sails straight through in a straight line.
        - As much as the **electric field** pushes up, the **magnetic field** pushes down. They cancel each other out.

The electric force on the charges that can be calculated using…

$$\vec{E} = \frac{F_e}{q} \quad \rightarrow \quad F_e = \vec{E} q$$

The force of the magnetic field is simply...

$$F_m = qvB$$

These two forces are exactly balancing each other, so they must be equal in magnitude...

$$F_e = F_m$$
$$\vec{E} \underset{cancel}{q} = \underset{cancel}{q} vB$$

$$\vec{E} = vB$$

$$v = \frac{\vec{E}}{B}$$

$$v = \text{velocity (m/s)}$$
$$\vec{E} = \text{electric field (N/C or V/m)}$$
$$B = \text{magnetic field (T)}$$

This equation is often referred to as the **velocity selector formula**.
- Only electrons that are moving at this specific velocity will result in forces that balance out.
- As long as Thomson set everything up well and tweaked the dials so he eventually got the electrons to hit dead centre, he was able to figure out the velocity based on the electric and magnetic fields he was using.

Example 1: You have just finished setting up a CRT like Thomson's. **Determine** the velocity of the electrons if the magnetic field is 3.65 T and the electric field is 7.62e7 N/C. **Explain** the significance of your answer.

$$v = \frac{\vec{E}}{B}$$

$$v = \frac{7.62e7}{3.65}$$

$$v = 2.0876712e7 = 2.09e7 \, m/s$$

These electrons are moving very fast. In fact, they are moving at almost 10% the speed of light. In university level physics you will learn that velocities this high actually have an effect on your final answer.

After he has taken down his readings and figured out the velocity, Thomson next turned off the electric field.

- With the electric field off, only the magnetic field remains to push the electrons around.

- The magnetic field's force downward on the electrons will cause them to start to accelerate downwards as we saw earlier.
  - If we were able to make the magnetic field cover a larger area, we could actually trap the electrons in the magnetic field and force them to move in a big circle.
  - Thomson took the path the electrons did follow in his magnetic field and extrapolated how big the circle would be if he was able to trap them.
    The magnetic force is causing centripetal motion, just like in Lesson 18 **Example 1**.

$$F_m = F_c$$

$$q v B = \frac{mv^2}{r}$$

$$qB = \frac{mv}{r}$$

$$\frac{q}{m} = \frac{v}{Br}$$

Warning!
You do not have to solve this formula for charge-to-mass ratio if the question asks for just one variable. This is just the way Thomson originally used it, and the way we use it for solving these question now.

$\frac{q}{m}$ = charge-to-mass ratio (C/kg)

v = velocity (m/s)
B = magnetic field (T)
r = radius of path (m)

Example 2: You decide to try to recreate Thomson's experiment to find the mass of an electron. You set up your cathode ray tube with an electric field of 1.86e4 N/C between the plates and a magnetic field of 5.80e-4 T. These settings result in electrons traveling straight through when they are both turned on. After shutting down the electric field, you measure the path of the electron. It has a radius of 0.325m. **Determine** the charge-to-mass ratio according to your experiment, and **compare** it to the accepted value.

We will need to solve this problem in a couple of steps.

Step One: How fast is the electron going?

We can calculate this since the balanced electric and magnetic fields will only let a specific velocity electron all the way through. We use the velocity selector formula.

$$v = \frac{\vec{E}}{B}$$

$$v = \frac{1.86\text{e}4}{5.80\text{e-}4}$$

$$v = 3.2068966\text{e}7 \, m/s$$

Step Two: What's the charge-to-mass ratio?

This is when the centripetal and magnetic forces are balanced.

$$F_m = F_c$$

$$q\,v\,B = \frac{mv^2}{r}$$

$$qB = \frac{mv}{r}$$

$$\frac{q}{m} = \frac{v}{Br}$$

$$\frac{q}{m} = \frac{3.2068966\text{e}7}{5.80\text{e-}4\,(0.325)}$$

$$\frac{q}{m} = 1.70127138\text{e}11 = 1.70\text{e}11 \, C/kg$$

Step Three: Compare it to the theoretical value.

It's easy to get the theoretical value for charge-to-mass for an electron based on the values we have on the data sheet.

$$\frac{q}{m} = \frac{1.60\text{e-}19}{9.11\text{e-}31} = 1.76\text{e}11 \, C/kg$$

This value is pretty close to the one we calculated from experimental data. We should calculate the percent error to finish our comparison.

$$\%\,error = \frac{measured - accepted}{accepted}$$

$$\%\,error = \frac{1.70\text{e}11 - 1.76\text{e}11}{1.76\text{e}11}$$

$$\%\,error = -0.0313386 = -3.13\%$$

Thomson's Plum Pudding Model

Based on all his work, Thomson came to some conclusions about the structure of atoms.

- First, his value for charge-to-mass ratio was thousands of times bigger than anyone had ever measured for something like a hydrogen ion.
  - o This meant that the cathode rays were super concentrated charge.
  - o Other scientists had shown that the cathode rays could even travel through a thin sheet of metal foil.

> Many textbooks now use the names "raisin bun" or "chocolate chip cookie" when referring to Thomson's model of the atom. Although it was other scientists that actually gave Thomson's model the nickname "plum pudding," I always use this name since I feel it more accurately reflects Thomson's British heritage.

- o Thomson concluded that these "corpuscles" (his name for the electrons) must be extremely tiny and densely charged.
- Although at first he believed atoms were entirely made up of electrons, he eventually realized that this was wrong.
  - o Since elements can exist as neutral atoms, there must be some positive substance that cancels out the electrons' negative charges.

Thomson suggested a model of the atom called the Plum Pudding model.
- Its name is supposed to make you think of a lump of stuff with little pieces floating inside it.
- This model of the atom is that small negatively charged electrons are floating around inside a lump of positively charged material.
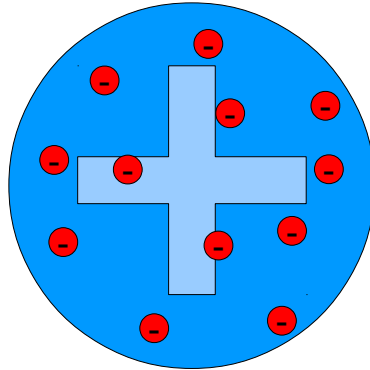
Illustration 3: J.J. Thomson's Plum Pudding Model.

Although we now know Thomson's model is wrong, at the time it was the first model of the atom to take into account separate negative and positive charges.

Homework

p756 #1, 2
p758 #1, 3