**Class 18: The Electron**

**18.1. Introduction**

The atom has been established as the fundamental unit of matter and scientists immediately started questioning whether the atom could be broken down further. The ability to change the charge of an atom brought up the question of whether something was being removed from the atom.

Atoms like to be neutral – you have to rub objects to charge them. This raised the question of what was happening when you rubbed the atom – what changed in the atom to produce the charge? DuFay suggested a two-fluid theory. A neutral object had equal amounts of the two fluids. Rubbing an object removed one of the fluids, leaving an excess of the other type of fluid. Benjamin Franklin argued that there was only one fluid – a positive charge results when a material has more of the fluid than it should and a negative charge results when a material has less of the fluid than it should. A charged body was anxious to balance the amount of fluid and could either accept or give fluid to other objects to become neutral again. Further experimentation was necessary to understand what was responsible for the ability to charge atoms.

**18.2. Goals**

- Explain how electric and magnetic forces can be used to change the motion of charged particles;
- Explain how cathode rays led to the discovery of the electron;
- Explain Thomson’s experiment and how it supported the existence of the electron;
- Explain Thomson’s Plum Pudding model;
- Explain how the mass and the charge of the electron were determined; and
- Explain the significance of the discovery of the electron in terms of the atom’s status as the fundamental building block of matter.

**18.3. Steering Using Electric and Magnetic Fields**

**18.3.1. The Force on a Charge due to an Electric Field.** Magnetic fields, and also electric fields, can be used to change the direction of charged particles. An electric field $E$ will exert a force $F_E$ on a charge $q$ according to

$$F_E = qE$$  \hspace{1cm} (18.3.1)

where the subscript on $F_E$ indicates that this force is due to an electric field. $F_E$ is in the same direction as the electric field for a positive charge and in the direction opposite the electric field for a negative charge. In Figure 18.1, the force is opposite the direction of the electric field because the charge is negative.

**Electric Charge in an Electric Field**

![Diagram of electric charge](image)

$F_E = qE$

The force due to $E$ causes the negative charge to move up

Figure 18.1: Force on a negative charge due to an applied electric field.
18.3.2. **The Force due to a Magnetic Field.**
A magnetic field \( B \) will exert a force \( F_B \) on a charge \( q \) moving with velocity \( v \) (where \( v \) is perpendicular to \( B \)) according to Lorentz’ Law:

\[
F_B = qvB \tag{18.3.2}
\]

where the direction is determined by right-hand-rule #2.

18.3.3. **Balancing E and B.** Although either magnetic or electric fields can be used to change the motion of a charge, much more flexibility is provided when both are used, as shown in Figure 18.2 and Figure 18.3. In Figure 18.3, a positive charge enters a region with an electric field pointing up and a magnetic field out of the page. The velocity of the charge is to the right. The force exerted by the magnetic field when the charge first enters the field is in the downward direction; however, the force exerted by the electric field is in the up direction. The path of the charge depends on which force is larger. If the magnitudes of the forces are equal, the charge can proceed in a straight line through the region with the fields. This requires that

\[
F_E = F_B \quad qE = qvB
\]

or

\[
v = \frac{E}{B} \tag{18.3.3}
\]

Equation (18.3.3) tells us that we can change the magnetic and electric fields to pick out only charges traveling at a particular velocity \( v \).

18.3.4. **Finding the Charge-To-Mass Ratio.** Consider what happens when we take charges all moving with velocity \( v \) and put them through a region with only a magnetic field of the same magnitude \( B \). The force of the magnetic field will cause the charge to curve, as shown in Figure 18.4. We saw in the last chapter (Equation (17.6.1)) that the radius of the curve is given by

\[
mv = qBR
\]

where \( m \) is the mass of the charge, \( q \) is the magnitude of the charge, \( v \) is the velocity of the charge, \( B \) is the magnetic field and \( R \) is the radius.
We know the velocity of the entering charges from Equation (18.3.3), we can measure \( R \) from our experiment, and we know the value of \( B \). That leaves us with two unknowns – we can’t solve for either one of them, but we can solve for their ratio. Rewriting Equation (17.6.1)

\[
\frac{q}{m} = \frac{v}{BR}
\]  

(18.3.4)

The equation is written this way the knowns are on the right and the unknowns on the left. We call the ratio \( \frac{q}{m} \) the ‘charge-to-mass ratio’ of the charges that are being deflected.

**EXAMPLE 18.1:** A negative charge travels to the right into an electric field of magnitude \( 5.5 \times 10^6 \, \text{N C}^{-1} \) pointing down and a magnetic field into the page. If the magnetic field has a magnitude of 2.5 T, what is the velocity of the negative charges that are not deflected (i.e. the negative charges that travel in a straight line)?

Draw a picture

- \( q \) is negatively charged.
- \( E = 5.5 \times 10^6 \, \text{N C}^{-1} \) = down is the electric field magnitude
- \( B = 2.5 \, \text{T out of the page} = \) magnetic field

Before we do any calculations, we need to think about the directions of the forces. The electric field will exert a force upward on the negative charge and (by RH R #2) the magnetic field will exert a force downward on the charge.

Equation to use (already solved for unknown)

\[
v = \frac{E}{B}
\]

Plug in numbers.

\[
v = \frac{5.5 \times 10^4 \, \text{N}}{2.5 \, \text{T}} = 2.2 \times 10^4 \, \text{N T}^{-1} \text{C}
\]
18.4. Cathode Rays

18.4.1. Cathode Rays are Discovered. Electrodes are materials (usually pieces of metal) that have a net charge. The cathode is the negative electrode (it has a negative net charge) and the anode is the positive electrode (it has a positive net charge). In the mid 1850’s, electricity was a hotly pursued topic for both fundamental research and new inventions. Humphrey Davy built the world's largest battery, with his efforts motivated by his desire to try to break down compounds and find new elements. Davy’s pupil Michael Faraday (1792-1867) tried to pass an electrical current through a vacuum, just to see what happened. He didn’t get any results until the German inventor and glassblower Heinrich Geissler developed the mercury diffusion vacuum pump in 1855. The diffusion pump removed many more air molecules than previous pumps could remove. When Faraday isolated a pair of electrodes in this improved vacuum and applied a large voltage (~10^4 V, thanks to Davy’s battery) a green glow appeared between the two electrodes, as shown in Figure 18.5. The next task was to identify what the green glow was.

Each subsequent measurement provided more information about the nature of the cathode rays. In 1871, C.F. Varley suggested that cathode rays are made up of particles. William Crookes proposed that cathode rays are molecules that picked up a negative charge from the cathode and are repelled by it, which forms the rays. In 1874, George Johnstone Stoney estimated the charge of the unknown particle from the cathode ray to be about 10^{-20} C. Stoney proposed the name "electrine" for the unit of charge on a hydrogen ion. (An ion is an atom that has a net charge.) In 1876, Eugen Goldstein showed that the green glow originated at the cathode and introduced the term cathode ray to describe the green glow. In 1891, Stoney changed the name of the unit of charge on a hydrogen ion to "electron." Important to our story is that he proposed that this unit represented a minimum quantity of electricity that could exist. In other words, he proposed that there existed some smallest unit of electricity, just as the atom had been proposed to be the smallest unit of matter.

Figure 18.5: A Cathode Ray Tube (CRT)
18.4.2. Properties of Cathode Rays. Sir William Crookes (1832-1919) inherited a large fortune as a young man and carried out research in his own private lab. Crookes’ original motivation for studying cathode rays was to try to produce current without a wire. Crookes discovered the following properties of cathode rays around 1880:

1. Cathode rays have the same properties, regardless of what metal is used for the cathode;
2. Cathode rays travel in straight lines that are perpendicular to the cathode surface if there is no magnetic field;
3. A magnetic field can deflect the path of cathode rays;
4. Some chemical reactions are observed: certain silver salts change color when hit by cathode rays;
5. Crookes believed that electrically charged objects should deflect the path of the cathode rays; however, he was unable to prove it.

18.4.3. Are Cathode Rays Deflected by Electric Fields? Why was Crookes so interested in whether cathode rays were deflected by electric fields? This went to the question of the charge of the particles that made up the cathode rays – if they are charged, they should be deflected by electric fields and the sign of the charge could be determined by the direction of deflection. The quality of the experimental equipment provided some false results. In 1883, Hertz showed that cathode rays are not deflected by electrically charged metal plates and that seemed to settle the matter.

In 1892, however, Hertz showed that cathode rays can penetrate thin foils of metal and interprets this to mean that cathode rays cannot be particles, as particles would be too large to go through metal. About a year later, Philipp von Lenard (1862-1947) developed a cathode-ray tube with a thin aluminum window that permitted the rays to escape the vacuum in which they had to be produced. This advance allowed scientists to study cathode rays in the open air, which greatly simplified experiments. Lenard found that cathode rays could pass quite easily through various thin metals without making holes, which supported Hertz’ assertion that cathode rays could not be made up of particles. In January of 1897 Emil Wiechert made a puzzling measurement indicating that the charge-to-mass ratio of cathode rays was over a thousand times larger than the charge-to-mass ratio of the smallest charged atom known. Lenard’s studies of cathode rays passing through a metal foil and how far they traveled through various gases led him to conclude that these particles – if they were particles – had to be very small.

18.5. J.J. Thomson Solves the Mystery

18.5.1. Cathode Rays are Deflected by Electric Fields. As vacuum technology improved, it became easier to study cathode rays. In 1897, J.J. Thomson used improved experiments to demonstrate that cathode rays move away from negative charge and toward positive charge. Earlier experiments didn’t have the necessary sensitivity to detect this effect. The deflection of the cathode ray allowed Thomson to determine that cathode rays must be negatively charged. He suggests that
cathode rays are made up of electrons. Figure 18.6 shows the effect of an electric field on the cathode rays.

Figure 18.6: A Cathode Ray Tube (CRT) with an electric field applied shows the deflection of the cathode rays.

18.5.2. Finding the Charge-to-Mass Ratio for the Electron. Thompson used the technique we introduced earlier—balancing the deflection due to the magnetic field with the deflection due to the electrical field—to determine the charge-to-mass ratio of cathode rays using Equation (18.3.4). Thompson measured the charge-to-mass ratio of an electron to be \(1.7584 \times 10^{11} \frac{C}{kg}\). Using \(e\) to denote the charge on an electron, the absolute value of the charge-to-mass ratio is:

\[
\frac{e}{m} = 1.759 \times 10^{11} \frac{C}{kg}
\]  

Thomson could not measure \(e\) and \(m\) separately. He knew that the value of \(e/m\) is very large, which means that the value of \(m/e\) is small. This could imply that either the mass is very small or the charge is very large. To decide which was the case, Thomson tried to measure the charge using methods other than balancing forces. His measurements were not accurate enough to yield an exact value, but they were good enough that he could conclude that the magnitude of the charge on the electron was similar in magnitude to that of the positive hydrogen ion. For an electron, \(\frac{e}{m} = 1.759 \times 10^{11} \frac{C}{kg}\). For a hydrogen ion, \(\frac{e}{m}\) is on the order of \(10^8 \frac{C}{kg}\). This suggests that the electron, since it has a charge comparable to that of a hydrogen ion, must have a much smaller mass than the mass of an atom. From these numbers, Thomson estimated the mass of the electron to be about \(1/1800\) of the mass of a hydrogen atom. He was awarded the Nobel Prize in 1906 in recognition of his contributions to our understanding of the electricity. 1900 is celebrated as the year of the discovery of the electron.

18.5.3. The Status of the Electron. Thomson came to the following conclusions regarding electrons.

- Since the electrons that make up cathode rays can be produced by many different cathode materials and they all have the same properties, the electron is present in many different materials.
• The charge of the electron is about the same as that of the charge on the hydrogen ion.
• The mass of the cathode ray particle is much smaller than that of the hydrogen ion (which was
  the smallest known mass at the time).

These measurements were extremely significant because they indicated the electron was a part of the
atom and could be removed. Thomson had shown that the atom had more than one component and
thus was not the most fundamental unit of matter.

18.6. MEASURING THE CHARGE OF THE ELECTRON

18.6.1. Determining the Charge of the Electron. We showed in an earlier section
that it is possible to balance the force on a
charge due to an electric field with that
due to a magnetic field. Robert Milikan
measured the charge of the electron in
1906 by using an experiment that balanced
the force of gravity with the force due to
an electric field. Through these
experiments, Milikan determined that the
magnitude of the negative charge on an
electron is $1.60 \times 10^{-19}$ C.

In Milikan’s experiment, small droplets of
oil were given a charge and released to fall
under the influence of gravity, as shown in
Figure 18.7. Milikan measured how
strong an electric field was necessary to
stop the charged oil droplets. He could
calculate the mass of the drops by finding their terminal velocity (their maximum falling speed, which depends on the mass of the drop and its air resistance). The force due to gravity is

$$F_G = mg$$

and the force due to the electric field is

$$F_E = qE$$

The electric field (which is supplied by the
battery shown in Figure 18.7) must exert a
force upward on the oil drops to counteract
the downward force of gravity. When
these two forces are equal,

$$mg = qE$$

Robert A. Milikan was born in Morrison, Illinois (1868-1953) but moved to Iowa for school. He entered Oberlin College as a classics major; however, he developed an interest in physics after being asked to teach physics during his junior year. When he was offered a fellowship in Physics at Columbia he accepted, but again only because it was the best offer he could get financially. After graduate studies at Columbia, he spent some time in Europe, and then accepted an appointment as an assistant in physics at the newly established Ryerson Laboratory of the University of Chicago. He devoted himself to teaching and research and began his studies of the electron charge in 1907 when he was almost 40. He was appointed full professor at Chicago in 1910 and in 1911 published his now famous paper on his oil-drop experiments in the Physical Review, vol. 32, page 49.

5 Compare how the center of science shifted from Europe to the United States during the coming decades. Physical Review is an American journal that also still exists, although there are now five separate “Phys Rev”s for different branches of physics.

6 This is unusual – many scientists do their best research early in their careers and few scientists start in administration and move into doing research – it’s usually the other way around.
or

\[ q = \frac{mg}{E} \]  \hspace{1cm} (18.6.1)

Since everything on the right-hand side of Equation (18.6.1) was known, Milikan was able to determine the charge on the oil droplet. Figure 18.8 shows the forces acting on the oil droplet.

By varying the charge on different oil drops, Milikan noticed that the charge always was a multiple of \(-1.60 \times 10^{-19} \text{ C}\). Milikan realized that this meant that this number represented a fundamental value – this was the increment in which electric charge was found. The value of \(1.60 \times 10^{-19} \text{ C}\) is called the fundamental unit of charge \(e\) because scientists were not able to find charges that were smaller than this value. (Don’t confuse \(E\), the electric field, with \(e\), the fundamental charge.) Knowledge of \(e\) allows us to calculate the mass of the electron from Thomson’s value of \(\frac{e}{m}\) using Equation (18.5.1)\(^7\)

\[
\frac{e}{m} = 1.759 \times 10^{11} \frac{\text{C}}{\text{kg}}
\]

\[
m = \frac{e}{1.759 \times 10^{11} \frac{\text{C}}{\text{kg}}} = \frac{1.60 \times 10^{-19} \text{ C}}{1.759 \times 10^{11} \frac{\text{C}}{\text{kg}}} = 9.11 \times 10^{-31} \text{ kg}
\]

or

\[ m = 9.11 \times 10^{-31} \text{ kg} \]

This is the value of the electron mass.

**18.7. Thomson’s ‘Plum Pudding’ Model of the Atom**

All of the measurements made thus far led scientists established the following:

1) Since atoms are electrically neutral, there must be equal amounts of positive and negative charge in each atom.

2) The negative charge is from the same particles that are found in cathode rays (electrons). The electron mass is so small that the electron must be a small part of the mass of the atom. The

\(^7\) Although his experiments were critical to our understanding of the electron, Millikan earned his Nobel Prize for his work verifying the photoelectric effect (which we will learn about later…)
Thomson proposed a model of the atom in which electrons were embedded in a positively charged material, just as raisins are embedded in plum pudding. This became known as the plum pudding model of the atom. The charge of the positive material cancelled the negative charge of the electrons, thus making an electrically neutral atom. A schematic illustration of Thomson’s model is shown in Figure 18.9. The discovery of cathode rays was a major factor in abandoning the fluid models of electricity.

### 18.7.1. Weaknesses of the Model

Although Thompson’s model was consistent with all of the data, there remained some unexplained data. Positive charges repel each other and Thomson’s model didn’t explain what held all the positive material in the atom together. Secondly, Thomson’s model couldn’t explain some chemical properties of atoms, suggesting that either the model was wrong or there was something missing. Regardless of these weaknesses, Thomson’s model was an important step forward in our understanding the structure of the atom.

Ironically, J.J. Thomson was awarded the Nobel Prize for showing that the electron is a particle. His son, George Paget Thomson was awarded the Nobel Prize in 1937 for showing that the electron is a wave. We will investigate this apparent dichotomy in Unit IV.

### 18.8. Applications

The first computer monitors were green on black because they were simple cathode ray tubes. Cathode ray tubes are still used in computer monitors and televisions, although they rapidly are being replaced by LCDs and plasma displays. (Appliances that use cathode ray tubes usually are large and bulky.) The colors on a color TV are made by cathode rays hitting phosphors, which glow in red, blue or green when stimulated by the cathode rays. The entire picture is made by using magnetic and electric fields to steer the beam of cathode rays across the screen, then up and down. If you take a picture of a computer monitor, the scan rate is slow enough that you may be able to see the screen being re-drawn.

### 18.9. Summarize

#### 18.9.1. Definitions:

Define the following in your own words. Write the symbol used to represent the quantity where appropriate.

1. Charge-to-mass ratio

2. Cathode

3. Anode
4. Ion

18.9.2. Equations: For each question: a) Write the equation that relates to the quantity b) Define each variable by stating what the variable stands for and the units in which it should be expressed, and c) State whether there are any limitations on using the equation.

1. Review the expressions for the forces due to electric and magnetic fields, and the path a charged particle takes in a magnetic field.

2. The relationship between the speed of a charged particle and the applied electric and magnetic fields.

3. The relationship between the charge-to-mass ratio and the path of a charged particle in a constant magnetic field.

4. The equation used by Milikan to determine the charge on the electron.

18.9.3. Concepts: Answer the following briefly in your own words.

1. What was the experimental evidence that Thomson had discovered the existence of a charged subatomic particle when working with cathode rays?

2. Describe in your own words Thomson’s plum pudding model.

3. What were the weaknesses of Thomson’s plum pudding model?

4. Explain how Milikan measured the mass of the electron.

5. Explain how combined electric and magnetic fields can be used to select particles that are moving with a particular speed? Does this phenomenon depend on the mass of the particle?

18.9.4. Your Understanding

1. What are the three most important points in this chapter?

2. Write three questions you have about the material in this chapter.

18.9.5. Questions to Think About

1. Explain how, prior to the measurement of the mass of the electron, scientists knew that mass must be much smaller than the mass of an atom.
18.9.6. Problems

1. If the charge-to-mass ratio of a proton is \( 9.58 \times 10^7 \frac{C}{kg} \) and the charge is \( 1.60 \times 10^{-19} \) C, what is the proton mass?
HW Covers Class 18 and is due February 21, 2007

1. What was the experimental evidence that Thomson had discovered the existence of a negatively charged subatomic particle when working with cathode rays?

2. If the charge-to-mass ratio of a proton is $9.58 \times 10^7 \frac{C}{kg}$ and the charge of the proton is $1.60 \times 10^{-19}$ C, what is the proton mass?

3. Describe Thomson’s plum pudding model in your own words. What were the weaknesses of this model?
18.10. **Resources**
Here’s a link to the behavior of a cathode ray in an electric field: http://webphysics.davidson.edu/WebTalks/AAPT_Guelph/CathodeRay.html

18.11. **Mass Spectrometry**
There is one subtlety here: in order to accelerate a particle, it must be charged. We have already seen that atoms prefer to be neutral. What is usually done is that the atom is ‘ionized’, which means that it is made into an ion. This is accomplished by removing an electron, which means that the atoms that move into the mass spectrometer have a positive charge of 1.60 x 10-19 C. ‘Singly ionized’ means that one electron has been removed, leaving the atom with a charge of 1.60 x10-19 C; a doubly ionized atom has a charge of 2 x 1.60 x 10-19 C.

**EXAMPLE 18.2:** A singly ionized particle is accelerated through 20 kV and enters a magnetic field of 2.5 T in a direction perpendicular to the field. If the radius through which the particles are bent is 0.03644 m, what is the likely identity of the charged particle?

We can use Equation (17.6.1)

\[ Mv = qBR \]

We know that the charge on the singly ionized atom must be \( q = 1.60 \times 10^{-19} \) C. The field is known and the radius is known; however, we don’t know the velocity.

To find the velocity, we need to return to what we learned in the chapter on electric fields. Recall that 20 kV is an electric potential. The kinetic energy of a charge of 1.60 x 10-19 accelerated through a potential of 20 kV is 20 keV. We can convert this to Joules:

\[ KE = 20 \times 10^3 \text{eV} \times \frac{1.60 \times 10^{-19} J}{1 \text{eV}} \]

\[ 3.2 \times 10^{-15} J \]

We also know

\[ KE = \frac{1}{2} Mv^2 \]

Solve this for \( v \)

\[ v = \sqrt{\frac{2(KE)}{M}} \]

and put in Equation (17.6.1)

\[ M \sqrt{\frac{2(KE)}{M}} = qBR \]

We need to get rid of the square root, so let’s square both sides
Finally, we can plug into this

\[
M = \frac{q^2 B^2 R^2}{2(KE)}
\]

\[
M = \frac{(1.60 \times 10^{-19} \text{C})^2 (2.5 \text{T})^2 (0.03644 \text{m})^2}{2(3.2 \times 10^{-15} \text{J})}
\]

\[
M = 3.32 \times 10^{-26} \frac{C^2 T^2 m^2}{J}
\]

Check out those units

\[
M = 3.32 \times 10^{-26} \frac{C^2 m^2}{Nm} \left( \frac{Ns}{Cm} \right)^2
\]

\[
M = 3.32 \times 10^{-26} \frac{N^2 s^2}{Nm}
\]

\[
M = 3.32 \times 10^{-26} \frac{Ns^2}{m}
\]

\[
M = 3.32 \times 10^{-26} s^2 \left( \frac{kgm}{s^2} \right)
\]

\[
M = 3.24 \times 10^{-26} \text{kg}
\]

Remember that there 1u = 1.66 x 10-27 kg

\[
M = 3.32 \times 10^{-26} \text{kg} \left( \frac{1u}{1.66 \times 10^{-27} \text{kg}} \right)
\]

\[
= 20.0u
\]

Looking at Table 3.3, we see that the element with the closest mass is Neon.

Although the actual detection mechanism is more complicated, you can think of it as having a movable slit that only allows through atoms of one mass at a time. If you count the number of atoms that get passed at each position of the slit, you can make a histogram that looks like the following:
The bottom axis is labeled in atomic mass units (u) and the vertical axis is labeled in proportion to the number of charged particles with that mass.

Note that not only atoms, but also molecules can be analyzed in this way. For example, the large peak at 18 u is due to water (H2O has an atomic mass of 2+16 = 18 u). The peak at 28 u is Nitrogen.