

# Charge to Mass Ratio of The Electron

## Physics Topics

If necessary, review the following topics and relevant textbook sections from Serway / Jewett “Physics for Scientists and Engineers”, 10th Ed.

- Electric Potential (Serway, Sec. 25.1)
- Accelerating a particle in a uniform electric field (Serway, Sec. 25.2)
- Magnetic Force (Serway, Sec. 29.1)
- Motion of a charged particle in a uniform magnetic field (Serway, Sec. 29.2)

## Introduction

The electron was first discovered by Sir J.J. Thomson in 1897 at the Cavendish Laboratory in Cambridge, England. His experimental apparatus is not very different from the one which you will use in this lab, and he was later awarded the Nobel Prize for his discovery. You will be doing some Nobel Prize winning work in this lab!

A charged particle traveling in a uniform magnetic field which is perpendicular to its velocity will travel in a circular path. The circular motion of a charged particle moving in a magnetic field depends on both the charge ( $q$ ) of the particle and the mass ( $m$ ) of the particle. However, it is interesting to note that it does not depend on each of these separately, but rather on their ratio  $q/m$ . Thus, we can measure the ratio of  $q/m$  by examining the particle's motion. Because  $q/m$  measured by Thomson was different than  $q/m$  for any other atoms known at the time, he was able to claim the discovery of a new particle.

## Pre-Lab Questions

Please complete the following questions prior to coming to lab. They will help you prepare for both the lab and the pre-lab quiz (Found on D2L).

- 1.) Read through the entire lab writeup before beginning
- 2.) What is the **specific** goal of this lab? Exactly what question(s) are you trying to answer? Be as specific as possible. (“To learn about topic X...” is **not** specific!)
- 3.) What **specific** measurements or observations will you make in order to answer this question?

- 4.) In this experiment, electrons are “boiled” off of a hot piece of metal (filament). They are then accelerated up to speed using a potential difference  $\Delta V$ . *After* they are accelerated, they enter a region of uniform *magnetic* field which is perpendicular to their velocity. Make a diagram of this entire process. Make sure you have drawn the magnetic field direction pointing into or out of your page, while the electrons travel in the plane of the page. Your diagram should show the electrons right as they come off of the metal, after they have been accelerated, and their trajectory as they travel in the magnetic field.
- 5.) Which force:
  - (a) Is responsible for accelerating the electrons from rest?
  - (b) Is responsible for bending the electrons into a circular path?
- 6.) Focus on the initial stage of accelerating the electrons. Can you relate the final speed of the electrons to the accelerating voltage  $\Delta V$ ? The following questions help you derive this relation using conservation of energy  $\Delta K + \Delta U = 0$ .
  - (a) How is the change in the electron’s potential energy  $\Delta U$  related to the accelerating voltage  $\Delta V$ ? [Note: remember the charge of the electron is  $-e$  with  $e$  being a positive number!]
  - (b) Assume the electron starts from rest, using the details above, derive a formula for the final speed of the electron  $v$  in terms of its mass,  $m$ , charge  $e$  and accelerating voltage  $\Delta V$ . Save this formula for later.
- 7.) Now focus on the motion of the electron in the magnetic field. Because we know a charged particle in a magnetic field  $\vec{B}$  perpendicular to its motion travels in a circular path, what can you say about its acceleration?
- 8.) Write an expression for the **magnitude** of the magnetic force acting on the electron.
- 9.) Use Newton’s Second law and your results from the previous part to relate the radius of the electron’s circular path to its mass  $m$ , charge  $e$ , speed  $v$  and magnetic field  $B$ .
- 10.) Quantities which are directly measurable in this lab are the accelerating voltage  $\Delta V$ , radius of the electron’s path  $r$ , and the magnetic field  $B$ . Combine your results from steps 6 and 9 to write a formula which relates the radius of the electron’s path  $r$  to other measurable quantities, and the ratio  $e/m$ . You should be able to write this equation in the form
 
$$r = \frac{C}{|\vec{B}|} \quad (1)$$
 where  $C$  is a constant. Determine an expression for the constant  $C$  in terms of measurable quantities and the charge to mass ratio  $e/m$ .
- 11.) In this lab you can vary  $B$  and measure  $r$ . Explain how you could plot your data in such a way that you could determine  $e/m$  from the slope of a graph.

## Apparatus

**Note:** There are several different versions of the apparatus for this lab. When performing the experiment, make sure you are following the directions appropriate for your particular apparatus.

An example of the experimental setup is shown in Fig 1. You can see more detailed diagrams for other versions of this apparatus in the Appendix.

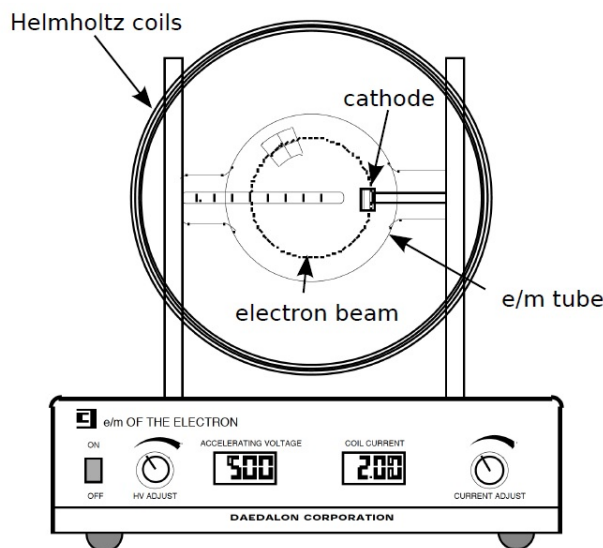


Figure 1: Typical e/m Apparatus (from Daedalon EP-20 Manual)

- e/m Tube (may or may not include inputs for heater, and accelerating voltage).
- Set of Helmholtz coils
- High voltage power supply (for accelerating voltage) - may or may not be integrated into e/m apparatus.
- Low voltage variable power supply (for Helmholtz coils) - may or may not be integrated into e/m apparatus.
- Banana cables
- Bar Magnet
- Wooden cover (to block out light)

## Procedure

**CAUTION:** This lab uses high voltages to accelerate the electrons, and can be hazardous! Do not touch any wiring or exposed metallic connections while the device is on. Be sure to turn off your equipment if you need to change connections, and also when you are finished taking data.

- 1.) Orient the Helmholtz coils so that their faces are parallel to the direction of the Earth's magnetic field (about  $15^\circ$  east of geographic north). This will minimize the effect of the Earth's magnetic field.

- 2.) With all power supplies OFF, take a moment to get familiar with your particular setup. Note the position of two knobs: one which allows you to adjust the current through the Helmholtz coils, and another which allows you to adjust the accelerating voltage. Turn both of knobs to their lowest (most counter-clockwise) setting, if possible.
- 3.) If your setup is NOT the Daedalon apparatus shown in Fig. 1 refer to the Appendix for additional equipment setup instructions. Once you are confident that your equipment is setup correctly and you understand how to operate it, proceed with the next step.
- 4.) Turn on all power supplies. Note the following inside the bulb: the silver “top hat” with a hole in it is the accelerating anode. The filament from which the electrons are boiled is just above this. If power is flowing to your filament, you should see it start to glow red after about 30 seconds.
- 5.) Slowly increase the accelerating voltage until it reaches a voltage  $\Delta V_1$  (see the table below) OR until you see a clear strong blue-green beam emanating from the anode\*. If you do not see the beam, after increasing the accelerating voltage to  $\Delta V_1$ , tell your lab instructor.

	Other Apparatus	Daedalon Apparatus
$\Delta V_1$	200 V	250V
$\Delta V_2$	400 V	400V

Table 1: Voltage Specifications for Different Apparatuses

- 6.) [Report] Bring a magnet close to the electron beam. Does the beam show a deflection as a result of the bar magnet? Does it move in the way you expected it to? Record your observations.
- 7.) Slowly increase the current in the Helmholtz coils. You should see the electron beam start to bend into a circular path inside the tube. If you do not see this, tell your lab instructor.

**Troubleshooting Notes:**

- (a) If the electron beam does not appear to completing a full circle, but instead a short “clover leaf” type orbit back to the filament, increase the accelerating voltage by 50V.

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\*The reason the beam glows blue-green is there is some helium gas inside the tube. The accelerated electrons are able to ionize the helium molecules by knocking other electrons out of their orbits. When these electrons recombine with their original atoms, they emit the light which you see.

- (b) If the electron beam bends in the opposite direction than you want, you need to reverse the direction of the magnetic field. To change this, turn all knobs on the power supply to their lowest settings and turn off all power supplies. Then, switch the leads going into the Helmholtz coils. Turn everything back on and then repeat the steps above.
- 8.) With the accelerating voltage set at  $\Delta V_1$  (see table above), change the radius of curvature of the electron beam by adjusting the Helmholtz coil current. Find the current required to make the electron path hold the smallest diameter your apparatus will allow. Note this diameter and it's associated current.
- 9.) Repeat the above step by finding the current necessary to produce circles with increasing diameters, recording the diameters and currents of each. You should attempt to collect measurements for at least 10 unique diameters.
- 10.) Turn down the knobs on the power supplies to their minimum settings, and turn off all power supplies.

## Analysis

- 1.) You may have noticed that you did not actually directly measure the magnetic field between the coils. In fact, the B-field between the coils is approximately uniform and given by the expression

$$|\vec{B}| = \frac{8\mu_0 NI}{a\sqrt{125}} \quad (2)$$

where  $I$  is the current flowing in the coils,  $\mu_0$  is the permeability of free space  $= 4\pi \times 10^{-7} \frac{\text{T}\cdot\text{m}}{\text{A}}$ ,  $a$  is the (average) radius of each coil, and  $N$  is the number of turns in each coil (our coils have 130 turns). Using this formula, calculate the magnetic field (in SI units of Tesla) for each of your measurements.

- 2.) Using your answer to the pre-lab questions, use MS Excel (or any program you choose) to plot your data in such a way that it is a straight line. Use the slope of your line to determine  $e/m$ . Compare to the accepted value and calculate a % error.

### 3.) Uncertainty Analysis

- (a) Both your recorded values of  $I$  and  $a$  should have some uncertainty associated with them  $\delta I$  and  $\delta a$ . Given these uncertainties, how would you calculate an uncertainty in the magnetic field  $|\vec{B}|$ ? You may need to review your notes, and/or the document *Introduction to Measurement Uncertainty* posted on D2L.
- (b) Create two new columns in your data for the uncertainty in the quantities which you are plotting. For example, if I was plotting a graph of  $y^4$  vs  $1/x^2$ , I would need a column for  $\delta(y^4)$  (the uncertainty in  $y^4$ ) and  $\delta(1/x^2)$  (the uncertainty in  $1/x^2$ ). Calculate the values of these uncertainties.

- (c) Use Excel (or any program you choose) to add error bars to your plot. If necessary, you can add error bars of varying sizes to each point. You can do this by following these steps:
- Select your chart
  - From the menu, click “Chart Tools” and then “Add Chart Element” (on the left side of the menu bar), and then select “Error Bars → More Error Bars Options”
  - In the dialog on the right side, click the “Custom” button and then click “Specify Value”. Another dialog box will allow you to select the columns which you have created containing the appropriate error bar sizes.

## Wrap Up - Complete in Lab

The following questions are designed to make sure that you understand the physics implications of the experiment and also to extend your knowledge of the concepts covered. Your report should seamlessly answer these questions in their noted sections.

- 1.) [Discussion] What is the direction of the magnetic field in your experiment? Explain your reasoning using Figure 1, assuming the electron is traveling in a counter clockwise circle in the plane of the page.
- 2.) [Theory] Suppose  $\Delta V$  is kept fixed so that the speed of the electrons is constant. Which electron has a larger acceleration: one traveling in a tight circle (small  $r$ ), or one traveling in a big circle (larger  $r$ )? Explain your reasoning. Which electron has a larger force acting on it: one traveling in a tight circle (small  $r$ ), or one traveling in a big circle (larger  $r$ )? Explain your reasoning. Is this consistent with the results you observed in the experiment? Explain.
- 3.) [Results] Imagine you are J.J. Thomson performing this experiment for the first time. The only known particle at the time (the proton) has mass  $1.67 \times 10^{27}$  kg and charge  $q_p = 1.602 \times 10^{-19} C$ . **Based only on your observations**, could the beam of particles you observe be protons, or could you claim the discovery of another particle? Explain your reasoning.
- 4.) [Theory] Suppose you had your accelerating voltage at  $\Delta V_1$  and the Helmholtz coil current was set so that the diameter of the electron path is 6.0cm. If you changed the accelerating voltage to  $\Delta V_2$  (see Table 1), what would you predict would be the new path diameter? Make a concrete prediction including uncertainty.
- 5.) [Discussion] When you are ready with your prediction, use the apparatus to test it. Turn back on the apparatus with the accelerating voltage at  $\Delta V_1$  (see Table 1) and a path diameter of 6.0 cm. Then, keeping the magnetic field fixed, increase the accelerating voltage to  $\Delta V_2$  (see Table 1) and measure the new path diameter. Record your result with uncertainty and compare with your prediction.

Finally, turn all knobs back to their lowest setting, and turn off all power supplies. Thank you for helping us extend the life of the equipment!

## Report

Here is a brief guide for writing the report for the lab. The report should include the following sections:

- **Title Page**

- Include: Report Title, Your Name, Course, Section Number, Instructor, TA Name, and Date of Submission.

- **Introduction**

- What is the experiment's objective?

- **Theory**

- Derivations of the physics being investigated, or reference to a source that provides a description/equation representing the physics being investigated.
- Providing graphs that illustrate or predict how the system under study is expected to behave.

- **Procedure**

- Briefly explain the systematic steps taken for the experiment.

- **Results and Calculation**

- Tabulate the measurements in an organized manner.
- Based on the procedure, one should have a sense of how the tables will look like prior to taking measurements.
- Graph the main results.
- Provide examples of any calculations.

- **Discussion and Conclusion**

- Discuss the main observations and outcomes of the experiment.
- Summarize any significant conclusions.

- **References**

- Very important to include to avoid plagiarism claims.

- **Appendices**

- If large quantities of data are obtained, or lengthy details are needed, but break the overall flow of the report, they should be referenced and placed in the appendix.

## Appendix - Equipment Details and Setup Instructions

This appendix has some additional details about the alternate experimental apparatus.

### Apparatus with External Power Supplies

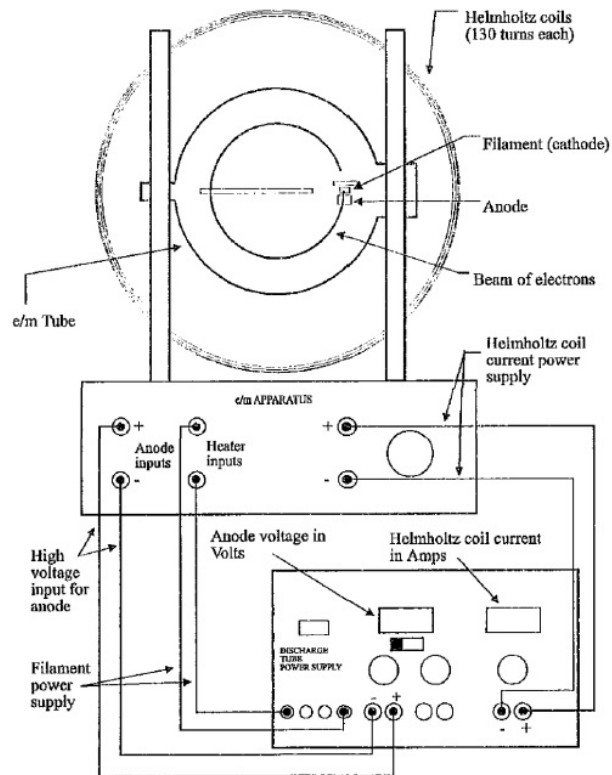


Figure 2: e/m Apparatus with no brand name

### Equipment Notes

- At the base of the e/m apparatus are inputs for the high voltage anode, heater filament voltage, and the Helmholtz coil current.
- Either a discharge tube power supply or a high and a low voltage power supply will be used to power the e/m apparatus.



### Setup Instructions

- 1.) Make sure that the power supplies are OFF.
- 2.) Follow the labels on the power supplies and  $e/m$  apparatus
- 3.) Locate the “filament/heater supply” outputs. Apply 6 volts from the output of the power supply to the heater inputs.
- 4.) Now find the High Voltage (0-500V DC) outputs on the power supply and connect these to the anode inputs on the  $e/m$  apparatus base.
- 5.) On the power supply locate the output for the Helmholtz coil current (0-20V DC) in the bottom right. Connect these outputs to the Helmholtz coil inputs on the  $e/m$  apparatus base.
- 6.) Double check your connections with the Fig 2. Make sure all voltage and current adjustment knobs on the power supply are set to their lowest (counter clockwise) setting and that the coil current adjustment knob on the base of the  $e/m$  apparatus is turned to its highest (clockwise) setting.