EXPERIMENT Q-1
Electron Charge-to-Mass Ratio

Abstract

The ratio \( \frac{e}{m} \) for electrons is determined by measuring the radius of curvature of the path followed by electrons of known velocity as they move in a known magnetic field.

References

Reese, University Physics, Brooks/Cole, 2000: Sections 17.7, 20.1 and 20.2 (pages 900 - 901)
Huggins, Physics2000, Moose Mountain, 1999: Pages 26-8 to 26-10 and 28-14 to 28-21

Pre-Lab

Please do this section before coming to lab. In this experiment, an electron gun accelerates electrons to a certain speed, \( v \), before they enter a region of magnetic field. The electron gun consists of two parallel metal plates, cathode and anode, connected to a power supply such that the anode voltage is \( V \) volts more positive than the cathode voltage. A filament heats the cathode, causing electrons to be ejected by thermionic emission. The ejected electrons have negligible speed to begin, but accelerate toward the positive anode, picking up kinetic energy along the way. When they reach the anode their kinetic energy is equal to the amount of electrical potential energy that was lost, i.e. \( KE = |eV| \). In this equation, \( e \) is the electron charge, and the absolute value signs are used to guarantee that \( KE \) comes out positive. Using the "regular" expression for \( KE \), solve this equation for the speed of the electrons when they reach the anode. There is a small hole in the anode, so some of the arriving electrons pass on through, thereby emerging from the electron gun with the speed \( v \) you just found.

The electrons then enter magnetic field \( B \), which exerts the "Lorentz force", \( \vec{F} = e(\vec{v} \times \vec{B}) \), in a direction perpendicular to the velocity and to the field. The acceleration is therefore perpendicular to the velocity, so that the speed stays constant and only the direction of motion changes with time. In other words, the electrons move in a circular path at constant speed, and their acceleration is \( \frac{v^2}{R} \), where \( R \) is the radius of the circle. Write Newton's second law for the radial direction, and eliminate \( v \) by plugging in the speed you found above. Finally, solve the resulting equation for \( \frac{e}{m} \), the "charge to mass ratio" for the electron. Using this equation, you can find \( \frac{e}{m} \) from the measured \( R \), the accelerating voltage \( V \), and the magnetic field \( B \).

To make sure you are prepared for lab, read the Procedure section below and feel free to ask questions!

Apparatus

Leybold fine-beam e/m tube
Helmholz coils
Illuminated scale with reflecting glass plate
5 Banana to Banana wires
2 DC outlet plugs (one spade, one banana)

DC Ammeter (0-3Amps)
Rheostat (20 Ohms)
Pasco SF-9585A DC Power supply
1 Banana to Spade wire
Procedure

Examine the apparatus. The Leybold fine-beam tube contains a cone shaped metal anode with a small hole in its apex. This is the hole through which electrons will be ejected. Hidden within the conical anode is a cathode and heater filament. Surrounding the tube are two coils of wire arranged in the "Helmholz configuration". In this arrangement, the separation between coils is equal to the radius of each coil. According to the manufacturer, each of the coils has exactly 130 turns of wire.

WARNING: The output voltage provided by the power supply can be LETHAL! Don't touch any terminals or wires connected to the supply unless it is unplugged from the AC wall outlet.

For safety reasons, the high-voltage connections between the power supply and the e/m apparatus have been pre-wired. Examine them carefully, to make sure they are wired as described below. Refer to the Commonly Used Lab Equipment link on the Physics 108 web page for a description of any components that are unfamiliar. The high-voltage output terminals are on the e/m apparatus are labeled with a ‘+’ and a ‘-‘. These positive and negative terminals should be connected to the terminals on the power supply that are labeled 0 and 500V with banana-to-banana wires. The light on the upper part of the power supply should read 500-Volts. If this is not the case, press the gray button below the indicator until the 500-Volt light is lit.

Study the controls on the high voltage power supply. Make sure the supply is unplugged and the power switch is off. Find the terminals that provide 6 volts AC on the right side of the power supply. Use two banana-to-banana wires to connect them (in any order) to the heater inputs on the e/m apparatus (labeled 6.3V). Check to make sure the dial on the power supply is set on 6 and leave it there. Leave the high voltage supply unplugged and turned off for now.

Figure 1: Helmholz Coil Setup

The circuit above shows the electrical assembly by wiring the Helmholz-coil circuit shown in Figure 1. For this circuit it is necessary to connect the rheostat, ammeter, coils (the terminals for the coils are located on the e/m apparatus either labeled or denoted in a schematic), and DC power in a series. This is a low voltage circuit, so you can touch its various parts without fear. The required 6 Volts comes from the DC terminals on the wall, not the high voltage power supply. Leave one input to the wall power unplugged. Refer to the Commonly Used Lab Equipment link on the Physics 108 web page if necessary to be sure you
understand which pair of terminals on the rheostat should be used to allow the circuit resistance to be varied. Make certain the "+" terminal on the ammeter is connected to the "+" power terminal. The order of connections for the coils is also important, but connect them either way for the moment - you can reverse them later if the electron beam curves in the wrong direction. Before turning anything on, ask a lab instructor to look over all your wiring.

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Figure 2: Use of Illuminated Scale

Observe the illuminated scale with its attached reflecting glass plate. When plugged into the AC outlet, the scale lights up, and if the room lights are off you will be able to see a reflected image of the scale by looking into the glass with the scale itself facing away from you, as shown in Figure 2. Note that the distance of this image behind the glass is equal to the distance between the scale and the glass, and that the magnification of this optical system is exactly 1.

Measure the diameter of each coil and the separation between coils. Keep in mind the relationship between the two when calculating uncertainty. Turn on the power supply and let the filament in the fine-beam tube warm up for a few moments. Then, with the room lights off, turn the anode voltage up to about 150 volts or until the electron beam is seen emerging from the hole in the "electron gun". Plug in the Helmholtz coil circuit and adjust the rheostat until the beam trajectory is a full circle. If the beam curves in the wrong direction, reverse the connections at the coil inputs on the e/m apparatus. Observe the effect of grasping the fine-beam tube and rotating it about the horizontal axis through its mounts. Turn the tube only, not the mounts or Helmholtz coils. QUESTION 1: What do you observe and why does this occur? Rotate the tube until the trajectory is circular.

To measure the diameter of the circle, hold the illuminated scale and reflecting glass plate so the virtual image of the scale is positioned exactly in the plane of the electron path. Remember the distance between the glass plate and the virtual image of the scale: if you position the scale image in the plane of the electron orbit, you can measure the orbit diameter just as if there were a real scale inside the fine-beam tube. A computer will be set up with an Excel template for you to quickly calculate a value for $e/m$ using your data. If your result for $e/m$ is not within 15% of the accepted value, find the source of the discrepancy. Once you are getting a result that is within 15% of the accepted value, measure the diameters of orbits for between 20 and 30 different combinations of anode voltage and coil current, recording in tabular form the values of the three measured quantities. As always, be sure to take the necessary measurements to calculate and justify uncertainty.

Sample Calculations

Using known equations, solve for $e/m$ in terms of $V$, $B$ and $R$. Find a value for $e/m$ using your first row of data and the formula for $B$ given in the Analysis section below.

Dismantle the apparatus, unplug any equipment, and return the lab to its original state.
Analysis

The magnetic field $B$ is related to the Helmholz coil current, $I$, as follows:

$$B = \frac{8 \mu_0 NI}{\sqrt{125} a}$$

where $\mu_0 = 4\pi \times 10^{-7}$ T m/A is the permeability of space, $N$ is the number of turns in each coil, and $a$ is the radius of each coil.

Following the examples for data and uncertainty analysis using Excel from previous labs (found at the Laboratory Handouts link on the Physics 108 web page), set up an Excel worksheet that uses your pre-lab work and the above expression for $B$ to calculate the best $e/m$ for each of your data sets of $V$, $I$, and $R$. Use short column headings, so you can make the columns narrow and fit everything on one page. Find the average of the $e/m$ results, and perform a standard deviation analysis to determine the uncertainty in this average. Also, do a partial uncertainty analysis using one row of data. State the final results. Compare the sum of the partials to the standard deviation in the average, and comment on the comparison. Check to see if a previously published $e/m$ value is in agreement with your result.

Questions

2. Do a complete unit analysis to substantiate the units you chose for $B$ and $e/m$ (see the Metric Units/Prefixes link on the Physics 108 web page).

3. For one trial of your measured $I$ and $R$ values, along with the calculated $e/m$, determine the best speed of the electrons in the beam.

4. How does the velocity obtained in question 3 compare to the speed of light? Should relativistic effects be accounted for in this lab?

5. Why are the electrons "visible" in the apparatus? (Hint: it is not a vacuum inside the tube)

Write a conclusion that summarizes and interprets your results. Suggest ways you could improve the results if you were to repeat the experiment, mention problems you had in lab, etc...