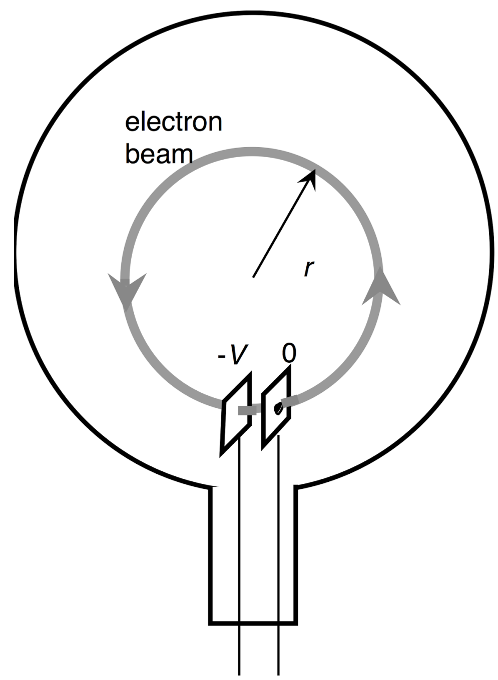
Lab 6: Charge-to-mass ratio of an Electron

In this lab, you'll perform one of the most important experiments of 19th-century physics, by measuring the ratio of an electron's charge to its mass (e/m_e). This experiment was first performed by J. J. Thomson in 1897. At the time, it was not clear that negative charge was carried by a massy particle – that is, m_e could well have been zero, so e/m_e might have been infinite. Thus, this was one of the first quantitative experiments in particle physics.

Now, it would be nice to measure the mass of an electron on its own, but this was impossible in 1897. Instead, the ratio e/m_e was established first using Thomson's experiment; R. A. Millikan's famous 1910 oil drop experiment (which you performed in Lab 2) found the electron charge on its own, which allowed m_e to be calculated.



The basic approach is as follows: Electrons are released from a hot metal surface – the "cathode". The cathode is given a strong negative voltage, so the negatively-charged electrons are repelled, accelerating toward a second plate held at zero voltage (the "anode"). They pass through a hole in the anode, and fly out into the vacuum chamber with a known velocity. This combination of heated cathode and anode with a hole is called an "electron gun".[1] The chamber is not completely empty of gas: the electrons excite the gas atoms in the chamber, forming a glowing beam of light. Outside the vacuum chamber, a pair of coils creates a constant magnetic field in the chamber. The magnetic force on the electrons causes them to move in a circular path: the radius of the path depends on the e/m_e ratio.

Equipment

• e/m apparatus (big clear glass globe with two coils of wire around it)
• Constant Current Power Supply (one variable current output, one 6.3V output)
• Constant Voltage Power Supply (200V, 6.3V outputs)
• Digital multimeter
• Lots of "banana plug" wires

[1] Old-fashioned tube TVs used electron guns as well. Thomson called the beam of electrons a "cathode ray", hence the name "cathode ray tube", or CRT for an old television set or computer monitor. Modern flat-screen TVs use a totally different technology.

Theory

Speed of the electron

In the Analysis section of your writeup, you'll solve the following problem. If an electron moves from a location (the cathode) with an electric potential -*V* to a location (the anode) where the electric potential is zero, how much kinetic energy does it gain? What is its final velocity *u*? You should find

$$u = \sqrt{2\,e\,V/m_e} \qquad (1)$$

Note that this expression only involves the *ratio* e/m_e.

Magnetic field

In a "Helmholz coil" arrangement, two circular current-carrying coils are placed on a common axis, separated by a distance equal to their radius *R*. This turns out to create a very uniform magnetic field between them. You will show in your analysis that if the coils each have *N* turns and carry a current *I*, the magnetic field at the exact center between them is

$$B = \frac{8}{5\sqrt{5}} \frac{\mu_0 I N}{R} \qquad (2)$$

To show this, it helps to make use of the equation for the magnetic field along the axis of a single circular loop, which is derived in the textbook and was used in Lab 5.

One common source of error is in measuring the radius *R*. There are several layers of turns in the coil; their average radius is *R* = .158 m.

Radius of circular motion

Finally, one can use the magnetic force law and Newton's second law to show that an electron moving at speed *u* perpendicular to *B* will travel in a circular path of radius *r*. In your analysis, you will show that the radius of this circular path is related to the charge-to-mass ratio of the electron as follows:

$$e/m_e = \frac{2\,V}{B^2 r^2} \qquad (3)$$

where *B* is the magnetic field strength, *V* is the voltage of the electron gun's cathode, and *r* is the radius of the circular path.

Assembling the equipment

- First, turn off both power supplies.
- Connect the red and black terminals of the current power supply to the "Helmholz Coil" terminals. You will need to connect both coils in series, making sure the current goes through each coil in the same direction. This circuit will send current through the coil, creating our magnetic field. If you're not sure you did it right, you should have needed three wires.
- Connect the AC 6.3 V output to the "Filament" inputs on the e/m apparatus. This will provide power to a heater which is needed to cause electrons to leave the negative terminal of the electron gun.

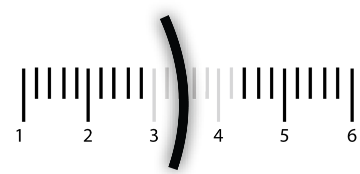
- Connect the high-voltage outputs (100-200V) to the “Accelerating Voltage” inputs on the e/m apparatus. Connect plus to plus, minus to minus!

Power On

- Turn the voltage and current knobs on both power supplies to minimum. The current control knob requires several turns.
- Turn on the current power supply. You should see an orange glow inside the electron gun as the cathode heats up.
- Turn on the high-voltage power supply, and turn it up until it reads 200V.
- <u>Dim the room lights</u>. You should see a pale green beam shooting straight out of the electron gun to the right, and hitting the glass wall of the vacuum chamber. If you don’t see it, check your high-voltage wiring.
- Turn on the low-voltage power supply, and turn gradually turn it up until 1.5 amps are flowing through the Helmholz coils. You should see the pale green beam start to curve, and then go around in a circle due to the magnetic force on the electrons.

Making Measurements

- You should see the electron beam begin to curve and travel in a circle.
- If the beam is traveling in a spiral instead of a circle, gently rotate the glass vacuum chamber about a vertical axis to align it. (If it’s making a perfect circle already, try rotating the globe anyway, the spiral is pretty cool looking.)
- Measure the radius of the circular beam. Use the mirrored centimeter scale behind the globe to measure the diameter, then divide by 2. (Don’t assume the center of the circle is at x=0 on the scale!) Parallax can be a problem. There are several techniques you can use to make sure your eye is aligned with the beam:
  - You may see a reflection of the beam in the mirrored ruler. Line the beam up with its reflection.
  - You may see a reflection of your eye in the mirrored ruler. Line the beam up with the image of your eye.



- Perform lots more measurements, choosing various values of cathode voltage V between 100 and 300 volts, coil current I between 1 and 3 amps. Note that if V or I are varied too much, the beam will strike the side of the electron gun or the glass wall of the vacuum chamber before completing a circle.

Goofing Off

- There should be a neodymium super-magnet on the whiteboard near the apparatus. Wave it around near the electron beam, and see how it responds. Can you steer the beam by hand?

Analysis

1. Derive Equation 1.

2. Derive Equation 2.

3. Derive Equation 3.

4. Calculate the value of e/m_e for each of your experiments, and report the average value, along with the 95% confidence interval. Look up the accepted value for this ratio: is your answer equal to the accepted value, given your margin of error? (If not, you should either figure out where you went wrong, or start writing your Nobel Prize speech.)

5. In Lab 2, you calculated *e*, the charge on an electron using the Millikan oil drop experiment. Use the values calculated in these two labs to calculate m_e, the mass of a single electron. Using the "propagation of uncertainty rule" from Lab 1 (see http://goo.gl/T0wjMB if you've lost the handout), estimate the 95% confidence interval of m_e.

6. Which of your experiments, the Millikan oil drop or the Thomson e/m experiment, has the higher relative uncertainty? If you wanted to get a more accurate measurement of m_e, which would you revisit?

I just want to point out what you've done here. You've measured the mass of one of the most fundamental and tiny objects in the universe, without billion-dollar particle accelerators: just some power supplies, an oil sprayer, a microscope, and a vacuum chamber. You're 100 years too late for a Nobel Prize, but give yourself a pat on the back anyway!

7. Note that our calculations don't take special relativity into account. Are the electrons moving fast enough that we should be worried about that?