Physics 2121
Lab Physics for Science & Engineering II
Experiment Name: Electron Charge-to-Mass Ratio

THEORY

Purpose

Students will manipulate an electron beam using Helmholtz coils to measure the electron charge-to-mass ratio e/m.

Electron Charge-to-Mass Ratio

The electron *charge-to-mass ratio* e/m (also known as the specific charge of the electron) is an important quantity in physics. The first significant measurement of the electron charge-to-mass ratio led to the discovery of the electron as a fundamental subatomic particle. Precise measurement of the electron charge-to-mass ratio has led to advances in microscopy, cathode rays, and cosmology.

In this experiment, a beam of electrons will move along a circular path in a uniform magnetic field inside a glass tube filled with helium gas. The electrons are accelerated by an applied voltage V, and the magnetic field $\vec{B}$ bends the resulting beam into its circular path via the Lorentz force.

As the electron beam interacts with the helium gas, the gas becomes ionized through collisions with the accelerated electrons. The ionized helium atoms become excited and emit visible light (a pale blue color) which lets us indirectly view the circular path of the electron beam.

It may be somewhat surprising that we can calculate the e/m ratio with knowledge of a few measurable parameters for the physical system: (i) the strength of the magnetic field $\vec{B}$, (ii) the accelerating voltage V, (iii) the radius r of the electron beam's circular path.

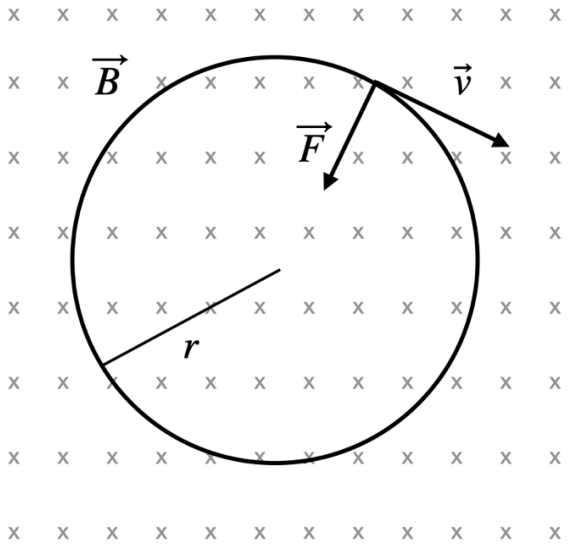


Figure 1: Diagram of circular electron beam in a uniform magnetic field

When a beam of electrons travels through a magnetic field, the force on the electron beam is given by the Lorentz force

$$\vec{F} = q\vec{v} \times \vec{B} \tag{1}$$

where q is the electric charge. Using conservation of energy, we find that the accelerating voltage V is related to the velocity $\vec{v}$ of the electron beam by

$$\frac{1}{2}mv^2 = eV. \tag{2}$$

With relations (1) and (2), we can use Newton's Second Law for a centripetal force $\vec{F}$ to show that the electron charge-to-mass ratio is

$$\frac{e}{m} = \frac{2V}{B^2 r^2}. \tag{3}$$

PROCEDURE

Safety Warning

This experiment will use high voltages so equipment must be handled with care. Avoid all contact with the glass e/m tube during the operation of the experiment.

Experimental Equipment

We provide a brief overview of the experimental apparatus to ensure safe use of the equipment. The e/m equipment will be assembled at your station, so you do not need adjust any wired connections to the power supplies.

The primary pieces of equipment are: (i) the e/m tube filled with helium gas, (ii) the Helmholtz coils that produce a uniform magnetic field throughout the e/m tube, (iii) the constant voltage power supply, and (iv) the constant current power supply.

The e/m tube contains a filament that is heated to release free electrons. The constant voltage power supply provides an accelerating potential V that collimates the electrons into a beam. The constant current power supply provides a current I to the Helmholtz coils to generate a uniform magnetic field $\vec{B}$.

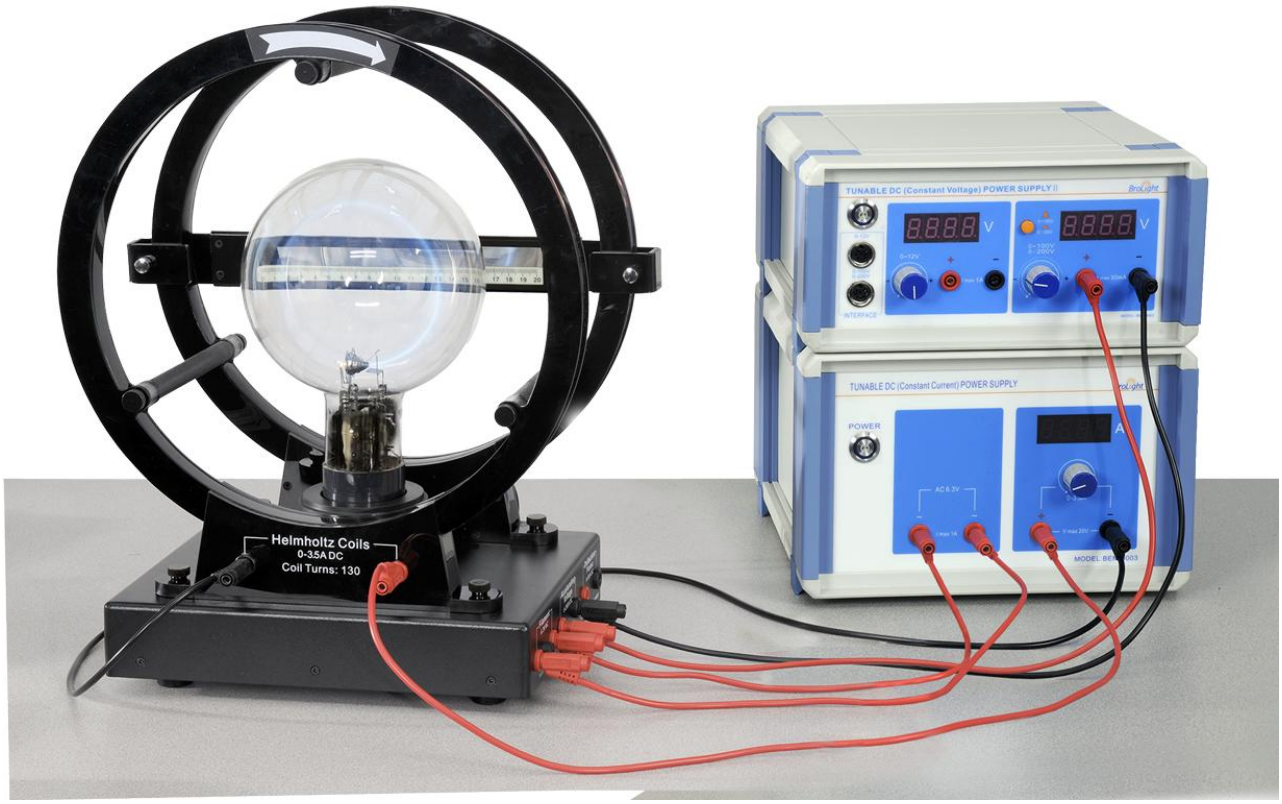


Figure 2: Experimental apparatus (Pictured: e/m tube, Helmholtz coils, voltage power supply, current power supply)

Power Supply Settings

(1) Before turning on either of the power supplies, ensure that all the voltage/current dials are turned fully counterclockwise. This will start the system at zero voltage and current.

(2) For both power supplies, push in the power switch to the ON position.

(3) Wait 5 minutes to allow the filament to heat up before proceeding.

(4) On the Tunable DC (Constant Voltage) Power Supply II, turn the Accelerating Voltage to 190V. You should be able to see the electron beam in the e/m tube.

(5) On the Tunable DC (Constant Current) Power Supply, increase the current to the Helmholtz coils. You should notice that the electron beam starts to bend upward. Continue to increase the current until the electron beam forms a closed circle.

Ask for TA approval before proceeding further.
If you notice that the electron beam deflects downward with increasing current, notify your TA.

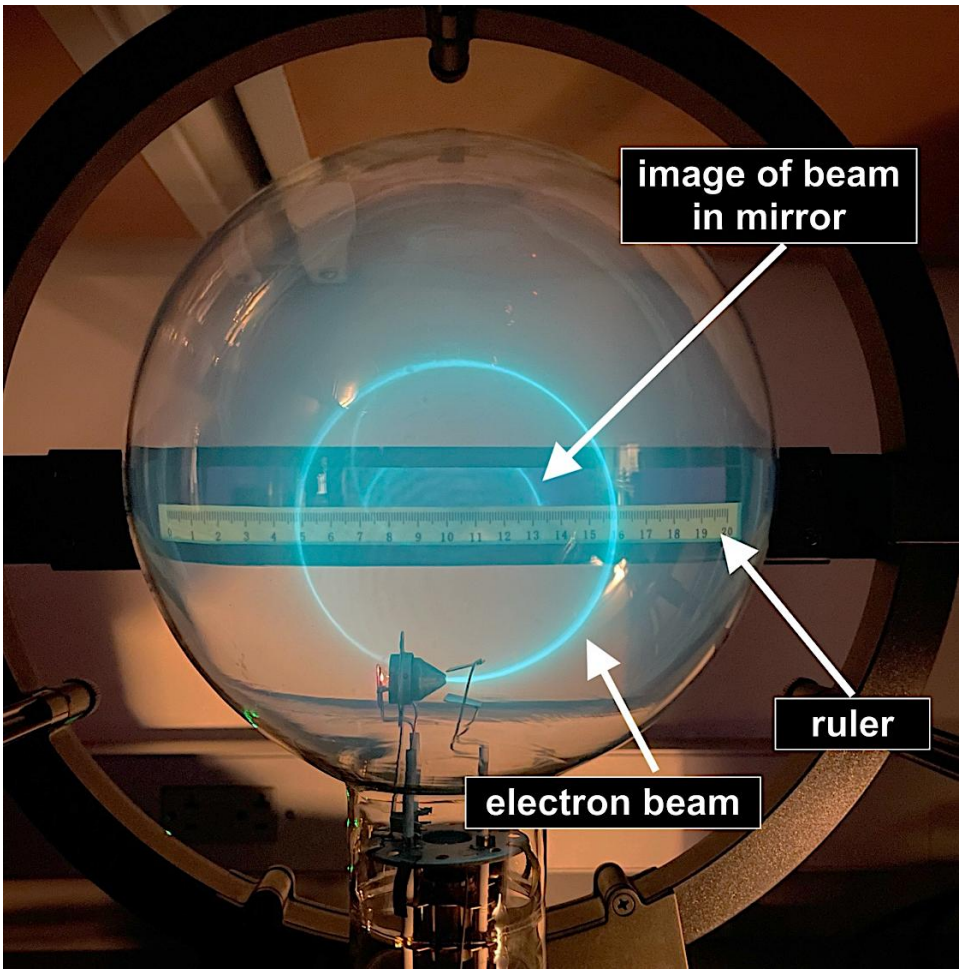


Figure 3: Closeup of electron beam with ruler and mirror

Data Collection

(6) Read the current display to find the current I through the Helmholtz coils. Record the current I in Table 1 of the worksheet.

(7) Read the voltmeter display and record the accelerating voltage V in Table 1 of the worksheet.

(8) Measure the radius r of the electron beam path using the mirrored ruler behind the e/m tube. To correct for parallax error, move your head so that the electron beam is aligned with the reflected image of the beam as you see it in the mirrored ruler.

Once both beams coincide, read the ruler scale. Take measurements from both sides of the electron beam to obtain the diameter. Record the radius r in Table 1.

Note: You may need to adjust the position of the ruler so that it coincides with the diameter of the electron beam. Move the ruler on the rear Helmholtz coil to ensure that the ruler crosses the diameter of the electron beam. (Take care not to touch the glass tube!)

(9) Change the voltage and current settings to different values. Repeat steps 6-8 for a total of 12 measurements of V, I, and r. Take turns with your lab group members so that each person takes data for a minimum of two trials.

Data Analysis

We can use the voltage and current measurements to obtain quantities that are present in the expression for the e/m ratio. Recall that the e/m ratio given in terms of magnetic field B, accelerating voltage V, and electron beam radius r is

$$\frac{e}{m} = \frac{2V}{B^2 r^2}.$$

(10) The magnetic field strength B for the Helmholtz coils can be calculated by the formula

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_0 NI}{R} \tag{4}$$

where $N = 130$ is the number of wire turns per coil, I is the current, $R = 15.8cm$ is the radius of the Helmholtz coil, and $\mu_0 = 4\pi \times 10^{-7} N/A^2$ is the vacuum permeability.

Calculate the field strength B for each trial of data and record the result in Table 2. You may use an Excel spreadsheet to calculate these results quickly.

(11) Calculate the variables $B^2 r^2$ and $2V$ for each trial of data.

(12) Make a plot of $2V$ *vs.* $B^2 r^2$ and add a line-of-best-fit. Record the slope of the line-of-best-fit.

(13) Calculate the percent error of your experimental value for e/m with the accepted value $1.75 \times 10^{11}\ C/kg$.

Exit Checkout

(14) Make sure that the power supplies are turned off and the voltage and current dials are turned completely counterclockwise to return them to their starting configuration.