Electron Charge-to-Mass Ratio

1 Introduction

In this experiment we will measure a fundamental property of the electron, the ratio of its charge to its mass.

In the experiment, a beam of electrons accelerated by a potential difference is bent into a circular path by a magnetic field. The beam is in a glass container containing a small amount of helium gas. Some of the electrons in the beam collide with these molecules, and this results in the emission of light. This process produces a visible track corresponding to the electron beam, so the radius of curvature of the electrons may be measured by eye.

By also measuring the accelerating voltage of the electrons, and the strength of the magnetic field the electron’s charge to mass ratio is determined.

The magnetic force acting on a charged particle is

$$F = qv \times B$$

in which $q$ is the electric charge, $v$ is the vector velocity, and $B$ is the magnetic field. If the magnetic field is spatially uniform, and the velocity vector $v$ is perpendicular to $B$, then since the force is perpendicular to the velocity, the particle moves in a circle. Using the expression for centripetal acceleration, Newton’s 2nd Law, and the magnitude of the cross product,

$$a = \frac{v^2}{R}$$

and

$$F = ma$$

equation 1 becomes, for an electron,

$$m\frac{v^2}{R} = evB$$

in which $R$ is the radius of the circular orbit, and $e$ is the magnitude of the electron charge. This can be solved for $e/m$:

$$\frac{e}{m} = \frac{v}{RB}$$

The electron speed, $v$, can be found from the accelerating voltage, $V$. The result for $e/m$ is

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

(2)

In your report, derive equation 2 from the previous ones.
Figure 1: A negatively charged particle moving in a uniform magnetic field which is directed out of the plane of the page.

2 Magnetic field

The magnetic field in this experiment is created by current in two circular coils which have parallel planes separated by one radius. This arrangement is called a set of Helmholtz coils. For such an arrangement, it can be shown that the magnetic field near the center is

\[ B = \frac{\mu_0 NI}{(5/4)^{3/2}a} \]

in which \( I \) is the current, \( N \) is the number of turns on each coil, \( a \) is radius of either of the coils, and \( \mu_0 = 4\pi \times 10^{-7} \) in MKS units.

The apparatus front panel provides a formula for \( B \), in which the appropriate values have been inserted:

\[ B = 7.80 \times 10^{-4} I \]

Here \( B \) and \( I \) are in MKS units.

3 Procedure

1. A schematic diagram of the apparatus is shown in Figure 2.

2. Make sure all power supplies are switched off and the dials are at the lowest settings. The heater power supply should be set to 6 volts. Make sure the toggle switch is up in the e/m MEASURE position. Turn the current adjust knob for the Helmholtz coils to the OFF position.
3. Verify that the apparatus is connected as shown in Figure 3.

4. The power supplies can be adjusted to over the ranges listed below.
   
   ELECTRON GUN HEATER: 6.3 VAC (Set the control to 6)
   ACCELERATING ELECTRODES: 150 to 250 VDC
   HELMHOLTZ COILS (magnetic field): 6-9 VDC

   CAUTION: The accelerating voltage is sufficiently high to result in a potentially lethal shock. It is important that you follow the instructor’s directions. The wires should be connected before turning on the voltage. If you think there may be a problem with the circuit, please request assistance from the instructor.

5. Turn on the power supply for the electron gun and the Helmholz coils. Adjust the accelerating voltage to 150 V. Wait several minutes for the cathode to heat up. When it does, you will see the electron beam emerge from the electron gun.
Figure 3: Electrical connections for the e/m apparatus. In our apparatus, the meters are built into the power supplies.

6. Slowly turn, clockwise, the current adjust knob for the Helmholtz coils. Watch the ammeter and take care that the current does not exceed 2 A. As the magnetic field increases, the electron beam will be bent into a circle. Check that the electron beam is parallel to the Helmholtz coils. If it is not, turn the tube until it is. Don’t take it out of its socket. As you rotate the tube, the socket will turn.

7. Record the current in the Helmholtz coils, and the accelerating voltage.

8. Measure the radius of the electron beam. Look through the tube at the electron beam. To avoid parallax errors, move your head to align the electron beam with the reflection of the beam that you can see on the mirrored scale. Measure the radius of the beam as you see it on both sides of the scale, and then average the results.

9. Repeat this procedure for several accelerating voltages between 150 and 250 volts. Then use equation 2 to find $e/m$ for each case. Find the average value and standard deviation of your measurements of $e/m$. Compare the average with the accepted value.

10. Estimate the uncertainties in $R$, $V$, and $B$. Find the uncertainty in $e/m$ by error propagation methods. You may do this for just one $e/m$ result (i.e. $R$, $V$, and $B$.) Does your result agree with the accepted value, within the uncertainty? If not, are there possible systematic errors which could account for the difference?