Electron Charge-to-Mass Ratio

I. Introduction

In this experiment we will measure a fundamental property of the electron: the ratio of its charge to mass (e/m).

The apparatus shown in figure 1 consists of a vacuum tube, a pair of Helmholtz coils and power supplies to them. The vacuum tube has an electron gun and is slightly filled with helium. A beam of electrons is generated from a heated cathode and accelerated through a pair of electrodes and released downward. The speed v of the electrons is determined by the accelerating voltage V and the ratio e/m. The electrons collide with the helium in the vacuum tube. The generated blue light makes the beam path visible. The Helmholtz coils supplied with a current I apply a constant magnetic field $\vec{B}$ perpendicularly to the velocity of the electron beam and bent the electrons into a circular path. The radius of the path depends on v, B, and e/m. The coil current I and the accelerating voltage V can be adjusted and read out on the front panel. The diameter (therefore, the radius r) of the electron path in the magnetic field can be measured using the etched glass internal scale in the tube. These will allow e/m calculated according to theory represented in the next section.

Figure 1. The apparatus.

II. Theory

a). *Accelerated Electron Beams*

When a beam of electrons is accelerated by electric potential (voltage V). The electric energy turns into kinetic energy for the electrons. $eV = \frac{1}{2}mv^2$. The electron speed v can be rewritten as

$$v = \sqrt{2V\frac{e}{m}} \qquad (1)$$

b). *Circular Motion in Magnetic Field*

When an electron enters a magnetic field, the Lorentz force, $\vec{F}_B = -e\vec{v} \times \vec{B}$, acts as a *centripetal force* and bends the electron beam into a circular motion of constant speed v. The magnitude of the centripetal force and acceleration, v^2/r, obeys Newton's second law, $F_c = mv^2/r$, which then equates to the magnitude of the Lorentz force.

$evB = mv^2/r$,

This can be rewritten as,

$$eB = mv/r \qquad (2)$$

Combining equations (1) and (2), we have,

$$\frac{e}{m} = \frac{2V}{r^2B^2} \qquad (3).$$

c). *Magnetic Field in Helmholtz Coils*

The magnetic field is created by current traveling in the two identical circular coils in parallel planes that are separated by one radius a of the coil. The magnetic field in the Helmholtz coils can be calculated by

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

where I is the current, N is the number of turns per coil, a is the radius of the coil, and $\mu_0 = 4\pi \times 10^{-7}$ in SI units for the permittivity of free space. Using the actual values of $N = 132$ and $a = 0.1475m$ in the apparatus, the magnetic field equation can be further simplified to

$B = 0.8 \times 10^{-3} I$,

where both B and I are in SI units (tesla or Wb/m^2, and amperes). Combining this with equation (3), we should have

$$\frac{e}{m} = 3.125 \times 10^6 \frac{V}{r^2I^2} \qquad (4),$$

in which all variables are in SI units (*V* → volts, *r* → meters, *I* → amperes).

NOTE: if you work through the unit conversions, the units for equation (4) do become C/kg (which is what you would expect).

III. Experiment

1. With the power switch off, connect the power cord of the control unit to an outlet on the power stripe around the station.

2. Turn on the power switch. Wait for the unit to perform a 30 second count down for self-test, indicated by the digital display on the front panel. This will also allow the cathode to heat to the proper operating temperature. When the self-test is complete, the display will stabilize and show "000".

3. Slowly turn the accelerating Voltage Adjust control up to 200V and observe the bottom of the electron gun. The bluish beam will be travelling straight down to the envelope of the tube.

4. Slowly turn the coil Current Adjust control up and observe the path of the beam. When the current is high enough, the beam will form a complete circle within the envelope. The diameter of the beam can be measured using the internal centimeter scale inside of the tube. The scale numbers fluoresce when struck by the electron beam. (Do not forget to turn the measured diameter to radius before using equation (4).)

Every team members should take a set of data, which means three sets of data for a group of three.

5. **Collect one set of data**. Fix the accelerating voltage to 200V, adjust the coil current to make the beam diameter to 10cm, record both current and radius. Then, adjust the current to make beam diameter to 9.5cm. Repeat this till the beam diameter reaches ~5cm. This gives you a set of 10-11 data points that you can use to calculate e/m for each data point, the average value and standard deviation.

7. **Collect more data**. Change the voltage to 300V, repeat step 5 to take another data set.

8. Change the voltage to 400V for the third data set.

Data processing:

a) calculate e/m for each data point. Then calculate the average and standard deviation(stdev.p) of each data set.
b) Estimate the instrument uncertainty in V , I , and r . Use the last digit place read from the power supplies as the uncertainties for V and I . Uncertainty in r should be estimated from the thickness of the beam path. Using error propagation, calculate the instrument uncertainty in e/m for each data point.

Discussion:

How does the calculated uncertainties in b) compare with the random error (stdev.p) calculated in a)? Explain how you decide the overall uncertainty in your measured e/m value.

Compare your measured e/m with the standard value. Do they agree or not. If not what are the possible source for random error and/or systematic error?

Lab report: standard report should be submitted to Blackboard

Including:

theory + relevant equation and variables,

brief procedure,

data table,

conclusion + discussion.