e/m with Teltron Deflection Tube

Fall 2025

1 Overview

In this lab you will measure the deflection of an electron beam by electric and magnetic fields infer the charge-to-mass ratio e/m for the electron.

2 Theory

A charged particle with charge q in an electric field $\vec{E}$ experiences a force given by:

$$\vec{F}_E = q\vec{E} \tag{1}$$

If the particle moves with velocity $\vec{v}$ in a magnetic field $\vec{B}$, the force on the particle is:

$$\vec{F}_B = q\vec{v} \times \vec{B} \tag{2}$$

For an electron, the charge $q = -e$, where $e = 1.6 \times 10^{-19}$ Coulomb is the fundamental unit of positive charge. The mass m of the electron is $m = 9.11 \times 10^{-31}$ kg.

In this experiment, the electrons are accelerated through a voltage V_a before entering the region containing the fields under study. Due to the accelerating voltage, the electrons acquire a kinetic energy equal to the loss of potential energy eV_a, *i.e.*:

$$\frac{1}{2}mv^2 = eV_a \tag{3}$$

2.1 Deflection In a Magnetic Field

We shall study the motion of an electron in a uniform magnetic field. Newton's second law states that $\vec{F} = m\vec{a}$. Let us apply this relation to a beam of electrons traveling perpendicular to the magnetic field at speed v. Since the magnetic force on an electron is perpendicular to its velocity, the electron speed stays constant and the electron travels in a circular path.

The magnitude of the magnetic force in Eq. 2 then simplifies to $F_B = evB$, and the acceleration of the electron in its circular path becomes $a = v^2/r$, where r is the radius of the circle. Substituting into Newton's second law, we get:

$$F = ma$$
$$evB = m\frac{v^2}{r} \tag{4}$$

Equations 3 and 4 may be combined to eliminate the electron speed v, and solved for the charge to mass ratio, e/m. One then finds:

$$\boxed{e/m = \frac{2V_a}{B^2r^2}} \tag{5}$$

In this experiment, the magnetic field is produced by a pair of identical coils carrying the same current. The coils are separated with spacing equal to the coil radius. A pair of such coils are known as **Helmholtz coils**, and produce a rather uniform magnetic field in the vicinity of the midpoint between the coils along the coil axis. It can be shown that the magnetic field in this region is given approximately by:

$$\boxed{B = \frac{8\mu_0 NI}{a\sqrt{125}}} \tag{6}$$

where $\mu_0 = 4\pi \times 10^{-7}$ Tm/A, N is the number of turns in each coil, I is the current through the coils, and a is the radius of each coil. For the Teltron Helmholtz coils, $N = 320$ and $a = 6.8$ cm $= 0.068$ m.

Using the Teltron tube, the electron beam is accelerated horizontally into the region where the magnetic field is present. Using the coordinate grid built into the apparatus, one can determine points through which the electron beam passes. If the circle formed by the electron path passes horizontally through the origin, and also passes through the point (x,y), one can easily show that the radius of the circle is given by: (See Figure 1)

$$\boxed{r = \frac{x^2 + y^2}{2y}} \tag{7}$$

3 Preliminary Questions

1. Obtain Eq. 5 from Eqs. 3 and 4.
2. Derive Eq. 7.
3. Using the given numerical data, write Eq. 6 in the form $B = CI$, where C is a numerical constant that you can evaluate from Eq. 6. What are the units of B and I?

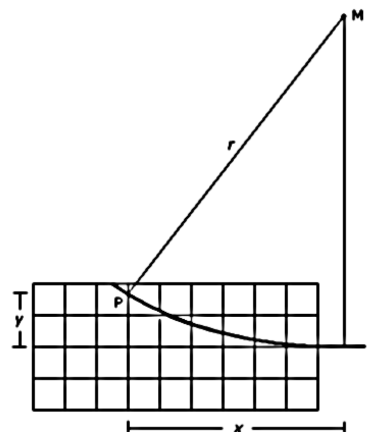

Figure 1: Geometry of electron's circular path through magnetic field.

4 Apparatus

See Figure 2 to reference the relevant features of the e/m deflection tube:

1. Fluorescent screen
2. Lower deflection plate (not used)
3. Boss with 4 mm plug for connecting deflection plate (not used)
4. Electron gun
5. 4 mm sockets for connecting heater supply and cathode
6. 4 mm plug for connecting anode (accelerating voltage)
7. Upper deflection plate (not used)

As shown in Fig. 3, the tube contains four terminals for electrical connections, two for the AC voltage (6 V) that serves to heat the filament and two for the DC accelerating voltage V_a. Note that the two larger receptacles on the base of the tube connect to AC terminals of the power supply. The smaller receptacle is to be connected to the negative DC terminal. The positive DC voltage terminal is connected to the plug pointing perpendicular to the tube axis located near the electron gun. The Helmholtz coils have a separate power supply, and should be connected in a series loop containing the power supply, coils, and ammeter. The full circuit diagram is shown in Figure 4.

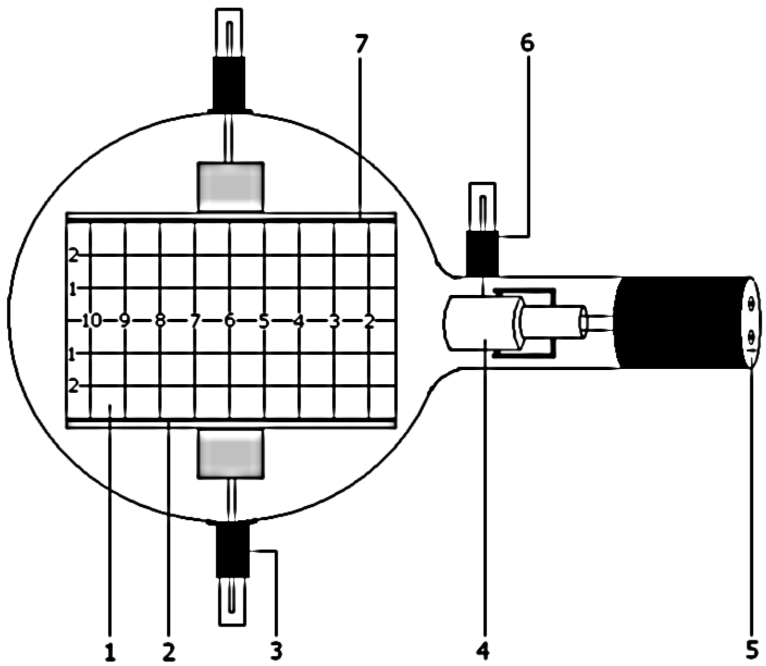

Figure 2: Location of terminals on Teltron 525 deflection tube.

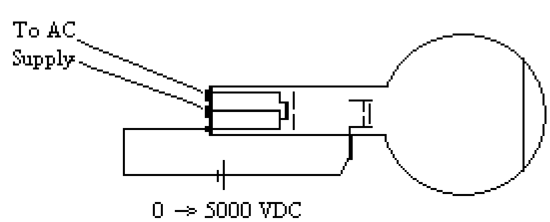

Figure 3: Schematic diagram of electron diffraction tube.

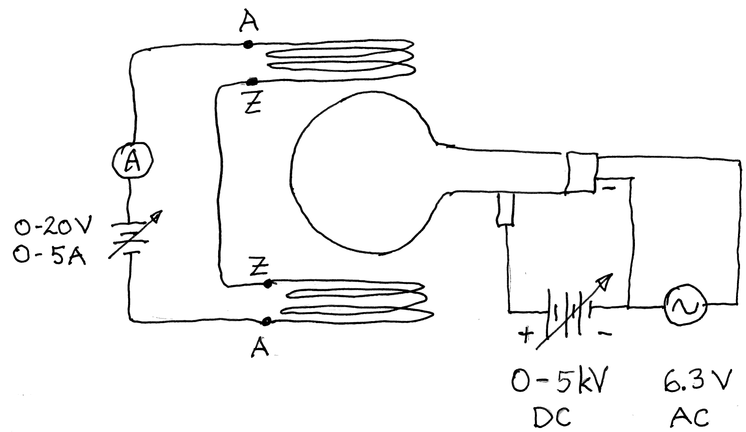

Figure 4: Wiring schematic for Teltron 525 deflection tube.

5 Procedure

CAUTION: High voltages are used in this experiment. Always slide the high voltage control on the power supply to its lowest setting before making any changes in the circuit. Have the instructor check your circuit when you change it before increasing the voltage.

1. Connect the circuit as shown, omitting the electric field deflection connection, and with no current running through the Helmholtz coils. Gradually increase the accelerating voltage until you see the path of the electron beam on the calibrated fluorescent screen.

2. Place a bar magnet near the tube to illustrate deflection of the beam. Try various orientations of the bar magnet. Which gives the largest deflection of the beam?

3. Place the bar magnet perpendicular to the beam with the north pole nearest to the tube. Using the right hand rule, predict the direction of the magnetic force on the electrons. Compare to the observed deflection of the beam.

4. Turn on the Helmholtz coil circuit. Try varying the magnetic field (by varying the Helmholtz coil current). What is the effect on the radius of curvature of the electron beam path?

   For fixed magnetic field, try varying the accelerating voltage. What is the effect on the electron beam path radius of curvature?

5. For an accelerating voltage of 2500 volts, adjust the magnetic field current so that the beam passes through a known point. For instance, the far

corner of the calibrated region has coordinates $(x, y) = (10 \text{ cm}, 2.5 \text{ cm})$. Record the current.

6. Repeat step 5 for larger voltages, incrementing in steps of 500 volts up to a maximum of 4500 volts.

6 Analysis

1. Explain the results obtained in Procedure steps 1-4 qualitatively in terms of the appropriate relationships. Hint: for 2 & 3, consider the magnetic force law, Eq. 2; for step 4, Eq. 5 will be helpful.

2. For each set of V and B data taken in Procedure step 5, compute e/m for the electron. Use SI units throughout.

3. Find the mean value of e/m and the uncertainty (standard deviation of the mean). Compare your results (including the uncertainty) to e/m as obtained from standard values of e and m.

7 Uncertainty Analysis

To determine the uncertainty on the electron-to-mass ratio, e/m, look again at Eqs. 5, 6, and 7. The expression for e/m depends on V_a, B, and r; r, in turn, depends on x and y, while B depends on I. The total uncertainty, $\sigma(e/m)$, therefore, is:

$$\sigma(e/m) = \sqrt{\left(\frac{\partial(e/m)}{\partial V_a}\sigma_{Va}\right)^2 + \left(\frac{\partial(e/m)}{\partial B}\sigma_B\right)^2 + \left(\frac{\partial(e/m)}{\partial r}\sigma_r\right)^2}, \qquad (8)$$

where σ_{Va}, σ_B, and σ_r are the uncertainties on V_a, B, and r, respectively.

Although this equation may appear intimidating, you can attack it in parts:

- First, derive an expression for $\partial(e/m)/\partial V_a$ and multiply by σ_{Va} to get the uncertainty due to the accelerating voltage.

- Next, derive an expression for $\partial(e/m)/\partial B$. Here, although you don't have an uncertainty in B, you can easily show that $\sigma_B = C\sigma_I$, where C is the constant determined in the lab, and σ_I is the measured uncertainty in the current. Substitute these results into your expression to get the uncertainty on e/m due to the B-field.

- Finally, first derive an expression for $\partial(e/m)/\partial r$ and use the following result (which you could also derive yourself!):

$$\sigma_r = \sqrt{\left(\frac{x}{y}\sigma_x\right)^2 + \left(\frac{y^2 - x^2}{2y^2}\sigma_y\right)^2}. \qquad (9)$$

Determine if any of the terms in Eq. 8 are negligibly small compared to the others and, if so, you can ignore them from your final calculations.

Finally, you can also compare the standard deviation of the mean of e/m you measure from multiple trials against the formal uncertainty you determine using the procedure above. Are they different and, if so, why?

8 References

- Thornton and Rex, Modern Physics, 3rd ed., pp. 85-89
- Equipment instructions: Teltron 525 Deflection Tube
- Tipler and Llewellan, Modern Physics,5th ed., pp. 116-118