

Laboratory 14: Ratio of Charge to Mass for the Electron

Introduction

The discovery of the electron as a discrete particle of electricity is generally credited to the British physicist Sir J. J. Thomson (1856-1940). His extensive studies of cathode rays culminated in the quantitative observations of the deflection of these rays in magnetic and electric fields. These researches led to methods for the measurement of the ratio of charge to mass (e/m) for the electron. In his famous oil-drop experiments, Robert A. Millikan (1868-1953) was able to measure the charge of the electron (1.60206×10^{-19} coulomb). The currently accepted value for e/m is 1.75890×10^{11} coulombs/kg, and hence the mass of the electron could be determined accurately.

From the definition of the magnetic induction in a magnetic field \vec{B} , the force \vec{F} acting upon a charge e moving with velocity \vec{v} in a magnetic field is given by:

$$\vec{f} = e \vec{v} \times \vec{B} \quad (1)$$

Since the direction of this force is always perpendicular to the velocity vector, it follows that the force is centripetal and causes the electron to move in a circular path. If \vec{v} is perpendicular to \vec{B} , then the mechanical centripetal force must equal the magnetic force, i.e.,

$$\frac{m v^2}{r} = e v B \quad (2)$$

where r is the radius of the circular path of the electron. Assume the electron falls through a potential difference φ to acquire its velocity. Then

$$e\varphi = \frac{1}{2} m v^2 \quad (3)$$

Solving equation (2) for v and substituting into equation (3) we obtain

$$\frac{e}{m} = \frac{2\varphi}{B^2 r^2} \quad (4)$$

The apparatus used in this experiment is shown in Figure 1, this apparatus makes it possible to measure the values of φ , B , and r , thus, to determine the ratio e/m .

Apparatus Function:

The magnetic field which bends the beam is produced by a current in two Helmholtz coils. These coils are mounted vertically and, therefore, produce a field in the horizontal direction. When the distance between the coils is equal to the radius of either coil, a nearly uniform field is produced at the midway point. This is because the field contributed by each coil is diminishing with a constant rate over a short distance. The diminution of the field of one coil is compensated for by the equal increase in the field produced by the other coil.

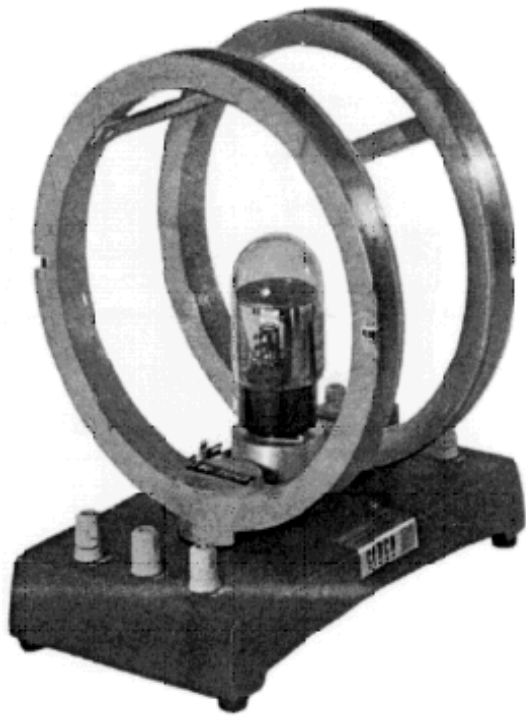


Figure 1: e/m Apparatus

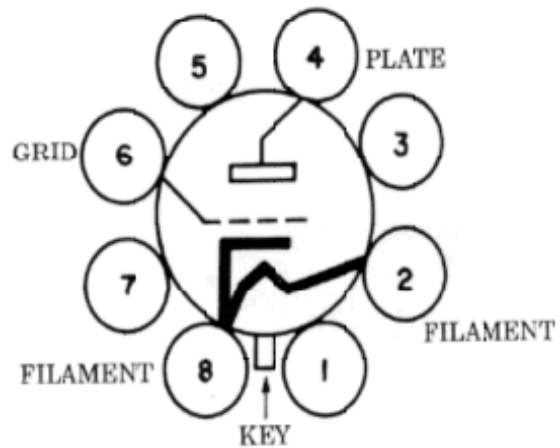


Figure 2: e/m Tube Pin Arrangement

The electron tube is held in a socket (Figure 2) mounted between the coils, and on their common axis. The currents in the coils have the same rotational sense. The magnitude of the magnetic field B at the central point is given by

$$B = \frac{8\mu_0 N I}{\sqrt{125} R} \quad (5)$$

where N is the number of turns per coil, I is the current in the coils in Amperes, R is the coil radius in meters, and μ_0 is the permeability of free space ($4\pi \times 10^{-7}$ weber/amp-m). The flux density is given in webers/meter².

By combining equations (4) and (5), an expression for e/m can be obtained that includes only constants for a given set of coils and the measurable quantities φ , I , and r :

$$\frac{e}{m} = \left(\frac{125 R^2}{32 \mu_0^2 N^2} \right) \frac{\varphi}{r^2 I^2} \quad (6)$$

when the specified MKS units are used, e/m is then expressed in coulombs/kilogram.

The major equipment items consist of two parts: 1) a specially designed Cenco three-element electron tube, and 2) a pair of Helmholtz coils. Within the electron tube, an "electron gun" is mounted, with its

center line coincident with the vertical axis of the tube. The gun consists of an indirectly heated cathode which supplies the electrons; a grid, charged to a positive potential with respect to the cathode, which serves to focus the electron beam; and a circular plate, which is held at a high positive potential, ϕ , and thus accelerates the electrons (see Figure 2).

The electron stream is projected vertically through a small hole at the center of a disk which is mounted horizontally on the upper end of the electron gun. Four circles, with centers coincident with the hole and of radii 0.50, 1.0, 1.05, and 2.0 cm are marked on the upper face of the disk. The bulb and disk are coated with a material which fluoresces when struck by electrons. The tube contains a trace of an inert gas that aids in focusing the electron beam as well as to causing the beam to make a visible trace.

The Helmholtz coils of the Cenco apparatus are wound on non-magnetic aluminum rings. The rings have their rims milled away at opposite ends of a diameter. The number of turns of the coils is marked on the base of the equipment. The strength of the magnetic field can be adjusted by changing the current in the coils. Variation of either the accelerating potential difference in the tube or the strength of the magnetic field will cause the radius of the circle described by the electron beam to vary.

IMPORTANT NOTE: If the beam is made to describe a semicircle above the disk and, on returning to the disk, strike one of the four circles marked on its face, the *diameter* of the electron semicircle is equal to the *radius* of the disk.

Precautions must be taken to see that no significant stray magnetic field affects the apparatus. The effect of the earth's magnetic field is not large, in comparison with that of the coils, but a correction can be made for this by reversing the magnetic field and averaging the results. In addition to the usual instrumental errors, it is instructive to consider some other sources that may limit the precision of the results of this experiment. Inability to judge accurately when the electron beam is exactly on the circle is one source of error. The errors may be minimized by taking the average of a number of readings. Since the entire tube is in the magnetic field, the electrons are deflected along a path having various radii of curvature as they are accelerated from the cathode to the anode. The electrons consequently emerge from the anode at an angle to the axis of the tube. The center of curvature of the emerging beam is, therefore, below the level of the anode. If conditions are adjusted so that the beam strikes a circle on the anode disk, the true diameter of the beam circle is larger than the observed value. This results in a value of e/m that is larger than the standard value. Electrostatic fields in the bulb may cause errors if the tube has a different potential than the anode. Contact potentials may produce some effect in the measured values of ϕ .

Procedure

1. **Be sure to start with the two power supplies off** and their control knobs turned fully clockwise or zeroed.
2. Assemble the circuit shown in Figure 3. Be sure that the lead to the grid is connected to the sliding arm connector of the resistor. This will produce a grid voltage at some fraction of the anode voltage. **Make all grounds common.** Be sure all meters are connected so as to respect their polarities.

3. GET THE INSTRUCTOR TO CHECK YOUR CIRCUIT BEFORE TURNING THE POWER ON!
4. Apply power to the filament. To start, adjust the plate voltage to around 50 volts and the grid voltage to around 10 volts. After a few seconds a pale blue beam of electrons will appear pointing straight up to the top of the tube out of the aperture at the center of the disk. Move the reversing switch into one of its two closed positions. Turn the field current power supply on and slowly increase the voltage. Do not exceed 5 amperes in the field circuit. You should see the electron beam begin to arc over and then touch the anode disk in a semicircle. Adjust the grid voltage to produce the best focused spot on the disc. Do not exceed 100 volts on either plate or grid.
5. Make at least 16 measurements with different plate voltage and field current settings that place the focused beam on the circles at 0.5, 1.0, 1.5, and 2.0 cm, and tabulate your readings. You will have to readjust the plate and grid voltages and the field current in each case. Make at least 4 different settings for each circle. To partially account for the effects of stray fields, such as the earth's magnetic field, use the reversing switch on the field coils and make adjustments to give the best reading in both directions. When not actually taking a reading, turn the high voltage supply off so as to prolong tube life.
6. Measure the Helmholtz coil radius, R , with a ruler. N is printed at the base of the Helmholtz coils.
7. To obtain your best value of e/m , Plot your data as φ/r^2 versus I^2 . Use the method of least squares to determine the best straight line fit. Force the intercept to be the origin, that is, you want the function to be of the type $y = cx$. The ratio of e/m can be determined from this slope and equation (6). Be sure to record the fitting error.

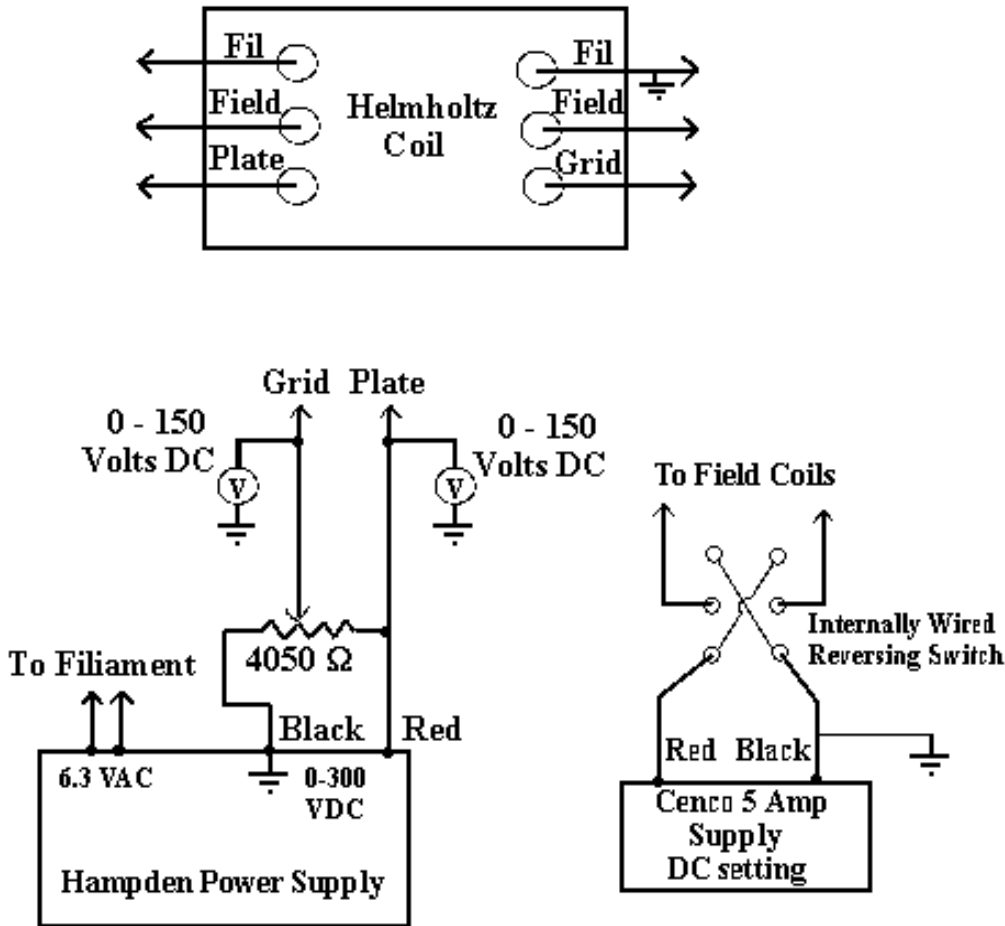


Figure 3: Wiring Diagram, note volt meters between grid/plate and ground.

Notes

1. Connect all grounds together.
2. **Plate and grid voltage should not exceed 100 VDC.**
3. Grid voltage should be much less than plate voltage for proper focus.
4. **Field current should not exceed 5 amps.**
5. When not using the apparatus, turn the power off to save the tube.

Questions

1. How does your value of e/m compare to the accepted value of $e/m = 1.76 \times 10^{11}$ coulombs/kilogram? If you are *way off* look for errors of factors of two, you may be using some constant incorrectly. If the error is more than 10% be sure to investigate the graph of the data. You

may find that certain points throw the plot off; thus, there may be reasons to eliminate those data points. If you do so, justify it.

2. Millikan's value for the electron charge is 1.6×10^{-19} coulombs. Use this to determine the electron mass. Compare this to the accepted value. What was the significance of this determination of electron mass?
3. What is the speed of an electron falling through a potential difference of 100 volts? Do you expect any relativistic corrections to this experiment? Answer with calculations.
4. What is the magnetic field at the center of the Helmholtz coil when the current is 5 amperes? How does this compare to the Earth's magnetic field? Is this supported by your observations?

WHEN YOU FINISH: DISCONNECT ALL WIRES

LEAVE THINGS AS YOU FOUND THEM!