

Charge to Mass Ratio of Electron

Equipment ELWE e/m tube, ELWE Helmholtz coils, ELWE 4 voltage power supply, Fluke multimeter, leads, desk lamp with 25 watt red bulb, dual beam LED, ruler, multiple banana leads

SAFETY

1. Treat the glass tube carefully. The glass tube could implode!
2. The accelerating voltage for the electrons is lethal. When the power supply is on, do not touch leads and terminals.

1 Background

The orbit of a charged particle in a uniform and constant magnetic field is a circle when the initial velocity of the particle is perpendicular to the magnetic field. The radius of the orbit depends on the charge to mass ratio of the particle, q/m , the speed of the particle v , and the strength of the magnetic field B . When the strength of the magnetic field and the initial speed of the particle are known, a measurement of the radius of the orbit determines q/m . This principle was used by J.J. Thomson to measure the charge to mass ratio of the electron, e/m , in 1897. The reason for a circular orbit can be understood by the fact that a charged particle experiences a force at right angles both to the instantaneous velocity and to the direction of the magnetic field. The particle therefore moves under the influence of a force whose magnitude is constant but whose direction is always at right angles to the velocity. Like a ball whirled on a string, the orbit is a circle. The measurement of q/m in modern physics provides a way to identify atoms and molecules by a device called a mass spectrometer. Similarly the measurement of q/m by devices such as cloud chambers and bubble chambers identifies sub-atomic particles, such as the electron and the muon. In this experiment e/m of the electron is determined from the relationship between the electric potential used to accelerate the electron to a given speed, the strength of the magnetic field that influences the electron's motion, and the radius of the circular path which the electron follows. The charge to mass ratio of a particle is often referred to as the specific charge.

2 Apparatus

The equipment consists of an evacuated glass bulb in which a beam of electrons execute a circular orbit. See Figs. 1 and 2. A pair of wire coils provide a reasonably uniform magnetic

field in the region of the bulb. Inside the glass bulb is an “electron gun” mounted so that the initial direction of the electron beam is horizontal. The electron gun consists of the following metallic elements. See Fig. 2 which is not very complete. Look at the electron gun yourself to verify these statements!

1. A hair pin heating wire or filament. A voltage is applied between the two ends of the wire to heat it.
2. An oxide coated cathode (not shown in Fig. 2), which supplies the electrons for the beam.
3. A small diameter inner cylinder surrounding the filament (hard to see and not shown in Fig. 2), probably a heat shield.
4. A cylinder for focusing the electron beam, which is maintained at a negative voltage with respect to the cathode.
5. An anode or plate, which is a thin circular plate with a hole in the center for the electrons to pass through and has a rim that is useful for attaching a wire to. It is maintained at a positive electric potential with respect to the cathode. The energy of the electrons is determined by the cathode-anode voltage.
6. A bent plate attached to the anode, which we will call the shield, electrostatically shields the electron beam region of the tube from the electron gun.

The glass bulb is filled with low pressure inert gas. Light emitted from this gas makes the electron beam visible. It is necessary that surface charge does not build up on the inside of the glass bulb. Either the glass of the bulb is slightly conducting or the inside of the glass bulb is coated with a very thin transparent conducting layer.

Referring to Fig 1, there are two vertical wires that stick up from the electron gun. These wires have 5 pairs of short horizontal wires attached to them. **The pairs of wires are located at 2, 4, 6, 8, and 10 cm from the axis of the electron gun.** By sighting along one pair of these short wires the diameter of the electron orbits can be determined. The electron beam goes between the two vertical wires. These vertical wires are attached to the anode and also press against the glass at the top of the tube. The glass tube, vertical wires, anode, and shield form a roughly equipotential region with no electric fields. To a good approximation the only field the electrons see is the magnetic field applied by the Helmholtz coils (see below) and the earth’s magnetic field.

The reasonably uniform magnetic field that bends the electron beam is produced by a pair of identical circular coils whose spacing is equal to their radius. With this spacing they are called *Helmholtz coils* after the great 19th century physicist. He recognized that this arrangement produces the most uniform field near the midpoint between the coils. **Each coil has 124 turns and a mean radius of 15.0 cm. The two coils are connected in series.**

The strength of the magnetic field B can be adjusted by varying the current passing through the coils. Variation of either the plate-cathode potential in the tube or the strength of the magnetic field will cause the radius of the circle described by the electron beam to change.

3 Theory

Let the mass, charge, radius, velocity, and acceleration of an electron be given by m , e , r , v , and v^2/r respectively. Denote the magnetic field by \vec{B} . The magnetic force on an electron is given by $\vec{F} = -e\vec{v} \times \vec{B}$. As \vec{v} is perpendicular to \vec{B} by experimental design, in terms of magnitudes $F = evB$. Newtons's second law gives $evB = mv^2/r$, or

$$v = \frac{erB}{m}. \quad (1)$$

To find an expression for v in terms of quantities that can be measured, we note that the kinetic energy imparted to an electron within the tube is given by eV where V is the potential difference through which the electrons have been accelerated and is the voltage between the cathode and the anode. (The focusing cylinder voltage does not affect the final electron energy.) We get

$$eV = \frac{1}{2}mv^2. \quad (2)$$

Substituting this into Eq. 1 gives

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

In SI units the left hand side has the units of coulombs/kilogram.

The magnetic field strength near the center of a pair of Helmholtz coils is given by (S.I. Units)

$$B = \frac{\mu_0NI}{R} \left(\frac{4}{5}\right)^{\frac{3}{2}} = 9.0 \times 10^{-7} \frac{NI}{R}, \quad (4)$$

where N is the number of turns in one coil, I is the current into each coil in amperes, and R is the average radius in meters of the turns forming a coil. For the coils, $N = 124$. Knowing the accelerating voltage, coil current, and the diameter of the electron orbit, the value of e/m from the last two equation is

$$\frac{e}{m} = \frac{3.62 \times 10^6 V}{r^2 I^2} \quad (5)$$

4 Electronics

Fig. 3 shows the wiring diagram. Four voltages are supplied by a single unit. The glass tube plugs into a base unit which has four lettered color terminals. The lettering and meaning are as follows.

1. A (Red): anode or plate
2. C (Black): cathode and one end of heating filament
3. W (Blue): focusing cylinder (Wehnelt in German)
4. H (Green): other end of heating filament

From left to right in Fig. 3, the four units of the power supply provide up to 500 V for the cathode-anode voltage, 50 V for the focusing cylinder, 8 V for the Helmholtz coils, and 12 V for the heating filament. The negative terminal of the 500 V supply, the positive terminal of the 50 V supply, and the negative terminal of the 12 V supply are connected together. This arrangement makes the focusing cylinder negative with respect to the cathode. A maximum of 300 V should be applied to the anode. A Fluke multimeter is used to measure the DC current of the Helmholtz coils.

The two output terminals of each of the four voltage supplies are electrically isolated. They are said to “float.” For each pair of output terminals a voltage can be applied to one of the terminals without affecting the voltage between the terminals. The ground or PE terminal of the supply unit is not connected to any element of the electron gun. The electron gun floats, but the voltages between the electron gun elements are appropriate for the operation of the electron gun.

5 Procedures

- Wire up the apparatus as illustrated in Fig. 3.
- **Confirm that you have wired up the apparatus correctly with your instructor!**
- The experiment needs to be done in a darkened room so that the rather faint light emitted by the neon atoms can be seen. The instructor will turn off the room lights. Use the lamp on the bench for preliminary adaptation to the dark. When observing the electron beam, adjust the position of the desk lamp so the light doesn't shine on the e/m tube.
- Before turning on the supply unit, turn all four knobs on the supply unit fully counter clockwise (CCW) so that the initial output voltages will be zero. This is almost always a good procedure when turning on a power supply. The knob on the 500 V supply is multiturn. Turn on the supply.
- So as to not thermally shock the heating filament, slowly turn the filament voltage (0 - 12 volt supply) up to 7.5 V. Observe the glowing filament as you do this.
- Adjust the anode voltage (0 - 500 volt supply) to 300 V. You should see the electron beam emerging from the electron gun and traveling in a straight line.
- Adjust the focusing cylinder voltage (0 - 50 volt supply) for the sharpest electron beam. **When you change the anode voltage, or if you change the heater voltage, you should readjust the focusing voltage.**
- If the electron beam is too faint to see easily, increase the filament voltage up to 8.4 V. **Too high a filament voltage will seriously shorten the life of the tube, and they are expensive!**

- Make sure your fluke meter is on. **Connect the fluke meter using the 10A and COM connector in series with the coil and power supply.** Sometimes the meter shuts down to conserve battery life. Next, set the fluke meter dial to large A and press the yellow button so the meter is set to measure DC current. To better assist you in the dark use the back light option button. Back light button is the round button located below the HOLD button.
- Apply a current to the Helmholtz coils (0 - 8 volt supply). The electron beam should curve upward. If the beam curves downward, reverse the polarity of the voltage to the coils. Increase the current until the diameter of the electrons' orbit is 10.0 cm. This is given by the topmost cross wires. The two cross wires are used to eliminate parallax.
- Record the beam voltage, the radius of the electron beam, and the coil current. Use Eq. 5 to calculate e/m .
- Increase the magnetic field until the electron beam has a diameter of 8.0 cm. Obtain another measurement of e/m . Keep repeating this procedure until the magnetic field is not strong enough to bend the electron into one of the standard circles.
- Reduce the beam voltage to 250 V. Obtain another set of values of e/m .
- Reduce the beam voltage to 200 V. Obtain another set of measurements.
- Determine the magnetic field at each electron orbit for each beam voltage. How does the magnetic field interact with the beam of electrons? For each beam voltage do you need the same current to bend the beam of electrons for each circular orbit? Why or why not?
- Compute the average value and the standard deviation of your values for e/m .
- Indicate the major sources of error in this experiment. Compare your value of e/m with the accepted value. What do you judge may be responsible for any significant discrepancy? Do you think the discrepancies are systematic or statistical? Explain.

6 Additional Questions

1. Why does the final electron energy not depend on the focusing cylinder voltage?
2. Do you think the electrons are emitted from the cathode with zero velocity, one velocity, or a range of velocities? Hint: The electrons inside the metal that are able to escape are a bit like a gas of molecules at finite temperature.
3. The coils are connected in series. Why would connecting them in parallel be a bad idea?
4. Why doesn't the magnetic field change the speed of the electrons? (Speed is taken to be the magnitude of the velocity. The velocity is a vector.)

5. At a coil current of 3 A, what is the magnetic field produced at the center of the Helmholtz coils in gauss? About what is the magnitude of the Earth's field in gauss?
6. If a current is applied to the two coils and there is no deflection of the electron beam, what would you suspect?

The following two questions depend on the equation for the force on a charged particle in a magnetic field, $\vec{F} = q\vec{v} \times \vec{B}$.

7. What would be the electron orbits if the initial velocity of the electrons was parallel or anti-parallel to the magnetic field?
8. What would the electron orbits be if the initial velocity of the electrons was 45 deg to the magnetic field? Assume the initial speed of the electrons is v .

7 Finishing Up

Disconnect the wires of the apparatus and please leave the bench and apparatus as you found it. Cheers.

- 1 Fine beam tube U18575
- 2 Measurement marks
- 3 Electron gun
- 4 Socket U8481435
- 5 Clip
- 6 Connectors

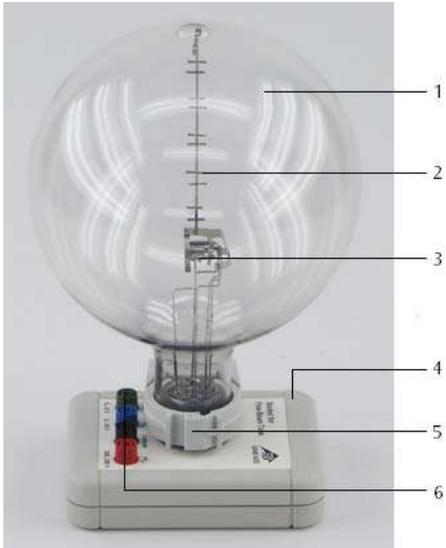


Fig. 1

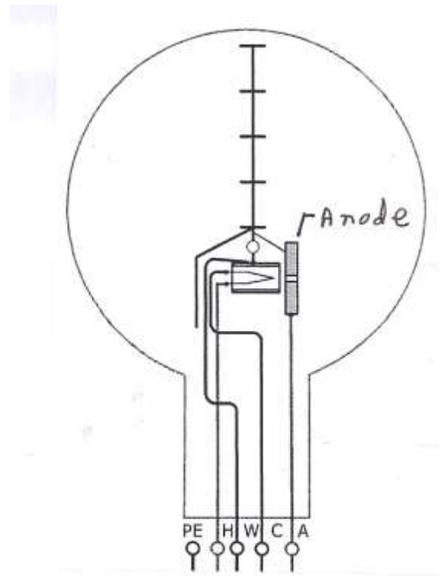


Fig. 2

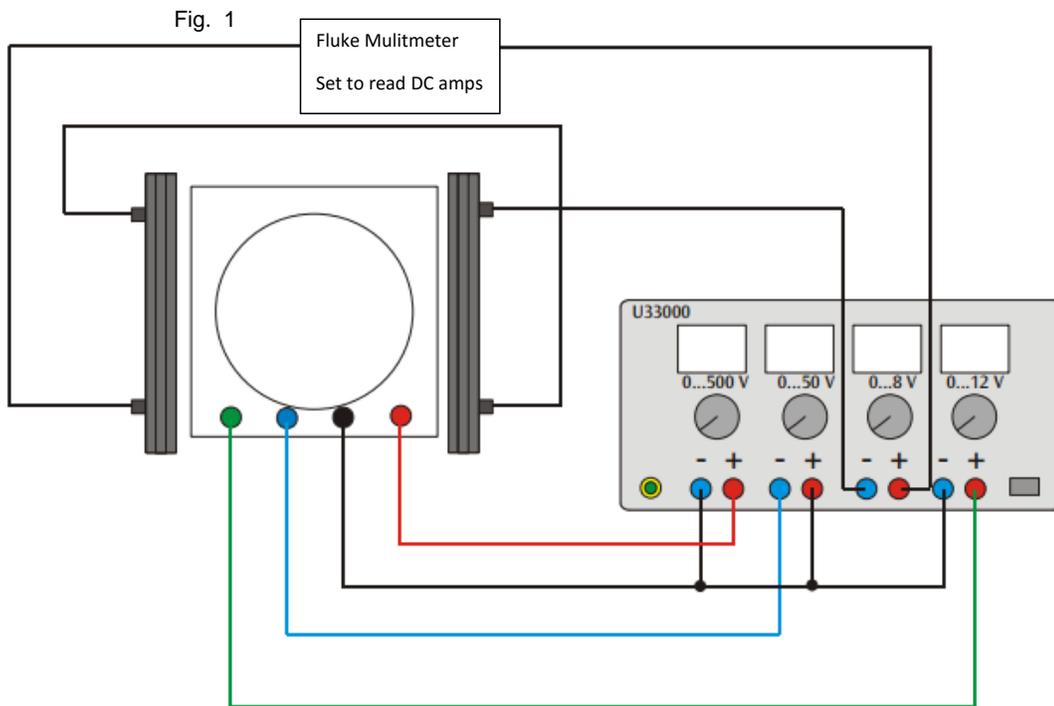


Fig. 3 Experimental set up