

qv x B FORCE: ELECTRONS IN A MAGNETIC FIELD

- Objectives:**
- To see the effect of a magnetic field on a moving charge directly.
 - To also measure the “specific charge of electrons” i.e. the ratio of electron charge e to mass m_e .

- To Do Before Lab:**
- Read this lab
 - Read Taylor 2.6 (review error propagation if necessary)
 - Do the derivations in the introduction

Introduction:

The discovery of the electron as a discrete particle carrying charge is credited to the British physicist J. J. Thomson (1856-1940). This work was the very beginning of the modern search for fundamental particles. His studies of cathode rays (streams of electrons) culminated in 1897 with his quantitative observations of the deflection of these rays in magnetic and electric fields. As we will find in this lab, this deflection provides a key to finding the value of e/m . Later, Robert Millikan (1868-1953) was able to measure the charge of the electron. Thus, these two experiments determine the mass of the electron. Thomson’s work also formed the basis of the mass spectrometer, which was further developed by Al Neir.

Our experiment is a descendent of J. J. Thomson’s original experiment which only studies the deflection of electrons in a magnetic field rather than both electric and magnetic fields. The basic experiment consists of a beam of electrons that are accelerated from rest through a potential difference V so that their final (non-relativistic) velocity can be determined from energy conservation

$$\frac{1}{2} mv^2 = eV \tag{1}$$

This is accomplished by “boiling off” electrons from the surface of a metal filament and accelerating them to the inside surface of the “can” that surrounds it (Fig. 1).

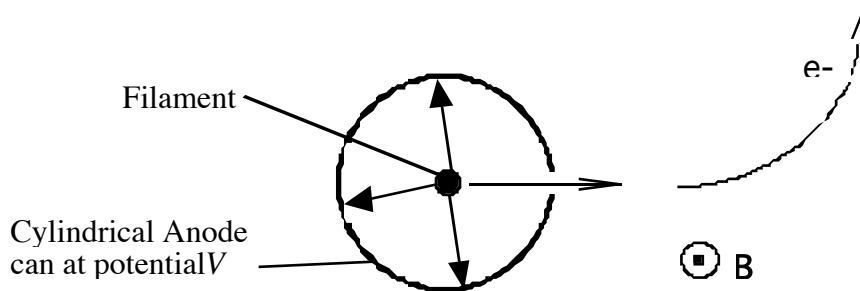


Figure 1. Electrons are accelerated through potential V and guided into circular motion by the magnetic field B (pointing out of the page).

After leaving the can, the electrons enter a region of uniform magnetic field B . In Fig. 1 the B field is pointing out of the page. The force on the electron is given by the Lorentz equation

$$\mathbf{F} = -e \mathbf{v} \times \mathbf{B}. \quad (2)$$

Note that if both \mathbf{F} and \mathbf{v} are in the plane perpendicular to \mathbf{B} , motion will be confined to that plane. The resulting motion is circular with radius of curvature

$$r = m_e v / eB. \quad (3)$$

From Eqs. 1 and 3 we can solve for e/m_e :

$$\frac{e}{m_e} = \frac{2V}{B^2 r^2}. \quad (4)$$

Derive equations (3) and (4).

The \mathbf{B} field of course depends on the apparatus. A fairly uniform field can be achieved with a pair of electromagnet coils (each containing N loops and carrying current I) with a common axis (Helmholtz coils, see Fig. 2).

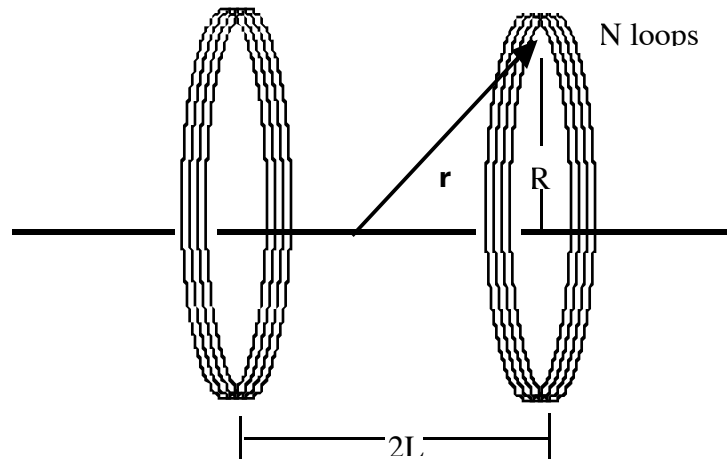


Fig. 2. Helmholtz Coils. Each coil has N turns and radius R .

The total \mathbf{B} field at the midpoint between the coils is directed along the axis of the coils and has magnitude

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

(You may have the delight of deriving this one day, but, sadly, not in this course.)

With B expressed in terms of known or measurable quantities, and the accelerating voltage V known as well, we can use Eq. (4) to calculate the ratio of charge to mass for the electron.

Apparatus:

The Uchida e/m apparatus is a modern version of Thompson’s apparatus (Fig. 3). It consists of a globe containing an electron “gun”. In the gun, electrons are emitted from an electrically heated filament and accelerated by means of a large voltage, V .

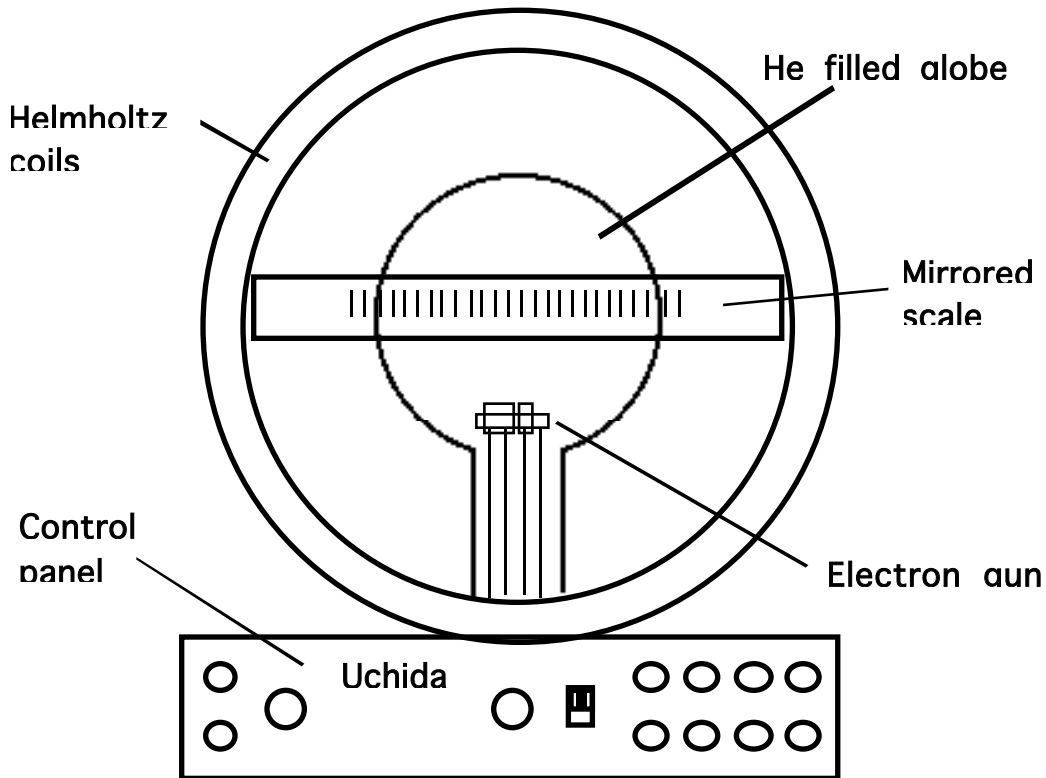


Fig. 3. The Uchida e/m apparatus

In order to see the path of the electrons emitted from the gun, the globe is filled with helium gas at a low pressure. Some of the electrons from the gun interact with helium atoms along their path and cause the atoms to lose an electron. The helium atoms are said to be ionized. A positively charged helium ion very quickly captures a free electron (not one from the beam, just a random one present in the gas), and returns to a neutral state, emitting blue-green light in the process. A similar process occurs inside a fluorescent or neon light. The trajectory of the electron beam can be seen as a trail of blue-green light.

As mentioned above, the magnet field, B , produced by a pair of Helmholtz coils is linear in the current I . For this apparatus, the relation is

$$B = 7.80 \times 10^{-4} I \text{ Tesla} \tag{6}$$

Thus, by measuring I we can calculate B .

Part I: Getting Started

(1) Connect the 6V A.C. filament supply terminals on the Discharge Tube Power Supply to the HEATER terminals on the Uchida apparatus. Turn on the power supply. The filament will glow, but no beam is produced. (Why not?)

(2) Connect the 0-500V D.C. terminals on the Discharge Tube Power Supply to the ELECTRODES terminals on the Uchida apparatus, making sure the voltage control knob is set to 0V. Connect the hand held digital multimeter to the ELECTRODES (in parallel), to monitor the potential difference. Gradually turn up the accelerating voltage (V). A beam is produced, but it is not in a circle. (Why not?) Do NOT exceed 300V on the accelerating voltage.

(3) Connect the Filtered D.C Power Supply to the HELMHOLTZ COILS terminals of the Uchida apparatus. Include the Keithley multimeter in the circuit (in series) to measure the current in the coils. Slowly turn up the current (I) to the Helmholtz coils. Do NOT exceed 2.0 amps, or you will burn out the fuse on the Keithley meter and overheat the Helmholtz coils. Use your compass to determine the direction of the magnetic field produced by the coils.

Part II: Collecting Data

To perform the experiment, you will first set the current, I , to some value, to determine the strength of the magnetic field. Then you will set the accelerating voltage, V , to determine the speed of the electrons. Finally, you will measure the radius, r , of the electron's trajectory. Then you will repeat this process for different values of V and I . The range of I that gives reasonable size circles is from about 1.0 to 1.8 amps.

WARNING: DO NOT GO HIGHER THAN 1.8 AMPS, as this is close to the maximum current that the apparatus can handle without overheating.

The accelerating voltage, V , cannot be set lower than about 100 volts because the trace will not be visible.

(1) Set the current at 1.0 amp and vary V until a circle of convenient size (easy to measure the radius against the mirrored scale) is formed. Carefully measure the position of the beam on each side of the circle using the mirrored scale to prevent parallax errors. From your left and right side measurements of the beam determine the radius of the circle. Record your data and uncertainty in a well-organized table (What an opportunity to use Excel!).

(2) Keeping I at 1.0 amp, increase V to a new value, but don't change it so much that the circle is difficult to measure. Determine the new radius. Does increasing the accelerating voltage increase or decrease the radius? Explain why. Record the uncertainties in I and V .

(3) Increase I by about 0.2 amps, without changing V . What effect does this have on the radius? Explain why. Adjust V to get a nice sized circle and determine r . Without changing the current, increase the voltage and determine r again.

(4) Continue to increase the current in approximately 0.2 amp increments and for each current,

measure the radius for two different voltage settings. Record the uncertainties.

Part III: Analysis

- (1) Using equations (4) and (6) find the best way to plot your data and to extract the ratio e/m . Try it. Invite your instructor to admire the fine plot.
- (2) Add your uncertainties to your table (use of Excel for the error propagation will be most useful).
- (3) Carefully examine your plot, do the geometric quantities match what you expect (e.g. Is the intercept close to what you expect?) Plot a best-fit and include the equation. Print your graph and use the min-max slope method to get a rough estimate of the uncertainty.
- (4) Calculate e/m of the electron (with uncertainty). Celebrate with a box! Compare with other groups to see whether there is agreement.
- (5) If you like, as a final exercise for this lab, choose one set of data from your table and use equation (1) to determine the velocity of the electrons in the beam. Compare to the speed of light and convert your answer to miles per hour (1 mile = 1610 meters).