1417-2 LABORATORY MANUAL

Experiment 2: charge-to-mass ratio *e/m* of electron

I. Introduction

The charge-to-mass ratio, q/m, for charged particles can be determined in principle by measuring their motion trajectories inside electric and magnetic fields. The basic way to measure the e/m ratio of electron is to use the electric and magnetic deflection
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1. Electric deflection

A potential difference *V* is applied across a pair of parallel plates with separation *d*, length *L*. When an electron with horizontal velocity *v* enters the electric field between the plates, it will deflect inside the field. After time $t = L/v$, the electron will pass through the plates having an upward deflection

$$\mathrm{Y} = \frac{1}{2}\mathrm{at}^2 = \frac{1}{2}(\frac{\mathrm{eE}}{\mathrm{m}})\mathrm{t}^2 = \frac{1}{2}(\frac{\mathrm{e}}{\mathrm{m}})(\frac{\mathrm{V}}{\mathrm{d}})(\frac{\mathrm{L}^2}{\mathrm{v}^2}) \qquad (1)$$

where *a* is the acceleration rate, $E = V/d$ is the electric field. So we obtain

$$\frac{\mathrm{e}}{\mathrm{m}} = \frac{2\mathrm{Yv}^2\mathrm{d}}{\mathrm{VL}^2} \qquad (2)$$

Fig. 1a   Fig. 1b   Fig. 1c
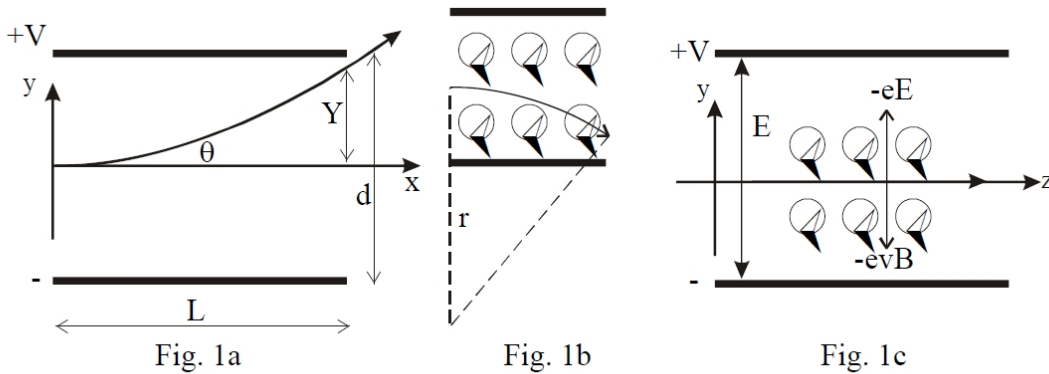
2. Magnetic deflection

When an electron enters a magnetic field *B*, a force *F* will act on it as the centripetal force. The electron will take circular motion. If the velocity is perpendicular to the field, the force will be perpendicular to both *v* and *B*.

$$F = evB = mv^2/r \qquad (3)$$

where *r* is the radius of the curvature of the electron trajectory. The charge-to-mass ratio is then

$$e/m = v/(rB) \qquad (4)$$

3. Thomson's determination of e/m

In 1897, J. J. Thomson determined the ratio e/m for electrons in a way which did not depend on measuring the radius of curvature of the electron trajectory. The principle is that when an electron with horizontal velocity (v) enters a deflection tube with both electric field (E) and magnetic field in effect. v is perpendicular to E and B. E is perpendicular to B (fig.1c). The initial horizontal velocity (v) can be obtained by measuring the acceleration potential (V_o) of the electron gun, i.e., $mv^2/2 = eV_o \Rightarrow v = \sqrt{2eV_o/m}$. Adjust the electric field by changing the potential difference across the metal plates (or adjust the magnetic field by changing the dc electric current I through the Helmholtz coils) to let the electric force and the magnetic force cancel each other so that there is no deflection for electron. When this happens, the upward electric force just balances the downward magnetic force and the electron moves along the horizontal direction. So

$$eE = evB, \ \ E/B = v = \sqrt{2eV_o/m}, \tag{5}$$

and the electron charge-mass-ratio can be determined as:

$$\frac{e}{m} = \frac{E^2}{2V_o B^2}, \tag{6}$$

where $E = V/d$ is the electric field, $B = 0.716\,\mu_o NI/R$ is the magnetic field between the Helmholtz coils. A pair of Helmholtz coils is a pair of coaxial coils, each of radius R and N turns, and separated by a distance equal to the radius of the coils.

II. Experimental

1. **Equipment**

The e/m Tube (see Figure 2) is filled with helium at a pressure of 10^{-2} mm Hg, and contains an electron gun and deflection plates. The electron beam leaves a visible trail in the tube, because some of the electrons collide with helium atoms, which are excited and then radiate visible light. The electron gun is shown in Figure 3. The heater heats the cathode, which emits electrons. The electrons are accelerated by a potential applied between the cathode and the anode. The grid is held positive with respect to the cathode and negative with respect to the anode. It helps to focus the electron beam.

CAUTION: The voltage to the heater of the electron gun should NEVER exceed 6.3 volts. Higher voltages will burn out the filament and destroy the e/m tube.

The radius of the Helmholtz coils is equal to their separation -- provides a highly uniform magnetic field. The Helmholtz coils of the e/m apparatus have a radius and separation of 15 *cm*. Each coil has 130 turns. The magnetic field (B) produced by the coils is proportional to the current through the coils (I) times $7.8 \cdot 10^{-4}$ tesla/ampere [B (tesla) $= 7.8 \cdot 10^{-4} \cdot I$].

The Controls – The control panel of the apparatus is straightforward. All connections are labeled. The hook-ups and operation are explained in the next section.
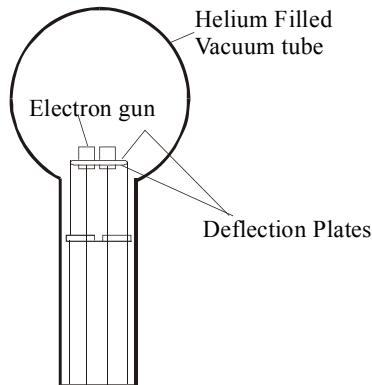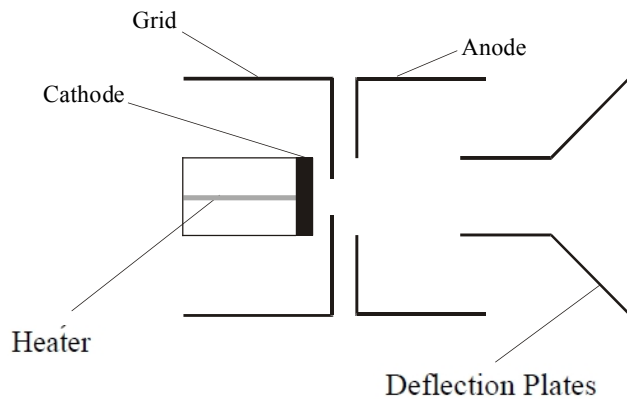

Figure 2 e/m Tube

Figure 3 Electron Gun

Additional Equipment Needed

Power Supplies:
- 6 - 9 V_{dc} @ 3A (ripple < 1%) for Helmholtz coils (PASCO Model SF-9584 Low voltage Power Supply)
- 6.3 V_{dc} or V_{ac} for filament
- 150-300 V_{dc} accelerating potential (PASCO Model SF-9585 High Voltage Power Supply)

Meters:
- Ammeter with 0-2 A range to measure current in Helmholtz coils (such as the PASCO Model SB-9624 Multimeter)
- Voltmeter with 0-300V range to measure accelerating potential (such as the PASCO model SB-9624 Multimeter)
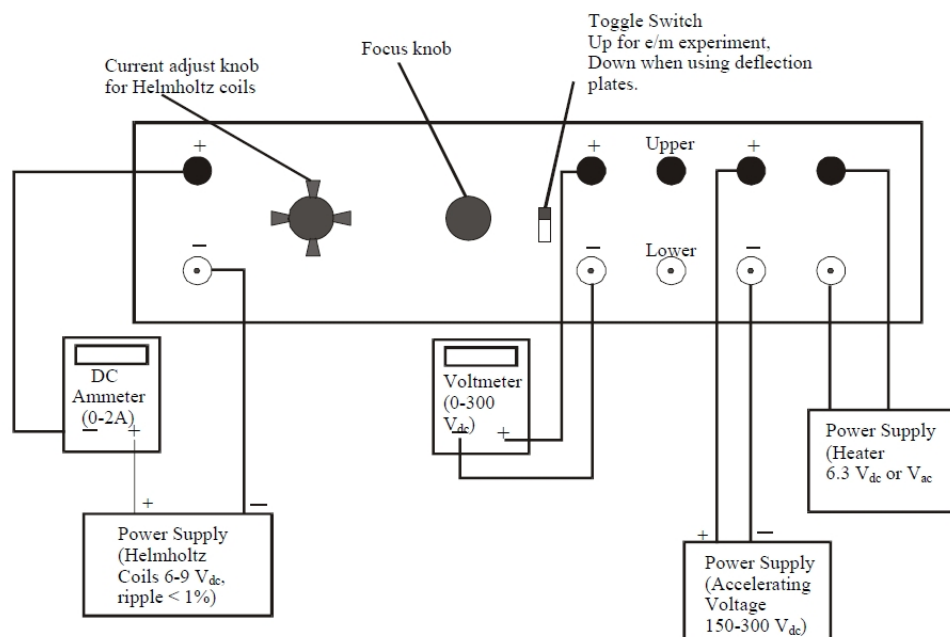
2. Operation and measurements

Figure 4 Connections for *e/m* experiment

A. If you will be working in a lighted room, place the hood over the e/m apparatus.
B. Flip the toggle switch up to the e/m MEASURE position.
C. Turn the current adjust knob for the Helmholtz coils to the OFF position.
D. Connect your power supplies and meters to the front panel of the e/m apparatus, as shown in Figure 4.
E. Adjust the power supplies to the following level:-
      Heater: 6.3 V_{dc} or V_{ac}
      Electrodes: 150 to 300 V_{dc}
      Helmholtz Coils: 6-9 V_{dc}
F. Slowly turn the current adjust knob for the Helmholtz coils clockwise. Watch the ammeter and take care that the current does not exceed 2A
G. Wait several minutes for the cathode to heat up. When it does, you will see the electron beam emerge from the electron gun and it will be curved by the field from the Helmholtz coils. Make sure that the electron beam is parallel to the Helmholtz coils. If it is not, turn the tube until it is. Don't take it out of its socket. As you rotate the tube, the socket will turn.
H. Adjust the electrode voltage or the Helmholtz coil current to produce a circular beam that is a few cm smaller in diameter than the bulb of the tube.
I. Carefully measure the radius of the electron beam. Look through the tube at the electron beam. To avoid parallax errors, move your head to align the electron beam with the reflection of the beam that you can see on the mirrored scale. Measure the radius of the beam as you see it on both sides of the scale, then average the results. Record your result on the answer sheet.
J. Carefully read the current to the Helmholtz coils from your ammeter and the accelerating voltage from your voltmeter. Record the values on the answer sheet.
K. Choose another value of accelerating voltage and adjust the Helmholtz coil current to restore the circular electron beam to the original radius. Record V_o and I again. Repeat until the Table in the answer sheet is completed.

The electron charge-to-mass ratio *e/m* can be obtained according to the following equation

$$\frac{e}{m} = \frac{v}{Br} = \frac{2V_o(5/4)^3 R^2}{(N\mu_o Ir)^2} \qquad (7)$$

where V_o = the accelerating potential
       R = the radius of the Helmholtz coils
       N = the number of turns on each Helmholtz coil = 130
       μ_o = the permeability constant = $4\pi \cdot 1\bar{0}$ TmA^{-1}
       I = the current through the Helmholtz coils
       r = the radius of the electron beam path

L. Derive the above equation in the answer sheet.
M. Plot a graph of V_o against I^2 and deduce the e/m ratio of an electron.

Deflections of Electrons in an Electric Field
IMPORTANT: Do not leave the beam on for long periods of time in this mode. The beam will ultimately go through the glass walls of the tube.

You can use the deflection plates to demonstrate how the electron beam is deflected in an electric field.

1. Setup the equipment as described above for measuring e/m except:
    1. Flip the toggle switch to ELECTRICAL DEFLECT.
    2. Do not supply current to the Helmholtz coils.
    3. Connect a 0-50 V_{dc} power supply between the banana plug connectors labeled DEFLECT PLATES (UPPER and LOWER).

2. Apply the 6.3 V_{dc} or V_{ac} to the HEATER and 150-300 V_{dc} to the ELECTRODES of the ELECTRON GUN (the accelerating potential). Wait several minutes to warm up the cathode.

3. When the electron beam appears, slowly increase the voltage to the deflection plates from 0 V to approximately 50 V_{dc}. Note the deflection of the electron beam. Note that the beam is bent towards the positively charged plate.

Two Simple Demonstrations

1. Instead of using the Helmholtz coils to bend the electron beam, you can use a permanent magnet to show the effect of a magnetic field on the electron beam. Provide the following power to the e/m apparatus:

    HEATER: 6.3 V_{ac} or V_{dc}
    ELECTRON GUN ELECTRODES: 150-300 V_{dc}

When the electron beam appears, use your permanent magnet to bend the beam.

2. The socket for the *e/m* tube is designed so that the tube can be rotated 90 degrees. The tube can therefore be oriented so it can be at any angle, from 0-90 degrees, with respect to the magnetic field from the Helmholtz coils. By setting up the tube at various angles, study how the beam deflection is affected.