

Physics 23 Fall 2003

Lab 3 - Charge to Mass Ratio of the Electron

Theory

Elementary particle physics has as its goal to know the properties of the many atomic and sub-atomic particles (mesons, quarks, lambda particles, etc) and to understand their place in nature. The first elementary particle discovered was the electron and the first property measured was the charge to mass ratio, e/m , determined by J. J. Thompson in 1897. Many particles once thought to be elementary, such as the proton, are now known to be composed of other particles such as quarks, but the electron has not lost its status as a true elementary particle. In fact, as far as we know it has mass, charge (also spin angular momentum and a magnetic dipole moment), but no size.

The experimental method you will use to measure e/m for the electron is designed after the experiment of Bainbridge. The apparatus consists of a large vacuum tube supported at the center of a pair of Helmholtz coils. An electron gun, composed of a filament parallel to the axis of the coils and surrounded by a coaxial anode containing a single slit produces a narrow beam of electrons whose paths are made visible by a trace amount of mercury vapor in the tube. A diagram of the vacuum tube-electron gun is shown in figure 1.

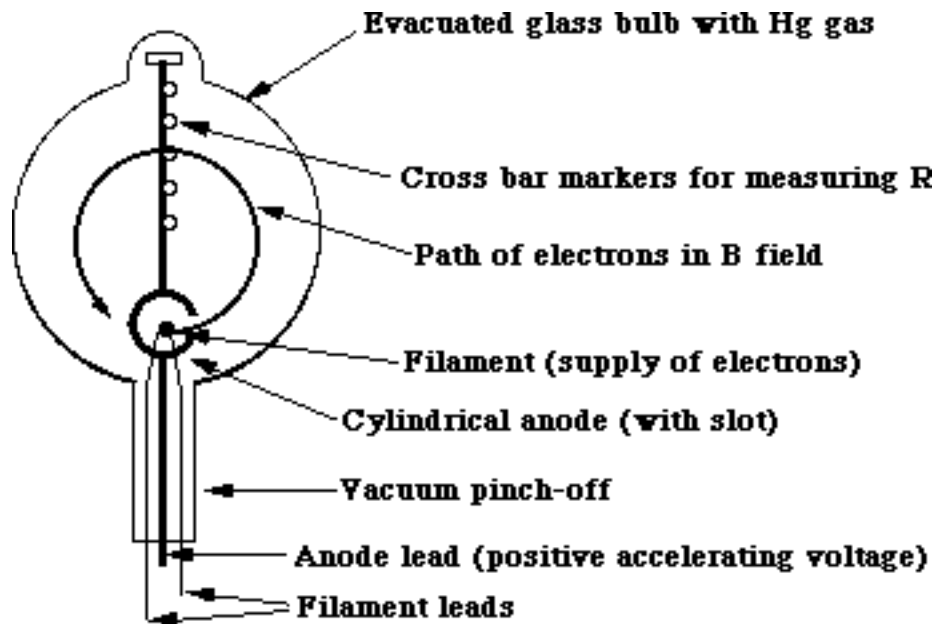


Figure 1

The apparatus works as follows. The filament is heated by running an electric current through

it (just as the filament in a light bulb is heated). When the filament is "red hot", electrons will evaporate from the filament material (just as water molecules will evaporate from the surface of a kettle of water when it is heated). The evaporated electrons will form a negatively charged "cloud" around the filament as shown in the figure 2 below. This process of electron emission from a hot metal surface is called thermionic emission.



Figure 2

To create a beam of electrons, the anode (or metal cap) is maintained at a potential of about +100 V with respect to the filament (this is the so-called "accelerating potential" written as V_{acc}). The electrons in cloud around the filament are attracted by the positive potential and are accelerated toward the metal cap. Some electrons escape from the cap into the field free space of the vacuum tube by passing through the narrow slit in the cap thereby forming a thin ribbon or beam of electrons. Note that the low pressure (vacuum) is essential here. At atmospheric pressure, an electron escaping from the filament would travel only about 10^{-4} cm before colliding with an air (or mercury) molecule. Forming a long "beam" of electrons would be impossible under such circumstances. At lower pressures there are fewer air molecules per unit volume and the electrons can travel farther, and at 10^{-5} atmospheres electrons can travel about 8 to 10 cm before hitting a mercury molecule. Electrons moving in such a low-pressure mercury environment are made "visible." When an electron strikes a mercury atom, if it has enough kinetic energy (10.4 electron volts), one of the mercury's electrons will be knocked off. A nearby electron soon takes its place, and the excess energy is given off as blue (primarily) light during the recombination. If the pressure were too low there would be too few mercury atoms to emit much light and the beam would be difficult to see; at about 10^{-5} atmospheres, however, there is still enough mercury in the glass bulb to make the beam of electrons clearly visible in a dark room. One sees a bluish glow from the struck mercury molecules.

Once the electron leaves the anode through the slit, all of its energy will be kinetic and this energy can be computed from the expression

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

where m is the electron mass, e is the charge of the electron, V is the accelerating voltage and v

is the velocity of the electron. With no current flowing in the Helmholtz coils and in the absence of any other sources of electric or magnetic fields, the path of these electrons is a straight line.

If a current is caused to flow in the Helmholtz coils, a magnetic field will be created in the region between the coils where the vacuum tube is located. If the electron beam exiting from the slit in the anode is oriented so that the path of the electrons is perpendicular to the magnetic field produced by the Helmholtz coils, then the electrons will feel a force perpendicular to their direction of travel of magnitude

$$F = evB \quad (2)$$

where e is the charge of the electron, v is its velocity and B is the magnetic field strength. Since the force is always perpendicular to the direction of travel of the electrons, the path followed by the electrons will be circular. The force on a particle undergoing circular motion can also be expressed as

$$F = \frac{mv^2}{R} \quad (3)$$

where m and v are defined as in equation (2) and R is the radius of curvature of the circular path. Substituting this expression for the force into equation (2) and solving for v^2 yields

$$v^2 = \frac{e^2 B^2 R^2}{m^2} \quad (4)$$

Substituting this expression for v^2 into equation (1) and solving for e/m yields

$$\frac{e}{m} = \frac{2V}{B^2 R^2} \quad (5)$$

V can be read directly from a multimeter attached to the electron gun circuitry. The value of B for a set of Helmholtz coils can be computed from the expression

$$B = \frac{8\mu_0 NI}{\sqrt{125} a} \quad (6)$$

where N is the number of turns in the coils, I is the current flowing in the coils, a is the radius of the coils and μ_0 is the permeability of free space. In the lab apparatus, $N = 72$, a can be measured with a meter stick, and I can be measured via an ammeter attached to the Helmholtz coil circuitry. As can be seen from equation (6), the strength of the magnetic field can be varied by changing the current in the Helmholtz coils. The distances from the filament to the posts is listed on each of the apparatus. By varying the current in the Helmholtz coils, the path of the electrons can be adjusted to pass directly through one of the posts. In this way, we know the radius of cur-

vature of the path. Since each of the quantities on the right side of equation (5) can be readily measured using the apparatus described above, equation (5) is the equation you will use to calculate an experimental value for e/m .

In summary, the experimental method for measuring e/m for the electron is as follows. You will create an electron beam by passing a current through the filaments of the electron gun and adjusting the accelerating voltage on the anode to a known value. With the plane in which the electrons are moving perpendicular to the direction of the field of the Helmholtz coils, you will increase the current flowing in the coils until the resultant B field is strong enough to bend the beam of electrons into a circular path which passes through a given post in the vacuum tube. V and I can be measured from multimeters hooked into the circuitry of the apparatus, B can be calculated from I with the use of equation (6) and R can be computed from the distance from the filament to the given post as listed on the apparatus. Equation (5) can then be used to compute a value for e/m .

References

The following are the sections in the texts which are pertinent to this lab. They should be read before coming to lab.

1. Serway, Modern Physics; Chapter 3 pp. 97 – 103 (handout).
2. Ohanian, Physics (second edition); Chapter 31 pages 759-761.

Also, read (but do not work) problem 30.33 on page 750 to see why Helmholtz coils produce a very uniform B-field.

Experimental Purpose

The purpose of this lab is to experimentally measure the charge to mass ratio of the electron using the method described in the theory section.

Procedure

1. Check to see that the electron gun is wired to the power supply as shown in figure 3. Make sure all of the knobs on the power supply are turned fully counterclockwise and turn on the power supply. Turn on the multimeters and set the multimeter hooked into the Helmholtz coils circuitry to read DC amperes.

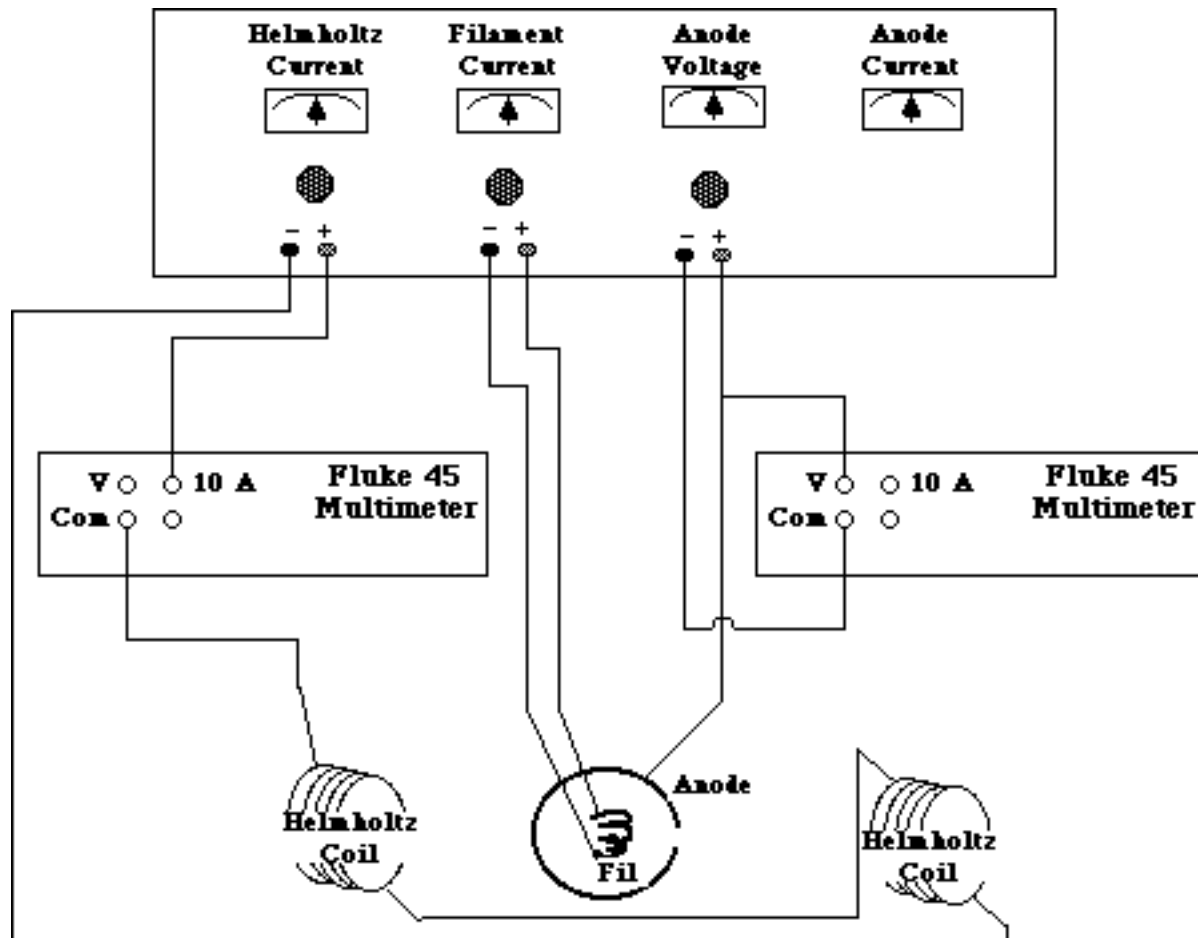


Figure 3

2. Produce an electron beam using the following procedure.
 - a. Set the anode voltage to 50V.
 - b. Turn the dial controlling the filament current to 1/2 amp. Wait one minute and increase the filament current another 1/2 amp. Continue doing this until you see the bluish electron beam. The filament should glow an orange-red color at 3 amps, and the beam should appear by 4 amps. Do NOT run the FILAMENT CURRENT ABOVE 4.5 AMPS. Always watch the anode current as you change the filament current or the anode voltage. Do NOT run the ANODE CURRENT ABOVE 5 mA (half scale).
3. Observe the effect of the electric field on the beam by varying the anode voltage between 20 and 100 volts. Note qualitatively the effect on the beam. Explain what you see in your lab notebook. What direction does the electric field point inside the cylindrical anode?

4. Observe the effect of a magnetic field on the beam using a cylindrically shaped "bar magnet" composed of a stack of strong magnetized disks. Before actually putting the magnet near the beam, draw a picture in your notebook showing what you would expect the beam to look like for the following situations.
 - a. You bring the north pole of the bar magnet near the top of the bulb (near the beam, but perpendicular to its direction).
 - b. You bring the south pole of the bar magnet near the top of the bulb.
 - c. You place a bar magnet along the axis of the beam. Then you move it slightly off the axis.

Now test these predictions, and explain your results. Remove the magnet. Can you see the effect of the earth's magnetic field? Turn the filament current and anode voltage slowly down to zero, but do not turn off the power supply or the multimeters.

5. As emphasized in the theory section, equation (5) is only valid if the plane of the electron beams motion is perpendicular to the local magnetic field. Therefore, before making any measurements you must align the plane of motion with the local magnetic field. The field produced by the Helmholtz coils is shown in figure 4. If this were the only magnetic field present, then alignment of the electron's plane of motion with the magnetic field would be a simple matter of turning the vacuum tube until the plane of the motion was perpendicular to the long axis of the Helmholtz coils. The local field, however, is actually the sum (as vectors) of the field from the Helmholtz coils, the Earth's magnetic field and the external fields created by the flow of currents in the electronic equipment and in the electric lines in the wall. The problem is simplified if we first align the Helmholtz coils along the earth's magnetic field. This is done with a dipping needle and a compass. Before doing this alignment, make sure all of the bar magnets used in step 4 above have been removed from the room and that all of the electronics you will be using is turned on.

- a. Use the small compass to locate the N-S direction in the vicinity of the vacuum tube. This is the horizontal projection of the local magnetic field. Align the long axis of the electron beam tube in this direction.

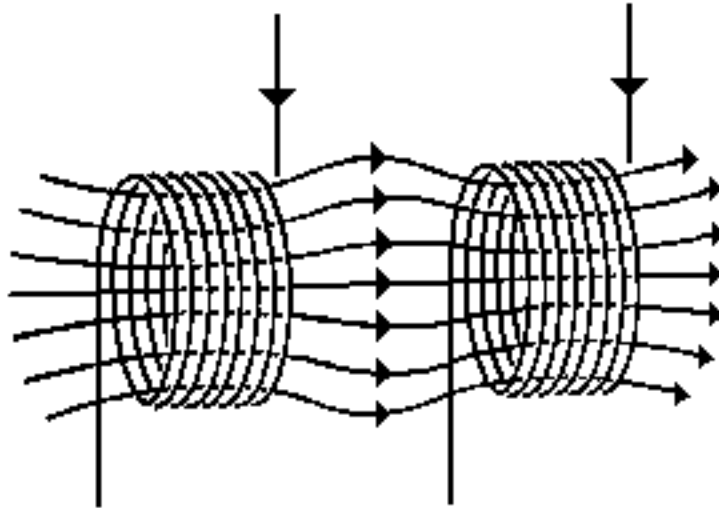


Figure 4

- b. Use the dipping needle to determine the angle of declination which the local magnetic field makes with the horizontal. Adjust the angle of the vacuum apparatus until the cross sectional area of the Helmholtz coils is perpendicular to the angle of declination.

The local magnetic field should now be parallel to the magnetic field that will be produced in the Helmholtz coils and the total magnetic field magnitude can be computed algebraically. Draw a sketch of the coils and the electron gun in your notebook. Clearly label the direction of the current in the coils and of B in the region of the electron beam. Show in your sketch how the path of a representative electron in the beam will appear with and without current in the coils. Describe (and/or sketch) how the electron path will change as the current in the coils is increased.

Now produce an electron beam in your electron gun. Turn on and then vary the current going through the Helmholtz coils. Does the beam do what you predicted it would? Comment in your laboratory notebook.

6. With no current flowing in the Helmholtz coils, observe the electron beam. You will note that the beam is curved. This is due to the local magnetic fields, primarily the Earth's magnetic field. Increase the current in the Helmholtz coils until the electron beam is straight. Record this current and from it calculate the magnitude of the local field. This value will need to be subtracted from the total B field computed when making measurements of e/m to determine the B field magnitude needed to bend the beam to a given radius of curvature.

7. With V_{acc} constant so that the speed of the electrons in the beam is constant, measure the magnetic field strength necessary to deflect the beam to each of the five cross posts.

Before actually doing this, however, a few comments on how to position the beam at the posts is in order. For several reasons, the electron beam spreads as it goes around the tube, but fortunately, because all of this spreading is toward the inside of the circle, none of it affects the measurement of e/m if the outside edge of the beam is used. The effects which cause the spreading are discussed below:

- a. Not all the electrons travel perpendicular to B . An electron traveling at an angle q to the direction of the field will have a component of its velocity parallel to B equal to $v \cos q$. This component is unaffected by the magnetic field. The radius of curvature for electrons moving at an angle with respect to the magnetic field is

$$R = \frac{m}{e} \frac{v \sin(\theta)}{B} \quad (7)$$

and is therefore a maximum when q is 90° . Hence the electrons at the outside edge of the beam are moving perpendicular to the field as assumed in equation (5).

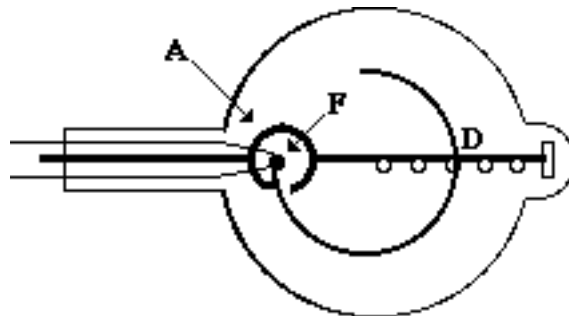


Figure 5

- b. Those electrons leaving the filament perpendicular to line FD which joins the filament and the post in the figure above will be bent into a circle whose center lies on the line FD . Other electrons leaving at an angle to the perpendicular will move in a circle of the same radius, but with center not on the line FD . One can show that electrons leaving at any angle, a positive or negative, will cross FD slightly inside those which left at $a = 0$, i.e., perpendicular to FD .
- c. Those electrons which leave the negative end of the filament fall through the greatest potential difference between filament and anode and thus have the greatest velocity. The accelerating voltage is referred to the negative end of the filament.

- d. The electrons collide with mercury atoms in the tube thus making their path visible. Such a collision is inelastic and results in a decrease in electron energy and thus a spreading of the beam toward the inside.

In summary, the electrons which produce light at the outside edge of the beam have lost a minimum amount of energy by inelastic collisions, were emitted from the negative end of the filament, departed perpendicular to the line joining filament and posts, and have no component of velocity parallel to the magnetic field. Finally, the filament post distances listed on the apparatus were measured from the filament to the bottom inside edge of the posts. Therefore, when aligning the beam with a post, position the outside edge at the bottom inside edge of a post.

8. Repeat the series of measurements done in step 7 for three more values of V_{acc} between 20 and 100V (for a total of $4 \times 5 = 20$ data points). Does the current required to cancel the earth's magnetic field depend on V_{acc} ? Should it?
9. Now keep the current through the Helmholtz coils constant (so that B is constant). Measure the radius of the circular path followed by the electron beam for three different electron velocities. Magnetic deflection of the electron beam such as that you have just observed is the method used to deflect the beam of electrons in a television picture tube and in video computer displays such as that in a Macintosh. (In contrast, an oscilloscope deflects the beam with an electric field).
10. Turn the Helmholtz coil current down to zero. Shut-down the electron gun by slowly turning down the filament and accelerating voltages until both are zero and turn off the power supply and multimeters.

Lab Report

Follow the usual lab notebook format. Your lab report should include the answers to all of the questions asked in the introduction or procedure, all raw and derived data, and an estimate of the magnitude and sources of error in any data recorded. When answering any question or when giving any comparison or explanation, always refer to specific data to support your statements.

For this lab also include the answers to the following:

1. What is the relationship you expect between the orbit radius and the Helmholtz coil current?
For a given V_{acc} how can you plot your first set of data so this is a straight line? Make such a

plot (by hand or using a Mac program such as Cricket Graph). What is the meaning of the slope? Of the intercept? Can you compare the intercept to something you have already determined? What?

2. Now, for a different V_{acc} , would you expect the data to lie on the same line? Why or why not? Should it have the same intercept? Make such a plot for each set of five radii. Compute the slopes and intercepts, and from them find the earth's magnetic field and the value of e/m .
3. Perform a similar analysis on the data you took of orbit radius as a function of accelerating voltage (what should you plot here to get a straight line?).
4. From all your data, find your best estimate of e/m (one of the fundamental physical constants). Estimate your uncertainty. Compare your value with the accepted value, and discuss any discrepancies.