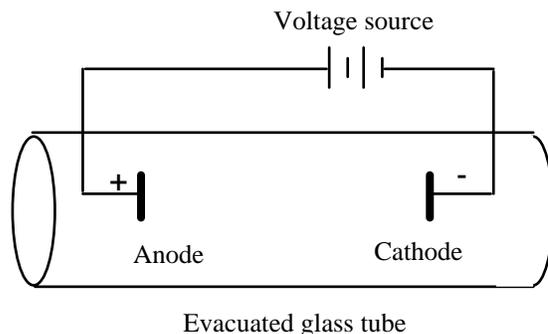


J.J. Thomson, Cathode Rays and the Electron

Introduction

Experimenters had noticed that sparks travel through rarefied (i.e. low pressure) air since the time of Franklin. The basic setup was to have two metal plates inside a glass tube. The air was removed from the glass container with a pump. One plate (called the cathode) was connected to the negative side of an electrical supply and the other (called the anode) was connected to the positive side of the electrical supply.



As pump technology improved, the appearance of the “spark” within the tube changed. A jumpy purplish stream replaced the spark, and in the 1830s Faraday noticed that a dark spot opened up in the beam near the cathode. By 1870, pump technology had improved considerably and the dark spot had expanded to fill the entire tube and experimentalists noticed that the glass glowed where the “cathode rays” (as they were being called at that time) hit the glass.

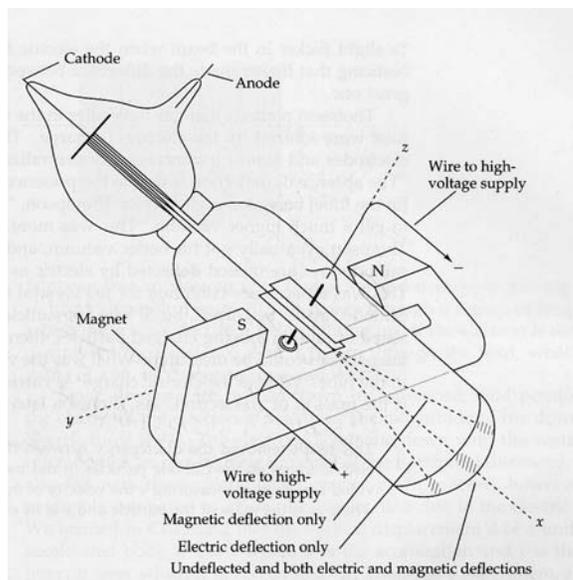
In the last half of the 19th century, scientists did many experiments with cathode ray tubes and tried to use the results to determine the nature of cathode rays. In 1879, Sir William Crookes demonstrated that cathode rays travel in straight lines by using the tube shown at the right. Crookes also demonstrated that magnetic fields could deflect cathode rays. He found that the properties of cathode rays did not depend on the metal used to make the cathode and anode.



The anode in Crookes' tube (shaped like a Maltese cross) prevents some of the cathode rays from hitting the far end of the tube, leaving a “shadow”. Photo credit: <http://members.chello.nl/~h.dijkstra19/page7.html>

According to Crookes, the current in the tube consisted of negatively charged gas molecules repelled from the cathode and traveling to the anode. Heinrich Hertz, a leading German experimentalist, tried to deflect cathode rays with an electric field, but was not able to do so. Since he knew that charged particles are deflected by electric fields, Hertz concluded that cathode rays were not charged particles, but waves that could be deflected with magnetic fields.

In 1894, J.J. Thomson, an English physicist, began a series of experiments that would resolve the controversy about cathode rays and lead to the discovery of the first subatomic particle. By constructing a cathode ray tube with the deflector plates inside the glass tube (at right), Thomson discovered --in direct contradiction with Hertz-- that cathode rays could be deflected by an electric field. Thomson's tube design allowed him to determine the ratio of the cathode ray particle's charge to its mass. The clever experiment exploits two ideas that were known about the interaction between electromagnetic fields and charged particles:



- A charged particle entering a region where there is a uniform electric field (and no magnetic field) will follow a parabolic path, much like a ball thrown horizontally off a building. The exact dimensions of the parabola depend on the mass of the particle, charge of the particle, its speed when it enters the field and the strength of the electric field.
- The speed of a charged particle can be measured indirectly by perfectly balancing the electric force against the magnetic force so that the charged particle goes in a straight line.

Thomson described his work as follows, "Cathode rays," *Philosophical magazine*, 44 (1897), 293-316:

As the cathode rays carry a charge of negative electricity, they are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter. The question next arises, What are these particles? Are they atoms, or molecules, or matter in a still finer state of subdivision? To throw some light on this point, I have made a series of measurements of the ratio of the mass of these particles to the charge carried by it [302].

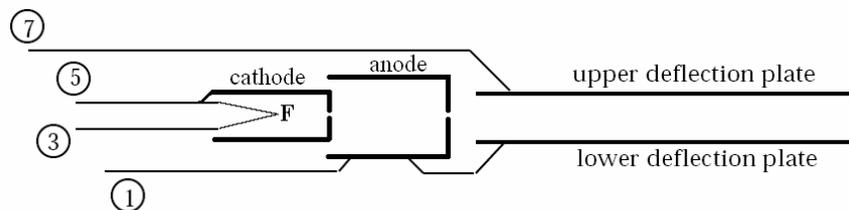
The value Thomson found for the charge to mass ratio led him to believe that the cathode ray particles were much less massive than even the lightest known atom:

... on this view we have in the cathode rays matter in a new state, in which the subdivision of matter is carried very much further than in ordinary gaseous state; a state in which all matter--that is, matter derived from different sources, such as hydrogen, oxygen, etc.--is one and the same kind; this matter being the substance from which all the chemical elements are built up [312].

In this lab, you will use a modern version of Thomson's tube to measure the charge to mass ratio for cathode rays.

Apparatus/Theory

Most of the apparatus is inside a glass vacuum tube. The diagram at right shows a side view of the essential features inside the tube.



By heating part of the cathode as a electric filament (marked F on the diagram) like a light bulb, the negatively charged particles can be freed from the metallic structure of the cathode. A voltage applied between the cathode and anode accelerates these negatively charged particles away from the cathode and toward the anode. Holes are arranged in the cathode and anode so that a narrow beam of "cathode rays" is produced, passing to the right in the diagram above. For our experiment, you will apply about 3000 volts between the cathode and the anode (recall that normal electrical outlets in the wall provide only 110 volts!).

Once the particles pass through the hole in the anode, they enter a region where you can apply an electric field and/or a magnetic field. The electric field is created by applying a voltage across two metal plates (the deflector plates in the diagram above). The strength of the electric field can be calculated if you know the voltage applied and the distance between the plates:

$$E = \frac{V}{d}$$

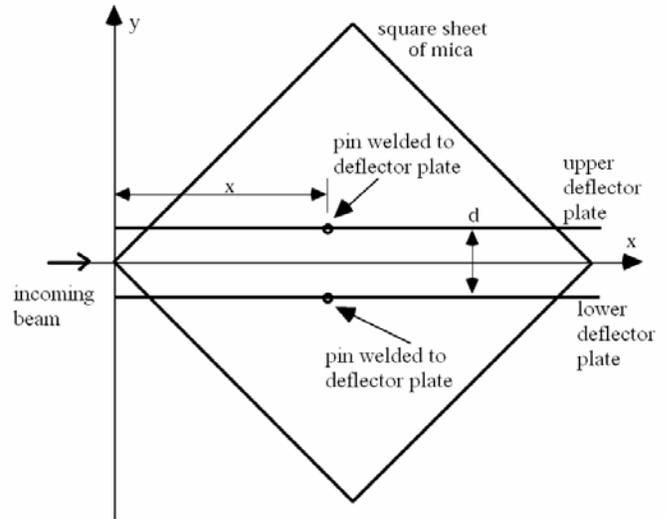
where V represents the applied voltage and d is the distance between the deflector plates ($d=0.80$ cm in our apparatus). The plates are oriented so that the negatively charged particles experience a downward electrical force.

The magnetic field is created by a current flowing through two coils of wire (these are called "Helmholtz coils") placed outside the cathode ray tube. The magnetic field strength, B (measured in tesla = N/ampere m), at the center of the coils is determined by the amount of current, I (in amperes), flowing through the coils. If the coils are set up according to the manufacturer's instructions:

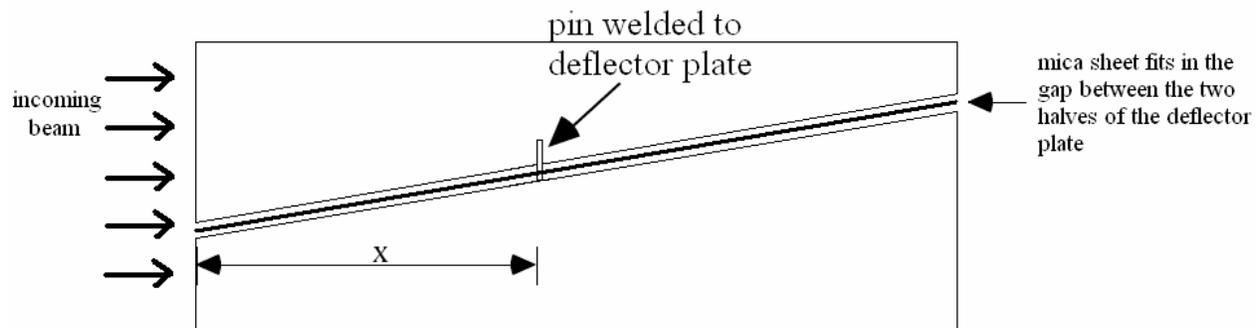
$$B = (4.17 \times 10^{-3} \text{ Tesla / Amp})I$$

The coils are oriented so that the negatively charged particles experience an upward magnetic force as they move through the apparatus.

To make the beam visible, a large square of mica has been set inside the tube. One side of the mica is coated with a luminescent material that glows blue when struck by electrons. This makes the beam path visible, even with the room lights on (see side view at right). Note also that a pin is welded to each deflection plate. The purpose of the pins is to help you measure the deflection of the beam. (For our apparatus, $x = 0.0500$ m and $d = 0.0080$ m).



You might wonder how the beam can possibly hit the mica sheet and how the pins can block the beam. The diagram below (a top view of the deflector plates) may help, particularly if you are looking at the apparatus at the same time you examine the drawing. The beam is shaped like a flat ribbon as it enters from the left. The mica is laid at an angle to the beam. The mica sheet passes through the gap between the halves of the deflector plates. Unless the beam is aimed at the pin, some of the beam will pass through the gap between the halves of the deflector plates.



Making the beam go straight

If there is no electric field or magnetic field, the beam will travel virtually undeflected through the apparatus. (What does this suggest about the force of gravity acting on the particles?) You can also make the beam go straight by adjusting the deflector plate voltage and coil current so that the downward electric force is exactly balanced by the upward magnetic force. If you've had physics before, you might remember that the

size of electric force on a charged particle equals the electric field strength times the amount of charge on the particle:

$$F_{electric} = qE$$

You might also remember that the size of the magnetic force equals the speed of the particle times its speed times the strength of the magnetic field¹.

$$F_{magnetic} = qvB$$

If the magnetic force and electric force are exactly equal, the beam goes straight. Setting the two forces equal, gives the following (somewhat surprising) result:

$$v = \frac{E}{B}$$

The upshot of this equation is that you can calculate the speed of the particles without knowing anything more than the values of E and B when the beam is straight. A note about units: If E is measured in Volts/meter and B is measured in Tesla, the velocity comes out in meters/sec.

Making the beam hit the pin (with B=0)

If you shut the magnetic field off and apply only an electric field, the beam will follow a parabolic path, much like a ball thrown horizontally from the top of a building. You can adjust the voltage across the deflector plates so that the beam hits one of the pins in the apparatus. Doing this will allow you to relate the things you can measure (the vertical deflection of the beam, the horizontal distance the beam travels before hitting the pin, deflector plate voltage and coil current) to the quantity you want to determine (in this case, the ratio of charge to mass: q/m). The technique would be analogous to changing the strength of gravity (if that were possible) while launching balls horizontally from the roof at a certain speed until the balls hit a target marked on the ground.

Just like the ball thrown from the roof, the charged particles in the electric field of our apparatus experience a constant downward force. Since the only (significant) force involved is the electric force, Newton's second law can be used to relate the acceleration to electrical quantities:

$$a = \frac{F_{electric}}{m}$$

or, combining this with $F_{electric} = qE$,

$$a = \frac{qE}{m}$$

As with the ball, the vertical displacement can be related to the acceleration² using

$$y = \frac{1}{2}at^2$$

Initially, this may not seem like a helpful equation. We can measure the vertical displacement y easily enough. If the beam hits the pin, y equals half of the distance between the plates. However, the time it

¹ You might remember a more complex relationship if you took physics before. The coils in this experiment are aligned so that the magnetic field is horizontal and perpendicular to the beam path. This arrangement makes the magnetic force on the beam point straight up and simplifies the math.

² This works because the initial vertical velocity of the ball (or charge) is zero.

takes the charged particle to fall that distance is not something we know or care to know. However, it is easy to remove the time from the equation above by noticing that it is related to the horizontal distance x traveled by the particle³: $x = vt$, or, equivalently

$$t = \frac{x}{v}$$

Combining these equations to eliminate variables that can't be measured directly (like a and t), you get

$$y = \frac{1}{2} \left(\frac{qE}{m} \right) \left(\frac{x}{v} \right)^2$$

Rearrange the equation and you have an expression for the charge to mass ratio:

$$\frac{q}{m} = \frac{(2y)v^2}{x^2 E}$$

If the velocity of the particles is the same as when you made the beam straight (which it should be, unless you've changed the cathode/anode voltage), you can use the equation above to calculate the charge to mass ratio. If all the distances are in meters, the speed in meters/sec and E in Volts/meter, the charge to mass ratio will be in Coulombs/kg.

Getting started

Safety first!

- This experiment involves **high voltages** and **delicate, expensive equipment**.
- If you have **any doubt** about a procedure, **consult your instructor!**
- If anything seems unsafe to you, **consult your instructor!**

Before turning anything on:

- Make sure the apparatus is correctly wired.
- Make sure all power supply knobs are turned all the way down (completely counterclockwise).
- Check alignment of the apparatus. Vacuum tube should be properly seated in its socket. The deflector plates should be parallel with the base of the apparatus. The Helmholtz coils should be aligned so that they are symmetrical about the center of the vacuum tube and are the correct distance from the center of the vacuum tube. See Appendix for details.

Getting started with the apparatus:

- Turn on the Digiramp power supply. This will provide a current to heat up the filament. After about 30 seconds, you should notice a glow from the back of the Thomson tube as the filament heats up, but there will not be a beam yet. In order to produce a beam you will need to

³ You might wonder how you can use the "distance = speed times time" equation even though there is an acceleration. Since the force is vertical, the horizontal component of the charge's velocity does not change. It moves equal horizontal distances in equal amounts of time.

increase the potential between the cathode and anode to about 2kV. See Appendix A (or consult your TA) for details on how to do this with the DigiRamp power supply.

- *Once you have set the cathode/anode potential, you should **leave it unchanged throughout the experiment**.* (Changing the anode/cathode voltage will change the velocity of the cathode rays).

Observation experiments:

How does an electric field affect a cathode ray?

Apply an electric field to the region in between the deflector plates. Record your observations.

Some things to consider:

- Is there still a coherent beam?
- How does applying the field change the beam? What effect does increasing the field have on the beam?

How does a magnetic field affect a cathode ray?

Turn off the electric field and apply a magnetic field to the region in between the deflector plates. Record your observations. (Consider the same questions as for the E-field).

Interpret the results: Once you have completed the observation experiments, answer the following questions, based solely on your observations above:

- Is it likely that cathode rays are made of identical particles? Explain how your observations support your position.
- Is it likely that cathode rays have a wide spread of speeds as they leave the anode and enter the region between the deflector plates? Explain how your observations support your position.



Discuss your findings with an instructor before continuing.

Application experiments:

A. Figuring out the speed of the particles in the beam

The apparatus described in this handout can be used to indirectly measure the speed of the cathode ray particles. Devise a way to determine the speed of cathode rays using this apparatus. For your method:

1. Describe the procedure you will use.
2. Construct the mathematical procedure you will use to analyze the data.
3. List the assumptions you have made in your design.



Check your procedure with an instructor before continuing.

4. Perform your experiment. Make sure you take steps to minimize uncertainty. Take steps to insure that assumptions made in the design are met.
5. Calculate the speed of the cathode rays in your apparatus based on your measurements and calculations.

After you have done the experiment,

6. Compare your results with a group nearby. Do they get the same results as you? Should they? Explain.
7. Compare the results with the speed of light.

B. Figuring out the charge to mass ratio of the particles in the beam

Devise a way to determine the charge to mass ratio of the particles in the cathode ray beam using this apparatus. For your method:

1. Describe the procedure you will use.
2. Construct the mathematical procedure you will use to analyze the data.
3. List the assumptions you have made in your design.



Check your procedure with an instructor before continuing.

4. Perform your experiment. Make sure you take steps to minimize uncertainty. Take steps to insure that assumptions made in the design are met.
5. Calculate the charge to mass ratio of the cathode rays in your apparatus based on your measurements and calculations.

After you have done the experiment,

6. Trade places with a group nearby and redo the experiment using their apparatus. Compare results. Do you get the same results as they did?
7. Compare the results from your original apparatus to the results from their apparatus. Some questions to consider:
 - Do the two apparatuses have the same value for speed of the cathode rays? Should they? If the results are substantially different, figure what difference in the equipment settings accounts for the difference.
 - Do the two apparatuses have the same value for charge to mass ratio? Should they? If the results are substantially different, figure what difference in the equipment settings accounts for the difference.
8. Compare the results for charge to mass ratio with the modern textbook value.

Safety first (and last)!

- Turn knobs on all power supplies to zero. (Don't leave *nasty surprises for the next user*).
- Turn all power supplies off.
- Shut off all meters.

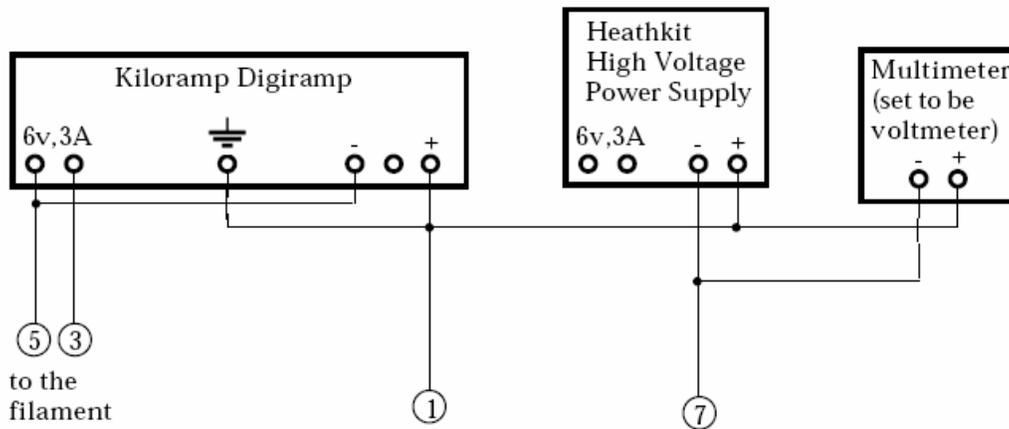
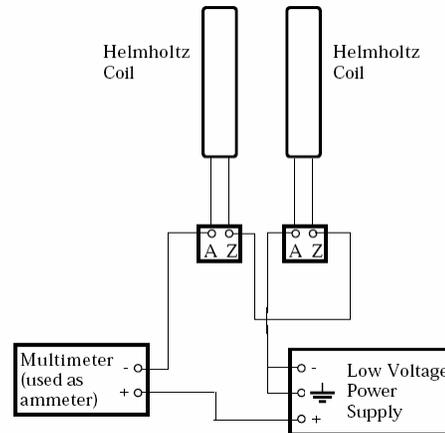
Wiring Diagram (FYI for TA's only! Students should not need to wire/rewire anything!)

The following diagram shows how the power supplies for the vacuum tube should be set up. (Note: This figure is taken from an old lab handout; in 2005, PASCO (rather than a Heathkit) power supply controls the plate voltage.

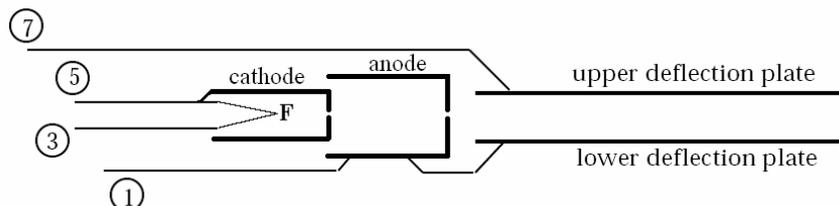
The circuit for the Helmholtz coils is shown at right. A GoldStar power supply controls the current through the coils. The GoldStar's internal ammeter is not very accurate, so a more accurate ammeter is placed in series with the coils.

A single power supply (Kilovolt DigiRamp) provides both the current (a few amps at 6V) for the filament and the high voltage (~2kV) that is maintained between the cathode and the anode. The power supply for the filament is connected across pins 3 and 5 on the vacuum tube. The high voltage (several kilovolts) between the cathode and anode is applied across pins 1 and 5.

A different power supply controls the strength of the electric field used to deflect the cathode rays. The power supply is connected across pins 1 and 7. A multimeter connected in parallel with the deflector plate power supply provides more accurate readings than the power supply's internal meter.



For convenience, a diagram of the innards of the glass vacuum tube is reproduced here.



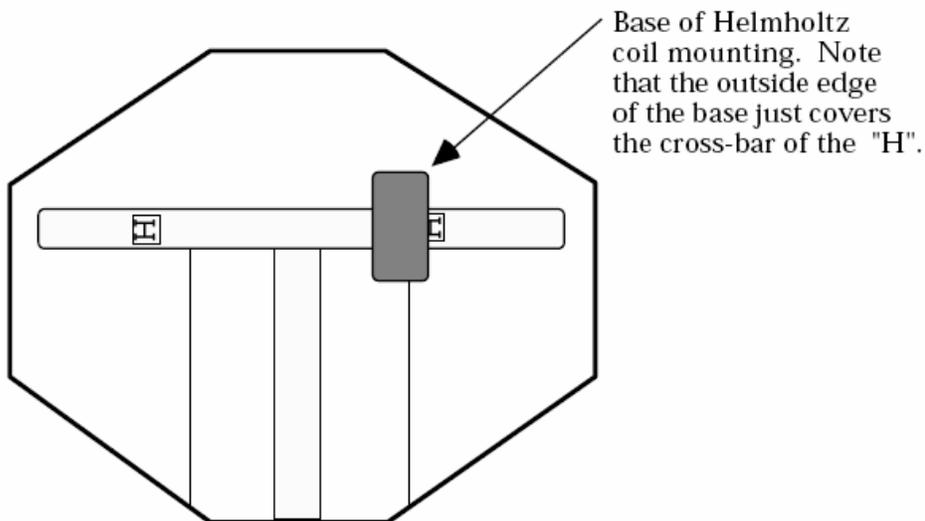
Appendix A: Digiramp power supply:

The DigiRamp power supply is two power supplies in one. One controls the voltage across the filament (and therefore the current through the filament). This first supply is low voltage, but can deliver a few amps of current. The second controls the voltage difference between cathode and anode.

The power switch is on the rear panel of the DigiRamp. The unit has a single knob and a single display. The blue switches select which function the knob has and consequently which quantity is displayed on the LED readout. Pressing the button marked "CT meter" sets the knob to control the low voltage output (the filament voltage in this experiment) and the display to show the corresponding. Pressing the button just to the right of the "CT meter" button selects the high voltage output circuit. The knob now controls the high voltage output (the anode/cathode voltage in this experiment) and the meter reads the high voltage. You should notice the "kV" indicator light up when you press this button (to reflect that the reading is in kilovolts).

Appendix B: Helmholtz coils alignment details

For proper alignment, the outer edge of each coil base should just cover up the cross-bar of the "H" symbol:



If the coils are aligned in this manner, the magnetic field at the center due to the coils is given by

$$B = (4.17 \times 10^{-3} \text{ Tesla / Amp})I.$$