# Junior Lab

# Cathode Rays — The e/m Experiment

In this lab you will get to play around with Cathode Rays, nowadays more commonly called electron beams. Remember such rays do have both particle and wave properties. Of course, e/m is more or less particle property. (If we have enough time we can demonstrate wave properties with a similar set of apparatus). To experiment with electron beams we need to know how to generate cathode rays, how to control their velocity, both magnitude and direction (i.e. accelerate them, bend them, etc.) and how to detect them. Work on cathode rays started at the end of the 1800's, and continued for more than the first half of the 1900's. Vacuum tubes, which use the physics of cathode rays, were the basis of the electronics industry, and still now electron beams are used in many applications, e.g. electron microscopes.

The discovery of the electron as a discrete particle, with charge e and mass m is generally credited to the British physicist Sir J.J. Thomson (1856-1940). His extensive studies of cathode rays culminated in the quantitative observations of the deflection of these rays in magnetic and electrical fields. These researches led to methods for the measurement of the ratio of charge to mass (e/m) for the electron. The currently accepted value is $1.759 \times 10^{11}$ C/kg. Thomson and others also used indirect techniques, based on the Wilson cloud chamber, to determine the order of magnitude of e itself, but and accurate value was first determined by Millikan in his oil-drop experiment (also set up in the room). With this experiment e was measured to be $1.60206 \times 10^{-19}$ C.

The set-up we will use to study cathode rays is on the table in Junior Lab. It is an evacuated glass bulb containing Helium at very low pressures. At one end there are two electron guns and surrounding the tube there are a pair of coils to generate the magnetic field. At the end opposite the e-guns, the inside of the bulb has a phosphor coating. Let's discuss these elements in more detail.

The e-gun consists of a hot filament (the source of the electrons) and a positively-charged (relative to the filament) can-shaped electrode, the anode, enclosing the filament. The anode extracts the electrons from the filament and accelerates. There is a hole at the center of the base of the can through which the electrons are emitted. *Why do we heat the filament? What energy, and hence what speed, will the electrons be traveling when they exit through the hole in the anode?* (Let the anode voltage be say 10 V and use accepted values of the constants you require). *Once outside the anode do the electrons feel the effect of the anode plate? Why or why not?* (It may be useful to think of a parallel plate capacitor). *Write down the equation that relates the final velocity of the electron to the anode voltage.* To make a very good e-gun i.e. monochromatic (all electrons have the same velocity) is more complicated. *What effects probably contribute to a spread in energy at the anode exit hole in the gun described above?*

Now we have a beam of electrons traveling in the bulb. *Does the bulb really have to be evacuated?* To understand this you must think about the size of the electron, use the classical size here (note it is very small), and the size of a typical atom. From the size of the atom, estimate the cross-sectional area, *A*, of the atom for which it will hit the electron. Consider a typical path length of the electron, *I*. For an electron to, typically (or on average), move this length, *I*, there can be very few atoms within this volume, *IA*. *Why is this*? *At STP, what is the average number of atoms in such a volume?* From this you have a relationship between pressure and the number of collisions and length, *I*. *Now, what must the pressure be so that on average there is only one collision in a length, I, with*

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*a diameter of the bulb of say 10 cm?* You need a pretty good vacuum, right? Actually, it will be through collisions with the background He atoms that we will be able to see the path of the electrons.

*Now, how does a B-field, oriented perpendicular to the electron's velocity out the gun, effect the motion of the electron?* Electrons moving in a circular trajectory result, right? Relate the radius of this trajectory, *R*, to the strength of the **B**-field and the accelerating voltage (anode voltage). Confirm that by measuring *R* for a given *B* and $V_A$, you can get *e/m*.

Think of a simple procedure to follow to determine *e/m*.

(I'll give you the formula relating B to the current through the coils.)

## MORE DETAILS

The RED BOOK contains nearly all the information you should require for this experiment including the schematic of the circuit. Below are brief discussions of various points regarding the measurements, *etc*.

## THEORY

This experiment is quite simple. The cathode rays (electrons) are produced and accelerated in the filament/heater-anode section.

{Electron energy, $E_e = q\,V_A = \frac{1}{2}m\,v_e^2$, where $v_e$ is the final electron velocity}

Then the electrons move in a circular path due to uniform B-field provided by the Helmholtz coils.

{Lorentz force on the electron, $F = q\,v_e \times B$   }

By appropriately combining the equations that govern the behavior in the two regions you can solve for *e/m* in terms of $V_A$, the anode voltage, and *B*, the magnetic field strength.

## APPARATUS

### Comment on Power Supplies

The power supply used for the Filament (heater) and that used for the Helmholtz Coils are somewhat more sophisticated than your average supply. They can control both the current out **or** the voltage out (not both!). Here I want you to leave the current limit control knob where I have set it and just control the output voltage with the voltage knob. I have set the current knob, so that the current output from the supplies cannot exceed the currents in red below. (*i.e.* even if you turn the voltage knob past where Ohm's law says that the current limit would be exceeded, the power supply is now in current limit mode so the current does not increase past the limit set.) This is a very useful feature for a power supply because it saves filament and magnet coils.

See the red Book for diagrams of the Filament (heater)/Anode assembly or the Helmholtz coils.

### Filament/Anode

Electrons "boil" off the filament and are accelerated to the anode. Those electrons directed through the hole in the anode escape the electric field and form the cathode ray.

Think of the filament and the anode forming plates of a capacitor. The energy of the emitted electrons is governed by the Anode Voltage, while the cathode ray current is related to the temperature of the filament, which governs the rate at which electrons boil off. Note not all electrons that leave the filament go through the hole in the anode. Most actually strike the anode to produce an anode current, which is now monitored in the experimental setup.

**Filament:**       **The maximum filament current, $i_f$ is 0.35 A.** Keeping the current slightly lower is even better. This corresponds to $v_f \approx 7\text{V}$, so $r_f \approx 20\ \Omega$. But be careful, the resistance changes with current because the steady-state filament temperature increases with steady-state current (the filament's temperature varies from 25 to about 1,000 $^o$C). So don't just turn the voltage up to 7.5 Volts - this will

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blow the fuse!. Instead increase $v_f$ until $i_f$ is about 0.3A, then let the filament equilibrate. The current drops with time right? Why? Repeat this, only this time increase $v_f$ until $i_f$ is again about 0.3A. Repeat this until the equilibrium $i_f$ is 0.3A. You should find that $v_f$ is about 7.5 Volts. These filament conditions will provide enough electron-beam current to illuminate the beam path sufficiently.

**Anode:** **The maximum Anode Voltage, $V_A$, is 300 V and the maximum Anode Current, $I_A$, 15 mA.** $V_A$ is controlled directly with the 0-400 Volt power supply. But the anode current is controlled by the filament current. Remember the filament current controls the filament temperature, which controls the rate at which electrons boil off of the filament. And this rate is exponentially sensitive to the temperature and the temperature is in turn super linearly related to the current in the filament. Or, more simply, the anode current is *very* sensitive to the filament current. Why do we care about the anode current? Well the electrons that hit the anode have a lot of energy, so that they can heat the anode assembly so that it can get very hot (250 Volts times 15 mA is 3.75 Watts) and this is very bad for the apparatus.

**Deflector:** The deflector plates are the Y-shaped plates between the two electron guns (D2 on Fig. 1 "Electron Gun", Apparatus Schematic). These plates act to slightly focus and deflect the beam. Note the potential applied to these plates is with respect to the anode voltage, as shown in Fig. 2 "Electron Gun Circuit", Apparatus Schematic. Setting the deflector voltage to about 25 Volts is generally fine.

## Helmholtz Coils

The theory of Helmholtz coils is described in the Red Book. Basically, such coils optimize the uniformity of the B-field within the coils.

For the coils we are using: $n$= 320 turns (in each coil), $r$= 0.068 m, and the separation of the coils is also $r$.

**The maximum coil current, $I_B$ is 1.0 Amps.** Do not exceed this current.

## EXPERIMENT

Only $V_A$ and $I_B$ are necessary for determining e/m, however, it is very important to record all the other parameters.

Play with the anode voltage, $V_A$, and Helmholtz-coil current, $I_B$, to explore how the circular path is affected by each. Keep $V_A$ between about 100 to 250 Volts. Make sure that the anode current $I_A$ stays below about 15 mA at all times. Also keep $I_B$ below about 1 A.

In playing with the circular path you will find that very odd things happen for low-energy small-radius beams. For example, for certain conditions the part of the circular path away from the gun may "disappear" while the path before and after is illuminated normally. Such a "dark" region is probably due to plasma effects. Also you may find that slowly sweeping either $V_A$ or $i_B$ that the radius of the orbit changes discontinuously. Typically this is most pronounced when you expand the beam. This to happens because of plasma effects within the tube. While these plasma effects are quite interesting it is not part of the lab to study them, rather it is important to make sure that these sort of effects are not affecting your measurements of *e/m*.

I recommend using the following procedure to get data. Select an appropriate orbit radius and determine the values of $I_B$ for which this radius remains unchanged for a selection of $V_A$ of say, 125, 150, 175, 200, 225 and 250 Volts. Repeat this for several other orbit radii. Then by plotting each set of data for each radius appropriately you can determine the value of *e/m*.