THE CHARGE-TO-MASS RATIO OF THE ELECTRON

Is the beam that produces images on a television tube or a computer monitor a beam of particles or a wave? This was a lively source of debate in the world of physics over one hundred years ago (long before there were televisions or computers). J. J. Thomson settled the matter in 1897, in an experiment which you will recreate today in class.

BEFORE LAB:

The 1890s were a Golden Age for research on beams, with the discovery of X-rays and natural radioactivity, and intense research on the cathode rays which we will study in the laboratory. Find a description of J. J. Thomson's experiment. What exactly did he do? What is the physics behind what he did? What were the results of his work? For bonus points, what was his technological edge that allowed him to succeed before his rivals did? (An interesting line of beam-physics research that *didn't* pan out is the story of *N-rays* .

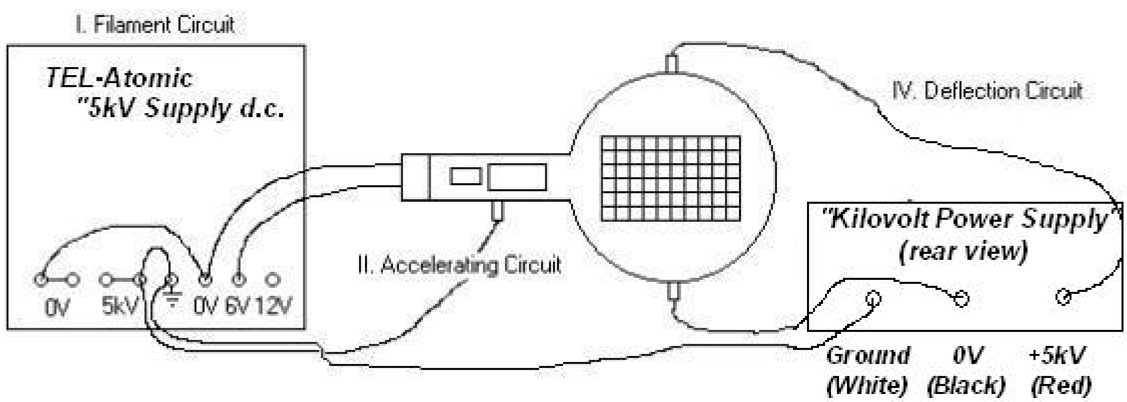

Figure 1: Wiring diagram of the e/m experiment (except for magnetic field circuit). Note the modular nature of the circuits.

THE EXPERIMENT:

CAUTION: In this experiment you will be working with potential differences of up to 5000 volts. As in other electrical experiments, you should be careful to avoid any exposed leads. Make sure that no wires that connect to high voltages show any exposed metal that you might accidentally touch.

Start with all power supplies turned off, and dial all voltage knobs to zero.

I. THE FILAMENT CIRCUIT (freeing the electrons):
Connect the two sockets on the 'barrel end' of the tube to 6VAC from the TEL-Atomic 5kV power supply (yellow sockets marked 0V and 6V). Check with your instructor to make sure you've done the right thing. Once you have these two wires connected, you may turn on the 5kV power supply. When you have turned on the power supply, there should be a white light glowing from the filament. If not, consult your instructor immediately. Turn the power supply off again.

II. THE ACCELERATING CIRCUIT (forming the electrons into a beam):
We haven't used the high voltage part of the power supply yet. Connect the leftmost 0V terminal of the TEL-Atomic high-voltage power supply (–) to the 0V terminal (yellow) of the filament circuit. Connect the rightmost red 5kV terminal to the metal pin sticking out of the side of the tube. To maximize your peace of mind, you will want to choose a wire that doesn't leave any metal exposed at this connection. Now connect either this side terminal or the (+) terminal of the power supply to the ground terminal of the power supply.

Do not turn on the power supply until your instructor has checked your circuit. Then turn it on, providing current to the filament, and increase the accelerating voltage slowly from zero until you see a blue line glowing on the paper grid in your tube. This is an electron beam. It should come on well before you hit 4kV. If not, don't panic. Call your instructor.

III. ELECTROSTATIC DEFLECTION:
Find the second 5kV power supply (the gray box marked "Kilovolt Power Supply"). Connect its ground (white socket at the rear of the unit) to the ground of the Tel-Atomic 5kV power supply (green socket with the ground symbol below it). Now connect the high-voltage terminals (red and black) to the two deflecting plates at the top and bottom of the spherical part of the tube. Once again, choose your wires so as to avoid exposed leads! Keeping the *accelerating* voltage constant, observe what happens when this *deflection* voltage is varied. The electrons can be shown to follow a parabola governed by

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

IV. THE MAGNETIC FIELD CIRCUIT: (not shown)
There are two Helmholtz coils, each with a terminal labeled A and a terminal labeled Z. Anchor the coils into the stand, with each one cradling the spherical end of the e/m tube. Connect the two Z terminals together, and connect the output of the adjustable 6V DC power supply to the terminal labeled A. Connect a DC ammeter in series with one of the power supply leads going to one of the A terminals.

ELECTROMAGNETIC DEFLECTION:
An electron of mass m and charge -*e*, moving with velocity *v* at right angles to a magnetic field *B* will experience a centripetal force giving it a circular path of radius *r*, where

$$Bev = mv^2 / r \tag{1}$$

Turn on the power supply to the Helmholtz coils. Answer the following qualitative questions in your lab notebook:
a) For a fixed accelerating voltage, V_a, how does the radius of the electron's orbit change with I_B, the current in the Helmholtz coil?
b) How can you change the velocity of the electrons? What effect does this have on the radius?

DETERMINATION OF e/m BY THOMSON'S METHOD:
Thomson showed that if an electrical field of strength E is applied at the same time as, and perpendicular to, an electromagnetic field B, so that the two deflections are in the same plane but opposite directions, these can be balanced by adjustment of the fields so that

$$eE = BeV \text{ , or}$$
$$v = E / B .$$

Turn the current to the Helmholtz coils back on and establish the condition of balance (no deflection) by varying the current I_B in the Helmholtz coils with a fixed V_P between the plates. Can you find a setting for voltage and current that gives a straight beam? What factors might be responsible for the curvature of the beam? (Answer these questions in your notebook.)

DETERMINATION OF *e/m* BY ELECTROMAGNETIC DEFLECTION:
More precise measurements of e/m can be made by assuming that the velocity of the electrons is governed by the 'gun' equation

$$eV_a = \tfrac{1}{2}mv^2 \tag{2}$$

together with measurements made when the electrons are deflected by the magnetic field alone. (The above equation assumes no relativity. For what values of V_a is that assumption justified?) Combining equations (1) and (2),

$$e / m = 2V_a / B^2 r^2 \qquad (3)$$

You can find the radius r of the curve if you know the position of two points on the curve. For circles passing through the origin (the exit aperture of the anode) and the points (x,±y), you can (and should) show that

$$r = (x^2 \cos^2 15^0 + y^2)/2y\ .$$

DATA COLLECTION:

1. Turn on the power supply providing filament current and accelerating potential, and turn up the high voltage until you get a faint beam. Adjust the position of the tube until the beam is as straight as possible.
2. Set the accelerating potential to 2000 volts, and adjust the output voltage of the power supply connected to the Helmholtz coils so that the center of the beam passes through the point (x=10cm, y=2cm) on the luminescent screen. Record the current in the Helmholtz coils.
3. Repeat step 2 for a total of at least five accelerating potentials.
4. Turn off the power supplies and interchange the leads supplying current to the Helmholtz coils so that the direction of the magnetic field will be reversed.
5. Turn on the power supplies and repeat steps 2 and 3 for the point (x=10cm, y=-2cm) on the luminescent screen.

ANALYSIS:

1. Calibrate your Helmholtz coils by finding the magnetic-field-to-current ratio, B/I. The instructor will have a calibrated magnetic field sensor. Carefully remove your e/m tube from its stand and put it back in its box. Send at least five different values of current through your coils, measuring the range of magnetic field values inside the volume of the coils. Calculate the *B/I* ratio (with uncertainty!) which you will need for converting *I's* to *B's* later. Measure magnetic field in units of Tesla (1Tesla = 10^4Gauss.)
2. Using the average value of Helmholtz current for each accelerating potential, calculate the magnetic field at each accelerating potential.
3. Compute a value for e/m at each accelerating potential. Compare your average value to the accepted value.
4. The equation for electromagnetic deflection (equation 3 above) can be rearranged to become:

$$V_a = \frac{e}{m}\frac{r^2 B^2}{2}$$

Plot V_a on the y-axis and $\frac{1}{2} r^2 B^2$ along the x-axis. From the slope of the graph, find an experimental value of *e/m* with uncertainty. Your actual uncertainty depends on other uncertainties in your experiment. Calculate it and compare your final results with the accepted value of *e/m*.