Cathode Tube Ray and Electron Mass-to-Charge Ratio

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Abstract

In this lab, we replicated Thomson's cathode tube ray experiment using a PASCO *e/m* apparatus that generated an electric and magnetic field using Helmholtz coils, cathodes, and anodes very similar to Thomson's cathode ray tube setup. The *e/m* ratio was calculated using the kinetic energy equation, centripetal force, and the Biot-Savart law. The final *e/m* equation is dependent on factors such as the accelerating voltage, the current through, and the radial measurement of the electron beam. The mean and standard error was found for each accelerating voltage and compared to the accepted *e/m* ratio of 1.758820e+11 C/kg. Results came within 3 standard errors which were likely due to personal error when recording measurements in which r in the *e/m* ratio was dependent on this measurement. Instrumental inaccuracies in outputting the correct voltage also likely occurred, affecting the final calculated values of *e/m*.

Introduction

The existence of the electron was first demonstrated by J.J Thomson who proposed that electron is composed of differing metals. He experimented on what was at the time called “cathode rays” by using cathode ray tubes. These cathode ray tubes are made of glass in which there is no air inside of the tubes. There is an electric potential difference, a cathode which is a negatively charged electrode and an anode which is a positively charged electrode on the other end. Then he applied a high voltage so the particles would flow from the cathode to the anode. Thomson noted that the cathode ray was deflected by the cathode and flowed toward the anode. Again, repeating this experiment using a magnetic field also showed the same results proving that this cathode ray was negatively charged [1]. Thomson experimented with cathodes of different metallic composition and noted that the cathode rays do not change properties. Using his experimental results, Thomson figured out the mass-to-charge ratio of the cathode rays allowing him to realize that they were much smaller than the particle itself, 1/2000 the mass of the hydrogen atom to be exact [1], that they were negatively charged, and that cathode rays or electrons are part of atoms. These cathode rays eventually became known as electrons.

The charge-to-mass ratio can also be measured using a similar method yet a different experimental apparatus that contains an electron gun, glass bulb, Helmholtz coil, and discharge tube. The glass bulb of the apparatus is filled with a low-pressure helium gas and it contains a heated filament that emits electrons that are accelerated downward due to the electric potential difference. This glass bulb sits between two parallel Helmholtz coils with the purpose of generating a uniform magnetic field within the glass bulb. These Helmholtz coils contain 130 turns and a radius of 0.150 m.

As electrons are emitted from the electron gun, the Lorentz force bends their path. The Lorentz force is a force exerted on a charged particle q that is moving at a velocity v through an electric and magnetic field [2].

$$\vec{F} = q\vec{E} + \overrightarrow{q_v} \times \vec{B}$$

The electrons are colliding with the helium particles from the gas within the glass tube, this emits a visible blue-green light showing the circular path that has been formed due to the magnetic field. Using built-in ruler contained within the apparatus, we can measure the diameter of this circular path and therefore calculate *e/m* values or the charge-to-mass ratio.

Experimental Procedure

This lab made use of a PASCO *e/m* apparatus containing a glass bulb filled with low-pressure helium gas, a heated filament for emitting electrons, and two parallel Helmholtz coils used to generate a magnetic field within the glass bulb.

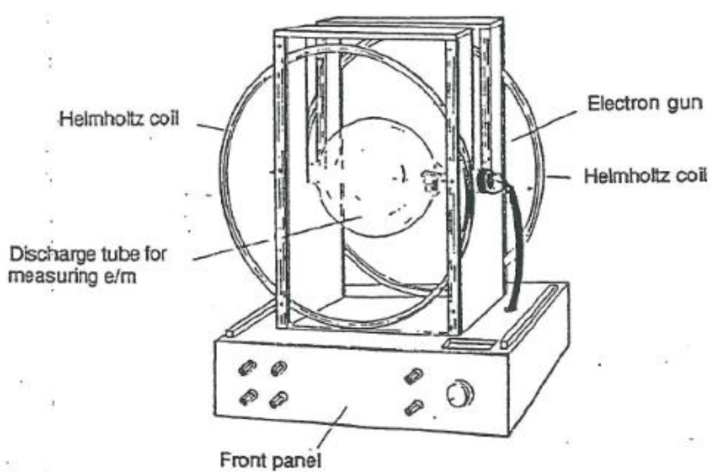

Fig. 1. Structure of the experimental apparatus

The number of turns is 130 and the radius of the Helmholtz coils is 0.150 m as specified by the manufacturer [3]. The maximum current it takes as also specified by the manufacturer is 3.5 A. Also, as per specifications, the acceleration voltage ranges from 0 - 200 V. This apparatus is configured to have electrons beamed through a metal anode from a metal filament attached to a cathode. The hole in the metal anode is purposed for allowing the electron beam to pass through, and this is what creates the "electron gun" effect.

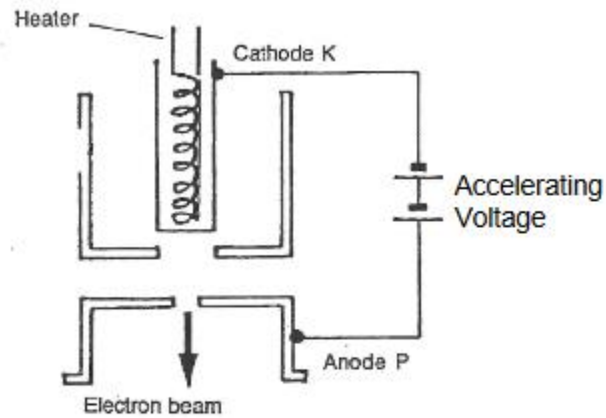

Fig. 2. Schematic detailing the function of the electron gun.

The following equations can be used to derive the *e/m* ratio:

Kinetic energy

$$\frac{1}{2}mv^2 = eV$$

Centripetal force

$$\mathrm{evB} = \frac{mv^2}{r}$$

Biot-Savart Law

$$B = \frac{8}{5\sqrt{(5)}} \times \frac{\mu_0 NI}{R}$$

The derived equation for *e/m* is as follows:

$$\frac{e}{m} = \frac{2V}{\alpha^2 I^2 r^2}$$

Where

$$\alpha = \frac{8}{5\sqrt{(5)}} \times \frac{\mu_0 NI}{R} = 8.767 \times 10^{-5}$$

N = 130, R = 0.150 m

$$\mu_0 = 4\pi \times 10^{(-7)}\mathrm{T} * \mathrm{m/A}$$

I = coil current

r = beam radius

V = accelerating voltage

We began this experiment by connecting a multimeter to measure voltage in parallel with a high voltage power supply (3B Scientific power supply) with a 0-500 V output and the accelerating voltage terminals of the *e/m* apparatus. A second multimeter to measure the current was also connected in series with the +/- terminals of the Helmholtz coils situated on the apparatus and the 0-12 V output of the power supply. Lastly, the +/- heater terminals on the apparatus were connected to the 0-8 V output on the power supply.

The bulb filament used for emitting electrons is heated when 5V is applied to the heater. We measured *e/m* by changing the accelerating voltages throughout the experiment between 200 V, 250 V, 300 V, 350 V, and 400 V. Once an accelerating voltage of 200 V is applied, the electron beam becomes visible. To bend it into a circular path, the current being passed to the Helmholtz coils is increased. After it is bent into this circular shape, using the ruler contained within the bulb, we measured the radius of the circular path beginning with the smallest possible diameter. As the accelerating voltage increased, the smallest possible diameter for the electron beam's circular path also increased. The current through the coils based on the accelerating voltage and beam diameter is recorded, along with the diameter of the circular path of the electron beam. Using our measurements for the current and radius of the circular beam, we calculated the *e/m* ratio for each accelerating voltage and each mean and standard error.

Results

The lab data are shown in figure 3. Specifically, the plot of the *e/m* values vs. the accelerating voltages. The accepted mean value for *e/m* is 1.758820e+11 C/kg and as expected most of the experimental values are close to this accepted value. Table 1 shows the mean and standard error for each accelerating voltage.

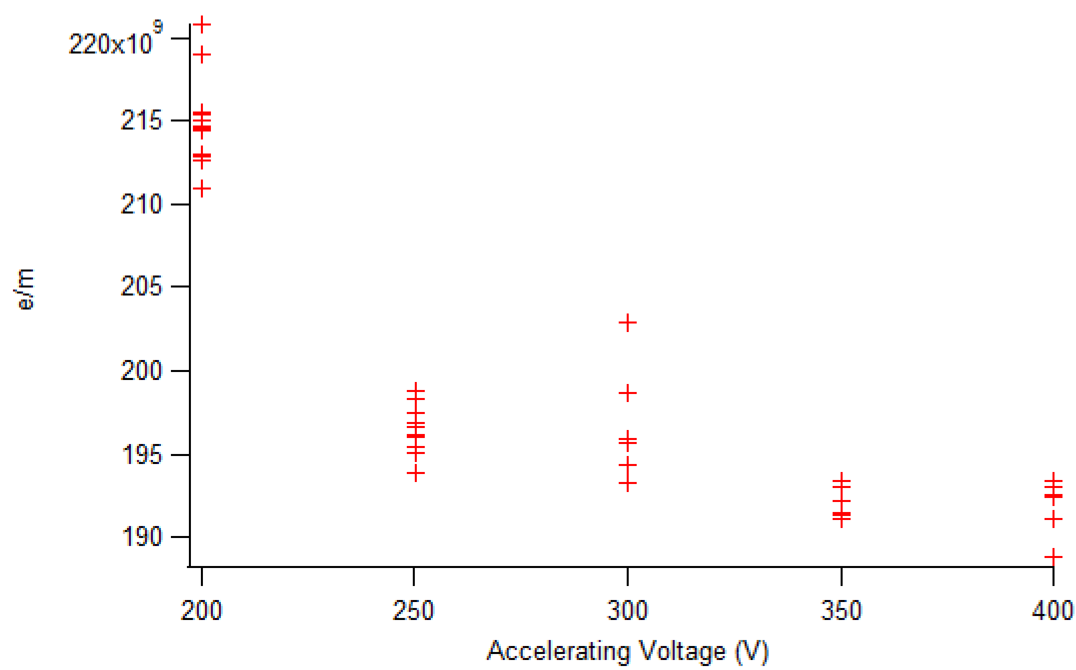

Fig. 3. *e/m* vs. accelerating voltage plot

The table below shows the mean and standard errors for each *e/m* values for each accelerating voltage. Since the *e/m* values are dependent on the radial measurement since we had to measure a circular electron beam rather than a linear beam, a measurement error could have occurred in trying to read the ruler built into the apparatus and it is possible that the radial measurement would be less accurate than a straight measurement of a linear beam. The *e/m* values are also dependent on the accelerating voltage output and the instruments used throughout the lab may have produced some uncertainty in not being completely accurate however close to the true value. The power supply used does not necessarily produce the correct value of the voltage being output, however, the voltmeter produces a more accurate reading and did assist in reducing this uncertainty by measuring the voltage output from the power supply. The accepted mean value for *e/m* is 1.758820e+11 C/kg.

e/m	200 V	250 V	300 V	350 V	400 V
Mean	2.14924e+11 c/kg	1.96462e+11 c/kg	1.96192e+11 c/kg	1.9194e+11 c/kg	1.91857e+11 c/kg
Standard Error	7.8184e+08 c/kg	4.70487e+08 c/kg	9.96322e+08 c/kg	3.62643e+08 c/kg	6.8716e+08 c/kg

Table 1. Mean and standard error of *e/m* values for each accelerating voltage

Curr_200v	Curr_250V	Curr_300v	Curr_350v	Curr_400v
2.022	1.999	1.994	1.93	1.942
1.828	1.841	1.894	1.818	1.836
1.703	1.722	1.763	1.725	1.748
1.58	1.609	1.671	1.635	1.655
1.49	1.525	1.578	1.549	1.591
1.385	1.437	1.496	1.478	1.504
1.304	1.372	1.43	1.412	
1.236	1.294	1.358		
1.166	1.234	1.3		
1.113	1.18			
1.053				
0.993				

Table 2. Current values per radial measurement for each accelerating voltage

r_200v	r_250v	r_300v	r_350v	r_400v
5.5	6.5	7	8	8.5
6	7	7.5	8.5	9
6.5	7.5	8	9	9.5
7	8	8.5	9.5	10
7.5	8.5	9	10	10.5
8	9	9.5	10.5	11
8.5	9.5	10	11	
9	10	10.5		
9.5	10.5	11		
10	11			
10.5				
11				

Table 3. Radial measurements in cm for each accelerating voltage

em_200v	em_250v	em_300v	em_350v	em_400v
2.13024e+11	1.95063e+11	2.02844e+11	1.93402e+11	1.93379e+11
2.19009e+11	1.983e+11	1.95851e+11	1.93076e+11	1.92982e+11
2.15011e+11	1.97441e+11	1.98666e+11	1.9129e+11	1.91081e+11
2.15381e+11	1.98763e+11	1.95892e+11	1.91105e+11	1.92376e+11
2.1097e+11	1.95997e+11	1.95934e+11	1.92155e+11	1.88811e+11
2.14604e+11	1.96892e+11	1.95658e+11	1.91438e+11	1.92515e+11
2.14449e+11	1.93852e+11	1.93257e+11	1.91117e+11	
2.12909e+11	1.96679e+11	1.9437e+11		
2.1472e+11	1.96163e+11	1.93257e+11		
2.1268e+11	1.95469e+11			
2.15517e+11				
2.20817e+11				

Table 4. Calculated *e/m* ratios for each accelerating voltage

Conclusions

For this experiment, the results were statistically significant. Any uncertainties are likely to have resulted from human error and minimal instrumentation errors. Recording the radial measurement of the circular electron beam was difficult as the built-in ruler was difficult to see. Also, since we were limited to a radial measurement as our beam took on a circular path, it is of question whether a straight beam would have yielded less uncertainty in the results since the *e/m* ratio was dependent on this measurement. Instrumentation errors may have occurred where it was difficult to get an accurate voltage reading, however, the voltmeter reduced this error. The significant finding that resulted from Thomson's experiment was the discovery of the charge-to-mass ratio of the electrons, therefore, proving that the electron is much smaller than the rest of the atom and that it is also a negatively charged part of the atom. Using a similar method in our experimental trials we have gotten similar results to Thomson. As previously noted, the accepted value for *e/m* is 1.758820+11 C/kg. The average values came within 3 standard deviations from the mean showing that the results are statistically significant and furthermore proves Thomson's findings.

References

[1] Khan Academy. (n.d.). *Discovery of the electron and nucleus*. Khan Academy. Retrieved October 5, 2021, from https://www.khanacademy.org/science/chemistry/electronic-structure-of-atoms/history-of-atomic-structure/a/discovery-of-the-electron-and-nucleus.

[2] S.T. Thornton and A. Rex, *Modern Physics for Scientists and Engineers* 4th ed., Boston, MA: Brooks/Cole (2013), pp. 5, 85-87.

[3]*E/M apparatus • se-9629*. PASCO scientific. (n.d.). Retrieved October 5, 2021, from https://www.pasco.com/products/lab-apparatus/electricity-and-magnetism/magnetic-fields/se-9629#specs-panel.