Measurement of charge to mass ratio of an electron using mass spectrometry

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1 Introduction

In this experiment our goal was to measure the charge to mass ratio of an electron by taking measurements using mass spectrometry.

2 Theory

An electron with charge e traveling through a uniform electric field $\vec{E}$ is subject to a force $\vec{F_E}$ given in (eq. 1).

$$\vec{F_E} = -e\vec{E} \qquad \text{(eq. 1)}$$

The same electron (w.r.t charge) travelling through a uniform magnetic field $\vec{B}$ at velocity $\vec{v}$ is subject to a force $\vec{F_B}$ given in (eq. 2).

$$\vec{F_B} = e(\vec{v} \times \vec{B}) \qquad \text{(eq. 2)}$$

These are visualized in Figure 1.

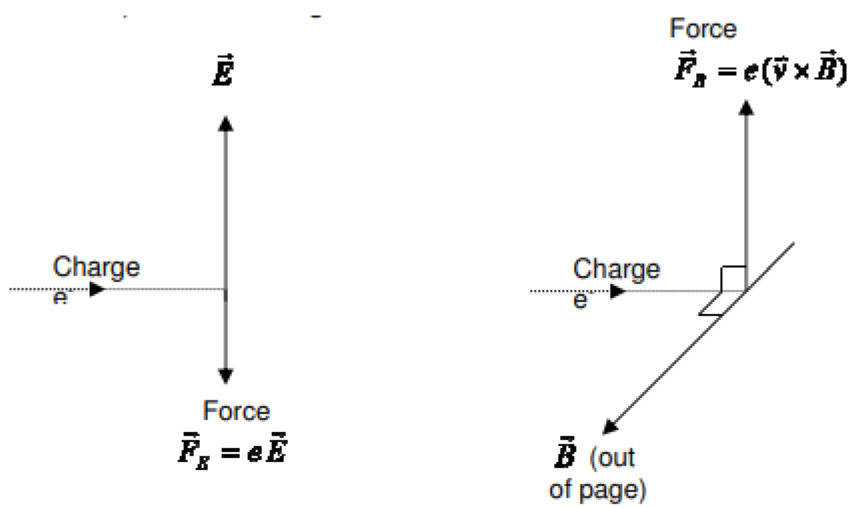


Figure 1: Visualization of electric and magnetic fields

If the magnetic field and electric field are perpendicular to the velocity of the electron and each other, the two forces can be along the same axis and therefore cancel out when the conditions in (eq. 3) are met.

$$e|\vec{E}| = e|\vec{v}||\vec{B}| \qquad \text{(eq. 3)}$$

In this experiment the electrons are accelerated using an electron gun through an electric potential difference V_a. The kinetic energy of the electron can then be determined from the voltage of this potential difference as shown in (eq. 4)

$$\frac{1}{2}mv^2 = eV_a \qquad \text{(eq. 4)}$$

Shuffling the variables around yields (eq. 5)

$$\frac{e}{m} = \frac{v^2}{2V_a} \qquad \text{(eq. 5)}$$

3 Experimental Equipment and Method

3.1 Apparatus

The apparatus is shown in Figure 2 and illustrated in Figure 3. The main components are listed below:

- Electron gun
- Helmholtz coils placed 6.9 cm apart from each other.
- Electric plates (inside the glass sphere where the electrons travel)
  - separated by 8.0mm
- Power supplies for each of the above
- Digital Voltmeters for V_a and V_p (explained below)
- Luminescent screen inside the glass sphere

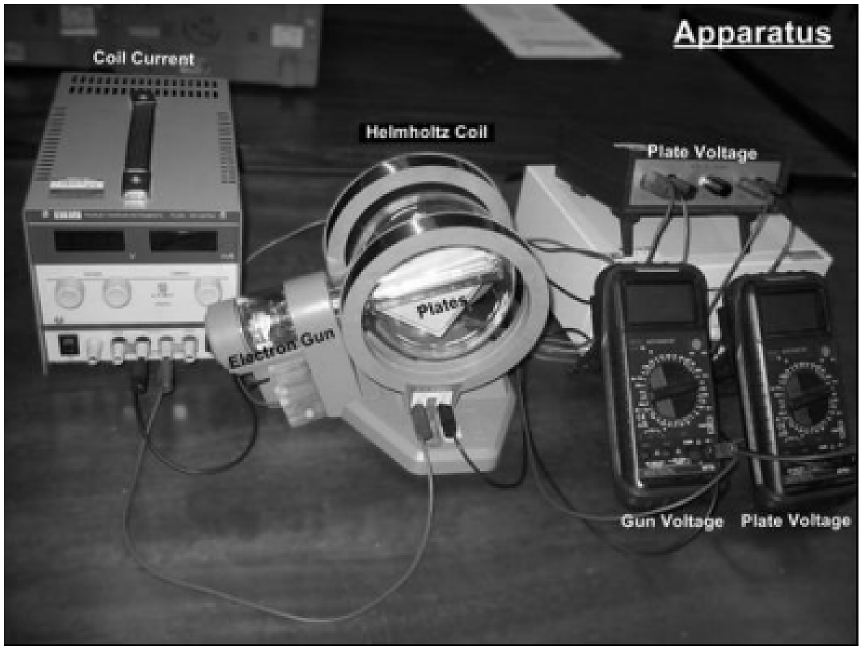


Figure 2: The experiment apparatus [2]

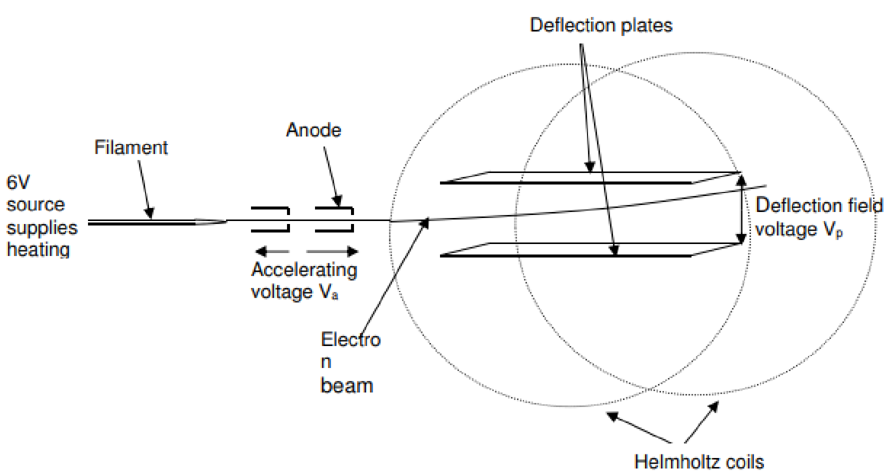


Figure 3: A diagram of the apparatus [2]

The magnetic field from the pair of Helmholtz coils B is derived by (eq. 6).

$$B = kI_h \tag{eq. 6}$$

where $k = 4.17 \times 10^{-3}\ TA^{-1}$ and I_h is the current flowing through the coils.

The electric field E between the plates is given by (eq. 7).

$$E = \frac{V_p}{d} \tag{eq. 7}$$

where V_p is the potential difference between the plates and d is the distance between the plates (in this experiment, the plates are 8.0 mm apart from each other.).

3.2 Protocol

The experimental protocol is described below:

1. Configure all the equipment according to the schematic in Figure 4
2. Set the voltage of the electron gun V_a to 3000V
   - Note that the Monitor voltage is always DC regardless of the actual voltage.
3. Main Measurement loop (parameters: $V_a \in [50, 300]$ and I_h [dependent variable])
   (a) Set V_a
   (b) Adjust I_h so the beam is straight and hits the opposite corner of the luminescent screen.
   (c) Take a measurement of that current.

4 Results

Our raw measurements are shown in Table 1.

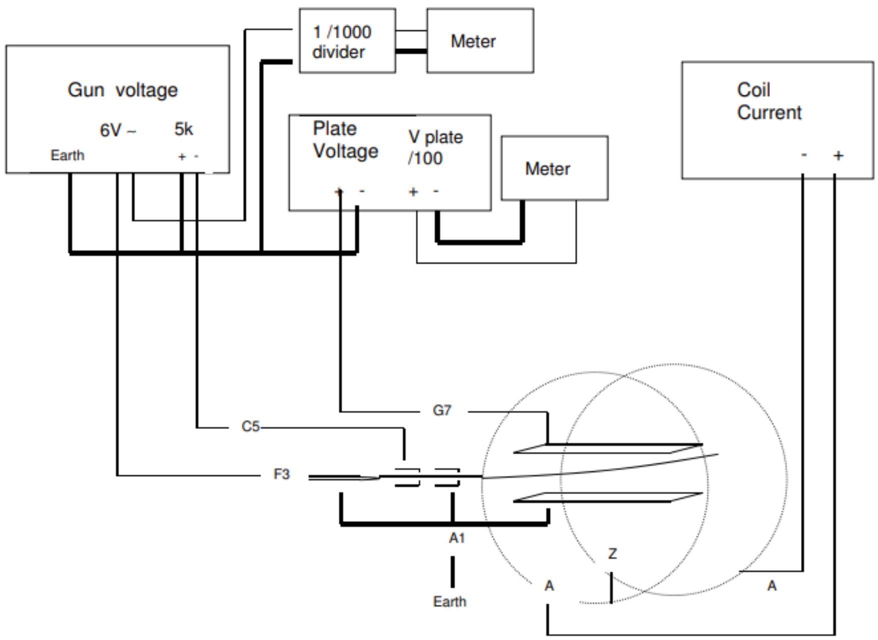
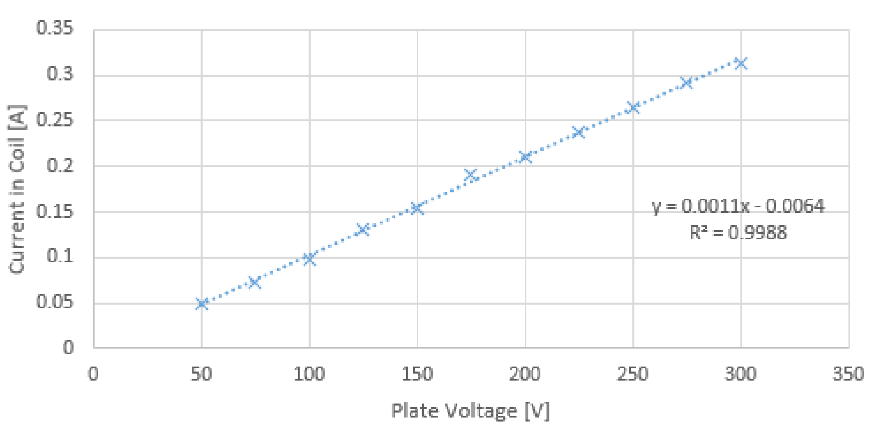


Figure 4: Schematic diagram of wiring for apparatus [2]

Vp [V]	**Ih [A]**
5.00×10^1	4.90×10^{-2}
7.50×10^1	7.30×10^{-2}
1.00×10^2	9.70×10^{-2}
1.25×10^2	1.30×10^{-1}
1.50×10^2	1.54×10^{-1}
1.75×10^2	1.90×10^{-1}
2.00×10^2	2.10×10^{-1}
2.25×10^2	2.37×10^{-1}
2.50×10^2	2.64×10^{-1}
2.75×10^2	2.92×10^{-1}
3.00×10^2	3.14×10^{-1}

Table 1: Raw measurements of I_h and V_a

The graph of I_h plotted against V_p is shown in Graph 1



Graph 1: Current in coil against plate voltage

By combining (eq. 5) with (eq. 6) and (eq. 7) we get (eq. 8)

$$\frac{e}{m} = \frac{V_p^2}{2d^2k^2I_h^2V_a} \qquad \text{(eq. 8)}$$

From (eq. 8) we can get (eq. 9)

$$G = \sqrt{\frac{m}{e} \times 4.49 \times 10^8 \times \frac{1}{V_a}} \qquad \text{(eq. 9)}$$

Which describes the gradient G of the graph.

5 Uncertainty Analysis

By using the Data Analysis package in Microsoft Excel, we measured the following values for the lower and upper 95% confidence for the gradient of Graph 1.

$$G \in [0.00105, 0.00111]$$

Therefore, the random error on our gradient will be:

$$\Delta G = 3 \times 10^{-5}$$

Using these values, our final measurement of the charge to mass ratio is given below:

$$\frac{e}{m} = 1.28 \times 10^{11} \pm 6.5 \times 10^{9} \text{ [C/Kg]}$$

6 Discussion and Conclusion

Our results seem to somewhat agree with the known measurements for the electron charge to mass ratio of 1.75×10^{11} [C/Kg] [1] (not an order of magnitude off). But our measurements seem to have some systematic errors.

Some possible reasons for this error could be due to the fact that we could not configure our Helmholtz coils precisely parallell at a distance of 6.9 cm apart. This could potentially affect the constant k since the value was most likely measured experimentally for the conditions described in the lab book.

Another potential source of error is from the thickness of the beam since the beam was very sensitive to perturbances in the coil current, the variance in the value for I_h is quite high from one edge of the beam to the other. We tried our best to align the center of the beam to the corner of the screen but that may have been a cause of error, although that should probably lead to a random error unless the operator was biased to offset the beam in a particular direction.

In conclusion, the experiment was a failure as it failed to capture the true value of the electron charge to mass ratio but we have identified some potential problems for future experiments.

References

[1] P J Mohr. "The 2014 CODATA Recommended Values of the Fundamental Physical Constants". In: (2016). URL: `http://physics.nist.gov/constants`.

[2] UPCSE. *Physics Laboratory Experiments*. 2018, pp. 1–80.