University of Tasmania

Second-year laboratory work

KYA212

The charge-to-mass ratio of the electron

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Safety

General information regarding lab safety can be found on POLUS, the lab website, whereas experiment-specific safety considerations are listed here.

Hazards

This experiment involves the creation of strong static magnetic fields. A serious hazard is posed to anyone with ferrous surgical implants and/or bioelectronic devices. Magnetically susceptible jewellery should be removed, and particular care should be taken with analogue watches and any form of magnetic storage media, as exposure to the fields may result in permanent damage.

The vacuum tube used in this experiment is energised with high voltage. Care must be taken to avoid discharge: do not power on the supplies unless the unit is safely wired, meaning that you are not part of the circuit, and the circuit must not be a shorted.

A risk assessment for this activity has been undertaken and approved by the relevant university authority; it can be accessed here.

Summary

A charged particle in electric and magnetic fields is subject to both the electric and Lorentz force. In the case where these fields are perpendicular, the motion of a charged particle will be helical, and using kinematics it is possible to relate the radius of circular motion to the charge-to-mass ratio of the particle. This in turn opens the door to undertaking *metrology*, which is the study of measurement, including the measurement of fundamental constants; in this experiment, the charge-to-mass ratio of the electron will be determined.

Experiment objectives and learning outcomes

The primary objective of this experiment is to measure the charge-to-mass ratio of the electron.

Following this experiment, it is expected that you will:

- Develop experience with the motion of charged particles in electric and magnetic fields.

Introduction

Prior to J.J. Thomson's discovery of the electron in 1897, the concept of the atom and theories about it's structure were basic. The term *atom* was coined around the 5th century BCE, when pre-Socratic Greek philosophers like Leucippus and his student Democritus proposed that all matter was composed of small, indivisible particles called "atomos" (the Greek word for indivisible). These early atomic theories were purely philosophical and lacked experimental evidence. For centuries, this idea was overshadowed by Aristotle's belief that matter was continuous and composed of four elements - earth, water, air, and fire, a view that dominated Western thought for nearly 2,000 years. Between 400 BCE and the late 18th century, not much headway was made on the atom front.

The revival of atomic theory began in the 17th and 18th centuries with the rise of modern chemistry. Thinkers like Robert Boyle challenged the classical elements and advocated for a more experimental approach. In the early 19th century, English chemist and physicist, John Dalton built on this foundation with his atomic theory, proposing that each chemical element was made of unique atoms and that chemical reactions involved the rearrangement of these atoms. Dalton's model was similar to the Ancient Greek's in that it described atoms as tiny, solid, indivisible spheres that combined in simple whole-number ratios to form compounds. This theory provided a scientific basis for understanding chemical behaviour, but it did not yet address the internal structure of atoms. The atom, up to this point, was still considered indivisible and without substructure.

In 1897, J.J. Thomson produced evidence for a tiny, negatively charged particle inside the atom through his experiments with cathode rays. Using a cathode ray tube, Thomson observed that the rays were deflected by electric and magnetic fields in a way that indicated they were composed of negatively charged particles. By carefully measuring the degree of deflection in these fields, Thomson was able to calculate the ratio of the particle's charge to its mass (e/m) and determined it was 1.0×10^{11} C/kg (compared to today's accepted value of 1.758820×10^{11} C/kg).

These particles, which he called "corpuscles" (later renamed electrons), were much smaller than atoms, and were common to all elements, suggesting that atoms were not indivisible after all. To accommodate this new understanding, Thomson proposed the "plum pudding" model of the atom in 1904. In this model, the atom was envisioned as a positively charged sphere in which negatively charged electrons were embedded, like raisins in a pudding or plums in a cake. Although this model was soon challenged and supplanted, it was the first to suggest that atoms were made up of smaller, charged components. Thomson's work marked a significant

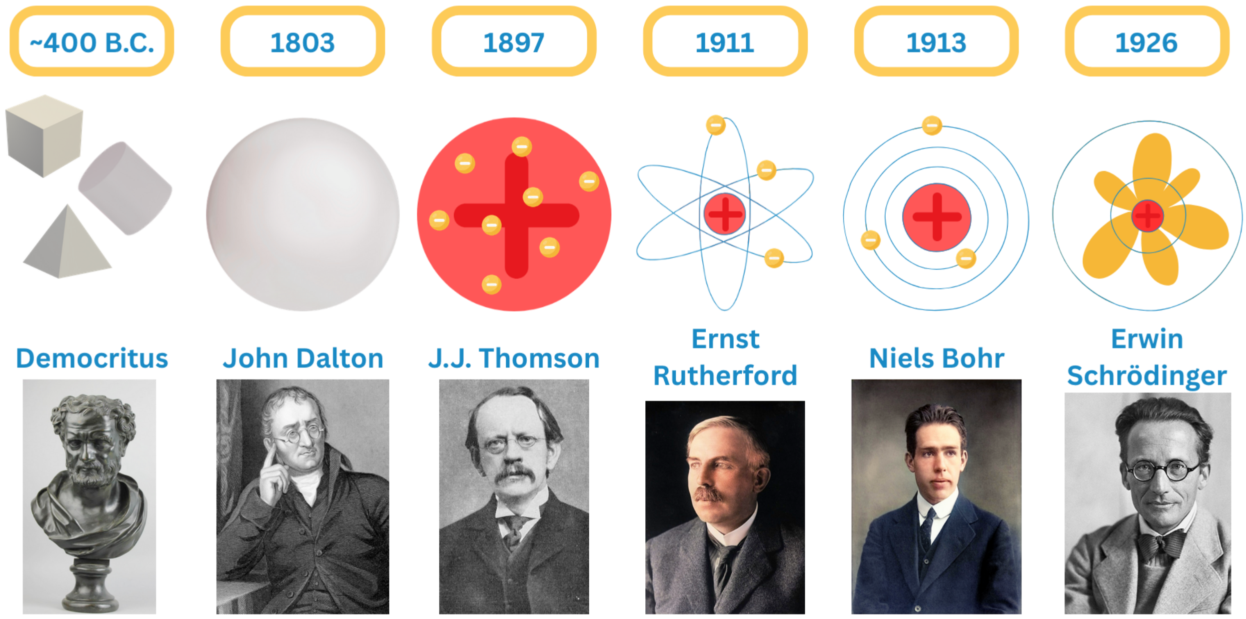

Figure 1: Timeline of the development of atomic structure.

turning point in atomic theory, laying the groundwork for more accurate atomic models, including the idea of a nucleus and the development of quantum theory.

Background

Pre-lab exercises

Pre-lab questions can be found sprinkled through the introductory section. These are to be completed and submitted *before* you commence a new experiment. The information needed to complete the exercises is contained in the experiment background section, your course notes, or in the appendices; however, your own independent research is highly encouraged. Make sure to include references where material has been foraged from elsewhere; this is not only "good form", but making notes of this kind - where to find useful information - is essential should you need to return to the origin of some information.

Context

Measurements of fundamental quantities often raise eyebrows. "Why would I need to measure that?" or "What is the benefit to precisely knowing <*that quantity*> to that degree of accuracy?" It turns out that there are many reasons to accurately know fundamental quantities, for example, the accuracy of the GPS system relies on corrections due to both special and general relativity, and thus require accurate knowledge of the speed of light and the constant of gravitation, along with the non-fundamental constants of the Earth's mass and radius. Moreover, the GPS system relies on atomic clocks, which are also fundamental to countless applications ranging from telecommunication (the internet) to navigation, and these rely on accurate knowledge of Plank's constant, the electron charge, and the Rydberg constant. The latter quantity, R_∞ is one of the most accurately measured quantities, with a relative standard uncertainty of 1.1×10^{-12}, and beyond the precise knowledge of R_∞ enabling the modern world to function (!), accurate and precise measurements of such quantities can give us fundamental insight into how are universe functions. Indeed, the degree with which R_∞ agrees with the value as predicted by quantum electrodynamics - the theory which marries quantum mechanics with special relativity - is seen as one of the great achievements of modern physics.

It would not be stretching the truth to say that our understanding of electrons and their interactions with the environment has underpinned the modern technological revolution. From being able to generate, transport, and store electrical energy, to enabling near-instantaneous worldwide communication, and performing calculations that would be otherwise intractable, the humble electron has fundamentally altered how we function as a species. Consequently, it can be jarring when people wonder whether it is worthwhile to interrogate the fundamental properties of the electron. And this line of reasoning ignores the utility that comes from being able to put our current understanding of the universe to the test: there are few simpler systems than an electron in an electromagnetic field, and thus it provides fertile ground for comparison of high-precision measurements and our best theories. In this experiment, you will use a method similar to that employed by J.J. Thomson to determine the charge-to-mass ratio of the electron. The setup includes a cathode ray tube, a pair of Helmholtz coils to generate a uniform magnetic field, and the necessary power supplies to operate them. An electron gun at the base of the tube emits a focused beam of electrons, which then enters the region of magnetic field produced by the coils.

Prelab 1 *Crossing the fields*

What force is experienced by an electron travelling with a velocity $\mathbf{v}$ in an electric field $\mathbf{E}$ and a magnetic field $\mathbf{B}$? Explain how a measurement of the charge-to-mass ratio of the electron could be measured with static electric and magnetic fields.

In this experiment (and the majority of experiments involving static electric and magnetic fields), the electric and magnetic fields are orthogonal.

Prelab 2 *Discriminatory behaviour*

What is the benefit of using orthogonal electric and magnetic fields? Now imagine we have a beam of electrons with a large velocity spread (that is, the temperature of beam is large); propose a system using perpendicular electric and magnetic fields which could be used to discriminate and tune the energy of the electron beam.

To introduce a magnetic field into the apparatus, an electromagnet comprised of two coils connected in series is used. The magnetic field due to a single coil of wire with radius R carrying a current I is given by:

$$B(z) = \frac{\mu_0 I R^2}{2\left(R^2 + z^2\right)^{3/2}} \tag{1}$$

where z is along the axis of symmetry. An electron moving with velocity v perpendicular to a constant, uniform magnetic field B experiences a Lorentz force F that acts at right angles to both the velocity and the magnetic field:

$$F = evB \tag{2}$$

where e is the charge of the electron. The result is a centripetal force applied to the electron causing it to move in a circular path of radius r as shown in Fig. 2. The centripetal force is given by

$$F = \frac{mv^2}{r} \tag{3}$$

where m is the mass of the electron.

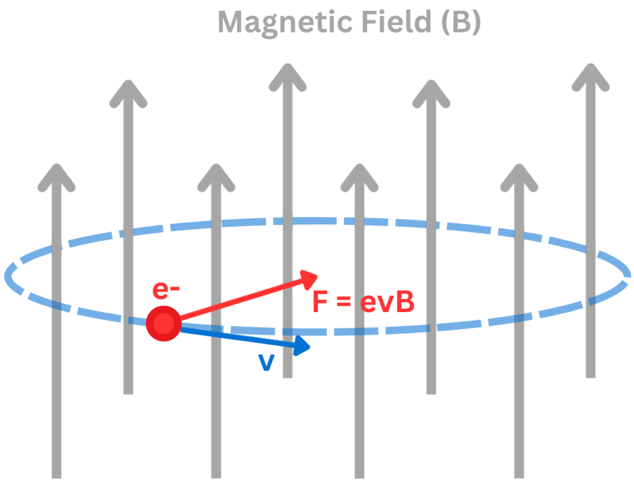

Figure 2: An electron moving in a direction perpendicular to a uniform magnetic field experiences a Lorentz Force, F, in a direction perpendicular to the velocity of the electron and the direction of the magnetic field.

Prelab 3 *Meat and potatoes*

In order to measure the charge-to-mass ratio of the electron, we are going to have to make some measurements. Show that for the apparatus used in this experiment, that the following equation is true:

$$\frac{e}{m} = 2U \frac{(\frac{5}{4})^3 R^2}{(\mu_0 N I r)^2}, \tag{4}$$

where each coil has radius R, number of turns N, and current I through each coil.

Prelab 4 *Chargeback*

If our charged particle source produced protons rather than electrons, what would be the differences in the experiment?

Prelab 5 *Misaligned*

What path would the electrons follow if their velocity were not totally perpendicular to the magnetic field (e.g. at 45°)? What if they were parallel with the field? How might this be achieved with this apparatus?

In this experiment, a cathode-ray tube is used to visualise the trajectories of electrons. The tube is filled with helium gas at a constant, low pressure. When a collision occurs between an electron and a helium atom, the helium is ionised and light is subsequently emitted.

Prelab 6 *The colour of electrons*

By what mechanism(s) would light be emitted following a collision? What is the minimum electron energy required to ionise helium, and how does this compare to the energies used in this experiment? What colour(s) do you expect the bulb to produce, and why?

Apparatus

To do this experiment, you will need the following components. A labelled diagram of the setup is shown in figure 3 and a schematic for how to connect them together is given in Fig. 4.

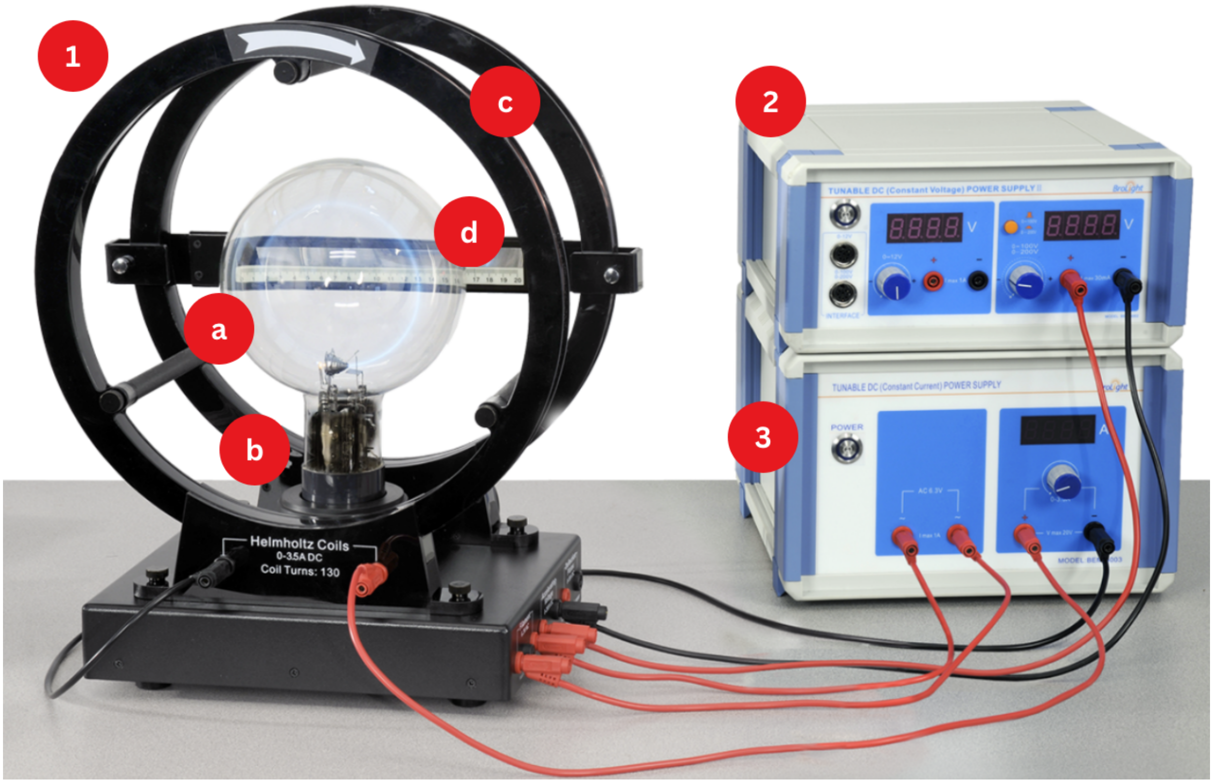

Figure 3: The components for the charge-to-mass experiment.

1. A **helium-filled glass bulb**, which houses an electron gun. produces electrons that are then accelerated towards the anode.

2. A set of **Helmholtz Coils**, which produce a near-constant magnetic field proportional to the current (I) that passes through them

$$B = \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{\mu_o N I}{R} \tag{5}$$

   where $\mu_0 = 4\pi \times 10^{-7}$ H/m is the permeability of free space, and each coil of has radius $R = 158\,\text{mm}$ and number of turns $N = 130$.

3. Ruler

4. Tunable DC power supply (constant voltage) (model SE-9644).

5. Tunable DC power supply (constant current) (model SE-9622).

6. Various electrical connectors

Connection Steps A schematic of the connection process is shown in Fig. 4. Take care to follow the process closely before switching on the apparatus.

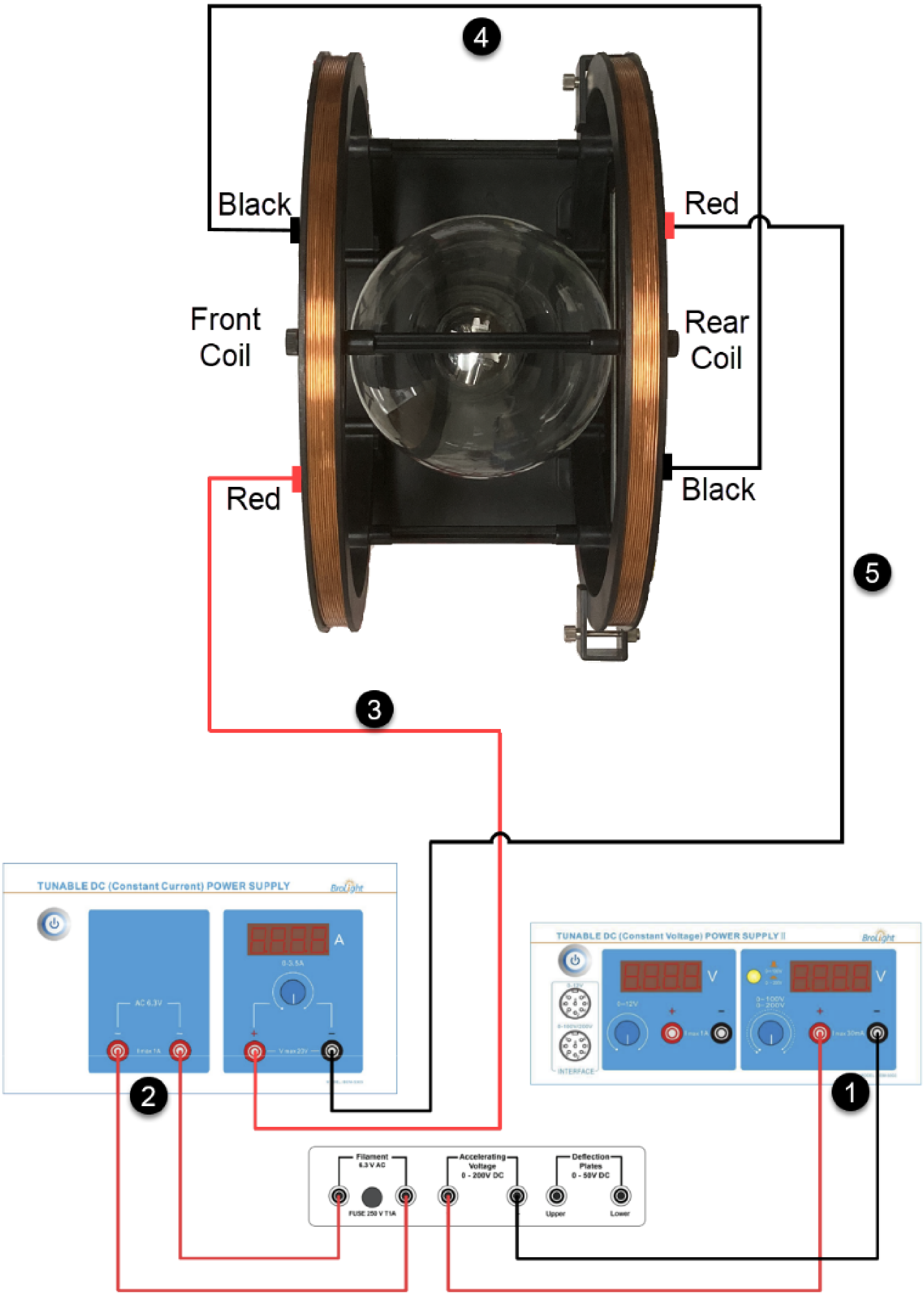

Figure 4: Correct connections for the coild, tube, and power supplies.

1. Looking at the Constant Voltage DC power supply, connect the positive terminal of the 200 V DC output to the accelerating voltage positive terminal on the e/m base.
2. Looking at the Constant Current DC power supply, connect both terminals of the AC 6.3 V output to the Filament terminals on the platform.

3. Still looking at the Constant Current DC Power Supply, connect the positive terminal of the 3.5 A output to the red terminal on the front Helmholtz coil.
4. Connect the black terminal of the front Helmholtz coil to the black terminal of the rear Helmholtz coil.
5. Connect the red terminal of the rear Helmholtz coil to the negative terminal of the 3.5 A output on the Tunable DC (Constant Current) Power Supply.
6. (Not shown) Connect the power cords to the power supplies, then use these cords to connect the power supplies to an electrical outlet.

Experiment

With the apparatus described and the relevant physics discussed, it is now time to design and execute an experiment that achieves the experiment objectives.

Exercise 1

With the apparatus provided, formulate an experiment that will allow you to measure the charge-to-mass ratio of the electron. It may help to think about:

- Considering Equation 4, what sorts of measurements should you take? What sort of plot will you produce and how does this help you determine e/m?
- How accurately can we measure the input current and voltage? Can you trust the power supplies?
- Should the radius of the produced ring be kept constant or allowed to change?
- How can we minimise parallax in our measurements?
- What other errors are present in this experiment? If any, consider how you might mitigate them.
- Will the ambient magnetic field produced by the Earth have a measurable effect on your measurements? If yes, is there a way you could deal with this?
- How many measurements should you take?

Once you have a clear plan, discuss it with a demonstrator.

Analysis

It's now time to turn our attention to calculating the charge-to-mass ratio for the electron.

Exercise 2

1. Using your data and Equation 4, determine the charge-to-mass ratio. How does this value compare to the accepted value of 1.758820×10^{11} C/kg? How does it compare to Thomson's original value of 1.0×10^{11} C/kg?
2. What is the advantage of using two coils over a single coil to make the magnetic field? The spacing of the coils is also an important consideration; what is the optimum coil spacing? Explicitly justify your response, evaluate the field at the centre of the two coils, and plot the expected magnetic field as a function of z.

References

Appendix