Specific Charge of the Electron Lab

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I. Introduction

This Labs purpose is to measure the specific charge of the electron. This can be done by producing a beam of electrons with a known energy and directing the beam perpendicularly into a static uniform magnetic field so that the electrons move in a circular orbit.

The theory behind this experiment can be explained if we let E be the energy of electrons moving in a circle of radius r perpendicular to a magnetic field B. We can set the centripetal acceleration equal to the Lorentz force divided by the mass as shown below.

$$\frac{evB}{m} = \frac{v^2}{r} \longrightarrow \frac{e^2B^2r^2}{2m} = \frac{mv^2}{2} \tag{1}$$

Setting the kinetic energy equal to eV, where V is the electric potential through which the electrons accelerate.

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

Our magnetic field is produced by a pair of Helmholtz coils driven by a constant current source. As it is difficult to measure V, B, and r accurately simultaneously, we will use the current in the Helmholtz coils as a parameter, changing the acceleration voltage while keeping the radius of the electrons path constant.

This experiment requires us to take two sets of measurements. For first frame, we can assume that the magnetic field increases linearly with current (look at equation (3)) and take multiple measurements of B as a function of I in order to obtain k_1. If we plot B as a function of I, k_1 would be our slope, and we can find its uncertainty with a least-squares fit model.

$$B = k_1 I \tag{3}$$

In the other frame, we would take a series of measurements varying V and I while keeping r fixed. Since the fractional uncertainty of I is probably larger than the fractional uncertainty of V, it would be best to plot I^2 as a function of V using the equation below,

$$I^2 = \frac{2m}{k^2r^2e}V \equiv k_2V \tag{4}$$

Where the slope of this plot would be k_2.

Combining equations (3) and (4) with equation (2), we would get the following result.

$$\frac{e}{m} = \frac{2}{k_1^2k_2r^2} \tag{5}$$

where,

$$\Delta\frac{e}{m} = \frac{e}{m}\left(\left(2\frac{\Delta k_1}{k_1}\right)^2 + \left(2\frac{\Delta k_2}{k_2}\right)^2 + \left(2\frac{\Delta r}{r}\right)^2\right)^{\frac{1}{2}} \tag{6}$$

Our goal in this experiment is to find k_1 and k_2, while keeping r constant to correctly measure the specific charge of the electron.

II. Layout and equipment

To conduct this experiment successfully, we must set up all the equipment in a dark chamber to accurately view the electron beam. We will be using a fine beam tube to contain the electron beam. Furthermore, we will be using Helmholtz coils and a measuring device, seen more clearly in Figure 4, and Figure 3 respectively. We will also be using a Leybold power supply to control a small voltage to the Weynelt cylinder in the beam source, and another power supply to power the Helmholtz coils. Finally, as we do not have a Teslameterr in the lab, we will be using a magnetometer app called “Gauges" found in the iphone App Store.

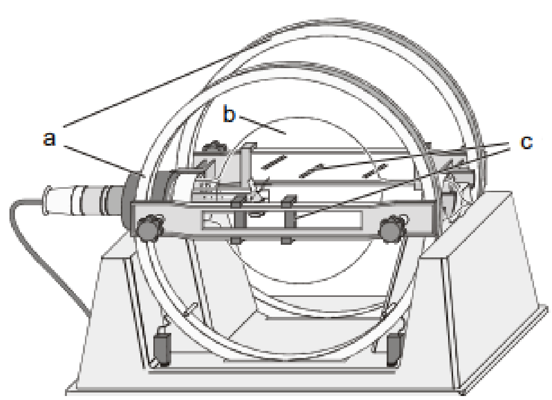

Fig. 1: Experiment setup for determining the specific electron charge. **a.** Helmholtz coils **b.** Fine beam tubes **c.** Measuring device

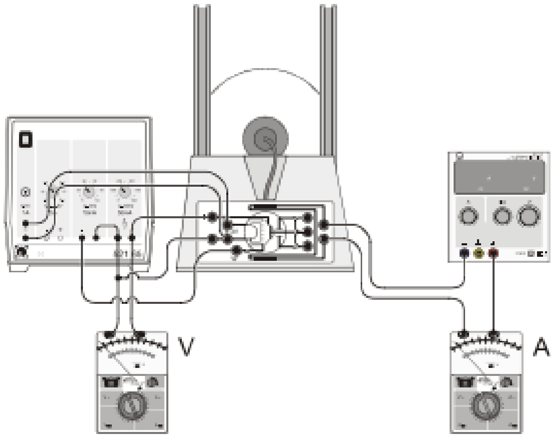

Fig. 2: Electrical connection for our experiment.

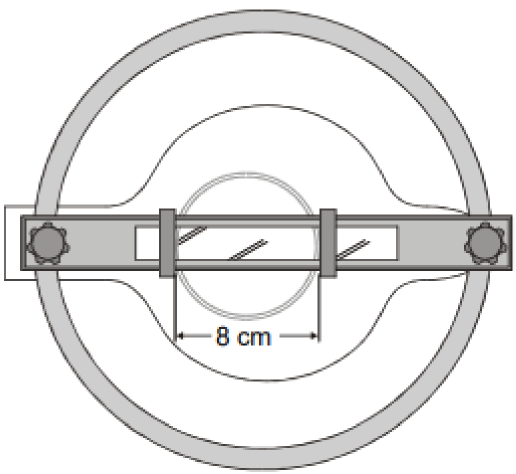

Fig. 3: Measurement of the orbital diameter with the plastic measuring device.

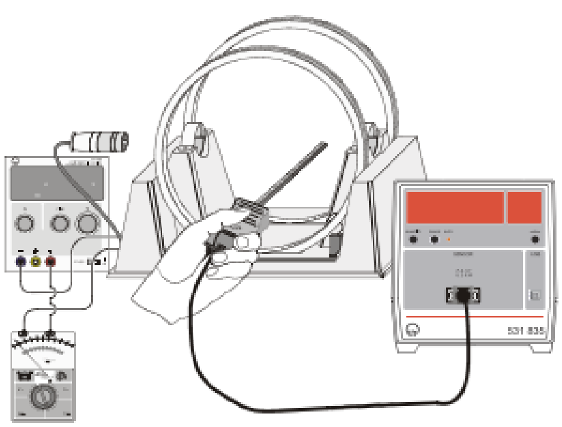

Fig. 4: Set-up for calibration of the Helmholtz magnetic field.

III. Procedure

A. Experimental Setup

To begin, we must first set up our experiment like Figures (1) and (2), ensuring the tube is centered inside the device. We must make sure that the mirror assembly is aligned horizontally and centered vertically with the Helmholtz coil on the other side of device (the furthest coil as seen in Figure 1). Next, we must attach the measurement device to the Helmholtz coil near us as seen in Figure 3.

Now we must turn on the Lybold power supply. To do this correctly, first ensure that all knobs on the power supply are fully counter clockwise, then turn on its power switch. Slowly turn up the acceleration voltage to approximately 300 Volts using the rightmost knob, labeled U. After the device warms up, we should begin to see a strong beam of electrons shooting from the mouth of the electron gun and colliding with the top glass of the tube.

Next we must turn on the Helmholtz coils using the power supply connect to them. We will be fluctuating between 1 and 2 Amps throughout this experiment. While doing so we must be cautious not to hold the current at 2 Amps for no more than a few minutes as this could be dangerous, we will set the current to around 1.9 Amps for now.

Now that the Helmholtz coils are powered, we will begin to see a slight circular motion of the electron beam, we must ensure that the beam is curving away from us, if it is not then the circuit has been assembled backwards and must refer to Figure 2 for guidance. If we look at the electron beam from above and it appears to follow creates a helical path instead of a circular, we must rotate the beam tube around its long axis. We must ensure to not touch the side of the tube with the plug attached.

We can focus the beam by adjusting the voltage emitting from the other knob on the Leybold power supply. The desired voltage would give off a strong edge definition on the side of the circular path opposite of the electron source.

Now that the electron beam is focused, we must move the measuring device to fall within the same line of sight of the mirror image and escape aperture of the electron beam. To correctly measure the diameter of the electron beam, we must set the inner right side to be 8.0 cm from the left.

B. Measurements

Next, we must adjust the current driving the Helmholtz coils until the circular orbit of the electron beam falls within the measuring device, resulting in a circle with a radius of 4 cm. At this point we must record our potential (V) and current (Amp). Continue this measurement by decreasing the potential in steps of approximately 10 V, adjusting the current to keep the electron beam at 4 cm.

We can perform a least-squares fit with this data using potential V as a function of current squared (I^2), the slope of this plot would give us our k_2.

We can use the following equation to ensure we correctly calculate the uncertainty in I^2.

$$\Delta(I^2) = 2I\Delta I \tag{7}$$

Once we finish with measuring the Potential and Current, we can turn off the Leybold power supply and reduce the current to the Helmholtz coils to zero. We will want to deconstruct the experiment where we will remove the measurement slide and the fine beam tube from the device. After placing the fine beam tube in its padded box, our set up should now look like Figure 4.

Now, using our smart phones' magnetometer app, we want to measure the magnetic field in the center of the Helmholtz coils as a function of current. Ideally we would want to take several measurements in the range of current that we just performed in the above experiment.

We can also perform a least-squares fit with this data to find our magnetic field B as a function of current I, the slope of this plot would give us our k_1.

IV. Data/Analysis

When performing our experiment, we were able to find k_2 by performing the first part of the experiment where we would adjust our potential and current to keep the radius of our electron beam constant. Our results are listed below:

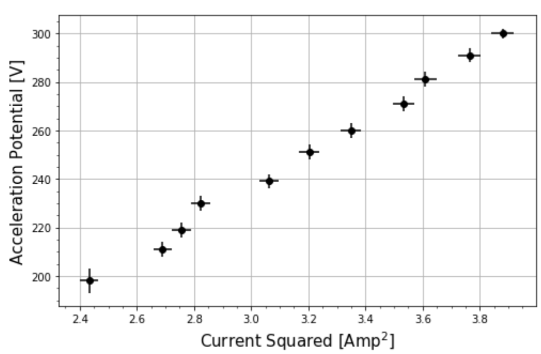

Fig. 5: Our Acceleration Potential Vs. Current Squared.

However, to accurately find k_2 we have to perform a least-squares fit on our potential as a function of current squared, using equation (7) to successfully calculate the uncertainty.

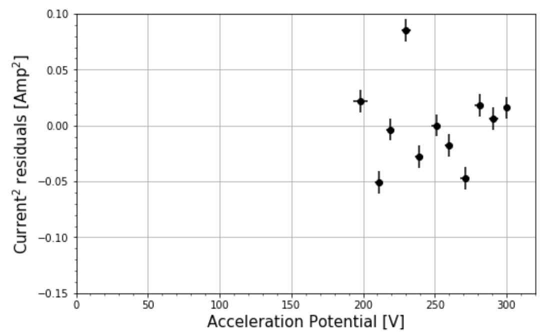

Fig. 6: Our Acceleration Potential Vs. Current Squared residuals.

In performing this least-squares fit, we found that our slope, $k_2 = 0.01413(28)$ Amps^2/V, with an intercept of -0.3403(78) Volts.

We were also able to find k_1 by conducting the second part of the experiment where we would remove the fine beam tube to find the magnetic field at the center of the Helmholtz coils. Our results are shown below:

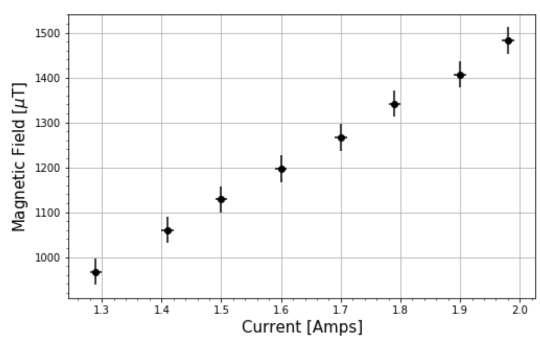

Fig. 7: Our Magnetic Field Vs. Current.

Just like in part 1 of the experiment, we must perform a least-squares fit on our Magnetic field as a function of current to correctly find k_2, the slope of our data. Doing so, we received this result:

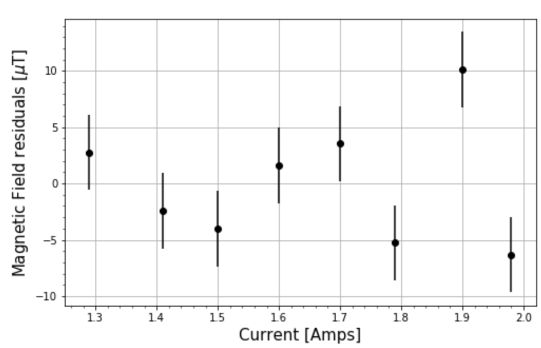

Fig. 8: Our Magnetic Field residuals Vs. Current.

In performing this least-squares fit, we found our slope, $k_1 = 732.821(61)$ μT/Amps, with an intercept of 25.0286(63) μT.

Now we can calculate the specific charge of the electron and its uncertainty by using equations (5) and (6). Using our measured radius to be $r = 0.0393(7)$ m, we found that the specific charge of the electron is:

$$\frac{e}{m} = 1.7004(36) \times 10^{11}\,\mathrm{As/kg} \tag{8}$$

With an uncertainty of,

$$\Delta\frac{e}{m} = 0.09901(37) \times 10^{11}\,\mathrm{As/kg} \tag{9}$$

Comparing this the the accepted value of 1.75882×10^{11} As/kg, our measurement is only 1.64(39)% off, and falls within our uncertainty.

V. Conclusion

The measurement that provided a majority of our uncertainty was k_2. This was due to a multitude of reasons, as when taking the data, the voltage coming from the Lybold power supply and into the fine beam tube seemed to fluctuate with a delay when adjusting. Furthermore, this value is held up to the most human error as the measurements are taken by eye. For example, when adjusting the voltage and current to keep the radius constant, we must move our head from its original observing point of the electron beam to adjust the equipment, when moving our head back to observe the change in the electron beam, it will not move back to the same exact observation position. To fix this, one may want to invest in a stronger measuring device and layout, possibly with a laser held perpendicular to the electron beam to ensure that measurement errors by eye would not appear so often. Or, we could go with a more simple option of having multiple people controlling the equipment while the observer of the electron beam keeps steady, not changing their observation position.

Furthermore, we encountered another error when taking our data on the magnetic field within the Helmholtz coils in part 2 of the experiment. As we used an iphone app to measure the magnetic field, the measurements fluctuated quite a bit. Possible reasons for this uncertainty could be that an app on a phone is not as sensitive as an official Tesla-meter. Furthermore, just like human error occurred in taking measurement for part 1 of the experiment, we found it difficult to return the phone to the same measuring location at the same angle, and as each angle and location within the Helmholtz coils gave a different value, this resulted in significant error.