

Lab #1: Bainbridge Tube Measurement of E/M

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INTRODUCTION

The purpose of the Bainbridge Experiment is to experimentally determine the charge-to-mass ratio of the electron. This is done by observing a beam of electrons as they travel in an arc due to the presence of a magnetic field. [Lab Manual] The diameter of the arc observed in the vacuum tube depends on how the charged electrons where affected by the magnetic field produced by a pair of Helmholtz coils to change its momentum. By measuring the current in the Helmholtz coils to bend the electron beam to known diameters for a set acceleration voltages, the charge-to-mass ratio of the electron can be determined as will be shown later.

In 1897, J.J. Thomson published a paper covering his experiments with cathode rays. In his paper, Thomson stated that the “unanimous opinion of German physicists [is that] they are due to some process in the aether.” [Cathode Rays] This aether, one popular theory at the time for explaining how information could travel through vacuum, was laid as an explanation for the bending of the cathode rays shot from the filament in cathode ray tubes due to the magnetic field. However, in his paper, J.J. Thomson relays that people should examine the possibility of an unknown negatively charged particle, not as a ray manipulated by the aether. In the latter sections of his paper he presented results from his experiments “to test some of the consequences of the electrified-particle theory.” [Cathode Rays]

Thomson concluded through his experimentation that the m/e ratio’s average was $1.29(17) \times 10^{-7} kg/C$, which is in the units that he used at the time, which are different from the units used today. He concluded that “the smallness of m/e may be due to the smallness of m or the largeness of e , or to a combination of these two;” although he knew his experimental data to not know the true m/e ratio, due to the variance in his data, he correctly concluded that “its value is very small compared with the value, which is... the value for the hydrogen ion in electrolysis.” [Cathode Rays] Thomson came back later in 1913 and ran another experiment where he found a closer approximation to our current e/m amount [Wikipedia].

Kenneth Bainbridge was a scientist in the 20th century who, among other things, created the device students use in this lab while he was at Harvard. [Bainbridge] He published this lab in *The Physics Laboratories*, entitled *The Specific Charge of an Electron*. [Bainbridge] Bainbridge,

in 1938, developed what we now know today as the Bainbridge Tube Measurement of e/m , which was not originally designed for scientists to use, but for students to use to develop skills for labs and experimental procedure. [Bainbridge] A version of his experiment is the basis for this lab report.

THEORY

Derivation of Charge-to-Mass Ratio

Th most important equation to determine the mass to charge ratio of the electron is:

$$\frac{e}{m} = \frac{2V_{acc}}{r^2 B^2} \quad (1)$$

Since it is such an important equation I will now derive where it comes from.

We begin with the Lorentz force:

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B}) \quad (2)$$

Since we know the electric current is not applied to the electrons E goes to 0, meaning the new equation is:

$$\vec{F} = q(\vec{v} \times \vec{B})$$

Now I will introduce a second equation, the one for the centripetal force, given by:

$$\vec{F} = m \frac{\vec{v}^2}{r}$$

Let us equate the two equations to create a new one:

$$q(\vec{v} \times \vec{B}) = m \frac{\vec{v}^2}{r} \quad (3)$$

We know by the set up of this experiment that the magnetic field generated by the two rings of current is perpendicular to the circle made by the path of the electrons, so $\vec{v} \times \vec{B} = vB$. We can now include this and solve for the velocity in equation 3.

$$v = \frac{qBr}{m} \quad (4)$$

Let us introduce the last needed equation, that of kinetic energy in relation to electron volts.

$$\frac{1}{2}mv^2 = eV \quad (5)$$

Lets plug in for velocity:

$$\frac{1}{2}m\left(\frac{qBr}{m}\right)^2 = eV$$

And now rearrange to get the final expression:

$$\frac{e}{m} = \frac{2V_{acc}}{r^2 B^2} \quad (6)$$

We see that equations 1 and 6 are the same!

Linearization of the Equations

Starting with the equation for the charge to mass ratio:

$$\frac{e}{m} = \frac{2V_{acc}}{r^2 B^2} \quad (7)$$

and the equation for the magnetic fields of the apparatus and the Earth:

$$B = B_0 I - B_E \quad (8)$$

Plugging the second equation in for the first, we get:

$$\frac{e}{m} = \frac{2V_{acc}}{r^2 (B_0 I - B_E)^2}$$

Since the dependent variable we are looking for is the current (I), we will solve for that:

$$I = \frac{\sqrt{2mV_{acc}}}{rB_0\sqrt{e}} + \frac{B_E}{B_0}$$

This form is correct analytically; however, this does not show the independent variables very well. The independent variables, the things we changed and fixed, were the radii and the V_{acc} . In light of this, let us separate this equation into $y=mx+b$ form, giving us:

$$I = \frac{\sqrt{2m}}{B_0\sqrt{e}} \cdot \frac{\sqrt{V_{acc}}}{r} + \frac{B_E}{B_0} \quad (9)$$

Now, in this final equation, we can clearly see which variables are the independent and dependent variables.

Questions

Which part of the beam should hit the post? I.e., what is the effect on the beam of hitting the gas molecules in the tube?

The part of the beam that should hit the post is the very outer edge because this is the part of the beam that carries the most energy, most closely approximating the energy the entire beam had at its inception. This is because the beam of light created before the post is using the outer, brightest electrons, which when imparting

their energy on the Mercury gas, lose some of their initial energy and fall into the middle of the beam. Since the electrons that have shone the brightest have lost some initial energy we do not want to use these in our calculations, so we use the new fresh outer electrons at the post.

How do maximize the range over which data can be taken? What are the experimental conditions that set the minimum and maximum data point?

We maximize and minimize the range over which data can be taken by varying the voltage of V_{acc} , this moves the beam in and out with respect to the posts inside the glass tube. The experimental conditions that set the minimum and maximum data points in this experiment are the posts in the glass tube. They give a frame of reference for which to measure the radius of the beam of electrons.

What is the optimal way to analyze the data set so that all data points are treated properly?

The optimal way to analyze the data set so that all of the data is analyzed properly is to linearize the data set and then use a linear regression to find the relation between data points. This is because linear plots are much easier to analyze to check for relations when compared to other types of relations.

EXPERIMENT

Setting up the Bainbridge Experiment was one of the most important steps in this entire experiment. There were two important steps: aligning parallel to the Earth's magnetic field and getting the bulb rotated.

There were two steps involved in aligning to Earth's magnetic field, that is aligning on our horizontal axis first, and then on our vertical axis. To align the horizontal axis, firstly we placed the Bainbridge apparatus on a table and a dip needle oriented horizontally was placed in near proximity to the device. Using the compass, we oriented the bulb's ends along the magnetic field lines. Next, the dip needle was rotated into a vertical orientation and the North end of the Bainbridge apparatus was raised to align the axis of the Helmholtz coils with the Earth's magnetic field. This alignment was performed to satisfy the requirements for the net magnetic field as described in theory section.

The last step in alignment of the setup was to rotate the bulb so that the electron beam was perfectly perpendicular to the magnetic field of the Helmholtz coils, as to create a circle instead of a helix.

DATA ANALYSIS

CONCLUSION