PHY 124 Lab 8 - Measurement of e/m for the electron

The purpose of this laboratory is the measurement of the charge (e) over mass (m) ratio e/m for the electron and to study qualitatively the motion of charged particles in a magnetic field.

Important! You need to print out the 2 page worksheet you find by clicking on this link and bring it with you to your lab session. [http://www.ic.sunysb.edu/Class/phy122ps/labs/dokuwiki/pdfs/124lab8worksheet.pdf]

If you need the .pdf version of these instructions you can get them here [http://www.ic.sunysb.edu/Class/phy122ps/labs/dokuwiki/pdfs/phy124lab8.pdf].

**Equipment**

- e/m apparatus
- meter stick
- black cloth

There are kinds of 2 e/m apparatus. Apparatus A has built in power supplies for delivering the magnet current and the accelerating voltage. Apparatus B uses external power supplies for these tasks. The settings you use for the two apparatus will be slightly different. Please make sure you have identified correctly your apparatus and use the settings and instructions that apply to it.

**Background to the experiment**

The principle of the e/m measurement is as follows (see the figure below): electrons are initially accelerated by an accelerating voltage V, and guided on a circular path by the magnetic field supplied by...
the two Helmholtz coils shown. The magnetic field $B$ at the location of the spherical vacuum tube, in which the electrons move is approximately perpendicular to the plane of the coils (the paper plane). It causes a magnetic force (see Ch18 sheet 7) to act on the electrons and guides them on a circular path which is perpendicular to the magnetic field in the middle between the two magnet coils. You can visualize this by using the right-hand-rule (remember the electrons have negative charge!).

![Image of the apparatus](image-url)

**e/m apparatus - top view**

- Coils
- Vacuum tube
- Electron circular path
- Coil diameter
- Angle $\alpha$
In the MapleTA prep assignment, you are going to derive the e/m relation you will use in your analysis for this lab. The kinetic energy KE and hence the velocity v of the electrons are determined by the accelerating voltage they have traversed (see Ch16 sheet 25). The radius r of the circular path can be related to the electron velocity and magnetic field (see Ch18 sheet 8,9). By combining these equations you will end up with a formula that relates e/m to the quantities you measure in this lab.

Use the equations on sheet 25 Ch16 and the relation \( KE = \frac{1}{2}mv^2 \), solving for the velocity to get a relation between the electron velocity v to the accelerating voltage V. Then use this relation and equation (18.2) for the radius r of the electron circular path (see Ch18 sheet 8,9). Substitute the equation for velocity into the equation for r and then solve for e/m. This will relate e/m to the accelerating voltage V and the magnetic field B. You should get the relation

\[
\frac{e}{m} = \frac{2V}{B^2r^2}
\]  
(8.1)

In Chap. 18, sheet 24 an equation is given for the magnetic field in the center of the plane of a single loop. In the lab prep exercise you are asked to modify this equation for N loops. Make sure you refer to the coil radius with the letter a.

To account for the 2 coils in our lab setup, we could approximately calculate the field by multiplying the field produced by 1 coil by 2 as you do in the lab prep exercise but this would not be quite right because the two coils are not stacked directly one on top of the other. A better equation for the magnetic field produced near the axis of a pair of Helmholtz coils at the location of the electron path is given by the equation (all units are SI)

\[
B = \frac{4\pi k'NI}{(5/4)^{3/2}a}
\]  
(8.2)

where

- N = the number of turns in each Helmholtz coil = 130
- a = the radius of the Helmholtz coils (see the figure above)
- k' = 10^{-7} in SI units, the universal magnetic constant (see Ch18 sheet 22)
- I = the current through the Helmholtz coils.

Substituting equation (8.2) for the magnetic field, B, in equation (9.1) gives, for e/m

\[
\frac{e}{m} = \frac{2V(5/3)^3a^2}{(4\pi k'NIr)^2}
\]  
(8.3)

You will use this expression (8.3) in the quantitative Part II.

NOTE: In this lab you will be measuring two radii, the radius of the circular path of the electron and the radius of the Helmholtz coils. The radius of the electron path will be referred to by the symbol r and the radius of the coils will be referred to by the symbol a.
Part I: Qualitative Exploration

Before you use the equipment to determine e/m, you will first investigate the relation between the voltage and current controls of the apparatus and the radius of the path of the electron. In this part you explore how the accelerating voltage $V$ and the magnet current $I$ influence the radius $r$ of the electron orbit. It is important to note that the voltage and current controls affect two different parts of the set up. The accelerating voltage, $V$, affects the electron beam and the magnet current, $I$, affects the magnetic field of the Helmholtz coils.

Procedure

<table>
<thead>
<tr>
<th>Apparatus A</th>
<th>Apparatus B</th>
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</thead>
<tbody>
<tr>
<td>Plug in the apparatus and turn the power on. Wait for 30 seconds during which the power supply runs a self-test. The power supply has dials (see the figure above) for the accelerating voltage $V$ (on the left) and the magnet current $I$ on the right. Set $V$ to ~ 150 V and $I$ to ~ 1.2 A.</td>
<td>The power supplies should already be connected before you begin. If not, ask your TA to do it for you. Plug in the power supplies and turn the power on for both units. Use the 500V adjust dial on the high voltage power supply to control the accelerating voltage $V$ and the current adjust on the e/m apparatus to control the current magnet current $I$. Set $V$ to ~ 250 V and $I$ to ~ 1.5 A.</td>
</tr>
</tbody>
</table>

You should see the electron circular path as a “blue-green” glow. This glow comes from the ionization of a small amount of Helium left in the vacuum tube by the electron beam. Note that you will probably have to either cover the coil with a dark cloth or dim the room lights to see the glow.

Keeping $V$ constant at either 150 V or 250 V, depending on your setup, increase $I$ in several steps and observe the radius $r$ of the electron path. Explain your observation in terms of the coil current $I$, the electron velocity $v$ and the relation (18.2) in Ch18 sheet 9.

Keeping $I$ constant at ~either 1.2 or 1.5 A, depending on your setup, increase $V$ in several steps and observe $r$. Explain your observation in terms of the accelerating voltage $V$, the electron velocity $v$ and the relation (18.2) in Ch18 sheet 9.
Part II: Measurement of e/m

In order to get an accurate coil radius, a, you will take several measurements and use their average for future calculations. Measure the vertical (from top to bottom) and the horizontal (from left to right) diameter (from the middle of the coil winding) for both coils and enter them on your worksheet. Notice that these values are referred to as 2a because they are diameters. Take the average of these 4 measurements to calculate the coil radius you will used in the analysis:

\[ a = \frac{1}{2}(2a_{v1} + 2a_{v2} + 2a_{h1} + 2a_{h2})/4 \]

Estimate the error of one diameter and assume it is the same for each of the 4 measurements. Calculate the error of the average value of a using equation (E.5b) and (E.5a) in the error and uncertainty manual.

Procedure

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<tbody>
<tr>
<td>To measure the electron beam radius, r, you will use the marks etched on the glass scale in the vacuum tube. Be careful to notice that these marks are in cm and give the diameter of the beam path! You will take your data by keeping a fixed I and varying V. Keep I fixed at ~ 2 A and start with V ~ 150 V. Increase V in ~ 6 steps such that at each step the electron beam hits the cm marks etched on the glass scale in the center of the vacuum tube. It is more important that the beam hits these marks than to have equal V steps. For each step record V, I, r and your estimate of the error Δr in the table on your worksheet.</td>
<td>On apparatus B the globe can be rotated, altering the direction of the beam path relative to the magnetic field. Before you begin to make this measurement you should ensure it is oriented so that the beam forms a circle and not a spiral. To measure the electron beam radius, r, you will use the illuminated mirrored scale on the back of the apparatus and the ruler in front of the apparatus. The mirrored scale helps to reduce parallax error, you do this by moving your head until the edge of the reflection of the beam in the mirror aligns with the edge of the actual beam. (This means that you are looking straight on at beam.) Then position the metal triangle on the front ruler so it touch the sides of the beam path and measure the beam path radius from the scale on the mirrored ruler. Take an average of your measurement of the radius when you are looking from the left and from the right as the radius of the beam. You will take your data by keeping a fixed I and varying V. Keep I fixed at ~ 2 A and start with V ~ 200 V. Step V up in 6 steps of ~ 50V. For each step record V, I, r and your estimate of the error Δr . For each step record V, I, r and your estimate of the error Δr in the table on your worksheet.</td>
</tr>
</tbody>
</table>

When estimating Δr for either apparatus, consider things like the fuzziness or the brightness of the beam. Note that Δr does not have to be the same for each measurement.
Assume that the errors of V and I are negligible. Solve equation (8.3) for V and write it such that it has the form \( V = \text{constant} \times \frac{e}{m} \times (Ir)^2 \) where "constant" stands for a factor containing only quantities that are constant during the experiment, including the magnet coil radius \( a \). Calculate the value of "constant" and enter it on your worksheet. Notice it includes the radius \( a \) of the magnet coils, which has an uncertainty so you must propagate the error of \( a \) into the error of the constant using expressions (E.1) and (E.8) in Error and Uncertainty.

Transfer your recorded data into the form below.

<table>
<thead>
<tr>
<th></th>
<th>V1</th>
<th></th>
<th>V</th>
<th></th>
<th>I1</th>
<th></th>
<th>A</th>
<th></th>
<th>r1</th>
<th></th>
<th>m</th>
<th>Δr1</th>
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<th>m</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2</td>
<td>V</td>
<td></td>
<td>I2</td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td></td>
<td>r2</td>
<td></td>
<td>m</td>
<td>Δr2</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>V3</td>
<td>V</td>
<td></td>
<td>I3</td>
<td></td>
<td></td>
<td></td>
<td>A</td>
<td></td>
<td>r3</td>
<td></td>
<td>m</td>
<td>Δr3</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>V4</td>
<td>V</td>
<td></td>
<td>I4</td>
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<td></td>
<td></td>
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<td>Δr4</td>
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</tr>
<tr>
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<td>V</td>
<td></td>
<td>I5</td>
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<td></td>
<td></td>
<td>A</td>
<td></td>
<td>r5</td>
<td></td>
<td>m</td>
<td>Δr5</td>
<td></td>
<td>m</td>
</tr>
<tr>
<td>V6</td>
<td>V</td>
<td></td>
<td>I6</td>
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<td></td>
<td></td>
<td>A</td>
<td></td>
<td>r6</td>
<td></td>
<td>m</td>
<td>Δr6</td>
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<td>m</td>
</tr>
</tbody>
</table>

When you click submit the computer calculates the quantity \( (Ir)^2 \) for each data point and then plots \( V \) vs \( (Ir)^2 \). Why do we plot \( V \) vs \( (Ir)^2 \) and not \( V \) vs \( (Ir) \)? Since you are considering the errors of V and I to be negligible, all the error of your plot will come from the error in \( r \), so you will only have horizontal error bars. The computer obtains the values for the error in \( (Ir)^2 \) by propagating the error of \( r \) into the error of the quantity \( (Ir)^2 \) using expression (E.1) and (E.8) in Error and Uncertainty. Write the slope of the graph and it's error on your worksheet.

Next, set up an equation that relates the slope, \( s \), to the "constant" and to \( e/m \). Solve the equation for the ratio \( e/m \). Using your errors for \( s \) and the "constant" calculate the error of \( e/m \) using expression (E.7) in Error and Uncertainty. Make sure you simplify units as much as possible. Compare your value to the established value which you can obtain by dividing the charge on the electron, \( e = 1.602 \times 10^{-19} C \) by its mass \( m_e = 9.109 \times 10^{-31} kg \).