GENERAL INTRODUCTION

The experiments for EP 354.2 serve a number of purposes. Firstly, they illustrate the concepts presented in the lectures. Secondly, the student is able to use more sophisticated equipment, similar to that which might be found in a research laboratory. Thirdly, it is hoped that in writing the reports the student will develop the ability to present results and conclusions clearly and logically.

All the experiments require some preparation before the laboratory period. Unlike laboratories for previous classes, most of the experiments involve unfamiliar concepts and/or equipment. Also, the experiments themselves are not as "cut and dried" as previous experiments. It is hoped that the student can obtain a basic understanding of the experiments from the material presented in this manual. Any questions arising from the manual material should be dealt with before attempting to perform the experiment.

As a safety precaution, it is recommended that no experiment be started without first consulting the supervisor.

1. Students must read the manual before coming to the lab in order to be as familiar as possible with the experiment to be performed.

2. Food or drink must not be brought into, or consumed in, the lab.

3. Students should wash their hands after leaving the laboratory.

Certain practices have become accepted standards for the recording of data and the writing of scientific reports. Some of these will be discussed to aid the student in the development of proper writing and reporting skills.

Reports should be written in the past tense and in impersonal form. Reports are to be written in pen, except for graphs and calculations which should be in pencil.

All data must be recorded permanently, directly into the lab notebook. The first page of an experiment report should be used for rough data. These can later be recopied into the appropriate section of the report. Erasers and correction fluid are not to be used in the rough data section. Corrections are to be made by putting a single stroke through the incorrect entry, and writing the correct value beside it.

A measured quantity consists of three parts: the numerical value, the experimental uncertainty, and a unit. Be sure to include the uncertainties and units in all your data. Keep two significant figures in the experimental uncertainty. When using scientific notation use the same power of ten for both the value and the uncertainty. Record the value of the measurement to the same number of decimal places as the uncertainty. Symbols for units do not end with a period and are not pluralized.
The following table contains names, symbols and definitions (where applicable) for commonly used units in the SI system.

<table>
<thead>
<tr>
<th>Physical Quantity</th>
<th>Name of SI Unit</th>
<th>Symbol of SI Unit</th>
<th>Definition of SI Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>distance</td>
<td>meter</td>
<td>m</td>
<td></td>
</tr>
<tr>
<td>mass</td>
<td>kilogram</td>
<td>kg</td>
<td></td>
</tr>
<tr>
<td>time</td>
<td>second</td>
<td>s</td>
<td></td>
</tr>
<tr>
<td>electric current</td>
<td>ampere</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>electric charge</td>
<td>coulomb</td>
<td>C</td>
<td>A·s</td>
</tr>
<tr>
<td>energy</td>
<td>joule</td>
<td>J</td>
<td>kg·m²/s² = N·m</td>
</tr>
<tr>
<td>force</td>
<td>newton</td>
<td>N</td>
<td>kg·m/s² = J/m</td>
</tr>
<tr>
<td>power</td>
<td>watt</td>
<td>W</td>
<td>J/s</td>
</tr>
<tr>
<td>electric potential</td>
<td>volt</td>
<td>V</td>
<td>J/C</td>
</tr>
<tr>
<td>electric resistance</td>
<td>ohm</td>
<td>Ω</td>
<td>V/A</td>
</tr>
<tr>
<td>magnetic flux</td>
<td>weber</td>
<td>Wb</td>
<td>V·s</td>
</tr>
<tr>
<td>magnetic flux density</td>
<td>tesla</td>
<td>T</td>
<td>Wb/m² = V·s/m²</td>
</tr>
<tr>
<td>frequency</td>
<td>hertz</td>
<td>Hz</td>
<td>s⁻¹</td>
</tr>
<tr>
<td>capacitance</td>
<td>farad</td>
<td>F</td>
<td>C/V</td>
</tr>
<tr>
<td>inductance</td>
<td>henry</td>
<td>H</td>
<td>Wb/A = V·s/A = Ω·s</td>
</tr>
</tbody>
</table>

Also, some conversions between various systems of units are frequently required. Some of the more commonly used conversions are:

- 1 angstrom (Å) = 10⁻¹⁰ m
- 1 gauss (G) = 10⁻⁴ T
- 2π radians = 360°
- 1 electron volt (eV) = 1.602 × 10⁻¹⁹ J
- 1 MeV = 10⁶ eV
- 1 MeV/c² = 1.7824 × 10⁻³⁰ kg
- 1 inch (in) = 2.54 cm
- T °C = (T + 273.15) K

There are also a number of physical constants that will be required from time to time. These values can be found in most physics textbooks and some of them are included here for your reference.

<table>
<thead>
<tr>
<th>Description (symbol)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>speed of light (c)</td>
<td>2.998 × 10⁸ m/s</td>
</tr>
<tr>
<td>elementary charge (e)</td>
<td>1.602 × 10⁻¹⁹ C</td>
</tr>
<tr>
<td>Planck's constant (h)</td>
<td>6.626 × 10⁻³⁴ J·s = 4.136 × 10⁻¹⁵ eV·s</td>
</tr>
<tr>
<td>Avogadro's number (N₀)</td>
<td>6.022 × 10²³ molecules/g-mole</td>
</tr>
<tr>
<td>dielectric permittivity of vacuum (ε₀)</td>
<td>8.854 × 10⁻¹² C/V·m</td>
</tr>
<tr>
<td>magnetic permeability of vacuum (μ₀)</td>
<td>4π × 10⁻⁷ V·s/A·m</td>
</tr>
<tr>
<td>electron mass (mₑ)</td>
<td>9.11 × 10⁻³¹ kg = .511 MeV/c²</td>
</tr>
<tr>
<td>Lande g-factor for free electron (gₑ)</td>
<td>2.0023</td>
</tr>
<tr>
<td>Bohr magneton (μₐ = eℏ/2mₑ)</td>
<td>9.274 × 10⁻²⁴ J/T</td>
</tr>
</tbody>
</table>
As already mentioned, when recording data an estimate of the experimental uncertainty must be recorded with each value. That is, an estimate of the confidence in the experimental value is required. In fact, a measured (or calculated) quantity without stated uncertainty limits is useless because it is impossible to draw conclusions from a value without knowing its range within the accuracy of the experiment.

Experimental uncertainty is introduced by interpolating between scale divisions, statistical fluctuations (e.g. counting experiments), the inherent limitations of the measuring instrument, etc.

Experimental uncertainty can be expressed as an absolute uncertainty, a relative (fractional) uncertainty, or a percentage uncertainty. The absolute uncertainty in a measurement defines the range of values which could be expected on repeating the measurement. For example, suppose that a measurement of a quantity \( x \) yields a value \( x = 12 \text{ cm} \) and that due to experimental uncertainty it is estimated that the actual value could be anywhere between 10 and 14 cm. This measurement would be expressed as \( x = 12 \pm 2 \text{ cm} \), where the absolute uncertainty (denoted \( \delta x \)) is \( \delta x = 2 \text{ cm} \). The relative uncertainty is defined to be \( \delta x / x \) (= 2 cm/12 cm = 0.167 for our example) and the percentage error is \( (\delta x / x) \times 100\% \) (= 16.7%).

For counting experiments involving phenomena which obey a Poisson statistical distribution (e.g. radioactive decay, gamma radiation absorption) the absolute uncertainty in a count \( N \) is \( \sqrt{N} \), the standard deviation for a Poisson distribution with mean \( N \).

When performing calculations involving measured quantities, the experimental uncertainties in the measurements must be propagated to yield an uncertainty in the calculated value.

The method that will be used to calculate uncertainties in calculated values is known as the Calculus Method with addition in quadrature. This method is based on the principle of differentiation: that the effect of a variation in one quantity on a second quantity can be determined by differentiating the second quantity with respect to the first. Note that the method described below is likely slightly different from the calculus method that you may have used (or are currently using) in other classes. The method can be summarized as follows:

Suppose that \( q \) is a function of the quantities \( x, \ldots, z \) having uncertainties \( \delta x, \ldots, \delta z \). If the uncertainties in \( x, \ldots, z \) are independent and random, the uncertainty in \( q \) is
\[ \delta q = \left( \frac{\partial q}{\partial x} \right)^2 + \cdots + \left( \frac{\partial q}{\partial z} \right)^2 \]

This method of combining the uncertainty contributions by squaring them, adding the squares, and then taking the square root is called addition in quadrature. It is valid only when the measurements of \( x, \ldots, z \) are made independently (which is often the case). The addition in quadrature method allows for the (likely) situation that random uncertainties in independent quantities will combine in such a way as to produce an overall uncertainty that is less than the sum of the individual uncertainty contributions.

When a calculation involves measurements that are not independent (for example, the sum of measurements made consecutively with the same ruler) the uncertainty in the result is calculated using the maximum possible uncertainty formula:

The maximum possible uncertainty in \( q \) is calculated as follows:

\[ \delta q = \left| \frac{\partial q}{\partial x} \right| \delta x + \cdots + \left| \frac{\partial q}{\partial z} \right| \delta z \]

(You likely used the maximum possible uncertainty formula in your previous method for calculating uncertainties in calculated values.)

Step-by-step description of the method:

1. Ensure that the original expression is in its simplest form and that each variable is independent of all other variables. (This ensures that use of addition in quadrature is valid. Remember that for any uncertainties that are not independent the maximum possible uncertainty formula must be used.)

2. Calculate the partial derivative of the expression with respect to each of the measured quantities. Multiply each partial derivative by the absolute uncertainty in the appropriate measured quantity.

3. Square each of the uncertainty contributions calculated in step 2, add the squares, and take the square root.

4. When angles occur in the expression, the absolute uncertainty in the angle must be expressed in radians (not degrees).

For example, consider the expression \( x = a_1(a_2 + 5a_3^2 \cos a_4) \). The calculation of the uncertainty in \( x \) (\( \delta x \)) due to its dependence on the independent measured quantities \( a_1, a_2, a_3, \) and \( a_4 \) proceeds as follows:

\[ x = a_1(a_2 + 5a_3^2 \cos a_4) \]

\[ \delta x = \sqrt{[(a_2 + 5a_3^2 \cos a_4) \delta a_1]^2 + [a_1 \delta a_2]^2 + [a_1 \cos a_4 10a_3 \delta a_3]^2 + [5a_1a_3^2 (-\sin a_4) \delta a_4]^2} \]
where $\delta a_4$ is in radians.

As mentioned previously, after an absolute uncertainty is calculated it is to be expressed to two significant figures. The corresponding quantity for which this is the uncertainty is then rounded to the same number of decimal places as the absolute uncertainty. (Be sure to use the same power of ten for the absolute uncertainty and the value of the quantity before applying this rule.)

For example, suppose that an experiment yields a value of $3.34529 \times 10^{-19}$ C with an absolute uncertainty of $1.8321 \times 10^{-20}$ C for the net electric charge, $q$, on an oil drop. Since the value is nicely expressed to the power $10^{-19}$, the absolute uncertainty is also expressed to this power, and rounded-off to $0.18 \times 10^{-19}$ C (two significant figures). The value is now rounded to the same number of decimal places as the absolute uncertainty, resulting in a value for $q$ of:

$$q \pm \delta q = (3.34 \pm 0.18) \times 10^{-19} \text{ C}$$

Whenever possible, data and results should be presented in tables. Column headings should contain a brief description of the quantity, its symbol, and its units. If scientific notation is used, the power of ten should be stated in the heading only. (Note that this requires expressing all values in a column to the same power of ten.) If the experimental uncertainty for a column of entries is constant, this should also be placed in the heading. If scientific notation is used for the values in the column, then use the same power of ten to express the uncertainty. **DO NOT** mix scientific and decimal notation for the values and uncertainties in a table column. The individual table entries should consist of numbers only, with their absolute uncertainties if necessary.

For example, suppose the lengths of the edges of a number of cubes were measured, and the volumes calculated. This would be tabulated as follows:

<table>
<thead>
<tr>
<th>Length of Cube Edge, $\ell$ (±0.1 cm)</th>
<th>Cube Volume, $V$ (cm$^3$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0</td>
<td>8.0 ±1.2</td>
</tr>
<tr>
<td>4.0</td>
<td>64.0 ±4.8</td>
</tr>
<tr>
<td>6.0</td>
<td>216 ±11</td>
</tr>
</tbody>
</table>

Often it is useful to present results in graphical form. A number of rules are to be followed when making graphs.

1. Each graph should occupy a full page of the report.
2. The only calculations to be done on a graph page are that of the slope and its uncertainty if the graph is linear.
3. The graph should be given a descriptive title.
4. The axes should be labelled (including units).
5. Scales should be chosen which allow easy interpolation, and which result in the data points being spread across the page. (Intervals of 3, 7, 9, 11 or their multiples must not be used.)

6. The origin need only be included if it is an integral point on the graph.

7. When plotting measured or calculated quantities, the absolute uncertainty is plotted as well, in the form of error bars. For example, a point \((x, y)\) where the absolute uncertainty in \(x\) is \(\delta x\) and the absolute uncertainty in \(y\) is \(\delta y\) would be graphed as:

![Error Bar Diagram]

Using the previous example of the volume of a cube, a proper graph of the tabulated values would be:

![Volume of a Cube Graph]

8. When the relation is linear, two lines are drawn through the error bars of the data points, one being the best-fit line and the other the line with the maximum or minimum possible slope. The slope value used in further calculations is simply the slope of the best-fit line and its uncertainty is:

\[
\delta m_{\text{best}} = m_{\text{max}} - m_{\text{best}} \quad \text{or} \quad \delta m_{\text{best}} = m_{\text{best}} - m_{\text{min}}
\]

The following is the format for the lab reports:
A. Heading
   • title of experiment, date, your name, partner's name.

B. Rough Data

C. Object
   • one or two sentences briefly explaining the purpose and how that purpose will be accomplished.

D. Theory
   • summarize the important theoretical concepts and discuss all equations used in the analysis

E. Experiment
   • diagram of equipment and **brief** explanation of principles of operation
   • **general** outline of procedure (**not step-by-step**)
   • good copy of data in tabular form.

F. Analysis
   • sample of each type of calculation (including units) with the corresponding uncertainty calculation.
   • a computer may be used, however a sample calculation is still required and a carefully documented program listing must be submitted (unless the program used was provided in the lab).
   • results should be tabulated. (The data and results tables may be combined into one table.)

G. Discussion
   • state results and compare with theoretical or accepted values.
   • all sources of error not included in the experimental uncertainty in the data should be discussed. Errors may occur due to the experimental methods, the instruments, environmental conditions, etc.
   • if a result does not agree with the accepted or theoretical value within experimental uncertainty, attempt an explanation.
   • suggestions for improvement of the experiment.

H. Conclusion
   • discuss the physical significance of your results.
   • discuss observations (qualitative as well as numerical) in terms of the predictions and expectations of the theory.
   • note that in some cases the numerical results may disagree with theoretical or accepted values, but the trend of the data (linear, exponential, etc.) may agree with theory.
   • rather than being too specific, decide if your results verify some **basic** physical concept.
   • include suggestions for applications of this type of experiment or its results

I. Summary
   • this section is the equivalent of the abstract of a scientific paper
   • summarize the important parts of the experiment, answering the questions: What did you do? How did you do it? What were your results? What do they mean?
Marking Scheme

The approximate marking scheme used is discussed below. This scheme is flexible and may vary slightly from one experiment to another. Although it may not be indicated in the report as to where, exactly, marks are lost, the comments are usually detailed enough that the student can determine which areas need improvement.

30% completeness of data

30% understanding of the physics
this is usually evidenced by the Theory, Discussion, Conclusion, and Summary.

20% mechanics
calculations, uncertainty calculations, tables, graphs, etc.

20% readability
neatness, use of proper English, spelling, use of proper format.

General Comments

*Lab reports are due one week after the experiment has been performed.*

Past experience suggests that reports for the modern physics labs cannot be properly completed if left until the night before they are due. Students should begin their report early enough so that they have time to talk to the instructor if they require assistance.

*Students are expected to be in the lab room at their scheduled time.*

Working on the report for a previous experiment while in the lab to do the current week's experiment is unacceptable.

*Copying from another student or an old lab book will not be tolerated.*

Because of the amount of time and effort required to produce a good lab report, any report found to contain copied material will be given a mark of 0.