Classical Physics Lab

CH-140-B

Fall 2020

Prof. Dr. Jürgen Fritz
Dr. Vladislav Jovanov

Group: ________________

Student: ________________

Lab Partner: ________________

This manual will give an overview about the experiments in the Classical Physics Lab in the Fall 2020 semester. It is mainly based on the manuals provided by Phywe Systeme GmbH - http://www.phywe.de (L.v. Alvensleben, "Laboratory Experiments Physics") and Leybold Didactic GmbH - http://www.leybold-didactic.de, as well as previous versions of the physics lab manuals at Jacobs University Bremen. In certain parts of this manual additional literature sources may be found. The authors would like to acknowledge the students of the former classes for their contribution in improving the quality of this manual.

Contents

Dear Student

Welcome to the Classical Physics Lab Course at Jacobs University!
This lab manual is an integral part of your lab course and will especially in the first semester be used to prepare, perform and evaluate your experiments. It will give you valuable information on the physics background, the setup and equipment, and the tasks for your physics experiments.

General information

Laboratory courses are a fundamental part of any scientific education. Experiments have always been a great inspiration for developing new theories and are the ultimate test for any description of the world around us. To pose the right questions in the right way in an experiment one has to follow certain procedures and strategies established over the centuries. But at the same time one also has to keep enough flexibility and creativity to cope with unexpected results and phenomena.

At Jacobs University the lab courses are designed that, starting with the first semester, students get hands-on experience on topics discussed in lectures. They help to link every day phenomena and experiments to their theoretical description. Students get familiar with technical equipment and learn to set-up, perform and evaluate experiments in close interaction with instructors and teaching assistants. Both, the First Year and the Second Year Physics Laboratory Courses, offer experiments with increasing complexity to support and detail the topics taught in physics lectures. First Year Labs introduce students to common laboratory equipment, procedures and scientific methods, whereas Advanced Physics Labs in the second year of studies are designed to deepen the technical and theoretical knowledge and to train students in the design of their own experiments.

The First Year Physics Labs offer experiments on Mechanics, Thermodynamics, Optics, Electromagnetism, and Modern Physics. Next to a deeper insight into the topics taught in the first year physics lectures, these courses will familiarize you with the major components of experimental work in physics. The main learning goals are:

- Getting familiar with typical experimental equipment and methods in physics.
- Design of experiments to get meaningful and reliable results.
- Identification and elimination of error sources in methods and instruments.
- Mathematical evaluation of data and quantification of errors.
- Critical assessment and discussion of experimental results.
- Accurate recording and scientific presentation of experimental data.

As any other first year lab at Jacobs University, the Physics Labs are offered in several consecutive timeslots per semester, each lasting for 3 weeks with two lab afternoons per week.

In the first semester, students will receive a general introduction on experimental science and error analysis in their first lab session. This will be followed by a short sample experiment to practice data acquisition and analysis. Since safety instructions are an absolute prerequisite to enter any scientific lab, they will also be provided in the first lab session.

General instructions

Before starting any experiment you have to be informed on the topic you will investigate and the equipment you will use. Whereas in research you pose relevant questions and design an experiment by yourself, questions and equipment in the first year lab course will be given and described by the manual. To prepare for an experiment, read first the physics background of the experiment in the manual and verify the formulas you will need. To get more background information you might have an additional look into a textbook. Then, get familiar with the setup, equipment and the procedures you should perform. A lab afternoon will start with an oral quiz on the physics, equipment and procedures of your experiment to ensure that you are well prepared. Nevertheless, some piece of equipment or task might only become clear when you actually operate it or perform the experiment.

Before taking measurements you should understand the operation of your equipment, ensuring that it is calibrated and well functioning and you should verify the quantities and units you want to measure. Experiments might go wrong, but don't be afraid when something is not working at the first run, just rethink and correct your procedure or finally ask the TAs when you get stuck. You actually might learn more from solving problems than from conducting a perfect experiment. For a scientific experiments, you also have to make proper notes and data recordings on the spot and in parallel of doing the measurements so that you (or someone else) can later reproduce what you have done. It is also important to do a first rough check of your results, because weird values or funny results could be an indication of errors in your setup or procedure, and they should be eliminated as early as possible in an experiment.

At the end of a lab afternoon your results will be checked and shortly discussed with TAs or instructors. Besides correct results also the form of your recordings will be checked (you should have clear and complete notes and all electronic tables or graphs at hand). For at least two experiments you have to write a detailed lab report with proper introduction, description and evaluation of an experiment using the lab manual and your notes (see appendix for lab report details).

We are continuously correcting and improving the manuals for the Physics Lab Courses and appreciate any corrections or suggestions you might have.

We hope you will enjoy the Physics Labs and get a first stimulating insight into experimental research in physics.

Your Physics Lab Instructors.

Summary

In the first experiment we will get familiar with the methods of data analysis and error analysis to properly describe quantitative results from scientific experiments. We use a mass attached to a mechanical spring to determine in two different experiments the elasticity or spring constant of the spring: by the extension of the spring when adding increasing masses, and the oscillation of the spring mass system. The two results are analyzed in terms of statistical error and propagated error, and are compared regarding their differences and reliabilities.

Key Concepts

Uncertainty, accuracy, precision, mean value, standard deviation, variance, Gaussian distribution, linear regression, error propagation, partial derivatives, significant digits, presentation of results.

Introduction and Theory

Force is an important concept in physics used to describe the cause of motion of objects from molecules to stars. Macroscopic mechanical forces can be easily measured by the compression or extension of a mechanical spring. We use the simple extension and oscillation of a spring to get familiar with typical procedures in data analysis and error analysis. The relation between the extension x of a spring and the force F it exerts is Hooke's law:

$$F = -kx \tag{1-1}$$

k is the so called spring constant which is a measure of the elasticity of a spring: Stiff springs have a large k, soft springs a low k. Attaching a mass to a spring, deflecting it from its equilibrium position, and then releasing it will lead to an oscillation of the spring-mass system with a period of

$$T = 2\pi \cdot \sqrt{\frac{m}{k}} \tag{1-2}$$

(Note: this can be derived from the solution of the differential equation $-kx = m\ddot{x}$, but this is not necessary here). The relation is valid for ideal massless springs and small extensions (You might think about why its validity is limited). In the experiment you should use two different approaches to determine the spring constant of a spring: by measuring the period of an oscillation, and also by measuring its extensions when attaching different weights to it. In the latter case, the force leading to a specific extension is the weight or gravitational force: To get the gravitational force of a mass you have to multiply the mass by the local gravitational acceleration (here: $g = 9.8133\,m/s^2$) by using $F = m \cdot g = k \cdot x$ (neglecting the direction of the force which should be obvious).
Deviations from an idealized behavior of the spring might come from different side effects, environmental parameters, or inaccuracies in the measurement method. An important part of being a scientist is to recognize a general behavior or pattern of a phenomena behind a variety of unwanted disturbances. One has to critically evaluate the insufficiencies of the own setup to be able to further develop new experiments or improve the existing methods.

Checking the reproducibility of an experiment by repeating it many times helps to verify the result and to determine the typical uncertainty of a result. The basic parameters to characterize large data sets obtained from identical experiments are the average or mean value of the data, the standard deviation of the mean, and the error of the mean. To get the explicit distribution of measured values one could even plot a histogram, indicating how often a value within a certain range was measured. Ideally, the distribution for random experiments as plotted in a histogram should reproduce the so-called Gaussian distribution. To reveal the uncertainty of a final value calculated from many different inputs, the uncertainty of individual inputs has to be taken into account. This can be done by the so called error propagation. The important formulas for error analysis are summarized below:

Arithmetic mean value $\overline{x}$:

$$\overline{x} = \frac{1}{n} \cdot \sum_{i=1}^{n} x_i \tag{1-3}$$

The **standard deviation**:

$$\sigma_x = \sqrt{\frac{1}{(n-1)} \sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{1-4}$$

Error of the mean $\Delta\overline{x}$:

$$\Delta\overline{x} = \frac{\sigma_x}{\sqrt{n}} = \sqrt{\frac{1}{n(n-1)} \sum_{i=1}^{n} (x_i - \overline{x})^2} \tag{1-5}$$

Averaged Error from error propagation

$$\begin{aligned}\Delta y_{avg} &= \sqrt{\left[\left(\frac{\partial y}{\partial x_1}\right)_{x_j \neq x_1} \Delta x_1\right]^2 + \left[\left(\frac{\partial y}{\partial x_2}\right)_{x_j \neq x_2} \Delta x_2\right]^2 + \ldots + \left[\left(\frac{\partial y}{\partial x_p}\right)_{x_j \neq x_p} \Delta x_p\right]^2} \\ &= \sqrt{\sum_{q=1} \left[\left(\frac{\partial y}{\partial x_q}\right)_{x_j \neq x_q} \Delta x_q\right]^2} \end{aligned} \tag{1-6}$$

Here n is the number of measurements.
More background on the formulas above and advanced topics can also be found in the *Error Analysis Booklet* for the Physics Teaching Labs at Jacobs.

Background Information

Calculations in error analysis and also thermodynamics make heavily use of so called "**partial derivatives**" indicated by $\frac{\partial}{\partial x}$. Here we give a short practical introduction to partial derivatives without any mathematical proof or rigorousness.
Partial derivatives deal with functions which depend not only on a single variable but on

two or more. For example the volume of a gas depends on temperature, pressure, and number of moles, given by $V(p, T, n) = \frac{nRT}{p}$. To calculate the influence of e.g. a change in temperature dT on the change in volume dV, one derives V with respect to T. This is normally written as $\frac{dV}{dT} = \frac{nR}{p}$. But V depends also on other variables, that is, a change in volume might also be caused by a change in pressure or in number of moles, and V can also be derived with respect to those variables. This fact is indicated by using the partial derivative symbol "∂ " and not a simple "d ". When deriving with respect to a specific variable, the others have to be kept constant (= they are treated as constants) for the operation of deriving. This is indicated by writing those variables which are kept constant as indices at the brackets around the partial derivative symbol. The correct writing for the partial derivative of V with respect to T, or p, or n is:

$$\left(\frac{\partial V}{\partial T}\right)_{p,n} = \frac{nR}{p}$$
$$\left(\frac{\partial V}{\partial p}\right)_{n,T} = -\frac{nRT}{p^2}$$
$$\left(\frac{\partial V}{\partial n}\right)_{p,T} = \frac{RT}{p}$$

The wording for the first equation is "the partial derivative of V with respect to T at constant p and n equals ...". For practical use in this course, partial derivatives of a function with respect to a specific variable can be treated as "normal" derivatives where all other variables are treated as constants. This is also valid for error propagation calculations where one quantity e.g. y depends on several others, e.g. $y(x_1, x_2, x_3)$, and one has to calculate for example the partial derivative of $\left(\frac{\partial y}{\partial x_1}\right)_{x_2,x_3}$.
One remark for the example above: If you want to know the total possible change of V that could happen, you have to calculate the total differential, taking into account the partial derivatives of all variables, that is:
$dV = \left(\frac{\partial V}{\partial T}\right)_{p,n} dT + \left(\frac{\partial V}{\partial p}\right)_{n,T} dp + \left(\frac{\partial V}{\partial n}\right)_{p,T} dn.$

A **histogram** is a plot showing the distribution of data points in an experiment, or in other words how often a certain value was measured in an experiment. It plots the values classified in certain ranges or intervals on the x-axis, and the number of how often a certain value within a certain range was recorded (called the "frequency" of the value) on the y-axis. The range of values or width of the interval for different classes of values is called the "bin-size". For a truly random distribution the measured values should be symmetrically distributed around the mean value and their frequency should decrease the further away they are from the mean. Such an ideal distribution is called a Gaussian or Normal Distribution. The half width at half of the maximum value (HWHM) of a Gaussian distribution is about the standard deviation of the distribution.

Experimental

Equipment

Mechanical spring with stand
Ruler or measuring tape
Weight holder with 5 weights
Stopwatch
Scientific calculator
Balance

Set-up and Procedure

In this experiment you will determine the spring constant of a spring using an oscillation and an extension method. The results from both methods should be evaluated and compared to each other. For the oscillation method many identical measurements will be done and the statistical error will be determined and compared to the instrumental error of time and mass measurements. For the extension method a linear regression line will be determine and its slope will be used to assess the spring constant.

To measure the period of the oscillation of a spring, hang the spring on the stand and add a weight holder with a certain mass. Gently deflect the spring an let it oscillate in small amplitudes. It should not perform large amplitudes and should not move randomly around. Take a stop watch and measure the time for 10 periods (be sure you account correctly for 10 full periods!).

To measure the extension of the spring when adding different weights, hang the spring on the stand and determine its equilibrium extension (that is the extension without weights but with the weight holder). Then add an increasing number of weights and determine the spring extension for each weight. Think about what is the best way to do the measurements - Should you record extension or position of the spring? Where exactly do you measure position or extension of the spring?

Result Form

Date:

1. **Determine the spring constant of a spring by measuring the oscillation period of the spring with an attached mass.**

   (1) Determine the total mass you will attach to the spring (weight holder and any number of weights you choose). Weight holder has a mass of (10.13 ± 0.05) g, while each weight has a mass of (10.10 ± 0.01) g.

   $m =$ __________ $\Delta m =$ __________

   (2) Attach a mass (weight holder and chosen number of weights) to the spring, deflect the spring (**not** more than $3\,cm$), and measure the time to complete 10 periods. Measure at least 10 values of the time for 10 periods. Then your lab partner does the same measurement.

   t_{10}:

(3) Calculate the mean value of your 20 data points, their standard deviation, and the error of the mean value. Then give your final result for the time for a single period and its error.

$\overline{t_{10}}$	
$\sigma_{\overline{t_{10}}}$	
$\Delta\overline{t_{10}}$	
$\overline{T}$	
$\Delta\overline{T}$	

$\overline{T}$ = ________ ± ____________

(4) Estimate also the general instrumental error for a time measurement with a stop watch.

ΔT = ________

(5) Discuss your result regarding the standard deviation and potential difference between statistical and instrumental error.

____

____

____

(6) Calculate the spring constant from the oscillation method.

$k_{osci} = \underset{Formula}{\underline{\hspace{4cm}}}$ $\qquad k_{osci} =$ ______________

(7) Now you have a first result for the spring constant. What is the error of your value of the spring constant? (*Comment*: In a typical experiment you can either do error analysis right after you calculated the results, or you focus on finishing the experimental part before doing an error analysis.)
Calculate the propagated error of the spring constant using as an input the error of the time and mass. By doing so you can also determine the most significant error source, that is the measurement which contributed most to the error of the spring constant.

$\Delta T =$ ________________ $\Delta m =$ ________________

Write down again the formula for the calculation of the spring constant, then write down the formula for the propagated error of the spring constant, then plug in the values and determine the propagated error. In addition determine the individual contribution of mass and period to the error of the spring constant.

____

____

____

$\left(\frac{\partial k}{\partial m}\right) \Delta m = \underset{Value}{\underline{\hspace{4cm}}}$ $\left(\frac{\partial k}{\partial T}\right) \Delta T = \underset{Value}{\underline{\hspace{4cm}}}$

Most significant error source : ____________________________

(8) Finally, give your best estimate and its uncertainty of the spring constant from the oscillation experiment. $k_{osci} =$ ________ $\pm$ ________

Notes and Calculations:

2. Determine the spring constant of the spring by measuring its extension for different forces.

(1) Attach the weight holder to the spring and use its equilibrium position as point of zero extension for the following measurements. Then attach successively five weights to the holder and measure the position for the different weights two times. Measure the position for a specific weight a second time *only after* you changed to a different weight. Again, mass of each weight is (10.10 ± 0.01) g. Calculate the extension of the spring (is this indeed necessary for the evaluation?) and calculate the related total force on the spring for each weight.

$P_{equilibrium} =$ ____________________

m	F	P_1	$x_1 = P_1 - P_{eq}$	P_2	$x_2 = P_2 - P_{eq}$	$\overline{x}$

(2) Plot a graph with extension on the x-axis and related force on the y-axis. Add a typical error bar (y-direction) to the plot.

(3) Fit a straight line to your result (do a linear regression). Calculate the spring constant from the slope of the fit line, and the error of the slope using the R values of the fit (Find the formula for the error of the slope of a linear regression line in the Error Analysis Handbook, or do it manually as described in the Error Analysis Handbook).

$k_{ext} =$ ____________________ (*Formula*) $k_{ext} =$ ____________________ (*Value*)

$\Delta k_{ext} =$ ____________________ (*Formula*) $\Delta k_{ext} =$ ____________________ (*Value*)

Notes and Calculations:

(4) Discuss the results and give your best estimate and error of the spring constant from the extension experiment.

$k_{ext} =$ ______ $\pm$ ______

______

______

______

______

______

3. Compare and discuss the results from both methods.

Do the methods come to the same result within their uncertainties? Is one more reliable than the other? Give some arguments why or why not.

______

______

______

4. Corrections for non-ideal conditions

(1) Measure the mass of the spring.

$m_{spring} =$ ______ $\Delta m_{spring} =$ ______

(2) Take the mass of the spring into account and recalculate k_{osc} using

$$m_{eff} = m_{mass} + \frac{1}{3} m_{spring} = \underbrace{\qquad\qquad\qquad}_{Value} \tag{1-7}$$

$$k_{osc} = \underline{\qquad\qquad \pm \qquad\qquad} \tag{1-8}$$

Can you imagine how one justifies the correction term and how one can determine the factor of $\frac{1}{3}$?

(3) Compare again k_{osc} and k_{ext} and comment.

Summary

In this experiment the local gravitational acceleration will be determined by measuring the period of oscillation of a mathematical pendulum. The pendulum consists of an iron sphere, considered as a point mass, suspended on a long thin metal wire. Students will compare manual and electronic time keeping, and further analyze the dependence of the period of oscillation on the initial deflection angle of the pendulum.

Key Concepts

(Mathematical) simple pendulum, simple harmonic motion, oscillation, period and amplitude of oscillation, potential and kinetic energy, linear restoring force

Introduction and Theory

Pendulums are an important type of physical systems. The best known use of pendulums is for time keeping. Up to about 1950 the most accurate clocks were pendulum clocks of special design which were accurate to within a few thousands of a second per day. In the early days of mechanics the Newton pendulum was used to elucidate the kinetics of collisions, and pendulums still serve as model systems for a harmonic oscillator. Simple pendulums are not quite as simple as their name implies. The simplicity is primarily in its structure which can be idealized as a point mass which is free to swing forth and back on a massless rigid string. But pendulums can also be more complex such as coupled pendulums or double pendulums which show nonlinear chaotic behavior. Here we will investigate a simple pendulum oscillating in small amplitudes around its equilibrium position. In the following we will derive the equations describing a pendulum, but the most important formula is formula (2-9). For larger amplitudes its motion gets nonlinear and more complicated described by formula (2-12).

By swinging forth and back, the path of the mass of a pendulum describes an arc of a circle with radius L, the length of the string. To simplify the description we will use polar coordinates. Analogous to the velocity of linear motion, the angular velocity ω is given by:

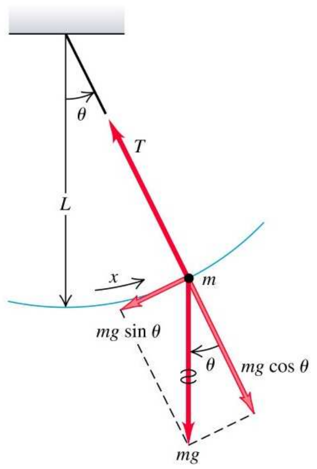
$$\omega = \frac{d\theta}{dt} = \frac{v}{L} \tag{2-1}$$

where angle θ describes the position of the body, v the tangential velocity and L the radius of the motion. The angular acceleration α is given by (linear acceleration $a = \frac{d^2 s}{dt^2}$):

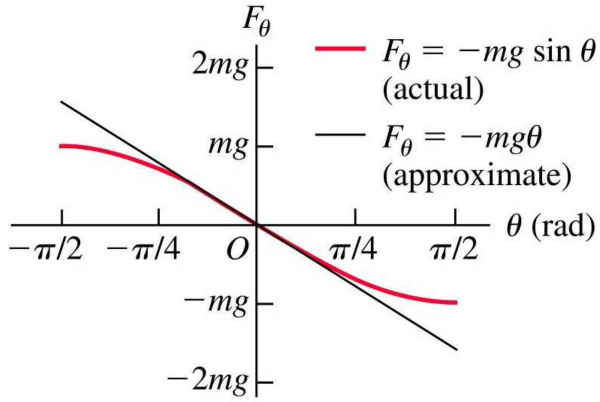
$$\alpha = \frac{d^2\theta}{dt^2}. \tag{2-2}$$

The gravitational force acting on the mass may be split into a radial component parallel to the string and a tangential component F_θ perpendicular to the string (see Figure 1(a) from Y & F).
The tangential restoring force pulling the mass back to its equilibrium position is:

$$F_\theta = -mg\sin\theta \tag{2-3}$$



(a) Forces acting on the mass of a pendulum.



(b) Approximation of sin function

Figure 2-1: Explanative sketches for derivation of period of oscillation of pendulum (Copyright ©2004, Pearson Education, Inc., publishing as Addison Wesley).

with gravitational acceleration g. Using Newton's Law $F = m \cdot a$ for the tangential force gives:

$$\begin{aligned} F_\theta = m \cdot a_{tang} &= m \cdot \frac{dv_{tang}}{dt} \\ &= mL\frac{d\omega}{dt} = mL\frac{d^2\theta}{dt^2} \end{aligned} \tag{2-4}$$

Equating (2-3) and (2-4) leads to the equation of motion of a simple pendulum:

$$-m\,g\sin\theta = mL\frac{d^2\theta}{dt^2} \qquad \text{or} \tag{2-5}$$

$$\ddot{\theta} + \frac{g}{L}\sin\theta = 0 \tag{2-6}$$

Unfortunately, this differential equation has no elementary solution because of its non-linear term $\sin\theta$.

A simple description of the pendulum is only possible when we restrict its motion to *small angles* of deflection. In that case $\sin\theta \approx \theta$ (here the angle is described in radians). You can check that this approximation is valid up to angles of about 10° (see Figure 1(b)).

Equation (2-6) then writes:

$$\ddot{\theta} + \frac{g}{L}\theta = 0 \tag{2-7}$$

which is the equation of motion of an harmonic oscillation. One solution of (2-7) is:

$$\theta(t) = \theta_{max} \cos(\omega t) \tag{2-8}$$

Plugging (2-8) into (2-7) leads to angular frequency ω and period of oscillation T

$$\omega = \sqrt{\frac{g}{L}} \qquad \text{or} \qquad T = 2\pi \sqrt{\frac{L}{g}} \tag{2-9}$$

of the simple pendulum. This is the most important formula for this experiment.

It is interesting to note that the period is *independent* of the mass of the pendulum and (for small deflections) independent of its initial deflection. The period depends only on the length of the string and the gravitational acceleration. This makes pendulums so interesting for time keeping. They also offer a simple way to measure the local g.
Newton, Huygens and others used pendulums with masses suspended from equal strings to study collision phenomena. As long as the small angle approximation is valid, two masses released at the same instant at arbitrary positions will reach their lowest point at the same instant with maximum velocity.
In the approximation for small angles, the pendulums restoring force is directly proportional to the displacement angle θ. Such forces are called *linear restoring forces*. Any system with a linear restoring force will undergo *simple harmonic motion* around its equilibrium position. Other examples for simple harmonic motions are oscillating springs or cantilevers.
We can also use an energy ansatz to describe the motion of a simple pendulum in general apart from the ideal small-amplitude case. The energy ansatz starts from the fact that the sum E_o of potential and kinetic energy of the pendulum is constant:

$$\frac{1}{2}mv^2 + m \cdot g \cdot h = E_o = m \cdot g \cdot h_{max} \tag{2-10}$$

Solving for v, writing v as $\frac{dx}{dt}$, then transforming the expression to $dt = \frac{1}{\sqrt{\cdots}}dx$, using angular quantities (e.g. θ_{max} instead of h_{max}) and integrating will lead to an integral of $T(\theta_{max})$ which can not be carried out exactly. The period of a pendulum with large deflections described by equation (2-6) or (2-10) is therefore given by using series expansion:

$$T = 2\pi \sqrt{\frac{L}{g}} \quad \left[1 + \left(\frac{1}{2}\right)^2 \sin^2\left(\frac{\theta_{max}}{2}\right) + \left(\frac{1 \cdot 3}{2 \cdot 4}\right)^2 \sin^4\left(\frac{\theta_{max}}{2}\right) + \ldots \right] \tag{2-11}$$

For not too large amplitudes it is sufficient to take only the first corrective term $(1/4 \cdot \sin^2(\theta_{max}/2))$ and to approximate it by substituting $\theta_{max}/2$ for $\sin(\theta_{max}/2)$. The result of this approximation is

$$\begin{aligned} T &= 2\pi \sqrt{\frac{L}{g}} \quad \left[1 + \frac{1}{16}\,\theta_{max}^2 \right] \\ &= T_0 \quad \left[1 + \frac{1}{16}\,\theta_{max}^2 \right] \end{aligned} \tag{2-12}$$

Where T is the "real" and T_0 the "ideal" period (for small amplitudes). For $\theta_{max} \leq 60°$, the deviation of this approximation to the correct result is below 1%.
This dependence of the period on the square of the angle of deflection, that is $T(\theta^2_{max})$, shall be proven in the experiment. To do so, equation (2-12) is transformed and the natural logarithm is taken of both sides of the term:

$$\frac{T}{T_0} - 1 = \frac{1}{16}\,\theta^2_{max}$$

$$\Rightarrow \ln\left(\frac{T}{T_0} - 1\right) = \ln\left(2^{-4}\,\theta^2_{max}\right) = -4\ln 2 + 2\ln\theta_{max} \tag{2-13}$$

The resulting formula describes a straight line when plotting $\ln(T/T_0 - 1)$ (on the y-axis) in dependence on $\ln\theta_{max}$ (on the x-axis). The slope of the plot then gives the order of the power of the dependence: a slope of two then shows that $T \sim \theta^2_{max}$. In the experiment, θ_{max} has to be determined from the position of the sphere before it is released:

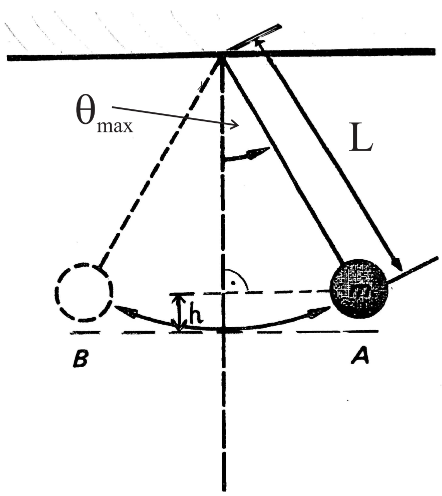


Figure 2-2: Relation between height h and angle of deflection θ_{max}

If h is the difference between the lowest position of the sphere and the height of the sphere at θ_{max}, θ_{max} is given by:

$$h = L \cdot (1 - \cos(\theta_{max}))$$

$$\Rightarrow \qquad \theta_{max} = \arccos\left(1 - \frac{h}{L}\right) \tag{2-14}$$

Experimental

Equipment

- Pendulum with mounting device
- Measuring tape 2 m
- Stop watch
- Cassy
- Light barrier
- Cassy timer box
- Laptop
- Meter scale with cursor

Set-up and Procedure

The experiment consists of a pendulum for which a steel ball is tied to a wire which is connected to a small metal blade. The pendulum is mounted on the ceiling by the sharp blade to minimize friction.
The period of the pendulum can be measured either by a stopwatch or by a light barrier connected to an electronic data acquisition system (Cassy). In the first part of the measurement, both experiment are compared with each other.

Stopwatch
When using a stopwatch measure the time needed for ten periods to reduce the error due to the determination of start and stop points.

Light barrier and Cassy
When using the Cassy, choose the measurement mode “Period” and activate the selection “Pendulum”. In this case, the period between every second shading of the light barrier, i.e. the period of the pendulum, is recorded. In addition, any error due to a misalignment with respect to the center of the set up cancels out.

To determine the gravitational acceleration you have to use small angles of deflection for the pendulum, e.g. deflect the pendulum only for 5 - 8 cm. To investigate the influence of large angles on the period, the angle of deflection is determined by measuring the height difference h between the release position (h_{start}) and the lowest position (h_{equi}) of the ball. The angle is then calculated according to equation (2-14).
The length of the pendulum will be given to you. The radius of the ball must be taken into account for this measurement.

Tasks

Always write an appropriate header on your notes and label your pages. Always make a scheme of the setup. Note down all experimental values, formulas, and calculations. Answer all tasks and questions in writing. Structure your notes by creating appropriate tables and highlite your final results.

1. Measuring gravitational acceleration: Preparation

(1) Measure the diameter d of the sphere and its error and note them down.

(2) Ask your TA for the length of the cord from pivot to the surface of the ball, and use it to calculate the total length L of the pendulum and its error.

(3) Solve equation (2-9) to calculate g from L and T.

(4) Discuss the best method to measure the period of the pendulum for small angles.

2. Measuring gravitational acceleration using a stopwatch

(1) Measure the time t_{10} needed for ten full periods with a stop watch. Repeat the measurement at least ten times. Think about the best method to get accurate results. Note down the values in a table.

(2) Get your best value and its reliability by calculating the mean $\overline{t_{10}}$ and its error $\Delta\overline{t_{10}}$ using the statistics function of a calculator or laptop.

(3) Get the period $\overline{T}$ including error $\Delta\overline{T}$ from $\overline{t_{10}}$ and $\Delta\overline{t_{10}}$.

(4) Use error propagation to account for errors in time and length when calculating the error in g: Give the formula for the partial derivative of g with respect to length and time multiplied with the errors of the respective parameter. Calculate the effect of both parameters on the error Δg by calculating $\left(\frac{\partial g}{\partial t}\right)_L \cdot \Delta t$ and $\left(\frac{\partial g}{\partial L}\right)_t \cdot \Delta L$.

(5) Which one is the dominating error for the measurement in g? Why?

(6) State your final value of g including its uncertainty Δg for the measurement with the stop watch.

3. Measuring gravitational acceleration using a light barrier

(1) Measure the period T for small deflection with a light barrier. Again, what is the best method to get most accurate results? Repeat the experiment at least ten times - stop and start the pendulum again every time. Note down the values.

(2) Calculate the mean $\overline{T}$ and its error $\Delta\overline{T}$. Are the values with light barrier stable or do they fluctuate?

(3) Calculate g from $\overline{T}$ and the length of the pendulum. Determine the error Δg using error propagion as before.

(4) Which one is the dominating error?

(5) State your final value of g including its uncertainty Δg for the measurement with a light barrier.

4. Comparison of results

The standard gravitational acceleration in Bremen North is given as $g_0 = (9.813310 \pm 0.000041)\frac{m}{s^2}$. Present your results from the two methods and comment on the measurements by taking into account the following:

a) Compare the two results you obtained for the gravitational acceleration. Do the results agree within their uncertainty ranges? If not, can you explain why?

b) How do both values compare to the official local g_0 value and which one is more reliable? Discuss.

5. Functional relationship between period and angle of deflection

Use the light barrier to determine the period of the pendulum in this part. The different angles of deflection have to be calculated from the different release positions of the pendulum.

(1) Determine the height h_{equi} of the ball in its lowest position.

(2) Calculate the height of the ball for a maximum deflection angle of 40°.

(3) Repeat the measurement of T for your largest angle (40°) at least 5 times and calculate $\overline{T}$ and $\Delta\overline{T}$ as a typical error for the time measurement for large angles. For every measurement let the pendulum start again from its initial position.

(4) Let the pendulum again start from the position of the largest angle, but now record 5 consecutive periods. Do they change or decrease significantly? How does the result compare to the previous measurement of 5 periods, where the pendulum always started from the initial position?

(5) Measure T for different initial heights h_{start} of the ball, i.e. different θ_{max}. Use at least six different heights between 10° and 40° including $\theta_{max} = 40°$.

(6) Use a data analysis program to create a table according to the following example, using as T_0 the value measured for small angles with the light barrier. T is the value you actually measured for the different angles.

T	h_{start}	h	$\theta_{max}[deg]$	θ_{max} [rad]	$\ln\theta_{max}$	$(\frac{T}{T_0})-1$	$\ln((\frac{T}{T_0})-1)$
...	...	...	...	...	...	...	...

(7) Note any special observations, e.g. how accurate is the measurement of T in this case?

(8) Make a plot of $T(\theta_{max})$, i.e. plot the measured periods T on the y-axis and the angle of deflection θ_{max} on the x-axis. Give θ_{max} in degrees for this plot.

(9) Note any special observations in your graph.

(10) Make a second plot to verify the power of the dependence of $T(\theta_{max})$. Plot $\ln((T/T_0) - 1)$ in dependence of $\ln(\theta_{max})$ and determine the linear regression line. Give the straight line function $(m \cdot x + c)$ and the correlation coefficient of

the fit line.

(11) Give the slope of the regression line and also the error of the slope.

(12) Comment on your result, e.g. what slope did you expect and what did you measure?

(13) Sum up.

- Does the result agree with the theory within its error ranges?
- What systematic or random error sources did you observe?
- Do they explain possible deviations from theory?
- Think about and recommend possible improvements of the experiment.

Summary

In this experiment the propagation of sound waves in different media is investigated. The speed of sound in different gases and different metal rods is determined and material properties such as adiabatic and elasticity modulus are derived.

Key Concepts

Waves, oscillations, planar wave, wave velocity, phase velocity, frequency, wavelength, compressibility, density, elastic modulus, longitudinal waves, transversal waves, interference, standing wave.

Introduction and Theory

The world is full of sound and most living beings make use of sound to communicate with each other, to navigate, or to identify their prey. Technologically most common applications for sound waves are echo sounders, sonars, or Doppler sonography e.g. for oil exploration, water depth measurements, or noninvasive medical examinations. Sound is disturbance traveling through a medium in space and time. **Sound waves** in a gas are periodic or oscillating changes in pressure traveling through the gas. For sound waves gases (but also liquids and solids) get periodically compressed and relaxed *in the direction* the wave is traveling (see Fig. 3-1). This type of wave is therefore called a ***longitudinal* wave** (compared to *transverse* waves where particles are deflected *perpendicular* to the direction the wave is moving). From the propagation of sound waves in a medium several material parameters can be determined e.g. material density, which is mainly used for the applications mentioned above. Sound waves can be described mathematically by:

$$y(x,t) = A \cdot cos(kx - \omega t) \qquad (3\text{-}1)$$

where in this case y is the deflection of a particle in x-direction (= longitudinal direction) from its original position x at time t (since we have longitudinal waves). A is the amplitude of particle motion, $(kx - \omega t)$ the phase of the wave, $k = \frac{2\pi}{\lambda}$ the wave number with wavelength λ, and angular frequency $\omega = 2\pi f = \frac{2\pi}{T}$ with frequency f and period T.

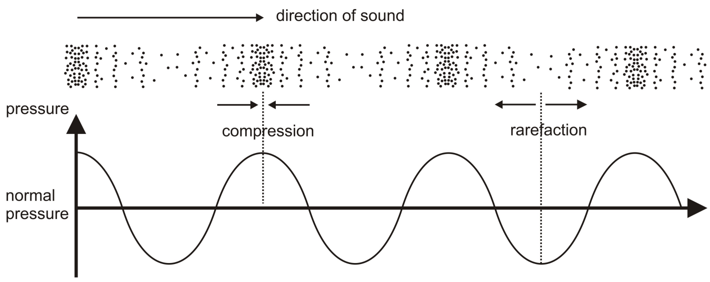


Figure 3-1: Longitudinal sound wave in a gas.

The speed of sound is expressed by a so-called wave velocity (the phase velocity v), describing how fast a wave propagates. The velocity has a simple relation to the frequency of the oscillation f and wavelength λ:

$$v = \lambda \cdot f \qquad (3\text{-}2)$$

When waves are confined within a certain space or object (e.g. in a pipe, rod, or along a string), they can be reflected forth and back at the ends or by the confinement of the medium. The waves will then interfere with each other and will lead to the formation of so-called **standing waves** with certain **nodes** (minimum amplitude) and **antinodes** (maximum amplitude) at fixed (= standing) positions. For longitudinal waves in solid rods, when rods are clamped exactly at their center, the basic mode of a standing wave has one node in the middle of the rod and one antinode at each free end of the rod. Accordingly, this basic mode of a standing wave in a solid rod of the length l has a wavelength of $\lambda = 2 \cdot l$. The related wavelength is two times the length l of the rod. The velocity of sound can then be calculated by taking into account the wavelength and period of a standing wave and the length of the rod:

$$v = 2 \cdot l \cdot \frac{1}{T} \tag{3-3}$$

Exciting oscillations in a metal rod can theoretically trigger several **standing waves** such as the basic mode or higher harmonics. But normally only the basic mode is excited and higher modes are nearly totally suppressed.

The wave velocity or speed of sound depends on several material parameters of the medium it is traveling through. For longitudinal waves in solid homogeneous rods, theory predicts:

$$v = \sqrt{\frac{E}{\rho}} \tag{3-4}$$

with density ρ and **elasticity (modulus)** E. Since sound waves in a rod compress or expand the material periodically, the elasticity of the material will influence the speed of sound in addition to the mass or density of the rod. The formula holds when the diameter of the rod is much smaller than the typical wavelength. To get the speed of sound for gases one can replace E by the pressure p so that we get:

$$v = \sqrt{\frac{p}{\rho}} \tag{3-5}$$

But for gases the velocity of sound depends also on temperature. Because sound oscillations are fast, the heat developed during the compression of air can not be dissipated fast enough. Because hot gases are harder to compress than cold ones, one has to correct for that. Using thermodynamics one can show that p has to be substituted by $p \cdot \gamma$, where γ is the **adiabatic index** or the ratio of specific heat at constant pressure and at constant volume. For ideal mono-atomic gases γ is $\frac{5}{3}$ and for diatomic gases $\frac{7}{5}$. The final formula is then:

$$v = \sqrt{\frac{p \cdot \gamma}{\rho}} \tag{3-6}$$

Since pressure p is proportional to the density of a gas and its temperature, the velocity is at constant temperature independent from pressure, but the velocity of sound is higher the hotter the gas. By using the ideal gas law $pV = nRT$ (Volume V, number of moles of molecules n, gas constant R and temperature T) and the molar mass of the gas M one can write:

$$v = \sqrt{\frac{\gamma \cdot R \cdot T}{M}} \tag{3-7}$$

For dry air (3-7) can be simplified to

$$v_{air} = (331.3 + 0.6 \cdot T)\frac{m}{s} \tag{3-8}$$

using the ideal gas law, standard values for air (for p, T) and mathematical expansion of the square root. T is here the temperature in degree Celsius. The value $0.6\frac{m}{s \cdot {}^0C}$ is called temperature coefficient.

In conclusion, measurements of the speed of sound in solids can be used to determine the elasticity of the material (or even identify a material by its elasticity), and for gases to get the adiabatic exponent which is used in thermodynamics.

Experimental

Equipment

- Sensor-CASSY
- CASSY Lab
- Cassy timer box
- Plastic tube with loudspeaker, inlets and outlets
- Multi-purpose microphone
- Meter scale with angular end stop
- Measuring tape 2 m
- Metal rods (aluminum, brass, copper, steel)
- Stand and clamps for rods
- Gas bottles (helium, carbon dioxide)

Set-up and Procedure for Velocity of Sound

Set-up for gases

While preparing for the experiment you should look-up the values of the density ρ of the different gases used in the experiment.

A plastic tube is used as a container in which the velocity of sound in different gases is measured. The plastic tube has a length of ca. 42 cm, and a diameter of ca. 9 cm. One end of the tube with a permanently attached gray cover has two hose nipples that allow the filling with gases and another hole to connect a microphone. The other end is closed by a small loudspeaker (see Fig. 3-2).

Setup the experiment according to Fig. 3-2. Loudspeaker and microphone are connected to the Cassy data acquisition setup. Insert the multipurpose microphone approx. 20 cm deep into the middle hole of the cover and align it along the axis of the plastic tube axis. Set the multipurpose microphone to "Trigger" mode ("rectangle" symbol). Don't forget to turn it on! It switches off automatically after 10 min.

Procedure for air

For the recording of your data use the Cassy-template "VelocityOfSoundInGasses.lab". To determine the velocity of sound v_{air} in air, the Cassy system measures the transit time t between generation of a pulse at the loudspeaker and its detection at the microphone. But since the exact point of origin of the sound in the loudspeaker and the exact position of the detection of sound in the microphone is unknown, one can not determine the velocity of sound directly. Instead, one has to do two measurements of transit time for two different positions of the microphone, e.g. once with the microphone located at a point P_1 (microphone approx. 20 cm deep in the tube), and another at P_2 (approx. only 1 cm deep in the tube). The velocity of sound is then determined from the path difference $\delta s = x_{P_1} - x_{P_2}$ and the corresponding difference in the transit time between the two points $\delta t = t_{P_1} - t_{P_2}$.

Once you have calculated the velocity of sound by this way, you now can determine the exact distance D between loudspeaker and microphone at the position P_2, by multiplying the measured transit time with the calculated velocity of the sound. Insert the distance you determined in the Cassy program. To do so, press button F5 → "click Parameter/Formular/FFT" → "Select Quantity: Distance speaker-microphone" and insert the value for D with 4 significant figures in the "Parameter" box. By default the value for D is 0.42 m. Now the software calculates directly the correct velocity of sound v for any transit time t_{P_2} *AS LONG AS you do NOT* change the position of the loudspeaker and the microphone. If you do not change the distance D you can now determine the velocity of sound of different gases directly with the Cassy setup. Check again if you now get the same value for air as before.

Procedure for gases

The gas bottles must only be handled by instructors! Set up the experiment which is shown in Fig. 3-2. Use the same position P_2 for the microphone as before. In order to fill the plastic tube with carbon dioxide, connect the silicone tubing on the *lower* hose nipple of the plastic tube. In this way, the gas is almost completely exchanged because the lighter air is pressed out through the upper hose nipple when carbon dioxide enters. Correspondingly, proceed the other way around when filling the plastic tube with the noble gases helium: when helium enters through the *upper* hose nipple, the air, which is heavier, is pressed out through the lower hose nipple. Concerning the measurements on helium, keep in mind that the measuring apparatus cannot be perfectly sealed so that part of the highly-volatile gas leaks out of the plastic tube and might distort the measurements. Therefore these measurements have to be carried out quickly. Before filling the tubes - check again the velocity of sound for air using the calibrated distance D.

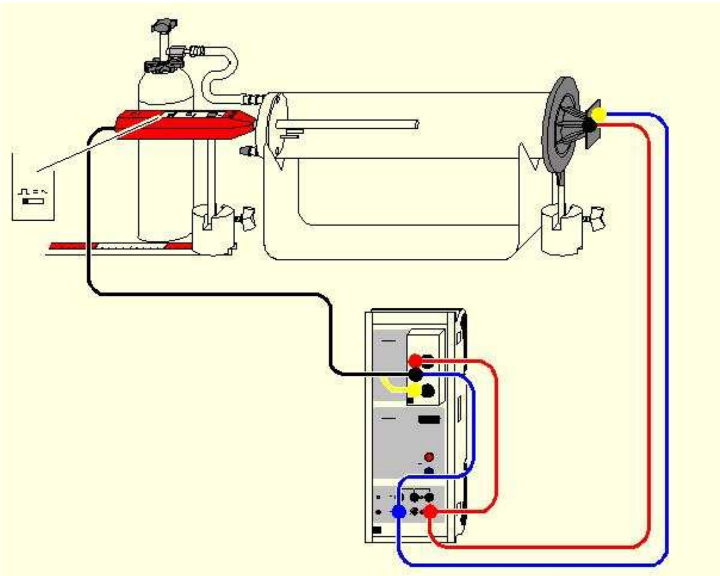


Figure 3-2: Setup 1 for different gases.

Setup for metals

The objective of this second set of experiments is to determine the velocity of sound in metal rods. Also the speed of sound in a metal rod can be determine by doing a distance and a time measurement, but this time not directly as in gases. A simple scheme of the setup is given in Fig. 3-3. A metal rod is clamped at its center and longitudinal standing waves are formed in the metal bar by gently hitting one end of the bar with a wooden block.

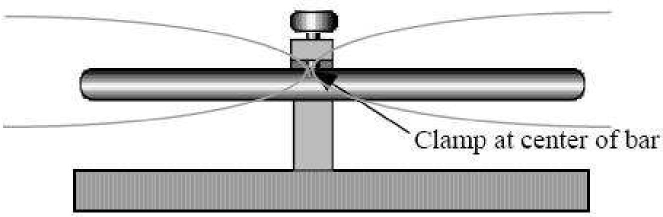


Figure 3-3: Setup 3 for metal rods.

The sound waves propagating forth and back in the rod will lead to an oscillation of the ends of the rod, which then act as a source for sound waves in air. A microphone is used to measure the resulting sound frequency f in air close to the end of the rod. The rod, when it is clamped in the center and struck along its end, will produce a fundamental frequency and this frequency will be displayed. It is this frequency that is used in conjunction with the wavelength of the standing wave in the rod (twice the length of the bar as defined by the clamping) and equation (3-3) to determine the speed of sound in the rod.

Procedure for metals

First determine the midpoint of the bar and secure it by a clamp at this position as exactly as possible.

Position the microphone near one end of the bar and set the function switch to "signal" [∼]. Gently tap the bar at its end in the direction of its long axis to excite a longitudinal wave and press the Start button (practice the tap until you hear a clean nice tone). You observe a sinusoidal oscillation on the computer screen from which you can determine the period and the frequency of the oscillation. Use at least 20 periods for the calculation.

Use the following Cassy settings: Connect the microphone directly to the Cassy voltage input (without Timer box) and use the measuring range $-3V$ to $+3V$. Select 10 μs for the measuring interval and 2000 measuring points.

Tasks

Always write an appropriate header on your notes and label your pages. Always make a scheme of the setup. Note down all experimental values, formulas, and calculations. Answer all tasks and questions in writing. Structure your notes by creating appropriate tables and highlite your final results.

1. Determine velocity of sound in air at ambient temperature

(1) Note room temperature and humidity.

(2) Measure the transit time of the sound from the loudspeaker to the microphone for two different positions of the microphone (note down the positions). For each position, take 5 time measurements and average them to minimize random errors. Determine the average transit time for each position $\overline{t_1}$ and $\overline{t_2}$ and their errors $\Delta\bar{t}$.

(3) Determine the distance between the two positions (including its error) and determine the difference in transit time for the two positions (including its error).

(4) Now calculate the velocity of sound from the ratio (distance between positions) by (difference in transit time). Determine the error of the velocity.

(5) After you have determined the velocity of sound in air v and its error Δv, compare your result with the theoretical value. Does it fit?

(6) Having determined the velocity of sound you can now calibrate the Cassy system and determine the actual distance between loudspeaker and microphone: Record the actual position of the microphone on the meter scale for further measurements and calculate the distance from the microphone D (including its error) using the actual transit time and the velocity of sound.
Note: You will use this value of D for all other experiments with gases - *DO NOT* change the position of the microphone and *DO NOT* move the tube! This will screw up your measurements!

(7) Discuss your results so far:

- Estimate the propagated instrumental error for v from the error in distance and time measurements.
- Which is the most contributing error for the determination of v?
- Compare statistical and propagated error.
- Present your a final value for v and Δv in air.

2. Measure velocity of sound in different gases
Make a table for the measurements of the velocity of sound in three different gases. Using the distance D in the Cassy software allows you to directly measure the velocity of sound in a gas.

(1) Flush the tube with gas for about 1 min. Then take 5 measurements within about 15 sec. Exchange the gas and repeat the measurement with CO_2, He, and Air. Note the values in a table.

(2) Calculate the averaged velocities and their errors for the different gases.

(3) Look up the molar mass of the gases. Calculate the adiabatic coefficient and its error for the different gases.

(4) Compare your result for γ with literature values.

(5) Discuss errors (statistical, instrumental and propagated) and potential error sources.

(6) Recommend possible improvements of the experiment, e.g. in setup or procedure.

3. Determine velocity of sound in metals

(1) For this experiment select two out of the four given metal rods and do all the following tasks with these two rods.

(2) Measure the length and diameter of each rod to determine its volume including its error. Measure its mass and then calculate its density including error.

(3) Use the procedure given above to determine the frequency of sound from the rods at least 3 times for each rod. Calculate the average and error.

(4) Using the wavelength of a standing wave in a rod, calculate the velocity of sound in the rods including their errors.

(5) Calculate the elasticity moduli of the different materials and their errors.

(6) Comment and compare velocity of sound and elasticity modulus values to literature values.

(7) Discuss errors (statistical, instrumental and propagated) and potential error sources.

(8) Recommend possible improvements of the setup and procedure.

Experiment 4 - Ideal Gas

Summary

In this experiment the relation between pressure, volume, number of moles and temperature of an ideal gas is investigated. The number of moles of air molecules and the temperature dependence of pressure or volume are determined and the resulting constants are compared with literature values.

Key Concepts

Pressure, temperature, volume, coefficient of thermal expansion, coefficient of thermal tension, coefficient of cubic compressibility, general equation of state for ideal gases, universal gas constant, Boyle's law, Gay-Lussac's law, Charles' law.

Introduction and Theory

Ideal gases are an important model system in physics. The experimental observations how pressure, volume, temperature, and number of gas molecules are related can be described by the kinetic gas theory. This theory describes the macroscopic gas parameters, such as temperature, only by the motion of gas molecules and the collisions between them. The success of this theoretical description has later contributed much to the acceptance of the existence of atoms. Ideal gases are a key model system in thermodynamics but are also important for the description of the human respiratory system. In this experiment you will investigate the basic properties of an ideal gas.

The state of a gas consisting of a fixed number of gas molecules, given as number of moles n (one mole are $6.022 \cdot 10^{23}$ molecules), is unambiguously described by its temperature T, pressure p, and volume V. If three of those variables are fixed, the fourth one is determined by the following relation which was experimentally established at the beginning of the 19^{th} century and called "Ideal Gas Law":

$$p\,V = n\,R\,T \tag{4-1}$$

Here $R = 8.3143\,JK^{-1}mol^{-1}$ is the gas constant, T is always the absolute temperature in K, and p is the absolute pressure $p = p_{atm} + p_{relative}$ in Pa. The relation is valid only for "ideal" gases which are assumed to consist of point-like hard-sphere particles (that is they have a negligible volume) which don't interact with each other except by elastic collisions. This condition is valid for most gases at low pressure and high temperature provided that the gas molecules do not chemically react with each other. Another amazing consequence of the ideal gas law is that equal volumes of different gases at the same pressure and temperature contain always the same number of molecules! So with the ideal gas law you are able to determine the number of gas molecules, and you can explain this just by basic mechanics.

For practical reasons, to compare experiments and calibrate instruments, standard conditions for gases were defined: one mole of a gas ($n = 1$) has at standard pressure $p^{\circ} = 1013.25$ hPa and standard temperature $T^{\circ} = 273.15$ K a standard volume of $V^{\circ} = 0.02241$ m^3.

The following individual gas laws have been established by experiments:

- The dependence of pressure on volume at constant temperature

The volume of a given amount of gas changes inversely proportional to the pressure if the temperature of the gas is kept constant. This relation was independently established by Boyle and Mariotte during the 17^{th} century and is known as *Boyle's law*.

$$p \propto \frac{1}{V} \quad \text{or} \quad p \cdot V = const. \qquad \text{at const. } T \tag{4-2}$$

- The dependence of pressure on temperature at constant volume

Following Boyle's work, the change of pressure and volume in dependence on temperature was investigated by Charles and the pressure was found to be proportional to the absolute temperature (for a constant number of gas molecules) as it is stated in the *Charles law*:

$$p \propto T \qquad \text{at const. } V \tag{4-3}$$

- The dependence of volume on temperature for constant pressure

The French chemist Gay-Lussac and again Charles established around 1800 that the volume of a constant mass of gas at a fixed pressure changes proportional to a change in absolute temperature. This is known as *Gay-Lussac law* or sometimes also as *Charles 2nd law*

$$V \propto T \qquad \text{at const. } p \tag{4-4}$$

The previous formulae have been verified for different gases, and one can introduce proportionality constants for the individual laws. For example, when investigating the change in pressure with temperature the *thermal tension* (β) is given by:

$$\beta_{T^\circ} = \frac{1}{p_{T^\circ}} \left(\frac{\partial p}{\partial T} \right)_{V,n} \tag{4-5}$$

Here, p_{T° is the pressure at standard temperature. Surprisingly, the thermal tension does not vary for different gases. This is especially interesting because it was known that the increase of volume for solids is proportional to temperature change but relative change of volume differ significantly among different materials.

Deviations from the *ideal gas law* are observed if intermolecular forces play a significant role or the volume of the molecules cannot be neglected compared to the total volume. Ordinary air should behave as an ideal gas if it is investigated at atmospheric pressure and room temperature.

The theoretical value of $\beta_{T^\ominus}$ can be calculated using:

$$p = \frac{nRT}{V} \tag{4-6}$$

The partial derivative of p with respect to T for constant V and n is therefore given as:

$$\left(\frac{\partial p}{\partial T}\right)_{V,n} = \frac{nR}{V} \tag{4-7}$$

The pressure at $T^\ominus$ is given as:

$$p_{T^\ominus} = \frac{n\,R\,T^\ominus}{V} \tag{4-8}$$

Plugging the equations into the equation for the thermal tension gives:

$$\beta_{T^\ominus} = \frac{V}{n\,R\,T^\ominus} \cdot \frac{n\,R}{V} = \frac{1}{T^\ominus} = 3.661 \cdot 10^{-3}\,\mathrm{K}^{-1} \tag{4-9}$$

Which can be verified in this experiment.

Experimental

Equipment

- Glass jacket system equipped with gas syringe and thermometer
- Pressure sensor with Cassy interface
- Immersion thermostat in water bath
- External barometer

Set-up and Procedure

Set up the experiment as shown in Fig. 4-1.
The central part of the experiment is a calibrated glass syringe to which a pressure sensor and a temperature bath are connected. The pressure sensor is connected to a data acquisition system, the Cassy© interface, which is used to display the relative pressure between the inside and outside of the syringe. Set this relative pressure to zero before closing the syringe and connecting the sensor to the system. Ensure that the pressure after closing the system is still zero.

The system can be heated by a glass jacket connected to a temperature-stabilized water bath. Connect the glass jacket to the immersion thermostat. The tip of the syringe is connected to the pressure sensor in a way that the gas volume in that connection (which is not heated by the water) is as little as possible. Choose a gas volume in the syringe of about 40 - 50 ml and a water temperature of room temperature or below (that is, dont heat the system) at normal pressure. Switch on the water circulation and keep the system closed (that is, keep n constant) for the following measurements:

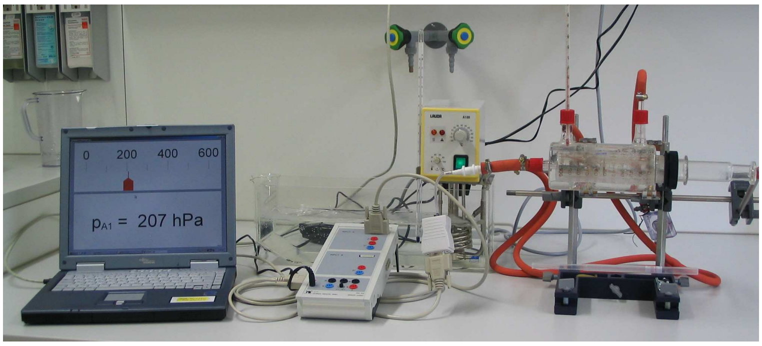


Figure 4-1: Experimental set-up: Equation of state of ideal gases.

Pressure in dependence of volume (at constant temperature) (Boyle's law)

During this experiment, the temperature in the syringe must be kept constant. Before starting the measurements set the heater slightly below room temperature and wait until the temperature has become constant. The gas in the syringe is temperature stabilized when the temperature in the immersion thermostat and the water bath are the same for at least 3 - 5 minutes. To investigate the correlation between pressure p and volume V, the gas volume of the syringe is varied by pressing or pulling the plunger of the syringe. The related pressure change in the gas is measured by the pressure sensor.

The volume change should be between -15 to $+15$ ml corresponding to a pressure change of less than 600 hPa. The actual outside atmospheric pressure can be read from a barometer.

Pressure in dependence of temperature (at constant volume) (Charles' law)

Verify again the volume at which you get a relative pressure of zero. Note it down and do not open the syringe. Do not reset the relative pressure to zero using the software. Remove water from the water bath and replace it by ice so that cold water runs through the immersion thermostat. Cool the system with the ice-cold water for approx. 5 min so that the water temperature is about 0 to 4°C. After that adjust the plunger so that the pressure in the syringe is about 150 mbar lower than the atmospheric pressure. Take care that the plunger is fixed well and does not move - neither for a low nor for a high pressure inside the syringe. Note the volume.

Slowly increase the temperature of the system in steps of about $5 - 10$ °C up to 50 °C and wait approx. 3 min for each step until the temperature reached a constant value. Measure the pressure at at least six different temperatures equally distributed over the entire temperature range. Check that the plunger does not move. Note pressure for all different temperatures.

Tasks

Always write an appropriate header on your notes and label your pages. Always make a scheme of the setup. Note down all experimental values, formulas, and calculations. Answer all tasks and questions in writing. Structure your notes by creating appropriate tables and highlite your final results.

1. Determination of number of moles in a system using Boyle's Law

(1) Record all basic settings: especially note temperature T and atmospheric pressure p_{atm} including their uncertainties.

(2) Measure the relative pressure p_{rel} for at least eight different volumes for the same amount of gas in the temperature stabilized syringe. Note also the volume for a relative pressure of $p_{rel} = 0$ and make a table of your measurements with V, p_{rel}, p, n.

(3) Give the formula to calculate the number of moles. Calculate the number of moles n for each measurement.

(4) Calculate the mean value $\overline{n}$ and its error. Use the statistic functions of your calculator.

(5) Estimate the error in V, p_{atm}, p_{rel} and calculate the error in p.

(6) Calculate the propagated error for n from the errors in p, V, T. Give the formula for the partial derivatives of n with respect to p, V and T multiplied with the error of the respective quantity, that is:

$$\left|\left(\frac{\partial n}{\partial p}\right)_{V,T} \cdot \Delta p\right| , and \left|\left(\frac{\partial n}{\partial V}\right)_{p,T} \cdot \Delta V\right| , and \left|\left(\frac{\partial n}{\partial T}\right)_{p,V} \cdot \Delta T\right| \tag{4-10}$$

(7) Calculate the values of all three partial derivatives and errors using a set of experimental values from your measurement which resulted in a number of moles closest to the average value.

(8) Is there a dominating error source? If so, which one?

(9) Calculate the final propagated error for n and compare it with the error of the mean.

(10) Present your final values for the number of moles and their uncertainty.

(11) Do you have any suggestions how to improve the experiment?

2. Pressure in dependence of temperature of an ideal gas

(1) Fix the volume of the gas in the syringe using the same amount of gas as in the previous experiment (dont open the syringe!). Note down the value of V. Vary the temperature T, and record the relative pressure p_{rel} for each temperature. Measure at least six different temperatures between $0 - 50$ °C, evenly distributed across the temperature range. Make a table of T, p_{rel}, and p.

(2) Plot the pressure values p over T. Include error bars and make a straight line fit.

(3) Extrapolate the graph to the standard temperature $T^{\ominus}$. Determine the slope and intercept which corresponds to $(\frac{\partial p}{\partial T})_{n,V}$ and $p_{T^{\ominus}}$, respectively.

(4) Give slope (m) and intercept (c) and calculate the coefficient of thermal tension *from the slope of your graph.*

(5) Determine also an error of the slope and give an error for the thermal tension.

(6) Compare your result with the theoretical value and comment on potential error sources and improvements.

Summary

The focal length of a lens is determined by measuring different object and image distances. Furthermore, simple optical instruments such as a slide projector, telescope, and microscope are constructed using different combinations of lenses.

Key Concepts

Geometrical optics, thin lenses, optical axis, focal length, object distance, real and virtual image, principal rays, convex and concave lenses, spherical aberration, chromatic aberration, magnification, microscope, telescope, condenser.

Introduction and Theory

Light is a complex phenomenon. The propagation of light is best described by a wave model, but understanding emission and adsorption requires a particle approach. In the 17th century the wave properties of light began to emerge and at the end of the 19th century Maxwell showed that light is indeed an *electromagnetic wave*. Then, at the beginning of the 20th century the particle picture of light began to emerge. The description of light as a stream of *photons* finally led the way to quantum physics.
Here we use the ray model for the description of lenses and simple optical instruments. It holds for situations where optical objects are much larger than the wavelength of light and we represent the direction in which light propagates by *light rays* which is the most simple description of light phenomena and optical instruments. This branch of optics is called *geometric optics* since geometry and trigonometry play the key role in describing how light rays form images. Simple optical instruments such as mirrors or burning glasses were known since ancient times. Then in the 17th century first optical instruments like telescopes and microscopes were built in the Netherlands and Italy and the first mathematical description of optics emerged, e.g. the law of refraction (Kepler 1611 and Snel 1621).
First we have to define some terms: An *object* is anything from which light rays radiate. Do rays coming from an object (after refraction or reflection) seem to diverge from a certain position other than the object, this position is called the *image* position. When rays from an object converge at a certain location, a *real* image can be observed on a screen. Compared to that, a *virtual* image can not be projected on a screen instead it is formed only in the eye of the observer. A virtual image is made by parallel or only slightly converging or diverging rays which are then entering the eye and are focused on the retina by the lens in the eye. In optical instruments such as telescopes or microscopes magnified images of real objects are created by combination of lenses and mirrors to investigate details of the objects not visible by the bare eye. The main component of optical instruments is the *lens* which focuses parallel light rays to a single point which is called the *focal point*. The focal point lays on the *optical axis*, a line normal to the plane of the lens and running through its center. The distance from lens to focal point is called the *focal length*. The focal length of a spherical lens depends on the refractive index n of the lens material and the radii of curvature of the two surfaces of the lens. Since n can vary with wavelength, f depends also on the color of the light ("chromatic aberration"). The smaller the curvature (i.e. radius R) of a symmetric lens, the shorter its focal length f and the stronger its refractive power. Here we will use convex lenses

described by thin-lens equations, that is the thickness of the lens is negligible.

The relationship between the **focal length** f of a lens, the **object distance** s and the **image distance** s' is obtained from geometrical optics. Three particular rays, the focal ray, the parallel ray and the central ray, are used to construct the image (Fig. 5-1).

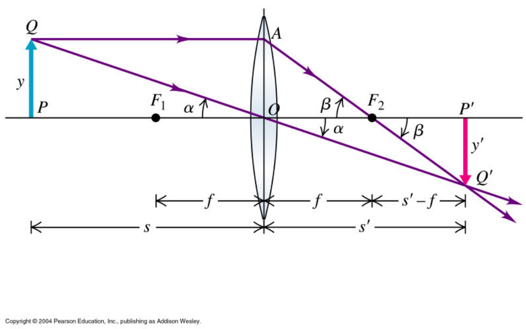


Figure 5-1: Image construction by two principal rays.

The central ray passing through the center of the lens is not deflected. The parallel ray running parallel to the optical axis is deflected through a focal point after passing the lens. And the focal ray (not shown) which runs through a focal point is proceeding parallel to the optical axis after passing through the lens.

From the laws of similar triangles we find for angle α and angle β in Fig. 5-1:

$$\frac{y'}{s'} = \frac{y}{s} \quad \text{and} \quad \frac{y}{f} = \frac{y'}{s'-f} \quad \text{or} \quad \frac{y'}{y} = \frac{s'-f}{f}$$

where y' is the image size and y is the object size, s' is the image distance, s is the object distance. By transformation we obtain the so-called "lens formula"

$$\frac{1}{f} = \frac{1}{s} + \frac{1}{s'} \tag{5-1}$$

In case two lenses are combined and their distance is much smaller than their focal length, their total focal length is given by:

$$\frac{1}{f_{tot}} = \frac{1}{f_1} + \frac{1}{f_2} - \frac{d}{f_1 \cdot f_2} \tag{5-2}$$

Here the last part of the equation above is a correction term, in case the two lenses are not directly touching each other and their centers are a distance d apart.
Since it is easier to deal with the inverse of the focal length the dioptric power of a lens was defined which is simply the inverse of the focal length: $D = \frac{1}{f}$ with the units $1D = 1m^{-1}$

which is called 1 diopter. The lens of a human eye has an approximate dioptric power of 59 D (corresponding to a focal length of about 17 mm). In case one is shortsighted, that is the focus from the eye lens is in front of the retina, one needs to add eye glasses with diverging lenses or a negative diopter. In case one is farsighted, the focus of the eye lens is behind the retina and one needs to increase the refractive power by using eye glasses with converging lenses or a positive diopter. In the following, the two basic formulas are applied to investigate the properties of lenses and setup different optical instruments.

1. **Lenses**
   The most simple way to determine the focal length of a lens is to create an image of an object by the lens and calculate its focal length by the respective distances using the formula above. When combining two lenses the image distance is shifted depending on the focal length of the lenses and if they are diverging or converging.

2. **Optical Instruments**
   Optical instruments can be used to project enlarged images of an object on a screen (slide projector), to have a closer look at small objects (microscope), or to observe distant objects through a telescope. The rays leaving an optical instrument can be designed for two different situations: either a real image is formed by the instrument on a screen (then the rays leaving the instrument have to converge at the location of the screen), or the rays go directly into the eye (then the rays have to leave the optical instrument as parallel rays which are then focused by the eye lens on the retina). A normal human eye can focus an object which is located anywhere between infinity and a certain point called near point (which is set by convention at 25 cm away from the eye).

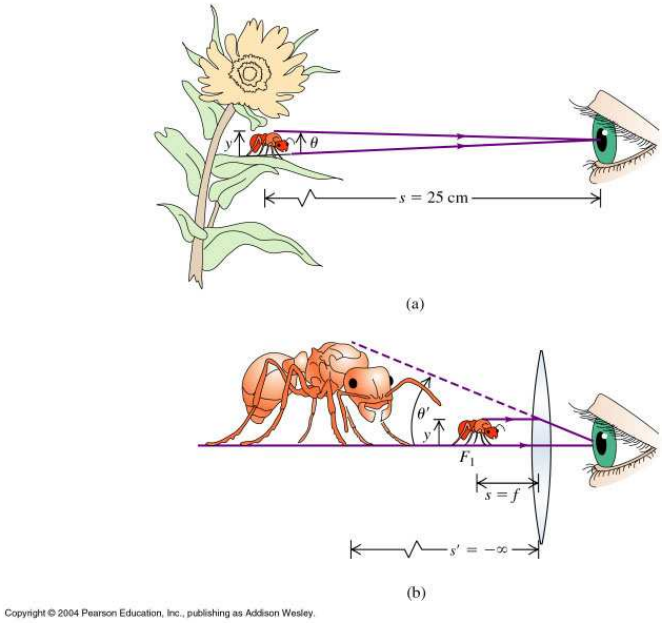


Figure 5-2: Magnification

   (a) *Simple magnifier*
   In order to see smaller details with the naked eye we must bring an object

very close to the eye. This increases the angular size of an object. The typical closest distance for a young adult is about 25 cm (the near point) from the eye. Bringing it closer the image will blur. But by using a convergent lens the object can be brought closer and still be focused by the eye. In this case the object is inside the focal length of the magnifying lens. Such a magnifying lens creates a virtual image with a large angular size from an object with small angular size (compare Fig. 5-2). The magnifying power or angular magnification is defined as the ratio of angular size of the virtual image to angular size of the object (when the eye is adapted to infinity and angles are small):

$$M = \frac{\theta'}{\theta} = \frac{25\,\mathrm{cm}}{f} \tag{5-3}$$

This is especially suited for situations where one can not assess the size of objects and images directly (e.g. when observing the moon or a distant tree). Otherwise a magnification can also be define as the ratio of image size to object size: $M = \frac{s'}{s}$.

(b) *Microscope*
A simple microscope consists of two lenses: an objective lens is placed near the object which forms a real, magnified image of the object. The ocular (or eyepiece) lens is then used to inspect this image, magnifies it further and forms a virtual image at infinity. Its magnification is the product of the magnification of the objective and the magnification of the ocular:

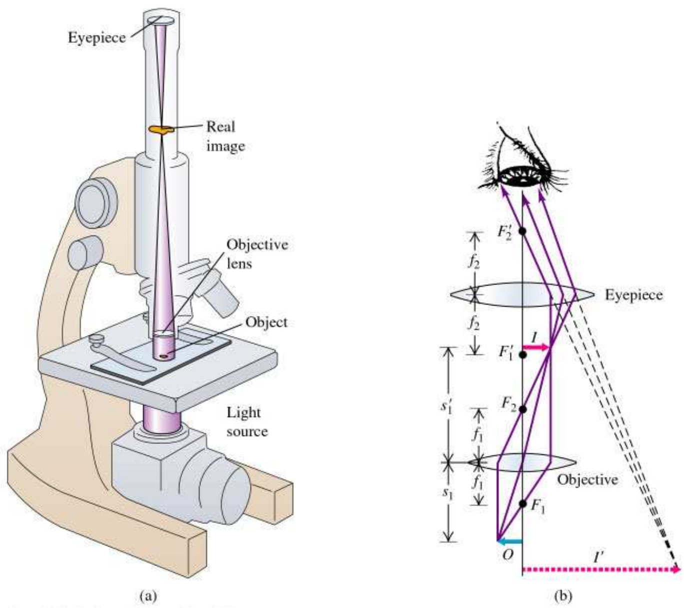


Figure 5-3: Microscope

$$M = M_{ob} \cdot M_{oc} = \frac{s'_{ob}}{f_{ob}} \cdot \frac{25\,\mathrm{cm}}{f_{oc}}$$

Both focal lengths are found in the denominator of the expression for magnification indicating that lenses with a short focal length are used in a microscope. The object is pretty small and light rays coming from the object are highly divergent and have to be collected by the objective. Theoretically the magnification can be increased by bringing the object even closer to the focal point of the objective or by increasing the distance between the two lenses but this is limited by technical issues such as the size of lenses and related lens errors, and the brightness of the image.
Therefore, the length s'_{ob} is set by convention to something of about 16 cm (depending if you buy a microscope from e.g. Zeiss or Nikon) and called the tube length of a microscope. When projecting the image from a microscope on a screen (or also on a CCD camera chip) one has to slightly adjust the position of the real intermediate image from the inside to the outside of the focal length of the eyepiece. Then also the distance of the screen from the eyepiece instead of the near point has to be used to calculate magnification, which is given as:

$$M = M_{ob} \cdot M_{oc} \approx \frac{s'_{ob}}{f_{ob}} \cdot \frac{s'_{oc}}{f_{oc}} \tag{5-4}$$

Of course, one can not increase magnification to infinity. At one point the lens geometry, its material, the illumination and the wavelength of light will limit the maximum magnification at which one still can clearly see and focus an image.

(c) *Telescopes*
Also a telescope consists of two lenses in series, but here the object is far away and rays from the object enter the objective lens as parallel rays (and not highly divergent as for the microscope objective). One can not magnify the object by bringing it closer to the objective. But in both instruments the real image formed by an objective is viewed and further magnified by an eyepiece. The primary function of a telescope is to enlarge the retinal image of a distant object. Since distant objects have nearly parallel rays their image lays in the focal plane of the objective lens. Adding an ocular will increase magnification and leads to an angular magnification of a **Kepler** type telescope consisting of two convex lenses, resulting in a magnification of

$$M_{Kep} = -\frac{f_{ob}}{f_{oc}} \tag{5-5}$$

Here we see that an telescope should have a long objective focal length, whereas an microscope should have a short objective focal length to achieve a good angular magnification. Note that a Kepler telescope produces an inverted image of the object.

Kepler type of telescopes are preferred as refracting telescopes because a scale or cross-hairs can be easily introduced in the focal plane. **Galilei** type of

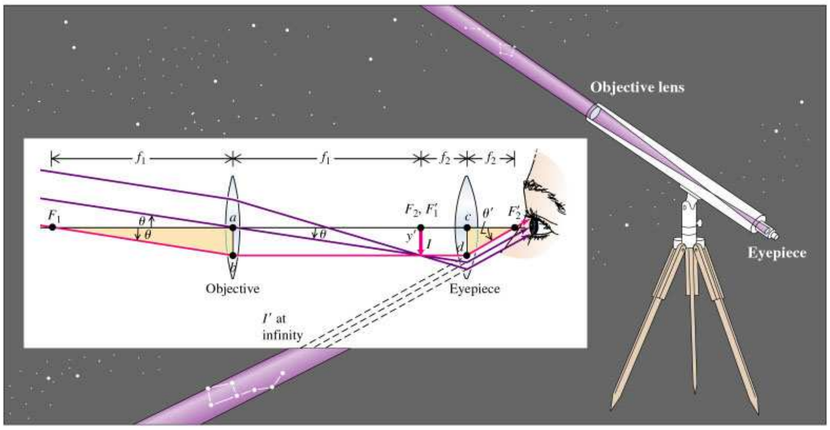


Figure 5-4: Kepler type telescope

telescopes produce upright images of distant objects by placing a concave lens in the path of rays in front of the real first image produced by the objective (compare Fig. 5-7 given in the procedure). The focal points of objective and ocular coincide and the magnification is again:

$$M_{gal} = \frac{f_{ob}}{f_{oc}}$$

Experimental

Equipment

- Optical bench with holders
- Set of converging and diverging lenses
- Screen
- Different objects
- Experimental lamp with condenser lens
- Power supply 0-12V DC/6V, 12V AC

Set-up and Procedure

In this experiment an optical bench will be used on which different combinations of light sources, lenses, and screens can be mounted to characterize lenses or to build optical instruments. The experimental setup of a slide projector is shown as an example for all experiments in Fig. 5-5.

Some general advice: Darken the room to improve your observations. A homogeneous and nearly parallel light beam is produced by the lamp in combination with the double condenser. Place the condenser in front of the lamp in such a way that the lamp filament is focused to infinity (e.g. on the opposite wall). Before any observation the optical set-up has to be carefully aligned. Check that all elements are positioned at the same height and along as well as perpendicular to the optical axis.

Figure 5-5: Experimental set-up of a slide projector.

1. **Determination of the focal length of lenses**
   Position the object (an arrow slit) close to the condenser of the light source and project

a clear image through the lens on a screen. The distances of image and object from the lens are measured (assume that the lens is a thin lens) and the focal length is calculated. Use at least three different distances between object and lens to calculate the focal length. Use as error the uncertainty of position of lens and object and the range in which you observe an image on the screen as "sharp". Determine the focal length of the lens.
In a next step use a 100 mm converging lens and add a +200 mm converging and also a -200 mm diverging lens as close to the original lens as possible and determine the focus of the combined lens system.

2. Optical instruments

(a) **Telescope after Kepler**
Use two lenses, one with a short focal length (e.g. 20 mm or 50 mm) and one with a long focal length (e.g. 200 mm or 300 mm) to build a Kepler telescope (compare Fig. 5-6).

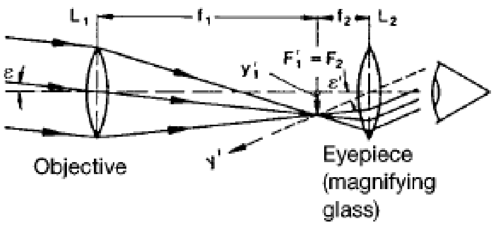


Figure 5-6: Rays in Kepler telescope.

If we look through the lens of short focal length, we can see an inverted, magnified image of a distant object.

(b) **Galileo telescope or opera glass (additional task)**
Use two lenses, a concave lens with a short focal length (e.g. 20 mm or 50 mm) and a convex lens with a long focal length (e.g. 200 mm or 300 mm) to build a Galileo telescope.

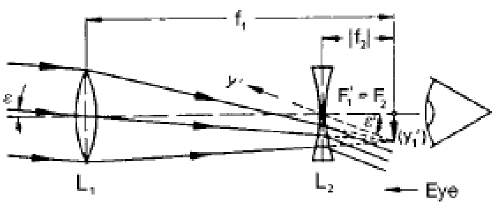


Figure 5-7: Rays in Galileo telescope.

Through the concave lens we can see distant objects magnified and the right way up.

(c) **Microscope**
Setup a microscope using two lenses, one of focal length of $f = 20$ mm (as ocular lens) and another of $f = 50$ mm (as objective lens). Use the cover glass with a dog flea as object and setup the microscope such that it projects an image of the flea on a screen. Since there are many possible combinations of distances and image sizes, use a distance between the two lenses of about 20 cm and place the screen in about 30 cm from the eyepiece. Find the position of the object such that a clear and enlarged image of the flea is produced on the screen.

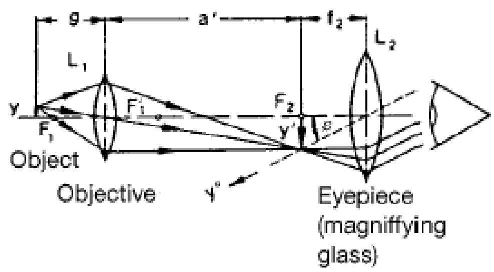


Figure 5-8: Rays in a microscope.

Tasks

Always write an appropriate header on your notes and label your pages. Always make a scheme of the setup. Note down all experimental values, formulas, and calculations. Answer all tasks and questions in writing. Structure your notes by creating appropriate tables and highlite your final results.

1. Determine the focal length of two lenses

(1) Make a sketch of your setup including the different parts (lamp, condenser, arrow) and indicate distances needed for calculation of f.

(2) Determine the positions for the object, unknown lens, and screen of your setup to get a sharp image.

(3) Calculate image and object distance from your measurements and calculate the focal length.

(4) Repeat the measurement at least 5 times, using each time a different distance between object and lens.

(5) Determine the average, standard deviation and error of the mean for f.

(6) Repeat the measurements for the second lens.

(7) What is the uncertainty of your position measurements and how does it effect the error for the focal length? Compare it with the obtained statistical error and comment.

2. Determine the focal length and image distance of a combined lens system

(1) Place a +100 mm lens in a distance of 20 cm from the object and adjust the screen for a sharp image. Record the position and compare it to calculations.

(2) Place a +200 mm lens as close as possible behind the first lens and move the screen until you get a sharp image.
Record the new image distance and compare it with calculations using a combined total focal length for the two lenses close together.

(3) Place a -200 mm lens as close as possible to the first lens and move the screen until you get a sharp image. Record the new image distance and compare it with calculations using a combined total focal length for the two lenses close together.

(4) Comment on how far the two lens combinations resemble glasses for a short- or farsighted eye. Compare experimental and theoretical values and possible systematic errors.

3. Build a telescope after Kepler

(1) Setup a telescope on an optical bench. Make a sketch of your setup and note all position of the lenses of the telescope.

(2) Calculate the magnification of the telescope and estimate its error.

(3) Determine the observed magnification of your telescope and compare the experimental result to your calculations.

(4) Describe and characterize the image quality (e.g. brightness, sharpness, distortions,...) in words.

(5) Demonstrate the telescope to a teaching assistant or instructor and discuss improvements.

4. Setup a microscope

(1) Build a micorscope on an optical bench and project the image on a screen. Make a sketch of your setup and note all position of the lenses for the microscope.

(2) Calculate the magnification of the microscope using the focal lengths of the two lenses.

(3) Determine the observed magnification of your microscope by measuring object and image size, and compare the experimental result to your calculations.

(4) Describe and characterize the image quality (e.g. brightness, sharpness, distortions,...).

(5) Demonstrate the microscope to a teaching assistant or instructor and discuss improvements.

Summary

Diffracting objects of different shape (single slit, wire, and gratings) are illuminated by a laser beam. The corresponding maxima and minima of the diffraction patterns are used to determine object dimensions or the laser wavelength. Using a diffraction grating the light from different vapors is inspected and the element in the vapor identified.

Key Concepts

Electromagnetic waves, phase, amplitude, intensity, coherence, laser, diffraction, interference, Fraunhofer and Fresnel diffraction, Babinet's theorem, slit aperture, diffraction grating, Bohr atomic model, light emission, electronic transitions.

Introduction and Theory

For the description of diffraction effects the wave-like nature of light has to be used. Light waves are **electromagnetic waves** which have a certain wavelength λ and frequency f related to each other by the speed of light c by $c = \lambda f$. If monochromatic light of a specific wavelength λ passes through a small aperture like a thin slit, one does not observe only a single bright stripe on a screen behind the object, but instead one can observe a pattern with alternating intensity minima and maxima - called a **diffraction pattern**. This pattern is due to the wavelike nature of light and the interference of elementary wavelets from different points of the light wave in the slit: When a wave enters an opening in a barrier, each part of the wave passing the opening can be seen as a tiny elementary wavelet spreading in all directions. This leads to the effect that light is spread out (it is diffracted) also into the region directly behind a barrier. Following Huygens-Fresnel's principles the intensity distribution on a screen is a superposition or interference of all the different wavelets in an opening. Here we assume also that the screen is far away from the aperture (this situation is called "Fraunhofer diffraction") so that the description of the effects get easier.
Diffraction is used in several analytical techniques: by analysing the diffraction pattern of an object when it is illuminated by light of a known wavelength one can determine the structure of a material, e.g. in x-ray crystallography. Or, when the light is diffracted by an object of known structure, e.g. a grating, one can identify the different components of the light, that is its spectrum, and can get information on the light source.
To understand diffraction we have first a look at the pattern of a *two beam interference*, or the interference of light waves from two sources to understand the general concept. Important is that the two light waves are **coherent**, that is that they are synchronized and have a distinct phase relation so that they can interfere. This is done by splitting light coming from the same light source into two beams. The experiment is called Young's Interference or Double Slit Experiment after Thomas Young who proved around 1800 that light has a wave-like character. With simple geometrical considerations one can describe the location of intensity maxima (bright spots) and minima (dark areas) in the interference or diffraction pattern from a double slit (see Fig.6-1 and Fig.6-5). Depending on the angle relative to the central axis, the light waves from the two slits travel a different path length until they hit the screen. When the difference is an integer multiple of their wavelength, then we have **constructive interference** and the two wave amplitudes at the screen add up resulting in a maximum, a high intensity light spot. If they have a path length difference of multiples of half of the wavelength then they show **destructive**

interference, the wave amplitudes from the two slits cancel each other, and we have a minimum or a low intensity region.

The mathematical relation for a double slit (according to Fig.6-1) is:

$$\sin\theta_k = \pm\frac{k\cdot\lambda}{d};\ (k = 0, 1, 2, 3, ...);\quad for\ maxima \tag{6-1}$$

$$\sin\theta_k = \pm\frac{2k+1}{2}\cdot\frac{\lambda}{d};\ (k = 0, 1, 2, 3, ...);\quad for\ minima \tag{6-2}$$

with wavelength λ, angle relative to central axis θ, and distance d between two light sources. In Fig.6-1, D is the distance between apertures and screen, b the path length difference between the two waves, and y the distance of maxima or minima from central axis.

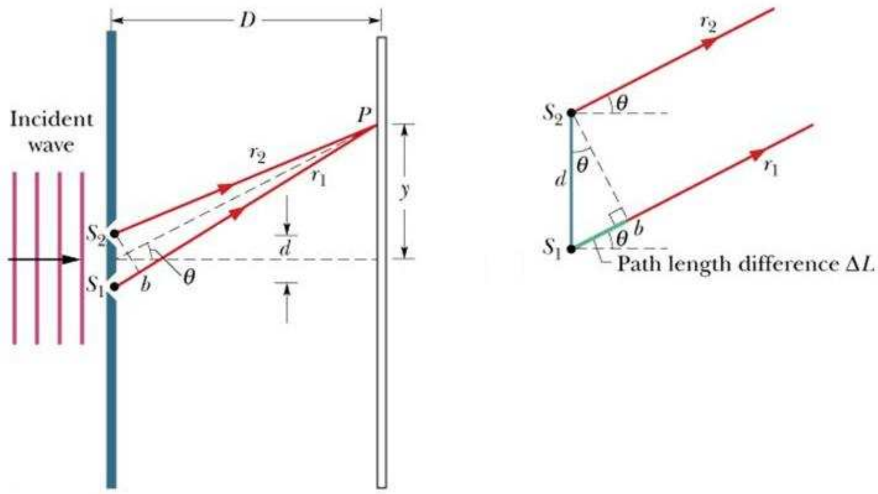


Figure 6-1: Scheme of two beam interference.

Not only light from two distinct sources but also the interference of elementary waves within the same planar wave passing a **single slit** can lead to easily observable diffraction effects. Such a diffraction pattern is investigated in this experiment. A thin slit (with sub-millimeter width) illuminated by a laser will herefore show a similar diffraction pattern on a screen placed behind the slit. One does not observe a simple single bright stripe directly behind the slit, as one would expect using geometrical optics with straight light rays, but an intensity distribution with minima and maxima. Every elementary wavelet in the aperture interferes with its neighbouring wavelets, creating a diffraction pattern with a central (or zero's order) maximum in the middle and higher order maxima with decreasing intensity on the sides (see Fig.6-5, top). Due to the continuous distribution of elementary wavelets the calculation of the location of maxima is complicated, but the approximation of the minima is straight forward: Dividing a single slit e.g. in two sections, wavelets from the top and the bottom section can interfere destructively when traveling under a certain angle. **The locations of minima for a single sli**t with diameter a can be described by:

$$\sin\theta_k = \pm\frac{k\cdot\lambda}{a};\ (k = 1, 2, 3, ...);\quad \mathit{minima\ for\ single\ slit} \tag{6-3}$$

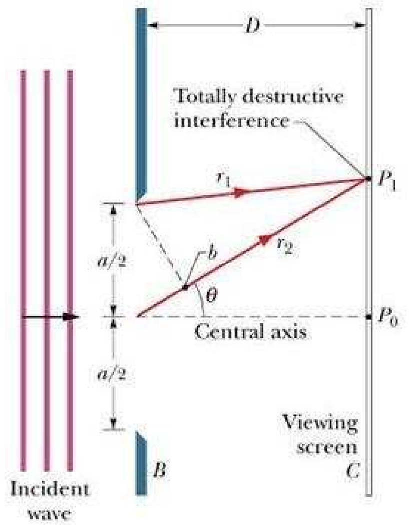


Figure 6-2: Scheme of single slit diffraction pattern

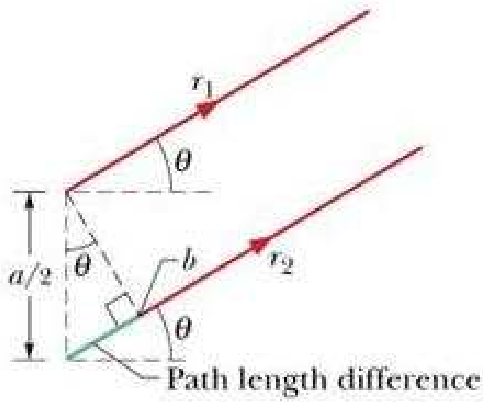


Figure 6-3: Details of Fig.6-2.

More complicated geometries, e.g. 3 slits, 4 slits etc., can be thought as combinations of the diffraction pattern of a single slit and interference effects from different slits.

An interesting observation can be made when illuminating a thin wire having the identical diameter as a thin slit: Both objects create identical diffraction patterns! According to **Babinet's theorem**, the diffraction patterns of complementary diffracting objects (e.g. holes and discs, or slits and wires with identical dimensions) are identical outside the central diffraction spot meaning that the positions of the peaks and of the secondary peaks of the wire coincide exactly with those of the complementary slit. Therefore one can use the identical formula to evaluate the diffraction pattern of a thin slit or a thin wire.

The intensity of the diffraction pattern of a single diffracting object is distributed among many maxima and is decaying quiet rapidly when moving further away from the central spot. In contrast, when using a periodic structure of parallel slits or wires, a so called **grating**, the diffracted intensities from each slit are combined and concentrated in a few spots with high intensities. As a general rule, the smaller the diffracting structures, the wider apart are the features in the diffraction pattern. See Fig. 6-4 and Fig.6-5.

When light is diffracted through such a transmission grating the diffraction angle θ of the **maxima** fulfills the following relation:

$$\sin\theta_k = \frac{k\lambda}{G}\qquad (k = 0, \pm1, \pm2, \pm3, ...) \tag{6-4}$$

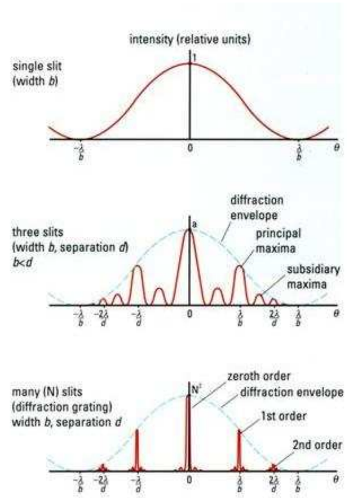


Figure 6-4: Scheme of intensity distribution of single slit to many slits.

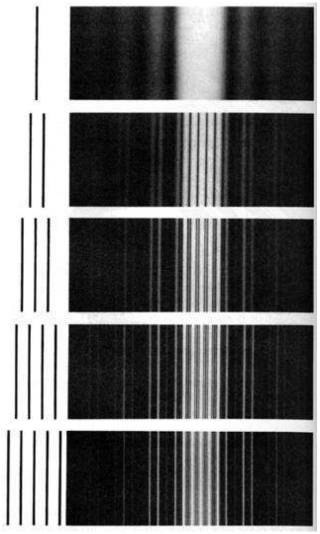


Figure 6-5: Diffraction pattern (right) of different slit numbers (left).

Here the **lattice constant** G is the distance from the center of one slit (wire) to the center of the next slit (wire). Also its inverse $\frac{1}{G}$ can be used to characterize a grating by its number of slits (wires) per length of the grating.
A grating can also be used to analyze the wavelength composition, that is the **spectrum of light**. Since diffraction is wavelength dependent, shorter wavelength (bluish light) will be diffracted less (smaller diffraction angles) than longer wavelengths (reddish light with larger diffraction angles). Like a prism, a grating splits white light in different colors (wavelengths) such that they can be observed under different diffraction angles.

Light emitted from a gas or vapor of a single element will show a composition of wavelengths which is characteristic for the electronic structure of the specific element. The light is composed of specific **emission lines** which originate from the different electronic transitions in an atom. To determine the wavelength of spectral lines by a grating with grating constant G, the angle θ_1 at which the first order diffraction pattern appears can be measured. According to equation (6-4) the wavelength λ is then given as:

$$\lambda = G \cdot \sin\theta_1 \tag{6-5}$$

The **Bohr model** for the hydrogen atom was among the earliest successes of atomic physics. It describes the most important properties of the hydrogen atom, especially its spectral lines, quite accurately. The Bohr model assumes that the electrons of an atom move around the nucleus on discrete orbits. When atoms being excited by absorbing some energy, their electrons are "lifted" to a higher orbit or energy level, and can then decay back to a lower energy level. During the decay they release energy by emitting light of the frequency ν related to the energy difference of the two energy levels $\Delta E = h\nu$. E.g. when the excited electron of the H atom takes a transition from an energy level E_m to an energy level E_n with $m > n$, then a photon is emitted which has an energy $\Delta E = h\nu$ corresponding to the electron's change in energy. The frequency can be transformed into

a wavelength by $c = \lambda \cdot \nu$ with c the speed of light and h Plancks constant (see below). Hydrogen shows some prominent **spectral lines** in the visible range with wavelengths of 656 nm (red), and 410 - 486 nm (violet - blue)
Here the light from different spectral lamps is observed through a grating and the element in the atomic vapor is identified by its spectral fingerprint, that is by the presence of specific lines of different colors and intensities. This measuring principle is the same as for modern spectrometers used to identify different atoms or molecules by their emitted light.

Experimental

Equipment

- Optical bench
- He-Ne laser with power supply
- Different slits, wires, and gratings with holder
- Wall screen
- Green laser
- Spectral lamps with holder and power supply
- Ruler

Set-up and Procedure

Caution: Never look directly into a laser beam! Even an attenuated laser beam can harm your eyes! Remove all reflecting watches or jewellery (e.g. rings) from your hands and arms when working with a laser!

Diffraction of laser light

The experimental set up is as shown in Fig. 6-6. Here a Helium-Neon-Laser is used which emits red light of $\lambda = 632.8\ nm$ from a transition in the Ne atom. Its light is monochromatic and highly polarized. The laser is fixed on an optical bench so that the laser beam hits a screen on the wall. The bench should be perpendicular to the wall. The laser should warm up for about 15 minutes before starting measurements, in order to avoid intensity fluctuations.

Mark the position of the laser spot on the screen with a vertical line. Then a diffracting object is placed in the laser beam in front of the laser. Now you can measure the distances between object and screen, and between the different minima and maxima of diffracted light on the screen.

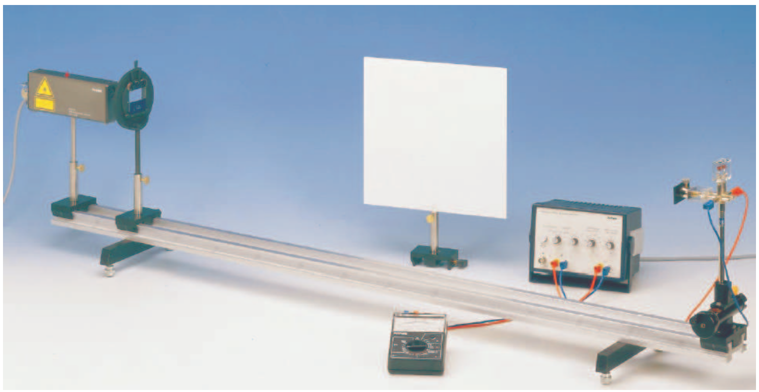


Figure 6-6: Experimental set-up for analyzing diffraction patterns.

Measurements of a single slit and a hair

Set the diffracting object in the object holder and adjust it such that you get a clear diffraction pattern on the screen. Measure the distance between the minima of identical diffraction orders using different distances between object and screen. Use at least two different distances between object and screen between 0.70 m and 1.50 m and do at least 6 measurements. Use Fig. 6-2 and formula (6-3) to calculate θ and a. The hair can be fixed in a provided slide frame.

Measurement of gratings

Place a grating as diffraction object in the object holder. Adjust the distance of grating to screen so that you get at least the 2nd order maxima on the screen on the wall. Determine the grating constant in lines/mm by measuring the location of the diffraction spots by using Fig.6-2 and formula (6-4). First the HeNe laser is used then an additional green laser.

Identifying atomic spectra

The experimental set-up is shown in Fig.6-7.

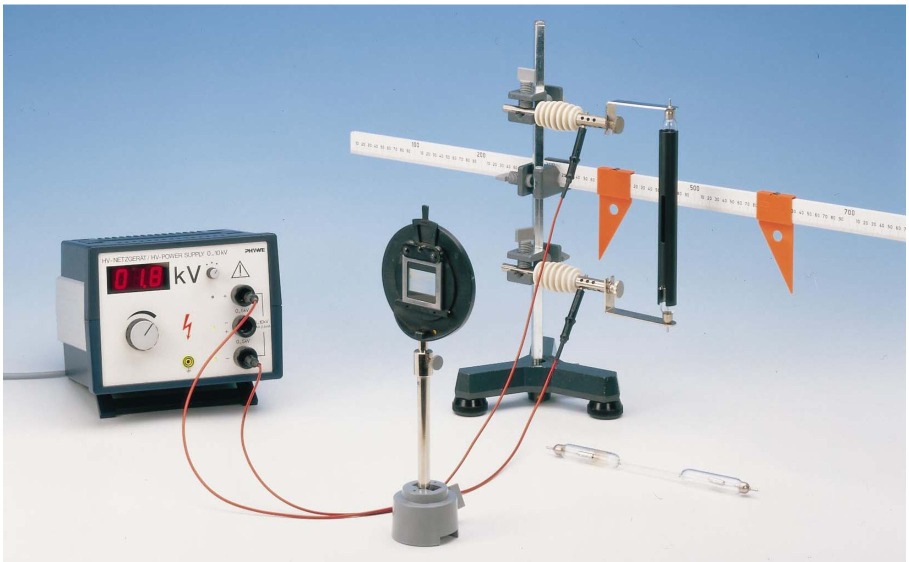


Figure 6-7: Experimental set-up to determine the spectral lines.

The light source is a gas discharge tube filled with a noble gas operating at high voltages (**Caution! DO NOT touch the electrodes or metal electrode holders!**). Perform the experiment with gas tubes according to the following steps:

> The spectral tube which is the source of radiation is connected to the high voltage power supply unit. Before switching it on let the spectral tube setup be checked by a TA.

The diffraction grating should be set up at about 50 cm and at the same height as the center of the spectral tube. The grating must be aligned as parallel to the scale as possible. (Try what happens if you tilt the grating.)

Switch on the power supply and adjust it to about 1.8 kV. If the voltage is chosen too high, the lamp starts flickering what should be avoided. Choose a voltage high enough for a good signal with low flickering.

The light from the spectral tube is observed through the grating. The room should be darkened.

Tasks

Always write an appropriate header on your notes and label your pages. Always make a scheme of the setup. Note down all experimental values, formulas, and calculations. Answer all tasks and questions in writing. Structure your notes by creating appropriate tables and highlite your final results.

1. Single slit diffraction

Focus the red laser on one of the slits and **mark the position of minima** of the resulting diffraction pattern on a graph paper attached to the wall. Note down the wavelength of the laser. Chose a distance between screen and diffracting object between 0.70 m and 1.50 m.

(1) Make a sketch of the setup indicating the different distances and parameters you use for your evaluation. Also indicate the angle between minima you have to determine.

(2) Use at least two different distances D between screen and diffracting object. For each distance D use at least three different diffraction orders k to measure the distances d between **minima** of identical order. Be sure to give the correct order of each minimum. Calculate the slit width a. Note everything in a table with D, k, d, and a.

(3) Give the formula to calculate the angle between the central maximum and the different minima by using D and d.

(4) Can you simplify your formula for the slit width? Give your final formula how you calculate the slit width a.

(5) Use the values of a from your table and calculate the average, standard deviation, and error of the mean of the slit width.

(6) Give the formula for the propagated error in a. Calculate the propagated error for a from ΔD and Δd, assuming a negligible uncertainty for the wavelength.

(7) Compare propagated and statistical error, identify the major error source and comment on your result. Is the propagated error dependent on k? Present your final result for the slit width including uncertainty.

2. Diameter of a hair by diffraction

Adjust the laser on the hair and mark the position of minima of the resulting diffraction pattern on a graph paper attached to the wall. Chose a distance between screen and diffracting object between 0.70 m and 1.50 m.

(1) Make a sketch of the setup indicating the different distances and parameters you use for your evaluation. Also indicate the angle between minima you have to determine.

(2) Make a table of D, k, d, and a. Use at least two different distances D between screen and diffracting object. For each distance D use at least three different diffraction orders to measure the distances d between minima of identical order.

(3) Give the formula to calculate the angle between the central maximum and the different minima by using D and d.

(4) Can you simplify your formula for the diameter of the hair? Give your final formula how you calculate the diameter a.

(5) Write the values for the hair width a in your table. Calculate its average, standard deviation, and error of the mean.

(6) Give the formula for the propagated error in a. Calculate the propagated error for a from ΔD and Δd, assuming a negligible uncertainty for the wavelength.

(7) Compare propagated and statistical error, identify the major error source and comment on your result. Is the error dependent on k? Give your final result including uncertainty.

3. Grating constant

Place the grating between laser and screen and **mark the position of maxima** of the resulting diffraction pattern on a graph paper attached to the wall. You might need to chose a shorter distance between grating and screen to get at least the 2nd order maxima on the screen.

Caution: Never touch the surface of a grating!

(1) Make a sketch of the setup indicating the different distances and variables you use for your evaluations. Also indicate the angle between maxima you have to determine.

(2) Make a table with D, k, s, θ, and G. Measure the position s of the **maxima** of the diffraction pattern as you did for the minima in the previous tasks. Use at least two different distances D between grating and screen and measure for each distance at least 2 different orders of maxima.

(3) Give the formula to calculate the angle θ between a maximum and the central maximum. Can you simplify this calculation?

(4) Give the final formula for the grating constant.

(5) Calculate the average and standard deviation of G and give the error of the mean.

(6) Estimate (!) the propagated error in G from the uncertainties in D and s (for its proper calculation you would have to use the full error propagation with partial derivatives). Give your estimate of the propagated error in G. Compare it to the statistical error.

(7) Present the final value for the grating constant including its uncertainty.

4. Determine the wavelength of a green laser

Exchange the red laser by a green laser. Are the maxima from the green laser closer together or further apart than those of the red laser?

Caution: Never look into ANY laser! High intensity laser beams damage your eyes!

(1) Make a sketch of the setup indicating the different distances and variables you use for your evaluations. Also indicate the angle between maxima you have to determine.

(2) Make a table with D, k, s, θ, and λ. Measure again the position s of the **maxima** of the diffraction pattern. Use at least two different distances D between grating and screen and measure for each distance at least 2 different orders of maxima.

(3) Give the final formula to calculate the wavelength of the green laser.

(4) Calculate the average and standard deviation of λ and give the error of the mean.

(5) Estimate the propagated error in λ from the uncertainties in D, s, and G.

(6) Present the final value for the wavelength including its uncertainty.

5. Atomic spectra

A TA or instructor will setup the gas discharge lamps. Use the grating from above to observe light coming from two different lamps. Document accuerately what you observe.

(1) Describe the setup and draw a scheme.

(2) Describe the spectra in words and draw a scheme indicating the number and order of lines, their color, and intensity.

(3) Identify the spectra by comparing them with different spectra from literature and describe their differences.

Guidelines for writing a laboratory report

Report writing is a generic skill required in many occupations. Engineers, scientists, and also administrators in the financial sector or politics have to provide assessments, evaluations, or analysis and write up their results in form of a report. Good report writing is an essential skill in modern society. The quality of an oral or written report is invariably one of the criteria used in job interviews to evaluate a candidate. Giving a report and being able to structure and express your thoughts, to convince and persuade other people of your ideas and conclusions will be an important factor for advancing your career.

A written report is a mean to disclose, spread or circulate information. At all times the person who reads the report should clearly understand what you are trying to say. Therefore, a report has to be written in a clear and concise style. It must convey the information in a logical step-by-step sequence so that the reader is led inescapably to the same conclusions as the author of the report.

In the reports you have to write in the Physics Lab Course, you will be given specific tasks and objectives towards which you have to work to. In order to meet these objectives, you must develop a logical argument which culminates in a conclusion. The report should therefore follow a carefully considered, logical sequence in order to arrive at that conclusion. Along the way you have to convince the reader (and especially the person who corrects your report) at each stage that you have done the right thing and have made the correct interpretations of your results. You must provide the necessary background, inform the reader what you did and persuade him of your conclusions. If you developed a logical and complete argument, supported by correct scientific facts, then the reader will arrive at the same conclusions. Any errors, missing information, or wrong wording will mislead the reader and will cast doubt on your results and conclusions.

In general, the form, length, content, and emphasis of a report are determined by its purpose, topic and the intended audience. It is clear that there exists no single perfect format of a report. However, the structure of all reports is similar and includes a section that describes the objectives and background (what is known), methods and procedure (what has been done), results and conclusions (what has been measured and what are the implications). This format has evolved over time in practice and in many fields. In the following, we will give you a format which is best suited for writing Physics Lab Reports.

The Physics Laboratory Reports should answer the following general questions:

- What was the goal, what were the objectives of the experiment?
- What is the background, what is the underlying physics of the experiment?
- Which methods or techniques have been used?
- How was the raw data evaluated, what was the result of the experiment, and how does it compare to theory?
- How reliable is the result and what have been possible error sources?
- What conclusion can be drawn?

In general the lab report is a text reporting on the experiment (background, setup, outcome) by addressing all the questions and tasks given in the manual. As said before, a good laboratory report will enable the reader to repeat your measurements and critically assess your evaluation and conclusions. The reader should be able to understand the experiment without consulting other sources except your lab report. This implies that the reader should be able to answer the questions above just by reading your report.

Structure and Content

Here, some guidelines for the content of the different sections of a lab report are given. If you encounter problems use your common sense and always stick to the general principles of clarity, brevity and a professional scientific style.
For the specific purpose of the Physics Teaching Labs at Jacobs the lab report should be independent from any other source of information, that is all raw and processed data, schemes, and graphs should be given in the report, not referring to your notes or the manual for any experimental data. Related to a more detailed content of the report, all questions posed and tasks given in the manual (under "Result Form") should be addressed in a report, but it again does not need to refer to the numbering or the structure of the manual.
The development of a logical argument is assisted by an hierarchical order and clear numbering of the following sections which you should use to structure the content of your report:

Abstract

This is usually the last section written, but it should head the report. In the real world an abstract will be the only section read by most readers, so it should briefly and truthfully summarize your report.
The abstract should be a very brief overview of the goals and the main results of the experiment. It shortly states the main objectives of the experiment. It names the main method used, states the main numerical result including error and gives the agreement or disagreement with theory or expectations. Sometimes, especially in case of disagreement, a statement about the main error source is recommended. An abstract does not include any tables, figures, lists, or equations. The abstract must not be longer than a short paragraph (maximum 10 lines).

Introduction and Theory

Here, the general background and the underlying physics of the experiment should be provided. This should be motivated by a short statement on the objectives and tasks. A historical account of the experiment is not necessary. This section should provide the theoretical background for the experiment and the data evaluation. Cite or derive any equations needed, and discuss all basic formulas necessary for data evaluation and for interpreting your results. Omit derivation of standard formulas but describe the relationship between quantities to be measured and standard formulas. It is essential to define all symbols used. In addition, any assumptions or limitations made by the theory or used for the experiment should be stated (and justified if possible). Give and cite all literature values you might compare your data to. This part should describe the experiment or method in general. Technical or method specific equations, e.g. how to read the numerical results from an instrument or what are the correct orders of magnitude of the data belong to the experimental section.

Experimental and Procedure

This section describes the main equipment used for the experiment and details of the procedures you followed. After reading this section, the reader should be able to repeat your experiment and should come to the same results. Hence, you have to list all relevant parameters which may influence your data and results, even if they are not directly used for data analysis. A detailed part list is **not** required.

- Describe shortly the overall measurement configuration and set-up. **Always** show a sketch or scheme of the set-up as a figure and explain what is seen in the figure. Highlight important experimental parameters in your scheme, e.g. length, angle etc.. State the chosen parameter ranges and instrumental settings and give the formulas you have to use to get meaningful quantities from the readings of instruments. Refer to formulas in the theory part and give the final formula used for the calculated result. This part should have all the information needed to reproduce the set-up independently.

- Write a short but sufficient account of the procedure used to carry out the experiment. Describe the steps you took to obtain the data. Do not forget to describe calibration procedures if they were needed. On the other hand, it is normally not necessary to give a too detailed step-by-step account of all your activities during the experiment. Instead, avoid unimportant and too specific details (like “a screwdriver was used to turn the red button at the instrument” etc. . .).

- To be concise, keep in mind that the experimental section is a report on what you actually did and not what one should do like in an instruction manual. So don’t write instructions and do not give a word-to-word copy of the lab manual.

Results and Data Analysis

This section provides the measured raw data, its mathematical treatment and the numerical results. It is the key part of the lab report. It should be **written as a text** describing what has been done and obtained. It should not just be a list of formulas, numbers, keywords or tables. All data and results need to be described and connected by sentences.
The raw data which was originally collected should clearly be identified as such. It is important to provide the original and non-manipulated data because later on your experiment may be evaluated in a different way or by someone else. Also, the corrector of your lab report may find that a faulty result was only due to wrong data manipulation and not due to a totally wrong data acquisition, or that you recorded the wrong data but did the right evaluation.

- raw data has to be directly written in the lab notes or uploaded as a pdf file with clear and correct captions of tables and graphs, and with the correct units and orders of magnitude. For the lab report, the original raw data has to be provided either directly in the text of the report or attached as an appendix. The type of data can vary and can include numbers, images, tables, graphs etc. If the raw data can be inserted in a table or figure filling less than half a page, the raw data should be provided directly in the text. In any case, the original units and orders of magnitude of the raw data have to be clearly stated.

- This section should also describe in a step-like manner and textual form what data analysis and calculations have been performed by citing formulas from theory and procedures. Present the data neatly and clearly in tables including clear headings and units. Sometimes this part may already be combined with the error analysis described in the next section. All equations needed for the data evaluation have to be given here (either by citing from the theory part or by simply restating). Especially in first year reports, you should show a sample calculation using numerical values and the corresponding units. To do so, it is easier to follow your calculations and to identify unnecessary mistakes, e.g. wrong orders of ten by switching from nm to m, or liters to m^3. Always do a quick reality check of your numerical result - does its order of magnitude make sense?

- This section concludes with the **statement of the final numerical result(s)** of your experiment without a detailed discussion (which is part of the next sections!). The result has to be identified as such and should be stated in a textual context. The end result of the data analysis should be the information which can be used to discuss the outcome of the experiment or project.

- Specify all values with an appropriate number of significant digits and with correct units. Errors should be given with at most two significant digits and the numerical value of a quantity has to have the same precision as the error. You will find more on error analysis in the next section and in the *Error Analysis Booklet*. Guidelines for presenting tables and graphs are also given below.

- Use the most compact layout and lowest number of tables. Avoid rewriting formulas, avoid rewriting the same procedure several times, don't repeat redundant values over and over, do not fill entire columns in tables with identical values. When reporting numerical values, always use the lowest number of zeros possible by making use of abbreviations for appropriate orders of ten such as k, m, M or G.

Error analysis

In this section, the numerical validity of the result has to be evaluated including the uncertainties of the measured quantities and their contribution to the uncertainty of the final result. Sometimes, for simple error calculations, this section may be combined with the data analysis.

- You should state or estimate possible error sources of the experiment, especially including the specifications of instruments and reading errors. Sometimes, after listing all error sources, certain errors can be neglected since they are much smaller than others. This may simplify the error calculation, but you should give a justification for it.

- For directly measured quantities, the error is given by the accuracy and/or precision of the instrument as well as by the statistical error in case multiple measurements were performed. This applies e.g. for a temperature measured by a thermometer or a length measured by a ruler. The error of a quantity which is derived from other measured parameters must be obtained by application of the error propagation theorem, respecting all parameters (see Error Analysis Booklet). This holds e.g. if the number of moles of an enclosed amount of gas is calculated from the three directly measured parameters pressure, volume, and temperature.
- Always state the type of error you use for calculations. You dont need to give the formula to calculate a mean value or the standard deviation. Just name them and indicate the number of measurements you used to calculate the values. But you should always give the final formula by which you calculate a propagated error, since it can be applied differently to different formulas.
- **Never** specify any error with **more than two** significant digits.

Discussion

In this section, you should discuss your observations and results and compare them to your expectations and theory. An unbiased critical judgment and a scientific discussion is at the heart of all science. You should be able to make a reasonable assessment of your experiment. Compared to other sections the discussion part especially demands critical thinking, a clear line of reasoning and creativity. It is even more important that you get a clear picture and a good argument why your experiment did not succeed instead of presenting "perfect" results but with a wrong discussion.

- Some questions you should keep in mind are: What does the data tell me? What is the quality and accuracy of my experiment or procedure? Does my result agree to other results or literature values? If yes or no what does this tell me about the experiment or model I used? Are there any potential systematic error sources in the experimental procedure? Which error sources are significant? What is the dominant error source and how could it be reduced?
- You should not just write down all possible error sources which come to your mind, but only the most likely error sources. Keep in mind that you always have to back-up your claims of error sources at least with numerical estimates.
- Avoid speculations except you have a valid basis of argumentation. Do not over complicate matter (e.g. using quantum mechanics to explain mechanics or optics) and argue on an appropriate level.
- If the expected or literature value is not in the range of uncertainty of the your result or your data does not follow a predicted trend, this has to be stated and possible causes to be named. For example, if you expect that a plot of your data

shows an intercept of zero but your experimental result differs from it, name the deviation and its possible causes.

- Any possible systematic errors that cannot be accounted for by error calculation should also be named and estimated. This may especially be important in case your result does not agree with a literature value.

- This is the place to mention observations relevant to the experiment but which have not been recorded numerically or systematically. This may be e.g. values changing in time, readings jumping when other equipment is switched on, background noise or light in the room, room temperature or humidity, ... etc..

- Finally, given the main goal of the experiment, you should formulate some suggestions how to improve the experiment or increase the precision of your result in case you or someone else will repeat it in the future (e.g. by modifying the set-up, using another procedure or evaluation method...).

Conclusion

This section of a report is the second most read part. It is not just a restatement of the abstract, instead it looks more into the future. Try to take an overview over the experiment, where you started, what you have reached and where further investigations may want to go. Base all conclusions on your actual results. Explain the implications of your results and put them in a broader context. The conclusions should be also short but a bit longer than the abstract.
The final result has to be restated including its uncertainty. If a physical constant has been measured, the result has to be compared with literature. Main errors and possible improvements of the experiment should be given by summarizing the discussion of the previous paragraph.

References and Appendices

In this section, you should give a list of references as well as all information that decreases the readability of your report if embedded in text in the previous sections.

- You should provide all references you used for preparing the report. This is either done by giving general references for the entire report or by indicating with a number in the text which source you used for a specific statement, equation, literature value or any thought or argument which is not your own. The references are then specified in a numbered list.
  A reference generally contains at least its author(s), title (of book or journal), position in book or journal (e.g. chapter or starting page number) and date of publishing. It may also contain the publisher, editor, issue of a journal, and total page numbers. The reader should be able to identify and access the source of information you used.

- In most cases, copies of your original recordings or raw data has to be added as an appendix. In case of a long report, the presentation of large tables and graphs or the lengthy derivation of an equation would disturb the readability of the report. These parts should then also be included as appendices.

As stated already, for some experiments it may be favorable to combine some sections in a single paragraph. For example, if intermediate results of different parts of an experiment have to be evaluated, it may be suitable to perform data analysis, error calculation and discussion in one paragraph for each part of the experiment.

Format and Language

Reports are judged not only on technical or scientific content but also on clarity, ease of understanding and on their format and layout. Please adhere to the following guidelines for the format of your physics lab report.

General instructions

- Reports are most effective if they are written in a language and style selected for the background of a specific audience or a principal reader. Try to write your report in such a way that a person familiar with physics but not familiar with this particular experiment would be able to follow what you did and why you did it.

- The report should be written as a coherent and continuous text with full sentences, NOT as a list of words and formulas or as separated statements. Results should be described in a sentence, NOT only presented as numerical values of a variable or as a number in a table. Refer to formulas, tables and figures in the text by their numbers or captions.

- Your guiding principles should be brevity, clarity and concision. Use the minimum number of words to write a text and to make your point. The quality of a report is in no way related to its length. A typical number of 5 to 10 pages can serve as a guideline. Print on A4 paper and use font size of 10 - 12 with single or 1.5 line spacing.

- Sometimes repetition of information in different sections of the report, perhaps with a different emphasis or detail is necessary.

- The style of the report should be formal and impersonal (avoid “we” or “I”). It should be written in the past tense since you are reporting something you did in the past. Sometimes the present tense may be justified, e.g. in the theory section or discussion. Do not give instructions. You are also expected to write legibly, using correct grammar and accurate spelling.

- DO NOT copy from the lab manual, a textbook or the internet. The report should be written in your own words. Normally, the manual provides more information and instructions than you need for the report (especially for “introduction and theory” and “procedure”). Select only the relevant information for your report. In cases when it is inevitable that you have to use additional literature, information from the internet, or parts from the manual, you have to reference paragraphs, figures or formulas accordingly at the end of the lab report in a reference section. *Using the work of another person and presenting it as your own constitutes plagiarism and will be punished according to the code of academic integrity.*

- Get used as soon as possible in using a PC or laptop with standard software to evaluate data and write reports. In the most simple case, Microsoft Excel can be used for data analysis and making graphs, Microsoft Word can be used to write text and formulas. But also any other comparable and more sophisticated software is fine. You might for example already use LaTeX for writing a report. In case you don't know how to format a table or graph or write a formula you might consider to plot it by hand and scan it in - but only in your first semester. Whatever you do - the report has finally to be submitted as a pdf file using A4 page sizes.
- You may underline your layout structure e.g. by using boldface formatting for headings and/or italics for figure captions, but take care to format paragraphs, subparagraphs etc. consistently. Avoid any overuse of structuring by using too many different formats.
- Include page numbers and use appropriate margins.
- The report should be proof-read in its final layout before submission. As you edit it you may delete unnecessary words, rewrite unclear phrases and clean up grammatical errors. *Both students are equally responsible for the final submitted version of the report.*
- The final report is then submitted as a single pdf file for grading.

Title page

Each lab report should be identified by the title of the laboratory course (including course number), the title of the experiment, the authors with group number, and the date the experiment was performed.

Quantities and Equations

In general, scientific notation and SI units have to be used in the Physics Labs.

- The decimal fraction of a number is indicated by a decimal point not a comma, e.g. "3.1415" and NOT "3,1415".
- Exponents have to be written as superscript, e.g. ten to the power of four is given as 10^4 and NOT as 10E4, 10ˆ4 or other notations.
- Numerical values have to be separated by a blank from their units e.g. 10 mN not 10mN.
- Vectors have to be identified as such and should clearly differ from scalars. The best way to identify a vector is by the arrow on top of a letter (you can also add these at the end by hand writing). In cases you are using bold letters to identify vectors, please define your choice of format.

- Equations should be embedded in the text and described by a sentence. All variables or constants have to be defined in the text close to the equation. If more than one equation is used they should be numbered sequentially throughout the text. In general, variables have to be defined only at their first appearance in the text, but it may increase clarity if they are restated when used in sections far apart.

- Equations have to be written with a proper formula editor or by hand. Do not use e.g. an asterisk " * " or " x " as a multiplication sign.

- As a general rule NEVER state errors with more than two significant digits. Adjust the significant digits of numerical values to their corresponding error values.

Data tables

Tables of raw data can be included as an appendix. Other tables should be embedded in the text. In any case, you have to refer to the table in the text of the report.

- Captions
  Data tables must be identified by a unique number. This helps to refer to the table from within the text (e.g. "Table 3. Electric field and forces"). In addition, a short description of the table contents is mandatory. The table caption should be on top of the table.

- Headers
  Each column or row in a table should have a heading that describes the physical quantity that is recorded in the column. The heading should also show the units of the physical quantity and its appropriate order of magnitude (and the uncertainty in the quantity (if constant)). For example "F [mN]" or "force [mN]" or for the error "ΔF [mN]" (without quotes).

- Data presentation
  Numerical values recorded in a table should be rounded to the appropriate number of significant digits. If the uncertainty is not constant for all values, add an additional column. Do not give inappropriate large number of digits.

Figures and Graphs

In general for layout purposes, every non-numerical or non-textual pieces of information such as graphs, pictures, schemes, etc. are called "figures". Any figure should be identified by a unique number in its caption. The figure caption must include a short description of the details in the figure (e.g. "Figure 2. Graph of force versus distance. The force is plotted in dependence of the inverse square of the distance."). The figure caption should help the reader to roughly understand a figure even without reading the related text.
Graphs should be prepared on graph paper or with data processing software according to the instructions in the manual. Bad layout due to insufficient (use of) software is not accepted. For clarity and to support the line of argumentation figures are normally inserted into the text. Hand-drawn figures can also be added as appendix. Again, take care to refer to them correctly in the text.

- Caption
  Every figure should be identified by a unique number, e.g. "Figure 1". The caption should also include some short descriptive sentence(s) telling exactly what is shown, e.g. "Experimental setup of the ideal gas experiment." This might be followed by a more detailed description of different parts of the figure (e.g. (a), (b), (c) ...). A figure caption is normally plotted directly below the figure in a different font so it can be easily identified as being separate from the normal text.

- Axes and Axes Labels
  Both axes (bottom and left) should be labeled with the physical quantity that is plotted on the axis and the units of the physical quantity in brackets, e.g. "F [mN]" (without quotes). For clarity numbers on axis should have a low number of digits.

- Size and Clarity
  All graphs should be produced at a size that is sufficiently large so that the information can be easily read. Choose axis limits so that the region of interest occupies most of the graph area.

- Data Display
  Data points in hand-drawn plots have to be indicated by crosses. Data values should never be connected with a line. Where applicable you should include a fit of a curve that represents the physical relation between the displayed quantities.

- Annotation
  Whenever results of best fit or smoothing procedures to the experimental data are displayed in the graph, the fit/smooth method must be clearly mentioned in its caption. In the case of a linear (straight line) fit, present the values of the slope and the y-intercept as well as their errors within the text (i.e. NOT in the graph itself). Be sure to also include the associated units. If possible, describe the physical significance of the slope and intercept.

- Uncertainty Bars
  Whenever the uncertainties of individual data values are known they should be indicated in the graph using error bars.

Final Remarks

The most frequent complain from students about report writing is the excessive amount of time needed for preparing a report. This may be true, but in fact, students who are able to report on their work in a clear, organized and conclusive report receive better grades (not only in physics) than those who can not. Report writing can be indeed time-intensive, but the time is well spent, because report writing is a general skill needed in most professions and it will be most valuable in your future career. The more experience you get the less time you will need in the future to prepare a professional scientific report. The report writing in the physics labs will prepare you well to finally write a BSc thesis or maybe even a first scientific publication at the end of your studies at Jacobs.
The time needed for writing a report can be optimized by proper planning. A good preparation of the experiment and knowing what you will do and what the physics is

behind an experiment will facilitate the recording and evaluation of the data. The clarity of writing depends on the clarity of thinking. Word processors and spread sheet software (e.g. Excel) will increase efficient writing and data analysis. Adhering to the given guidelines will also help to save time. Often it is helpful to first make a rough draft of the report and a layout of its structure and content. Thereby, a first selection of important features of the experiment, theory and data should be made. Then after writing the text you should reconsider, edit and polish the report into a final version.

The content of these guidelines has evolved over time and will be used to grade lab reports for undergraduate physics majors at Jacobs University. They also contain information and instructions extracted from standard textbooks, instructions for authors from scientific journals and from other lab report guidelines published on the internet (especially from: www.iit.edu, physics.usask.ca, physics.wku.edu, physics.mq.edu.au). Any ideas or comments for further improvement are welcome.