

PHYS 2022

Physics from Evidence I

Laboratory Manual

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1. MODULE INFORMATION

1.1 Overview of Module Structure

PHYS2022 Physics from Evidence I course consists of three parts: Teaching Labs, Computing and Student Conference. Teaching Labs and Computing both run within the first 11 weeks and the Student Conference is expected to be in week 16.

Students are split into 8 groups - Groups A to H. Each group has five Teaching Labs sessions and Computing sessions within the first 11 weeks, in alternate weeks. A Teaching Laboratory experiment consists of one lab sessions so there will be 5 experiments in total to complete.

Preparation is required for the first lab session. Preparation includes answering **preliminary questions** and writing (in your own words) the **aims of the experiment**. Such preparation has to be completed before the lab session starts and this rule applies to all experiments. You have to submit a pdf in Blackboard before you start the experiment.

For the Conference, students will be allocated into groups of ~5. Details will be provided on Blackboard at the beginning of the semester. Each group will prepare a 25-minute presentation based on one of the experiments completed in the Lab, followed by questions. The presentation will be given at the Student Conference in January and will be marked by an academic.

The division of marks contributing to the final grade is 55% from the Teaching Labs, 35% from the Computing Module and 10% from the Student Conference. Note that a 40% pass mark is required in **EACH** part (Teaching Labs, Computing Module and Student Conference).

1.2 Timetable

1.2.1 Lab Sessions

<u>Weeks 1 to 11</u>	
Group A: Mondays	9:00 – 12:00, 14:00 – 17:00 (even weeks 2-10)
Group B: Tuesdays	9:00 – 12:00, 14:00 – 17:00 (even weeks 2-10)
Group C: Thursdays	9:00 – 12:00, 14:00 – 17:00 (even weeks 2-10)
Group D: Thursdays	9:00 – 12:00, 14:00 – 17:00 (even weeks 2-10)
Group E: Mondays	9:00 – 12:00, 14:00 – 17:00 (odd weeks 3-11)
Group F: Tuesdays	9:00 – 12:00, 14:00 – 17:00 (odd weeks 3-11)
Group G: Thursdays	9:00 – 12:00, 14:00 – 17:00 (odd weeks 3-11)
Group H: Thursdays	9:00 – 12:00, 14:00 – 17:00 (odd weeks 3-11)

1.3 Lab Referrals

There are no referrals or deferrals for PHYS2022 module in the Summer Supplementary Examination period. If you fail PHYS2022 (or are deferred), the normal referral (deferral) procedure is to take the module again in the following academic year. You will not pass the corresponding Part of your degree programme until you pass this core module.

1.4 Student Conference

The student conference is the final stage of the course and is closely linked with the Teaching Labs. Each student will take part in a group presentation of one experiment. There will be five students per group.

Parallel sessions will run in week 16. Your group will be signed up to a slot in one of these sessions, which includes 25 minutes for your group presentation plus 10 minutes for questions.

Illustrate with Microsoft PowerPoint (*.pptx format) only please.

The audience will be other students/presenters plus a member of staff acting as a chair and as an assessor/marker. The audience has to actively participate in the conference, asking questions and in discussions.

Marking of your talks will be in three categories: Scientific Content 60%, Structure 20%, and Delivery 20%. A copy of the mark sheet is shown on the next page.

Make sure to stick to the 25-minute slot – exceeding time will lower your mark. Also, you are not meant to read from your notes. It's an oral presentation and you should know what you're talking about!

The conference will be held virtually, using Teams. You must turn up in your assigned slot to give your conference presentation. It is unlike other forms of coursework: there is no equivalent of late hand-in, so you need to show up if you want to pass the course.

Further details and advice regarding conference presentations will be available on the module's Blackboard site.

PHYS2022 - Physics from Evidence I Conference Presentation

Name:					
Topic:					
Date:					
Marker:					
Science Content /5		Structure /5		Delivery /5	
Comments:					

Marks and Range: 0 / 1 / 2 / 2.5 / 3 / 3.5 / 4 / 4.5 / 5

Scientific Content:

- *depth of the physics background*
- *focus on topic*
- *clarity of explanations and of experimental data and graphs*
- *errors discussed*
- *data analysed and correct conclusions drawn*

Structure of Presentation:

- *well designed and prepared*
- *clearly structured, easy to understand and follow, there was a logical order*
- *there was a suitable introduction and summary*

Delivery:

- *presentation was well delivered and engaging*
- *the speaker was confident and maintained contact with the audience*
- *visual aids were appropriate and supported the arguments*
- *the speaker did not just read out aloud the text from the slides or notes*
- *well timed presentation*

Weighting: Scientific Content 60%, Structure 20%, Delivery 20%

2. TEACHING LABORATORIES INFORMATION

2.1 Teaching Laboratory Experiments

The laboratory part of this module aims to support and enhance the depth of understanding of the topics covered in core lecture courses. The topics of experiments range from photonics, solid state physics, classical mechanics and quantum physics.

While doing lab work, it is important that you develop independence and confidence in completing experimental tasks from collecting data to their analysis and discussion. You will be supported and guided by a team of academic, post-graduate and technical demonstrators and we hope you are going to enjoy the experience.

There is no eating or drinking in the lab, iPods etc. or open toe sandals/open toe shoes. Please read safety instructions and be sensible.

During the lab part of the course you need to complete 5 experiments over 10 weeks, i.e. there are two weeks per experiment. The current, full set of experiments is:

- **Atomic Excitation**
- **Normal Modes**
- **Diffraction and Interference**
- **Black Body Radiation**
- **Speed of Electromagnetic Waves**
- **Semiconductor p-n Junctions**

Each week, the lab consists of three elements:

- 1) Preparation at home before the lab session: Background reading about the assigned experiment, answering prelim questions in your logbook and a statement of the aims of the experiment in your own words.
- 2) Prelim marking sessions: Group instruction from a demonstrator; one-to-one marking of your answers to prelim questions.
- 3) Main lab session: Independent work on experiments carefully recorded in your logbook under the guidance of demonstrators.

2.2 Time Management

PLEASE NOTE: Punctuality is essential for laboratory sessions as well as for marking. Late arrivals are not allowed.

Preliminary questions have to be answered and written in your logbook and background reading completed before the prelim marking session. A lack of answers or preparation means a zero mark for prelims. Furthermore, in such cases the students will not be allowed to start their experiment, getting **zero mark for the whole experiment**.

The attendance list will be taken down 15 minutes after the scheduled start of the lab

session, so late arrivals will not be allowed to do their experiment and get **zero marks for that experiment**.

PLEASE Contact Mark Ashley (m.d.ashley@soton.ac.uk) if you know you are going to (or did) miss attendance of labs ASAP.

2.3 Preparation and Marking of Prelims

Preparation is required *before* each experiment, including the first experiment in the first lab session for each group.

Before coming to the lab (including your first lab session) you **must**:

- Read the script thoroughly
- Watch introduction videos on Blackboard
- Research anything you do not understand
- In your logbook:
 - have the answers to set prelim questions
 - all the main aims of the experiment clearly stated in your own words

Prepare to answer questions on:

- describing the main stages/parts of the experiment, what will be measured and how it will be measured
- describing the effect to be explored
- the method(s) and the apparatus you will be using
- background knowledge to carry out the experiment (to benefit and enjoy it)

PLEASE NOTE: DO NOT copy material/text from lab hand-outs.

Your preparation for each experiment will be assessed by one of the academic demonstrators (marks from 0 to 10) and the prelim mark is worth 15% of the total mark for each experiment. Lack of preparation means **zero mark for the whole experiment** and you will not be allowed to do the experiment.

2.4 Practical Work

The lab sessions start with a short technical presentation by either an academic in charge of the experiment. This brief introduction will enable you to ask any remaining question you have about the experiment after looking at the lab manual and video introduction. The meeting with the demonstrator is set between 10:00-11:00 for each session.

You will be either working on your own on the experiment. When working with a lab

partner for the final experiment you should keep your own record of results and carry out your own data analysis and discussion. However, talking to other students doing the same experiment is very much encouraged, of course without copying their results. The whole experiment has to be completed by the end of the week of the lab session for that experiment. You should have plenty of time to record, plot and analyse your data in your lab book before the end of the session.

COVID19 and lab safety

In 2020, we are implementing strict new social distancing measures in the labs. The unprecedented COVID19 pandemic is causing substantive changes to how we will be interacting with you.

The School of Physics & Astronomy has created effective bubbles which you will be part of throughout the year during your teaching hours. The University is also hoping to have a track and trace system operational by the start of the academic year.

We still aim and hope to run labs as seamlessly as possible and have introduced new ways to keep in contact. This includes new screens and computers at every lab station, new safety measures on room occupancy and procedures for interaction with demonstrators

The most important things you can do are:

- If you exhibit symptoms of COVID19, do not come to the department. Go straight home, isolate yourself, and follow government guidelines regarding testing, rest, and social distancing. Use the University's COVID reporting form.
- When you enter (and exit) the lab, your first (and final) task must be to sanitise all equipment and surfaces that you touch.
- During your lab sessions, interact with your tutor group via Teams, and minimise interactions with others.
- Take personal responsibility and follow government guidelines even when you are not in the lab.

This setup is all very new to us as well, but we are keen to make your experience and time in the labs valuable.

2.5 Keeping Your Laboratory Record

You should study the information on 'Writing a Laboratory Notebook' included in section 3 of this manual before you begin your first experiment.

Note these vital points:

1. R & D professionals do not "write up" their lab notebooks after the event. You must WRITE YOUR RECORD STRAIGHT INTO YOUR LOGBOOK as you go along. Loose sheets of paper with data on them may be confiscated and destroyed. You risk getting low marks for a tidy book that has clearly been "written up" in the evening.
2. Your logbook should be a chronological record of everything that has been done;

the order it was done in; the problems that arose; all the data; all the experimental conditions; a note of everything you observe and anything that puzzles you; estimates of the precision of the measured values you record.

3. YOUR DATA TAKES CENTRE STAGE. Record all the experimental conditions; present large clear labelled graphs, whether hand drawn or computer generated. Plot each graph as soon as you have recorded the data – see what you have got.
4. ALWAYS ESTIMATE THE PRECISION of the measured values that you have extracted from your data. Discussion of the error in the measurements and the use of error bars in the graph is NOT optional, it is essential!
5. A logbook will contains mistakes. Cross them through with a single line, and a note of what went wrong. Leave them legible – you may later decide they were right.
6. You may be working alone or with a lab partner but either way you must have your own record of results, your own data analysis and conclusions.
7. Have lots of lively discussions with other students doing the same practical, but NEVER copy another person's results, or their analysis.

All that there should be left for you to do at home after the end of the lab session is to read through your experimental record, think a bit more about your data, and draw one or two final conclusions. However, there is no reason why you should not walk out of the lab at the end of the second session with your logbook ready to be marked.

2.6 Lab Marking

The experimental reports in your lab books are awarded marks out of 4 in four categories as shown on the sample mark sheet that is reproduced on the next page. Outline criteria for the award of marks are also included. Make sure you read these carefully.

The “baseline mark” for an experiment that is complete, correct, and nicely done is 3/4 i.e. 75%. If the marker awards less than 3 on any section, they will add comments to explain where credit was lost. If the marker awards a 4 on any section, they will add comments highlighting the outstanding features.

In order to get 4 (outstanding), you need to prove to have gone beyond expectations: if you carry out extra measurements that were not required, show an understanding much deeper than what comes from the script, prove outstanding dedication or exceptional quality in reporting your data. If none of these is matched, the highest mark will be 3.

Note: If you are taking extra measurements, DO NOT adjust equipment beyond what is written in the script without consulting a lab technician.

Please Note:

- The marking sessions last 20 minutes. Each marker reads your logbook, discusses your log book record and then provides detailed feedback.

- Your 20 minute marking slot will be assigned to you via Blackboard.
- You must attend your marking session on time and bring your log book with you. Late attendance is not allowed.
- PLEASE – Contact Mark Ashley (m.d.ashley@soton.ac.uk) if you know you are going to (or did) miss a marking session.

MARK SHEET & FEEDBACK

PHYS2022 - Physics from Evidence I Experimental Logbook Record

Name:						
Experiment:	Week:					
Date:	Group:					
Marker:	Prelim Mark (/10):					
A. Is this a proper logbook record, or has it been "written up" after the event? Is it concise, and in your own words, or have passages been copied from the script?	0	1	2	3	4	
Comment:						
B. Data Quality: Appropriate sampling? Adequate signal-to-noise ratio? All experimental conditions recorded? Large clear graphs with correct units and error bars? Completeness?	0	1	2	3	4	
Comment:						
C. Interpretation of Data: Careful fitting? Derived values correctly calculated? Estimation of experimental uncertainties plausible? Results agree with accepted values?	0	1	2	3	4	
Comment:						
D. Discussion: Brief conclusions that are well-supported by the data? Any obvious features of the data that have not been commented upon?	0	1	2	3	4	
Comment:						
Suggestions made on the last report: Has the student responded appropriately to the suggestions made on the last report?						
What needs to be improved in next lab report?						
0 = UNSATISFACTORY	4 = OUTSTANDING					

Comment	Description
Excellent: 4	<p>Thoughtful use of apparatus giving data of outstanding quality</p> <p>Evidence of curiosity and deep understanding</p> <p>Work that goes beyond the prompts in the script</p>
Good: 3	<p>Good quality data giving results within the accepted range</p> <p>All aspects of the experiment completed well</p> <p>Evidence of good understanding</p>
Satisfactory: 2	<p>Experiment performed according to script, but with only moderate understanding of what is required</p> <p>Not all aspects completed</p> <p>Experimental conditions not adequately recorded/commented</p>
Poor: 1	<p>Little understanding, poor quality data</p> <p>Poor analysis, no discussion of precision</p> <p>Would not accept result without an independent check</p> <p>Record that has been “written up”</p>

3. WRITING A LABORATORY NOTEBOOK

This section provides guidance and suggestions on how to keep your logbook and record your work when doing experiments. Other courses may have different or more stringent guidelines. You can consult a model example of a logbook record for an experiment called "Beans on Toast" in section 4.

3.1 Style and Language

The whole point of a logbook is that it should:

- State exactly all the important tasks that were done and their order.
- Make it clear who did it and why it was done.
- Contain sufficient information and details to enable someone else to do the same experiment or procedure at some future date.
- Be durable and verifiable.

Any rules that are used must attend to these points; anything else is spurious. Plain language is the least spurious of all.

3.2 Software

This year we are not using hardware notebooks, but moving to digital ones for safety reasons. In this way it is possible to hand in your work through Blackboard and be marked on-line (both marker and student looking at their own files or sharing a screen).

- We suggest using OneNote for your log book.
- Writing can be done using both keyboard and tablet, as long as the writing is legible.
- Do not delete sections that you think are wrong, cross these sections and change them to a different colour. It is good practise to note also mistakes in the logbook, and the reason why something is not working.
- For hand-in, export your file as a single .pdf file and submit in Blackboard.

3.3 Organising Your Logbook

Anyone should be able to pick up your logbook and understand what you have written. This is one of the most important purposes of a logbook – writing for someone else or indeed for yourself as a record for future reference. If the writing is clear to them, then it certainly will be to you. Achieving this requires some organisation, as well as a certain style.

In a software notebooks:

- **Save the file on your Southampton OneDrive space**, you will be able to access the file in different locations and you have a backup if a computer fails.
- **Start each new piece of work on a fresh file/page.**
- **There is no need to repeat/copy the information/text provided in the lab manual and/or hand-out for each experiment.** Assume that they will accompany your logbook. Use your own words and style for any description you put in your logbook.

Other suggestions you might like to implement are:

- **Table of Contents.** Devote a page to the Contents, so that you can list the experiments and find them easily when needed.
- **Number the pages.** Do it when the logbook is new.

3.4 Essential Logbook Practices

- This does **not** have to be a work of art – **but** it does need to be legible.
- **Do not** delete pages out of your logbook – just cross it out with a single line.

3.5 The Experimental Introduction

The introduction to your experimental record should contain the following information:

- The title of the experiment.
- The date. In industry or research this is exceedingly important, patents can be won or lost on this little bit of information!
- A statement of the problem or task - short and to the point. This is the aim of the experiment.
- This section should highlight the physics and theory that will be used in the experiment.
- You should also think about and check the references for the real-world applications or relevance of the experiment.

Before you start a new experiment in PHYS2022, you will have to complete the preparation, including answers to set prelim questions, before coming to the labs. Your preparation will be checked and marked by a demonstrator.

In this way we can see that you have fully understood the objectives of the experiment that you are about to perform.

3.6 The Experimental Method/Procedure

The procedure is a set of directions on how to perform and complete a lab experiment. The directions should contain the right level of detail, namely be such that if any person needed to perform the experiment again, they could use only your directions to guide them safely through it. Therefore your description of an experimental method should contain:

- Simple, direct statements or a bulleted or numbered list of instructions.
- Descriptive diagram(s) of the equipment to be used (in each set-up).
- Comments on any special features of the materials to be used or safety features that you may need to pay special attention to.
- The order of taking measurements.
- Consideration of any extra measurements that may need to be carried out.

Bear in mind the time and the duration of the lab sessions; keeping track of time is very important, especially if a practical involves several steps and different measurements. Remember the marking process checks how well and how completely you carried out each practical.

3.7 Observations and Data

When carrying out research, the observations and the data recorded determine the acceptance or rejection of one's hypothesis and indeed decide what future experiments may be done. The observations and data are therefore **central to the whole laboratory work**. You should apply the same principles to your work and in particular follow these rules:

- Record the results honestly.
- Collate your data in a labelled (and headed) table; give it a title or name. When taking a lot of different sets of data, think carefully about their titles, so later you can easily and quickly identify the experimental conditions and parameters that applies to them.
- Record every step or observation as you go along, in your logbook, *immediately* - no matter how trivial you may think it is.
- Don't try to memorise, even for a minute - someone talks to you, and that data is forgotten.
- Don't use odd scraps of paper or the edge of your lab-coat/back-of-your-hand to record data. All data should be recorded *directly* into your logbook.
- The data must be recorded as *completely as possible*. Don't worry too much about fully interpreting the data as you go along – You *should* however be able to spot inconsistencies or if the results *contradict* what theory predicts.
- Consider the uncertainties and the sources of errors when taking data to check, for example, how many times you may need to repeat the measurements.
- Take care with numbers and comments - **never over-write**, never scrub out erroneous material, but *cross it out with a single line and re-write the correct data*. Don't use Tippex.

3.8 Format

- Think about the layout of your notes in your logbook; make sure you spread your work out – it makes it easier for demonstrators, markers (and you) to read it back later.
- Tables must be written in vertical columns, each column being headed with the relevant quantity or parameter and their units.
- Drawings should be simple, tidy, highlight the main points and large enough to allow labelling.
- Each graph should have the experimental title and a link to the title or name of data - write this clearly.
 - Use a computer if you like to plot your data, do this as you go along. **Copy and paste in your logbook immediately.**
 - The axes must be labelled with the quantity and its units.
 - Include error bars if you know the error limits.

3.9 Analysis and Conclusions

- Write clearly all the essential equations.
- Write all the steps if the equations need to be rearranged to calculate a particular quantity and use units throughout.
- State laws and assumptions that you make in your calculations.
- Relate your results to your hypothesis - do they support or refute it? Any comparisons must be as quantitative as possible.
- Record any relevant ideas and explanations that you have, however brief - if you don't write them down, you may forget them, and we won't know about them. Remember, we talk about your results when we mark your write-up.
- **conclusions** should state
 - What you measured – *highlighting key results*.
 - Whether the initial *hypothesis* was supported or not, if appropriate.
 - If applicable, the comparison of your data with the theoretically predicted values or experimental ones from reference materials.
 - The error limits on your answer(s) and how they relate to the comparison with the reference/theoretical values; a qualitative assessment of error should be made at least.
 - Suggestions for improvement in experimental design, if appropriate; the error analysis will be useful here.
 - Any follow-up measurements, if appropriate, e.g. if an experiment showed an interesting/strange result – what experiment would you suggest to clarify it.

3.10 Questions

Each practical contains a certain number of questions for you to complete.

- Don't forget to **answer all of the questions** in the text as you proceed through the experiment.
- **Attempt all the questions;** remember that your answers will be assessed in the marking process.
- **You do not need to complete your answers during lab sessions.** This is particularly important if, for example, one question proves difficult and take more time to work out the answer. If you get stuck on a question, you can always finish it at home later and, naturally, you can ask a demonstrator for help.
- The answers to the set questions do not have to appear in the same order as they are presented in the lab hand-out notes.

Remember....

Science does not take place on the pages of textbooks or learned journals, *but it is recorded there*. The quality of any work is only as good as the record that contains and describes it.

4. EXAMPLE LOGBOOK RECORD (BEANS ON TOAST)

A hand-written example of how to record an experiment in your logbook.

Introduction

These experiments aim to investigate the efficient techniques for making the ubiquitous student meal, beans on toast. I shall be looking at the speed of alternative methods of heating the beans. ~~and the precise duration and degree of~~

The cooking methods are:

- Pan on an electric ~~heat~~ hob.
- Microwave oven

The hob technique uses a resistive heater element which transfers electrical energy to heat. This heat is conducted to the beans via a 1L stainless steel saucepan.

Microwaves, ^{oven} use the electromagnetic radiation at 2.45 GHz called microwaves. This frequency is both absorbed by water and fats, ~~and~~ the resulting energy transfer causes heating of the beans.

The increase in temperature of the beans is dependant on the transfer of energy to the beans.

In the hob case this depends upon the energy output of the cooker, thermal and radiative loss of the saucepan, the conduction of the pan to the heating element and finally the thermal properties of the beans.

A microwave is much simpler to understand. Assuming the container that the beans^{are} are in, does not significantly absorb the ^{microwave} energy. The energy transfer efficiency is 64%, see reference ①. Therefore a 900Watt microwave will transfer $(0.64 \times 900) = \underline{576 \text{ Watts}}$ of heat to the beans.

A Standard Student house cooker (resistive ring element) has a power consumption of 2kW. Reference ② states that the energy transfer efficiency between electricity and heat is 45%.

Therefore a hob provides 900W (0.45×2000) of heat.

A single tin of Acme baked beans contains 415g of semi-edible material, comprising of Haricot beans and tomatoe sauce. The specific heat capacity, C_p , is given below:

Ingredient	Specific heat capacity C_p ($\text{kJ kg}^{-1} \text{K}^{-1}$)
Haricot beans	$1.017 \text{ kJ kg}^{-1} \text{K}^{-1}$
Tomato sauce	$3.98 \text{ kJ kg}^{-1} \text{K}^{-1}$

Previously measured concentrations of Acme baked beans, is shown:

81% beans
19% tomato sauce

Therefore the C_p of the composite is

$$C_{p_{BB}} = 0.81 \times 1.017 + 0.19 \times 3.98 = \underline{\underline{1.70 \text{ kJ kg}^{-1} \text{K}^{-1}}}$$

Reference ① International Journal of BB gastronomy

② Wikipedia article referencing the Japanese journal of noodle making.

Assuming 100% of the heat is transferred from hob to saucepan and hence 100% to the beans. The energy required to bring a tin of baked beans from room temperature (21°C) to the boiling point of tomato sauce (85°C) is given by the relationship,

$$\Delta Q = mC_{p_{BB}} \Delta T$$

Where ΔQ is the heat energy required to increase the temperature of a material of mass (m) by an amount ΔT .

Therefore 415 grams of BB raised by $85 - 21 = 64^\circ\text{C}$ with a specific heat capacity of $1.7 \text{ kJ kg}^{-1} \text{ K}^{-1}$ requires:

$$\Delta Q = 0.415 \times 1.7 \times 64$$

$$\underline{\Delta Q = 43.2 \text{ kJ} = 45.2 \text{ kJ}}$$

\leftarrow usable

Using \leftarrow the output powers of the microwave & hob from page 2. we are able to theoretically predict the time each method would take to heat the beans.

Microwave $\Rightarrow 0.576 \text{ kW}$

$$T_M = \frac{43.2}{0.576} = \frac{78.5}{80.3} \text{ seconds}$$

Hob $\Rightarrow 0.9 \text{ kW}$

$$T_H = \frac{43.2}{0.9} = \frac{50.2}{48.6} \text{ seconds.}$$

Summary of theoretical prediction.

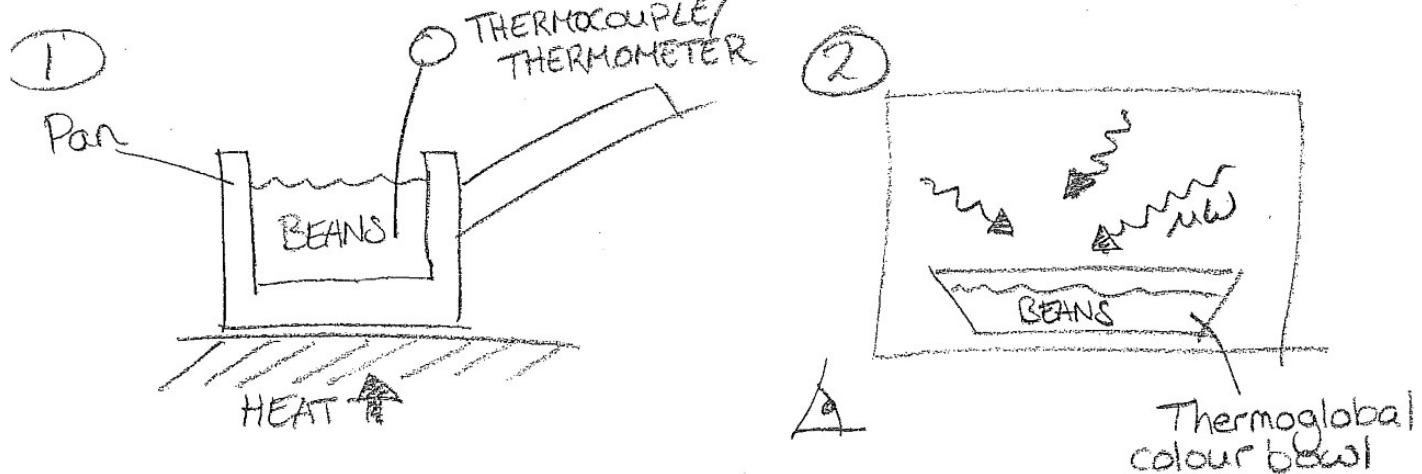
A very simplistic consideration of the power output of a microwave oven and electric hob shows that a hob should be almost twice as quick as a microwave.

These calculations do not take into account the heat transfer of the hob to pan and pan to beans. Nor does it allow for thermal and radiative losses.

These findings have global importance, such time savings could save millions of student seconds. Thereby allowing more time for students to study.

Signed
A Demonstrator

Experimental method.



The two experiment set-ups are shown above.

Experiment ① uses the hob/pan method, exp ② uses the microwave technique.

Safety/considerations: Good laboratory practice.
Wear heat resistant gloves

① Hob/pan method

- 1) Turn on cooker ring and leave to reach max temp.
- 2) Open BB can and pour contents into pan.
- 3) Start timer - place pan on hob.
note temperature with temperature transducer.
- 4) Record temperature every 15 seconds until $> 85^\circ\text{C}$.
- 5) Remove pan from hob.
- 6) Turn off hob.
- 7) Pour beans on pre-prepared toast.
- 8) Chow-dowm.
- 9) Wash up much later.

② Microwave method.

- 1) Open BB tin and pour into thermoglobal colour bowl (bowl changes colour with temperature).
- 2) open μ -wave door and program 10 minutes (max power)
- 3) Place BB into μ -wave. note: temperature with ~~thermometer~~ thermometer. do not leave thermometer in μ -wave.
- 4) Shut door - Start timer.
- 5) Note temperature on colour scale every 15 seconds until 85°C .
- 6) Open door - stop timer - remove beans. - note final temperature.

7/8/9 as above.

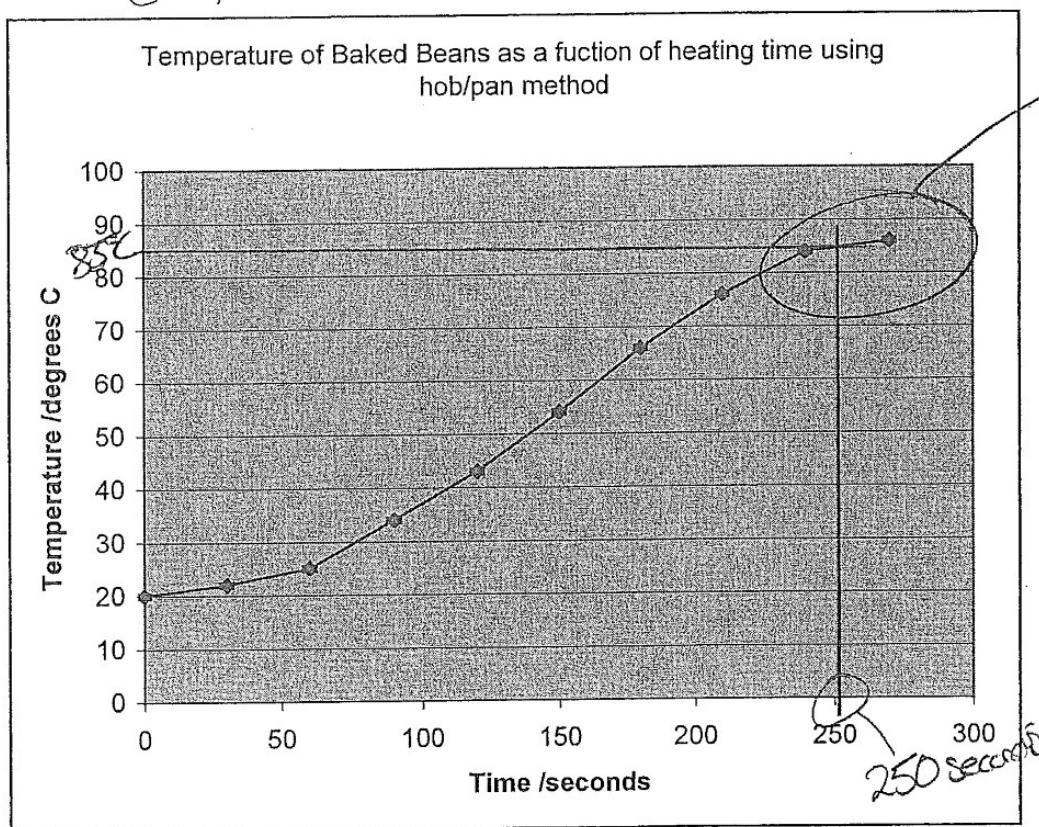
Note: Heating rate was much slower than theory predicted increased observation time from 15 to 30 seconds.

Data

Data for experiment 1 pan/hob

Time (s)	Temperature / $^{\circ}\text{C}$	Comments
0	20 \pm 0.5	error from scale of thermometer
30	22	
60	25	
90	34	Started bubbling at edges
120	43	
150	53.4	
180	66	
210	76	
240	84	Sauce started to boil
270	86	

Exp 1 graph



Data looks reasonable, good errors.

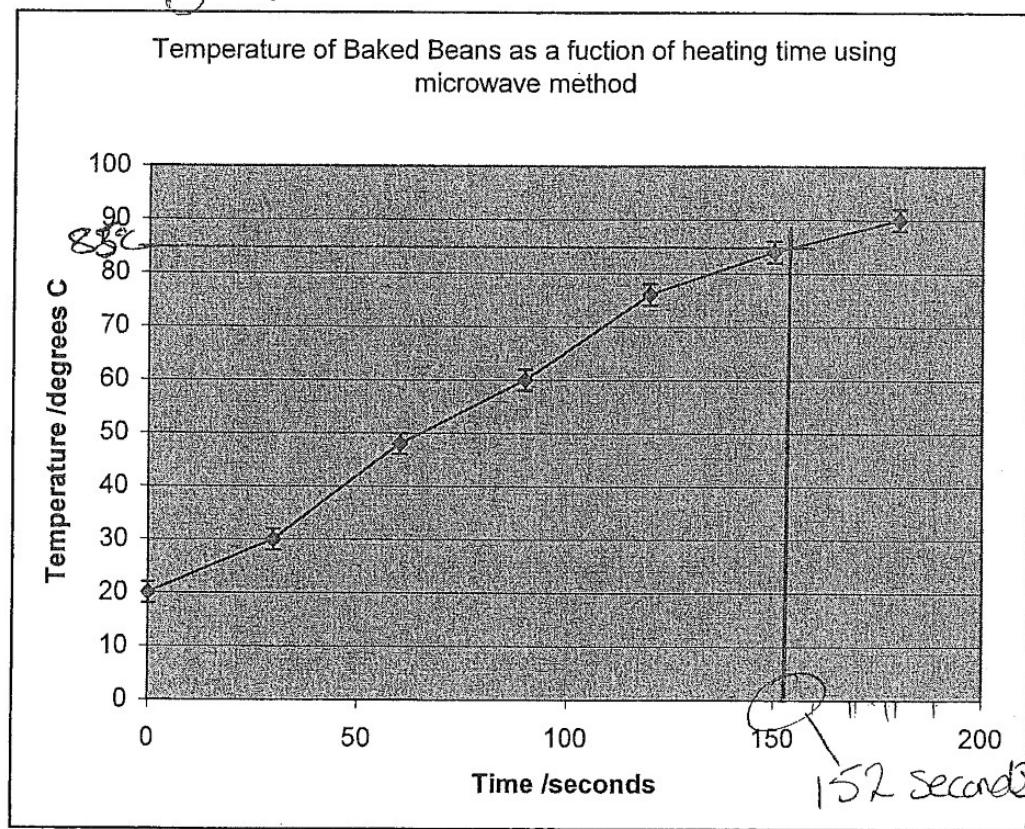
Exp 2. data microwave method.

Time (s)	Temperature (°C)	Comments
0	20 ± 0.5	Thermometer measured
30	30 ± 2	
60	48 ± 2	+ starting bubbles at edges.
90	60 ± 2	
120	76 ± 2	+ Started to bubble all over
150	84 ± 2	
180	90 ± 2	
210		estimated 2°C error, due to visual/colour perception.

Exp2 graph

taken from table ②

8



Again data look reasonable, much larger error-bars, due to much larger measurement uncertainty of the thermoglobal colour bowl.

Analysis

From the graphs we can approximately measure the time taken to warm the beans to 85°C .

The hob technique took 250 ± 5 seconds and the microwave method took 152 ± 10 seconds. The errors as approximate.

However more importantly the results contradict the hypothesis in the introduction. The most likely cause of this disagreement is due to neglecting of several processes such as energy transfer between hob and pan, pan and beans and convection/radiation losses.

With our experimental results we're able to calculate the effective energy transfer of the two methods.

Note: I will ignore effects of the latent heat of the sauce.

Takes $\frac{45.2}{45.7 \text{ KJ}}$ of energy to warm the beans from $21 \rightarrow 85^\circ\text{C}$

So energy required to go $20 \rightarrow 85^\circ\text{C}$ is

$$\frac{45.2 \times 85}{84} = \underline{45.7 \text{ KJ}}$$

The hob technique took 250 seconds so per second the energy output (same as power) is:

$$\frac{45.7 \text{ K}}{250} = \underline{183 \text{ Watts}}$$

So the energy transfer efficiency is $\underline{9\%} \left(\frac{183}{2000} \right)$

The microwave method took 152 seconds

$$\frac{45.7 \text{ K}}{152} = \underline{301 \text{ Watts}}$$

But the energy transfer efficiency is $334\% \left(\frac{301}{900} \right)$

Conclusions

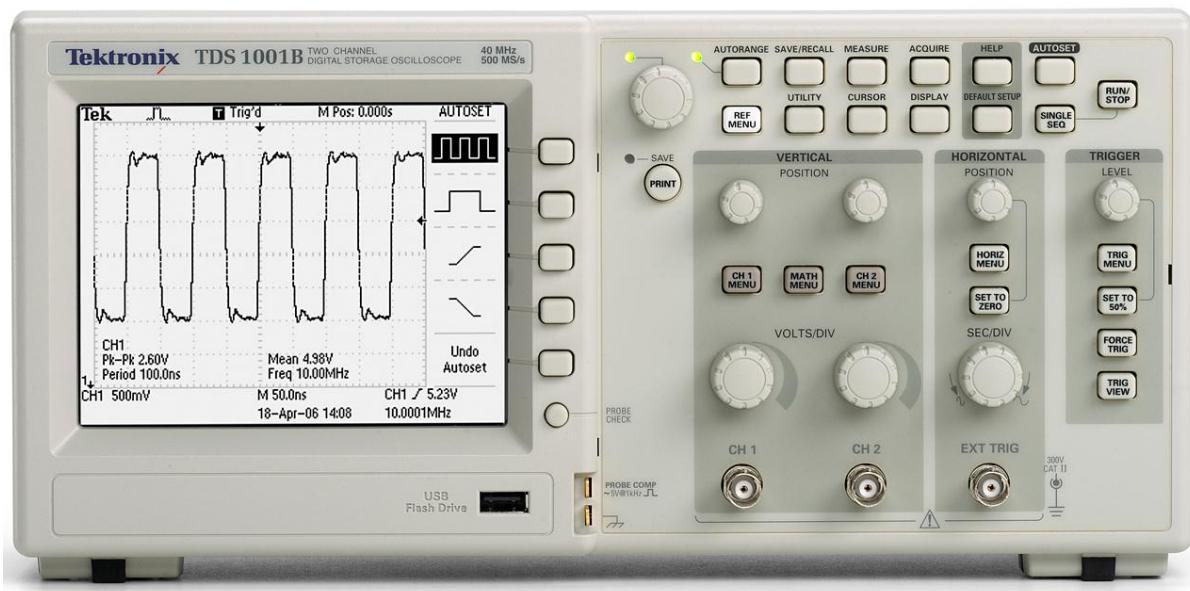
The key result from this work is that the microwave is faster than the hob/pan technique, 60.8% faster. The experimental results did not agree with the theory, this is due to the incomplete model.

This theoretical model could be improved by including convection & radiative, this would clarify if there are any other sources of loss of energy from the system.

The experimental procedure could be improved by using a more accurate temperature transducer with the microwave.

The experiment has shown that hobs are superfluous in student accommodation, as the microwave provides the most efficient method of making breakfast, lunch and dinner. The microwave is also over 3 times more energy efficient, saving both energy and time.

5. OSCILLOSCOPES



Above is the image of a typical digital oscilloscope that you are going to use for the detection in your experiment. Other models will be used but their functions are very similar. Many of the functions of the oscilloscope are controlled by the use of menus. When a menu button is pressed the menu options for that button are displayed on the right side of the oscilloscope screen. Five selection buttons along the right side of the screen are used to select from the various menu options that are available. When the selection button next to menu item is pressed the option will toggle through several setting choices for that option. If the button is pressed enough times it will return to the original setting. There are three menu buttons that are of general use on the oscilloscope; they are the **CH1**, **CH2**, **TRIG** menus buttons. A good starting point is to press **AUTOSET**. This will set up the oscilloscope initially to display signals.

CH1 and CH2 Menus Buttons

The oscilloscope has two channels (**CH1** and **CH2**) that can measure voltages independently. The settings for each of these channels are menu driven. By pressing the **CH1** or **CH2** menu button various options can be selected. Pressing the menu button once turns on the channel. Pressing the menu button a second time turns off the channel. When the channel is selected **CH1** or **CH2** appears above the menu indicating that the menu options will be applied to that channel. If two channels are turned on at the same time, then one of the channels will be selected and its label (**CH1** and **CH2**) will appear above the menu option on the screen. To select the other channel simply press its menu button.

The options that are most important on the **CH1** and **CH2** menus are the 'coupling' and the 'probe' settings. The 'coupling' option has three settings, DC, AC, and Ground. In the DC setting you see the total signal voltage. In the AC position the DC (direct current) portion of the signal is "blocked" (i.e. the mean value of the signal is subtracted), which is useful if you want to investigate a small, time-varying signal sitting on a large DC voltage. In the Ground setting the input is grounded, so that you have a zero reference point.

Channel Controls for Channels 1 and 2 (CH1 and CH2)

Each channel (**CH1** and **CH2**) has the following set of independent controls:

- A gain setting that sets the number of **VOLT/DIVISION**. This value is displayed on the bottom of the oscilloscope screen. The gain does not increase the size of the signal being measured, only how it is displayed on the screen.
- A vertical position control, above the **CH1** and **CH2** menu buttons.

Trigger (TRIG) Menu button

The oscilloscope sweeps out a trace of the voltage as a function of time. The oscilloscope needs to know when to start this sweep. The trigger signal is the way the oscilloscope determines when to start the sweep. The **TRIG** menu button allows you to tell the oscilloscope what signal to trigger the sweep on and on what part of that signal. The options on the TRIGGER menu that are most often used are Type, Source, Slope, and Mode. The trigger Type option will always be set to 'Edge' in this lab but the other setting is useful when looking at special signal such as those from a video source. The trigger Source option is the voltage signal that will start the sweep. This signal can come from either **CH1** or **CH2**, an external line, or from the 60 Hz AC power sources. Usually the trigger signal will come from **CH1** or **CH2**. The Slope option allows the sweep to be triggered either when the trigger signal is rising or falling. In this lab triggering on the rising signal will work for all the cases we will do. The Mode option has two settings: Auto and Normal. In the Auto setting the trigger is automatic so that the sweep display is visible even if there is no input signal. This is most useful for setting up and for looking at DC voltages. When the Mode option is set to Normal the sweep starts only when the trigger source changes as was selected in the other setting.

Trigger Controls

The level of the signal that triggers the sweep can be adjusted by using the trigger Level knob. A small arrow appears on the right side screen indicating the level of the trigger voltage on the trigger sources (**CH1** and **CH2**). The **SET TO 50%** sets the trigger level automatically to 50% of the current trigger source. This is a very convenient feature to find an appropriate trigger level. The **FORCE TRIG** button forces the oscilloscope to trigger in Normal mode even if it doesn't see a trigger signal on the source. The **TRIG VIEW** button allows the trigger setting to be displayed on the bottom of the screen.

The oscilloscope should be setup correctly and the slope should be visible without you doing anything to setup the scope if you need to setup the scope using the following settings, you can set the scope settings as follows:

- Select channel 1 by pressing the **CH1** menu button
- Press the "Coupling" menu until DC is displayed. Press the "Probe" menu until "x1" is displayed. Using the voltage per division knob choose 100mV per division.
- Select channel 2 by pressing the **CH2** menu button
- Press the "Coupling" menu until DC is displayed. Press the "Probe" menu until "x1" is displayed. Using the voltage per division knob choose 500mV per division.
- Press the **TRIG MENU** button and select AUTO trigger mode
- Press the "**SET TO 50%**" TRIGGER LEVEL button
- Set the horizontal sweep rate (sec/div) to 5 msec/div, the value is displayed on

the bottom of the screen next to an "M". You should see two scope traces; Use the Vertical position and horizontal position knobs to place the traces in a convenient place in the display.

Average Controls

By pressing the **acquire** button you can select the average or the sample mode. You need sample mode when you change things and you need average with 128 samples when you measure. It needs some time for the oscilloscope to stabilize if parameters are changed (e.g. VOLT/DIVISION OR SEC/DIVISION) and it is in average mode (as 128 samples take a long time to be acquired).

Save Recall Controls

In order to save your measurements to a USB key you have to use the **save/recall** button, select the save all action and press the **print** button which will save your data to the USB stick under the folder ALL#. If the USB stick has been used many times then there will be lots of ALL# folders, the one that you want will be the folder followed by the greater number (last save). In the USB you will find a .CSV file with the channel 1 data, a CSV file (which can be opened with Excel) with the channel 2 data and a bitmap file showing the oscilloscope display. You can confirm that are your data by seeing the date and time when the files were created.

XT vs XY Mode

Usually, when both CH1 and CH2 are used, they are plotted against time (XT mode). It is also possible to display a plot of CH1 against CH2 on the oscilloscope (XY mode).

To do this press <**Display**> - <**FORMAT**> - <**YT, XY**>

However, it is not possible to save the traces in XY mode. They must be saved in YT mode and combined in software such as Excel.

6. ERROR ANALYSIS

Error Analysis and Significant Figures

Errors using inadequate data are much less than those using no data at all --- C. Babbage (1791 - 1871)

No measurement of a physical quantity can be entirely accurate. It is important to know, therefore, just how much the measured value is likely to deviate from the unknown, true, value of the quantity. The art of estimating these deviations should probably be called uncertainty analysis, but for historical reasons is referred to as error analysis. This document contains brief discussions about how errors are reported, the kinds of errors that can occur, how to estimate random errors, and how to carry error estimates into calculated results. We are not, and will not be, concerned with the "percent error" exercises common in high school, where the student is content with calculating the deviation from some allegedly authoritative number.

SIGNIFICANT FIGURES

Whenever you make a measurement, the number of meaningful digits that you write down implies the error in the measurement. For example if you say that the length of an object is 0.428 m, you imply an uncertainty of about 0.001 m. To record this measurement as either 0.4 or 0.42819667 would imply that you only know it to 0.1 m in the first case or to 0.00000001 m in the second. You should only report as many significant figures as are consistent with the estimated error. The quantity 0.428 m is said to have three significant figures, that is, three digits that make sense in terms of the measurement. Notice that this has nothing to do with the "number of decimal places". The same measurement in centimeters would be 42.8 cm and still be a three significant figure number. The accepted convention is that only one uncertain digit is to be reported for a measurement. In the example if the estimated error is 0.02 m you would report a result of 0.43 ± 0.02 m, not 0.428 ± 0.02 m.

Students frequently are confused about when to count a zero as a significant figure. The rule is: If the zero has a non-zero digit anywhere to its left, then the zero is significant, otherwise it is not. For example 5.00 has 3 significant figures; the number 0.0005 has only one significant figure, and 1.0005 has 5 significant figures. A number like 300 is not well defined. Rather one should write 3×10^2 , one significant figure, or 3.00×10^2 , 3 significant figures.

ABSOLUTE AND RELATIVE ERRORS

The absolute error in a measured quantity is the uncertainty in the quantity and has the same units as the quantity itself. For example if you know a length is $0.428 \text{ m} \pm 0.002 \text{ m}$, the 0.002 m is an absolute error. The relative error (also called the fractional error) is obtained by dividing the absolute error in the quantity by the quantity itself. The relative error is usually more significant than the absolute error. For example a 1 mm error in the diameter of a skate wheel is probably more serious than a 1 mm error in a truck tire. Note that relative errors are dimensionless. When reporting relative errors it is usual to multiply the fractional error by 100 and report it as a percentage.

SYSTEMATIC ERRORS

Systematic errors arise from a flaw in the measurement scheme which is repeated each time a measurement is made. If you do the same thing wrong each time you make the measurement, your measurement will differ systematically (that is, in the same direction each time) from the correct result. Some sources of systematic error are:

- Errors in the calibration of the measuring instruments.
- Incorrect measuring technique: For example, one might make an incorrect scale reading because of parallax error.
- Bias of the experimenter. The experimenter might consistently read an instrument incorrectly, or might let knowledge of the expected value of a result influence the measurements.

It is clear that systematic errors do not average to zero if you average many measurements. If a systematic error is discovered, a correction can be made to the data for this error. If you measure a voltage with a meter that later turns out to have a 0.2 V offset, you can correct the originally determined voltages by this amount and eliminate the error. Although random errors can be handled more or less routinely, there is no prescribed way to find systematic errors. One must simply sit down and think about all of the possible sources of error in a given measurement, and then do small experiments to see if these sources are active. The goal of a good experiment is to reduce the systematic errors to a value smaller than the random errors. For example a meter stick should have been manufactured such that the millimeter markings are positioned much more accurately than one millimeter.

RANDOM ERRORS

Random errors arise from the fluctuations that are most easily observed by making multiple trials of a given measurement. For example, if you were to measure the period of a pendulum many times with a stop watch, you would find that your measurements were not always the same. The main source of these fluctuations would probably be the difficulty of judging exactly when the pendulum came to a given point in its motion, and in starting and stopping the stop watch at the time that you judge. Since you would not get the same value of the period each time that you try to measure it, your result is obviously uncertain. There are several common sources of such random uncertainties in the type of experiments that you are likely to perform:

- Uncontrollable fluctuations in initial conditions in the measurements. Such fluctuations are the main reason why, no matter how skilled the player, no individual can toss a basketball from the free throw line through the hoop each and every time, guaranteed. Small variations in launch conditions or air motion cause the trajectory to vary and the ball misses the hoop.
- Limitations imposed by the precision of your measuring apparatus, and the uncertainty in interpolating between the smallest divisions. The precision simply

means the smallest amount that can be measured directly. A typical meter stick is subdivided into millimeters and its precision is thus one millimeter.

- Lack of precise definition of the quantity being measured. The length of a table in the laboratory is not well defined after it has suffered years of use. You would find different lengths if you measured at different points on the table. Another possibility is that the quantity being measured also depends on an uncontrolled variable. (The temperature of the object for example).
- Sometimes the quantity you measure is well defined but is subject to inherent random fluctuations. Such fluctuations may be of a quantum nature or arise from the fact that the values of the quantity being measured are determined by the statistical behavior of a large number of particles. Another example is AC noise causing the needle of a voltmeter to fluctuate.

No matter what the source of the uncertainty, to be labeled "random" an uncertainty must have the property that the fluctuations from some "true" value are equally likely to be positive or negative. This fact gives us a key for understanding what to do about random errors. You could make a large number of measurements, and average the result. If the uncertainties are really equally likely to be positive or negative, you would expect that the average of a large number of measurements would be very near to the correct value of the quantity measured, since positive and negative fluctuations would tend to cancel each other.

ESTIMATING RANDOM ERRORS

There are several ways to make a reasonable estimate of the random error in a particular measurement. The best way is to make a series of measurements of a given quantity (say, x) and calculate the mean \bar{x} , and the *standard deviation* σ_x from this data. The mean is defined as

$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$$

where x_i is the result of the i^{th} measurement and N is the number of measurements. The standard deviation is given by

$$\sigma_x = \left(\frac{1}{N} \sum_{i=1}^N (x_i - \bar{x})^2 \right)^{1/2}$$

If a measurement (which is subject only to random fluctuations) is repeated many times, approximately 68% of the measured values will fall in the range $\bar{x} \pm \sigma_x$.

We become more certain that \bar{x} is an accurate representation of the true value of the quantity x , the more we repeat the measurement. A useful quantity is therefore the *standard deviation of the mean* $\sigma_{\bar{x}}$ defined as $\sigma_{\bar{x}} = \sigma_x / \sqrt{N}$. The quantity $\sigma_{\bar{x}}$ is a good

estimate of our uncertainty in \bar{x} . Notice that the measurement precision increases in proportion to \sqrt{N} as we increase the number of measurements. Not only have you made a more accurate determination of the value, you also have a set of data that will allow you to estimate the uncertainty in your measurement.

The following example will clarify these ideas. Assume you made the following five measurements of a length:

	<u>Length (mm)</u>	<u>Deviation from mean</u>	
	22.8	0.0	
	23.1	0.3	
	22.7	0.1	
	22.6	0.2	
	<u>23.0</u>	<u>0.2</u>	
sum	114.2	0.18	sum of the squared deviations
	$\div 5$	$\div 5$ and take the square root	(N = number data points = 5)
mean	22.8	0.19	standard deviation
		divide by \sqrt{N}	
		0.08	standard deviation of the mean

Thus the result is $22.84 \pm .08$ mm. (Notice the use of significant figures).

In some cases, it is scarcely worthwhile to repeat a measurement several times. In such situations, you often can estimate the error by taking account of the least count or smallest division of the measuring device. For example, when using a meter stick, one can measure to perhaps a half or sometimes even a fifth of a millimeter. So the absolute error would be estimated to be 0.5 mm or 0.2 mm.

In principle, you should by one means or another estimate the uncertainty in each measurement that you make. But don't make a big production out of it. The essential idea is this: Is the measurement good to about 10% or to about 5% or 1%, or even 0.1%? When you have estimated the error, you will know how many significant figures to use in reporting your result.

PROPAGATION OF ERRORS

Once you have some experimental measurements, you usually combine them according to some formula to arrive at a desired quantity. To find the estimated error (uncertainty) for a calculated result one must know how to combine the errors in the input quantities. The simplest procedure would be to add the errors. This would be a conservative assumption, but it overestimates the uncertainty in the result. Clearly, if the errors in the inputs are random, they will cancel each other at least some of the time. If the errors in the measured quantities are random and if they are independent (that is, if

one quantity is measured as being, say, larger than it really is, another quantity is still just as likely to be smaller or larger) then error theory shows that the uncertainty in a calculated result (the propagated error) can be obtained from a few simple rules, some of which are listed in Table I. For example if two or more numbers are to be added (Table I.2) then the absolute error in the result is the square root of the sum of the squares of the absolute errors of the inputs, i.e.

$$\begin{aligned} \text{if } & z = x + y \\ \text{then } & \Delta z = \left[(\Delta x)^2 + (\Delta y)^2 \right]^{1/2} \end{aligned}$$

In this and the following expressions, Δx and Δy are the absolute random errors in x and y and Δz is the propagated uncertainty in z . The formulas do not apply to systematic errors.

The general formula, for your information, is the following;

$$(\Delta f(x_1, x_2, K))^2 = \sum \left(\frac{\delta f}{\delta x_i} \right)^2 (\Delta x_i)^2$$

It is discussed in detail in many texts on the theory of errors and the analysis of experimental data. For now, the collection of formulae on the next page will suffice.

TABLE I: PROPAGATED ERRORS IN z DUE TO ERRORS IN x and y . The errors in a , b and c are assumed to be negligible in the following formulae.

<u>Case/Function</u>	<u>Propagated Error</u>
1) $z = ax \pm b$	$\Delta z = a\Delta x$
2) $z = x \pm y$	$\Delta z = \left[(\Delta x)^2 + (\Delta y)^2 \right]^{1/2}$
3) $z = cxy$	$\frac{\Delta z}{z} = \left[\left(\frac{\Delta x}{x} \right)^2 + \left(\frac{\Delta y}{y} \right)^2 \right]^{1/2}$
4) $z = c \frac{y}{x}$	$\frac{\Delta z}{z} = \left[\left(\frac{\Delta x}{x} \right)^2 + \left(\frac{\Delta y}{y} \right)^2 \right]^{1/2}$
5) $z = cx^a$	$\frac{\Delta z}{z} = a \frac{\Delta x}{x}$
6) $z = cx^a y^b$	$\frac{\Delta z}{z} = \left[\left(a \frac{\Delta x}{x} \right)^2 + \left(b \frac{\Delta y}{y} \right)^2 \right]^{1/2}$
7) $z = \sin x$	$\frac{\Delta z}{z} = \Delta x \cot x$
8) $z = \cos x$	$\frac{\Delta z}{z} = \Delta x \tan x$
9) $z = \tan x$	$\frac{\Delta z}{z} = \frac{\Delta x}{\sin x \cos x}$

Atomic Excitation Potentials: Direct Demonstration of Energy Quantisation in Atoms.

Safety

There are no special safety issues in this experiment.

Atomic Excitation Potentials: Direct Demonstration of Energy Quantisation in Atoms.

Aims and Objectives

- Observe the interaction of energetic electrons with helium atoms using an electron beam tube.
- Identify the electron energies at which step changes occur in the electron-helium atom collisions.
- Clearly demonstrate that the energy of electrons bound in a Helium atom is quantised.

1. Introduction

The fact that atoms can only emit and absorb energy in discrete, not continuous, amounts is something that Classical Physics cannot explain. Actually Classical Physics cannot even explain why atoms exist at all - the structure of an atom, demonstrated experimentally by Rutherford, J.J.Thomson and others to be a miniature planetary system with a massive, positively charged nucleus and orbiting electrons, is not stable classically. Quantum Mechanics is needed to understand both the very existence and the discrete energy levels of atoms.

How can we demonstrate experimentally that atoms have discrete energy levels?

One way is to observe the light emitted from atoms. The problem with this, however, is that we need to do two separate experiments and also invoke the idea of photons - particles associated with electromagnetic radiation - to prove the existence of energy levels; first we do an experiment showing that atoms emit only discrete frequencies of electromagnetic radiation (i.e. their characteristic spectrum) when heated or excited in some other way, such as bombardment in a discharge tube; then we have to demonstrate the connection between frequency, ν of the radiation and energy, E , emitted ($\nu=E/h$, where h is Planck's constant) in a subsidiary experiment such as measurements of the photoelectric effect.

A more direct experiment is to bombard the atoms (helium atoms in this case) with charged particles accelerated to a known kinetic energy and look to see what happens. If atoms have discrete energy levels, then charged particles with kinetic energy less than the energy of the minimum energy excitation of the ground state of the atoms should not undergo inelastic scattering. One might expect resonances in the scattering when the charged particles have energies equal to one of the possible excitations of Helium. By using charged particles, such as electrons, we can vary

their energy very easily by varying an electrostatic voltage, V , between two electrodes which we use to accelerate them ($E = eV$ where e is the electron charge).

In this experiment we shall be using this direct method to show that helium atoms have discrete energy levels. Its only real merit is that it is direct - it turns out to be rather imprecise. Consequently virtually all our detailed understanding of energy levels actually comes from the electromagnetic emission spectra of atoms.

We will describe how the Franck-Hertz effect works with a simple example in helium. The apparatus you will use will allow you to send electrons through helium gas with kinetic energies varying from 10 eV to 50 eV. The minimum energy needed to excite the helium atom from its ground state is 19.80 eV, which is the energy needed to reach the first excited level in helium. When the incident electrons are adjusted to have that kinetic energy, they will excite the helium atoms through inelastic collisions and then lose most of their energy. Your apparatus will be able to detect those inelastically scattered electrons. So you will see an increase in the number of detected electrons when you adjust the kinetic energy of the incident electrons to 19.80 eV. As you increase the kinetic energy of the incident electrons you will see further peaks at 20.61 eV, 20.96 eV, ... until the helium atom is finally ionized when you hit 24.58 eV. Finally, you will notice that you also see a group of peaks at around 40 eV (for helium). This corresponds to electrons that have undergone inelastic scattering twice. An example might be an incident electron with energy of 39.6 eV that excites the first excited state in one helium atom at 19.80 eV, reducing its energy to 19.80 eV. Then, it can inelastically scatter with another helium atom reducing its energy to almost nothing, at which point our detector will detect it.

0 eV (ground state)
19.80 eV (1st excited state)
20.61 eV 20.96
eV 21.21 eV
22.71 eV 22.91
eV 23.00 eV
23.08 eV
24.58 eV (ionization energy)

Table 1: Energies of the excited states in helium (up to the ionization energy)

2. Apparatus

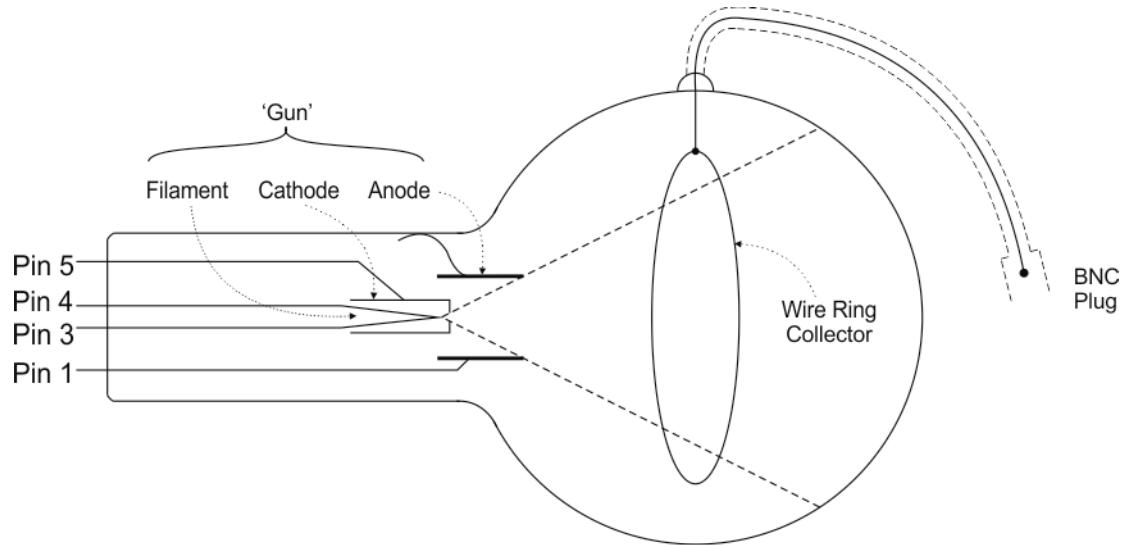


Figure 1 Schematic of the Hertz Critical Potentials Tube

A sealed glass bulb, seen in figure 1, contains helium gas and an electron gun which is located in the side tube. The gun consists of the heated filament cathode, which emits electrons at low energy, and the anode, which is set at a positive voltage to accelerate the electrons away from the cathode. The cathode filament has to be heated because in order for electrons to escape from the bulk metal they have to pass over/through an energy barrier. This is much easier to do if the kinetic energy is higher. As the metal is heated, the number of thermally excited high energy electrons increases. Thus, a hotter filament gives a bigger current. Unfortunately the final kinetic energy of the electrons is the sum of the energy given to the electrons by being accelerated by the potential differences between cathode and anode and their original thermal energy. This means that a hotter filament produces electrons with a wider spread of kinetic energies.

There is a hole in the anode, which allows an electron beam through into the bulb to interact with the helium atoms. The inside of the bulb is coated with a thin layer of a transparent semiconductor (Indium-Tin Oxide) and is connected electrically to the anode. Therefore the whole space inside the bulb is at the same electrostatic potential. Hence, after passing through the anode, the electrons travel across the bulb as a beam with no further electrostatic acceleration. Most hit the far side and are returned to the cathode via the accelerating voltage supply.

Inside the bulb is a loop of wire called the collector which may be biased by a small voltage with respect to the anode. For positive bias, any electrons which are slowed down enough by collisions with the helium gas, will be drawn to the collector giving a negative-current which is measured using an operational amplifier in transconductance mode i.e. a current-to-voltage-converter. For negative collector bias, any positive ions produced by electron-helium collisions are collected by the

loop and give a positive-current. Notice that the collector is held at earth potential, the input of the operational amplifier being a 'virtual ground', and *the anode and cathode voltages are set with respect to this virtual ground.*

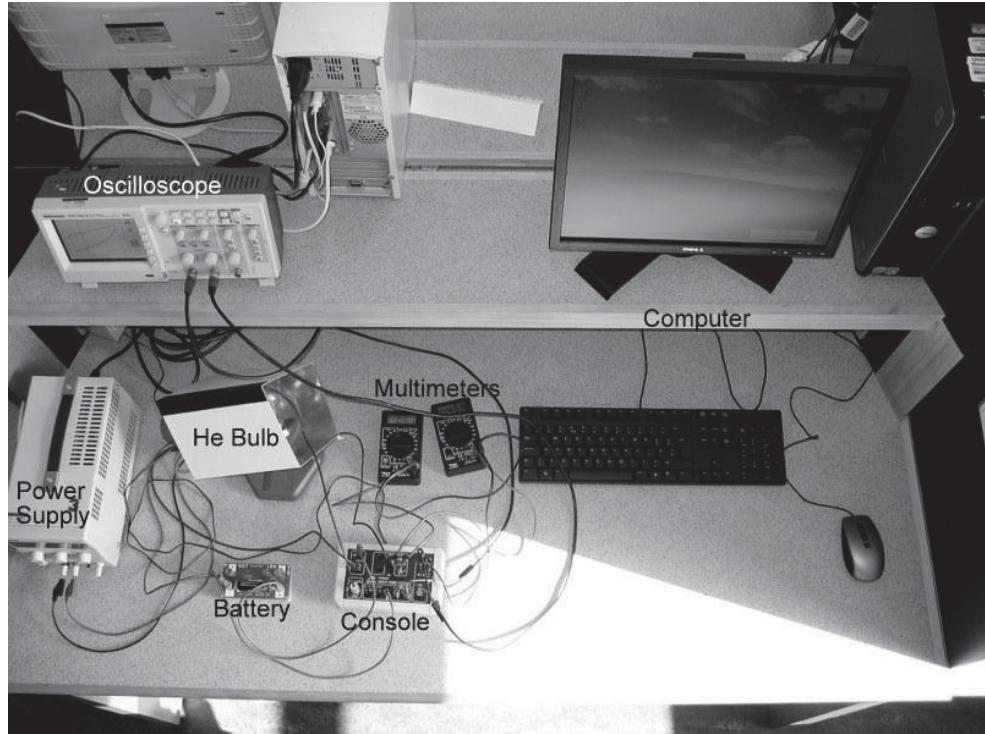


Figure 2. *Photograph of the experiment.*

Figure 2 shows the main components of the experiment:

- In the experiment the filament is connected to a power supply, the voltage should always be less than 3V and the current limited to 1 Amp.
- In the console unit we can set min and max voltage of the anode, the typical setting is between 10 and 50 Volts. We can take a reading of the min and max voltages using the multimeters connected to console (set at the 200m scale).
- The ring collector is biased by the battery unit and depending if we reverse the polarity or not, it can detect Helium ions or electrons, respectively.
- In the oscilloscope we can measure the ramp voltage from min to max in channel 1. However, output of the console that gives the ramp voltage reading to the oscilloscope has a circuit that reduces the voltage (to protect the oscilloscope). Therefore not the actual voltage that is shown on the multimeters (e.g. 10 V and 50 V) will be measured, but lower voltages. We will have to assume a linear relation between the real V_{min} and V_{max} and the displayed oscilloscope readings. So, after we take our data we have to convert the oscilloscope reading to the real ramp voltage that also gives us the energy of electrons.

- Using the oscilloscope, we can measure also a voltage that corresponds to the amplified current which is picked up by the ring collector. This is connected to channel 2 and will give us the necessary spectroscopic data. It is not necessary to know the actual measured current as we only want to locate the peaks. To analyse the data we have to use a USB key and transfer the data to the computer.
- The computer is set up with Origin (and Excel); software often used by scientists to plot graphs and analyse data. When you save your data on your USB key, you have to import them into Origin in order to plot the collector current (y -axis) against accelerating voltage (x -axis). When the collector bias is positive, the current will indicate the number of electrons of a given energy which are sufficiently slowed by interaction with helium atoms to be drawn to the collector loop or, for negative bias, the number of helium ions produced in such interactions. The strength of the signal and the discrimination between different electron energies (the resolution) depend on the setting of the collector bias and the filament voltage.
- To understand more how the oscilloscope and Origin work you can see the appendix of the script.

3. Prelim Questions

(Write full answers in your lab book before the start of the prelim marking session)

- 1) Explain exactly what you measure with the experiment, show by what events the peaks in the graph are generated.
- 2) A) Does increasing the magnitude of the collector bias and filament voltages increase or decrease the magnitude of the current and the resolution?
B) Why do the collector bias and filament voltages have these affects, what is the thermionic emission of electrons?
- 3) A) Why are there two sets of peaks?
B) Draw up before and after diagrams for the collision of an electron with a helium atom assuming that the helium atom has only one excitation energy which is 15eV that if an electron can excite the atom during the collision it does for the three cases that the electrons energy is 13eV, 15eV and 17eV. What is the velocity of the electron after each of these collisions?
- 4) Assume that a helium ion can be ionised with 24.5eV of energy. If an electron of kinetic energy 27 eV collides with a helium atom causing it to ionise what is the ions velocity after the collision?

4. Experimental Method

Experiment 4.1 Measure and record an optimum characteristic for the scattered electron current.

Bias the collector positively, to collect scattered electrons, to measure the collector current 'characteristic' as a function of accelerating voltage (10V - 50V for a broad scan). Measure at different values of filament voltage. From these different recordings it should be possible to see negative peaks in collector current at a number of different accelerating voltages which are independent of the filament voltage. Use your USB key to record a measurement and copy it to the computer to plot it in Origin.

The figure that you want to record is similar to figure 3a, you want then to record separate data sets that zoom in to the first set of peaks (figure 3b) and second set of peaks. This you can do by playing with the voltage range of the anode and/or with the oscilloscopes range.

When you record a data set you have to balance the signal-to-noise by changing the filament voltage and the oscilloscope averaging for the clearest peaks.

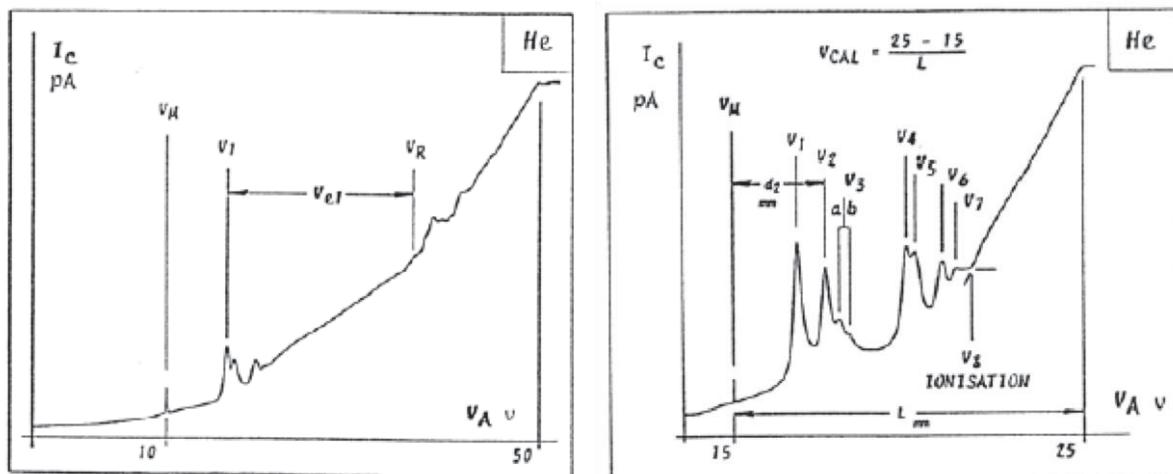


Figure 3. Typical graphs for the full range scan and a zoom in the first peak set where we can see the energies needed for energy transitions.

Experiment 4.2 Measure and record an optimum characteristic for the helium ion current.

Bias the collector negatively (turn the battery) so that helium ions are collected and repeat the process to record an optimum characteristic set the minimum and maximum anode voltages to be 12 and 25 V, respectively. Measure the accelerating voltage for any feature(s) which appear essentially independent of collector and filament voltages. You will get a graph that should resemble figure 4; unfortunately, due to noise, the figure may be different as the first flat part will be sloping due to noise in the experiment.

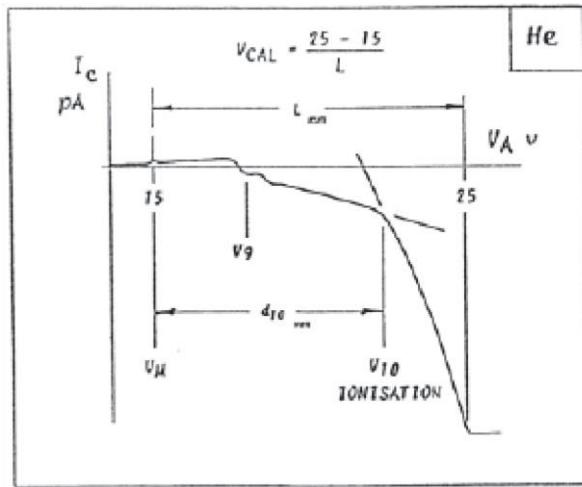


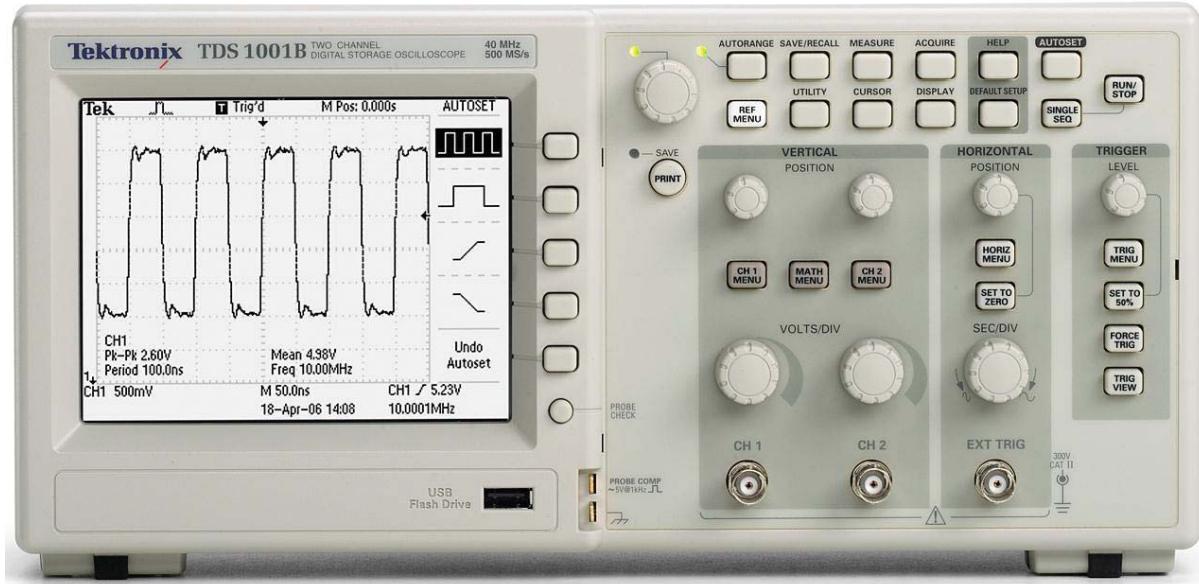
Figure 4. Typical scan with reversed bias where He ions are collected. Three slopes can be observed that show us some important characteristics of the He electronic states.

5. Interpretation of the Data

- Q: Using Excel, plot the collector current (y-axis) against accelerating voltage (x-axis) for all the requested graphs, like the graphs figure 3 and figure 4.
- Q: The fact that the characteristic for collected electrons has sharp negative peaks shows that helium atoms can interact strongly with electrons of particular energies. Explain why the features in the electron characteristic are much sharper than those in the helium characteristic.
- Q: Based on your measurements, draw an energy level diagram for a helium atom, indicating the ground state and energies of excited states and indicating the correspondence between transitions between the states and steps in the recorded characteristic.
- Q: Explain what the phenomenon is that creates the two sets of peaks; find the excited state energies and the ionisation.
- Q: Look at the energy level diagram for helium (determined by measuring its optical spectrum) and compare it with your proposed scheme.
- Q: Compare the characteristic for collection of helium ions to the characteristic for electrons, indicate on your energy level scheme the lowest energy at which ions are produced. Find the ionisation energy but also explain why you think that ionisation may start before this voltage.

Appendix A:

Oscilloscope



Above is the image of the digital oscilloscope that you are going to use for the detection in your experiment. Many of the functions of the oscilloscope are controlled by the use of menus. When a menu button is pressed the menu options for that button are displayed on the right side of the oscilloscope screen. Five selection buttons along the right side of the screen are used to select from the various menu options that are available. When the selection button next to menu item is pressed the option will toggle through several setting choices for that option. If the button is pressed enough times it will return to the original setting. There are three menu buttons that are of general use on the oscilloscope; they are the **CH1**, **CH2**, **TRIG** menus buttons.

CH1 and CH2 Menus Buttons

The oscilloscope has two channels (**CH1** and **CH2**) that can measure voltages independently. The settings for each of these channels are menu driven. By pressing the **CH1** or **CH2** menu button various options can be selected. Pressing the menu button once turns on the channel. Pressing the menu button a second time turns off the channel. When the channel is selected **CH1** or **CH2** appears above the menu indicating that the menu options will be applied to that channel. If two channels are turned on at the same time, then one of the channels will be selected and its label (**CH1** and **CH2**) will appear above the menu option on the screen. To select the other channel simply press its menu button.

The options that are most important on the **CH1** and **CH2** menus are the ‘coupling’ and the ‘probe’ settings. The ‘coupling’ option has three settings, DC, AC, and Ground. In the DC setting you see the total signal voltage. In the AC position the DC (direct current) portion of the signal is “blocked” (i.e. the mean value of the signal is

subtracted), which is useful if you want to investigate a small, time-varying signal sitting on a large DC voltage. In the Ground setting the input is grounded, so that you have a zero reference point.

Channel Controls for Channels 1 and 2 (CH1 and CH2)

Each channel (CH1 and CH2) has the following set of independent controls:

- A gain setting that sets the number of VOLT/DIVISION. This value is displayed on the bottom of the oscilloscope screen.
- A vertical position control, above the CH1 and CH2 menu buttons.

Trigger (TRIG) Menu Button

The oscilloscope sweeps out a trace of the voltage as a function of time. The oscilloscope needs to know when to start this sweep. The trigger signal is the way the oscilloscope determines when to start the sweep. The **TRIG** menu button allows you to tell the oscilloscope what signal to trigger the sweep on and on what part of that signal. The options on the TRIGGER menu that are most often used are Type, Source, Slope, and Mode. The trigger Type option will always be set to 'Edge' in this lab but the other setting is useful when looking at special signal such as those from a video source. The trigger Source option is the voltage signal that will start the sweep. This signal can come from either **CH1** or **CH2**, an external line, or from the 60 Hz AC power sources. Usually the trigger signal will come from **CH1** or **CH2**. The Slope option allows the sweep to be triggered either when the trigger signal is rising or falling. In this lab triggering on the rising signal will work for all the cases we will do. The Mode option has two settings: Auto and Normal. In the Auto setting the trigger is automatic so that the sweep display is visible even if there is no input signal. This is most useful for setting up and for looking at DC voltages. When the Mode option is set to Normal the sweep starts only when the trigger source changes as was selected in the other setting.

Trigger Controls

The level of the signal that triggers the sweep can be adjusted by using the trigger Level knob. A small arrow appears on the right side screen indicating the level of the trigger voltage on the trigger sources (**CH1** and **CH2**). The **SET TO 50%** sets the trigger level automatically to 50% of the current trigger source. This is a very convenient feature to find an appropriate trigger level. The **FORCE TRIG** button forces the oscilloscope to trigger in Normal mode even if it doesn't see a trigger signal on the source. The **TRIG VIEW** button allows the trigger setting to be displayed on the bottom of the screen.

The oscilloscope should be setup correctly and the slope should be visible without you doing anything to setup the scope if you need to setup the scope using the following settings, you can set the scope settings as follows:

- Select channel 1 by pressing the **CH1** menu button

- Press the “Coupling” menu until DC is displayed. Press the “Probe” menu until “x1” is displayed. Using the voltage per division knob choose 100mV per division.
- Select channel 2 by pressing the **CH2** menu button
- Press the “Coupling” menu until DC is displayed. Press the “Probe” menu until “x1” is displayed. Using the voltage per division knob choose 500mV per division.
- Press the **TRIG MENU** button and select **AUTO** trigger mode
- Press the **“SET TO 50%” TRIGGER LEVEL** button
- Set the horizontal sweep rate (sec/div) to 5 msec/div, the value is displayed on the bottom of the screen next to an “M”. You should see two scope traces; Use the Vertical position and horizontal position knobs to place the traces in a convenient place in the display.

Average Controls

By pressing the **acquire** button you can select the average or the sample mode. You need sample mode when you change things and you need average with 128 samples when you measure. It needs some time for the oscilloscope to stabilize if parameters are changed and it is in average mode (as 128 samples take a long time to be acquired). **Save recall controls**

In order to save your measurements to a USB key you have to use the **save/recall** button, select the save all action and press the **print** button which will save your data to the USB stick under the folder ALL#. If the USB stick has been used many times then there will be lots of ALL# folders, the one that you want will be the folder followed by the greater number (last save). In the USB you will find a .CSV file with the channel 1 data, a CSV file with the channel 2 data and a bitmap file showing the oscilloscope display. You can confirm that are your data by seeing the date and time when the files were created.

Appendix B:

Excel

In order to work with your data open Excel, go to file>open, locate the USB key and your folder, and choose files of type: comma delimited to open your files. Select the columns that correspond to the columns that you want to plot and on the left select the type of graph that you want (e.g. Scatter). By pressing on parts of the graph you change titles, axis; by using the menus on top for the fonts you can change your graph.

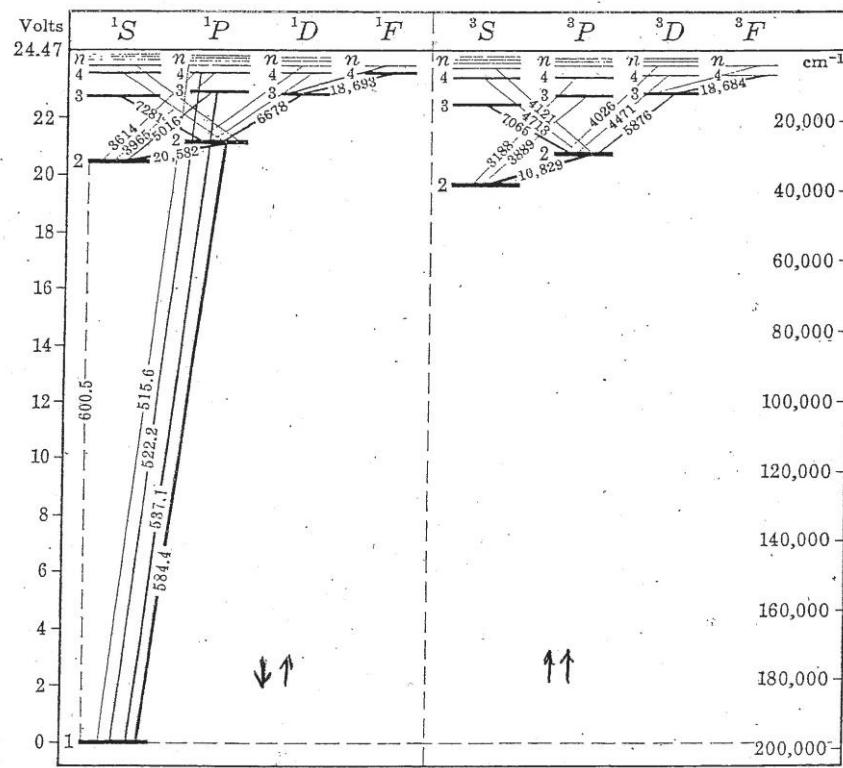
Create plots for the channel 1 and channel 2 and then if you want you can combine the data in one spreadsheet (using copy, paste) that will have all the data, so you can find at which energy the peaks occur. What you need to do is, using the functions of Excel, to create a new graph that the x-axis is the energy of the electrons and y-axis is the ring-collectors voltage.

In the ring collector we collect a minute current which we amplify and it shows in the oscilloscope as a small voltage, it is ok to use this voltage without any conversion as we are not interested in the values of the actual collected current. As we have said at the description of the apparatus, it is important that the oscilloscope also does not show really the ramp Voltage as we can see it in the multimeters, it shows a reduced voltage. You have to convert the readings of the oscilloscope to the real readings. This is very easy if you know the min-max values of the multimeters for each of your scans and you compare to the values of the oscilloscope. If you need to do calculations in Excel you have to go to a cell write your calculation and then drag it to apply it to other cells. So you have to create a simple transform that will give you the real voltage from the oscilloscope readings. You will have better results if you just make the transform using the min and max value and assume a linear relation to connect them, as this approach will not use the intermediate values of the oscilloscope that may have noise.

Appendix C:

Helium Ion Energy Level Diagram

The Helium atom contains two electrons and so in principle the excited states of helium have two sets of labels corresponding to the states of the two electrons. In practice in many circumstances only one of the electrons is excited thus it is enough to draw up a state diagram for the case where one electron is in the same state as the ground state of helium and the other is excited. This is shown below with the energies given relative to the ground state. The line at the top of the graph labelled 24.47eV corresponds to the single ionisation energy of a Helium ion, i.e. the energy to remove one electron from the atom to produce a single positive ion. At the moment you don't need to understand the labels for the different states. The diagram is split into two halves; the half on the left involves states in which the two electrons' spins which have a total spin of zero (called Ortho) and the half on the right involve states which have a total spin of one (called Para). The lines between states shown on the diagram are so called dipole allowed optical transitions. Dipole allowed means that the transition can be caused by an alternating uniform electric field. In practice strong light emission only occurs for dipole allowed transitions. It should be noted that there are no lines joining the Ortho and Para halves of the diagram. This is because an electric field does not interact with an electrons spin and so can't change the spin of an electron. Light emission to take an electron from an excited state to a lower energy state is a fast process and has a characteristic half life of about 1nS. If a transition is not dipole allowed it can still happen but by much slower processes which characteristic half lives of milliseconds.



Energy Level Diagram for Helium.

Diffraction and Interference

Safety

There are the following safety issues for this experiment:

Laser radiation (class 3A).

The risk is moderate. Risk of temporary damage to vision. The experiment uses a laser with visible (red) beam of power ~ 1 mW. Do not look directly into the laser beam or into reflected or scattered beams. Take precautions to prevent exposure of other people to the beams.

Diffraction and Interference

Aims and Objectives

This experiment explores patterns that form when laser light passes through narrow apertures. The main goals of the experiment include:

- investigating interference and diffraction using different types of slits
- exploring how diffraction and interference patterns depend on the size or separation of the slits
- comparing the interference patterns recorded experimentally with the theoretical predictions

1. Introduction

The wave nature of light is most clearly demonstrated in the phenomena of interference and diffraction. Different types of waves, such as electromagnetic or sound waves, can undergo interference or diffraction. In this experiment you will use visible light, a form of electromagnetic wave and confirm its wave nature.

Diffraction (figure 1a) is the spreading of a wave as it propagates through space and is most obvious as bending of waves around an obstruction or spreading out after passage through a narrow aperture. The light emerging from the slit is equivalent to several point sources of oscillating in phase. Diffraction allows us to hear around corners and results in waves from the open sea reaching into harbours.

Interference (figure 1b) occurs when two wave-trains, such as two light beams, intersect. So long as they have the same frequency, a stationary pattern of light and dark fringes occurs in the region of overlap, caused by constructive and destructive superposition or interference of the light waves. This is similar to standing waves on a string are caused by superposition of two waves of equal frequency propagating in opposite directions and are thus a special form of interference fringe.

Two waves arrive at a single position on a screen and depending if they are in or out of phase, bright or dark fringes can be observed. The crucial element for creating such an interference pattern is to produce a phase shift between the two waves. The usual method to achieve that is to add extra path for one of the waves with respect to the other. It is easily achieved as the distance between the slits' stand and the screen changes as a function of the lateral position on the screen.

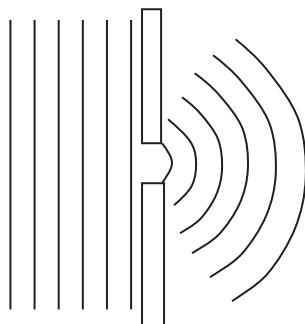
Both diffraction and interference contribute to the famous double slit experiment (figure 1c) first performed by Thomas Young in 1801. A single beam of light illuminates two separate apertures in an opaque screen. The light passing through each aperture is diffracted, namely spreads out into the space beyond

and so overlaps with light from the other aperture. Interference fringes are then formed in the region where the beams overlap.

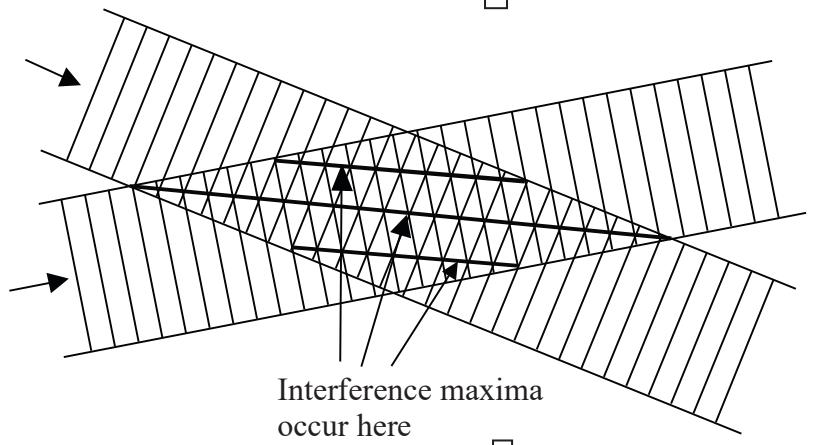
The double slit experiment is of central importance in Quantum Theory. In the extreme case, where the light is so weak that no more than a single photon of energy $h\nu$ is present at a time, the interference pattern is still observed. The pattern develops slowly as more and more photons are detected, despite that each photon appears more or less random on the detecting screen. The experiment teaches us that a wave is associated with each separate, quantum or particle and that its *intensity* gives the *probability* of detection.

Figure 1 Diffraction and interference of waves.

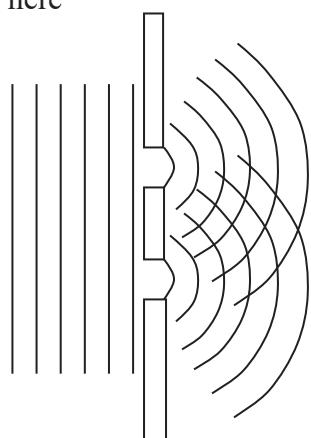
- a) *Diffraction of waves at an aperture.*



- b) *Interference fringes are observed where two wave trains overlap.*



- c) *Young's double slit experiment combines diffraction with interference to produce light and dark interference fringes in the region of overlap.*



2. Near-field and far-field

The theory of diffraction distinguishes between two different regimes - near-field, where the viewing plane is close to the diffracting object, and far-field, when a pattern is viewed far away from the aperture, as illustrated in figure 2.

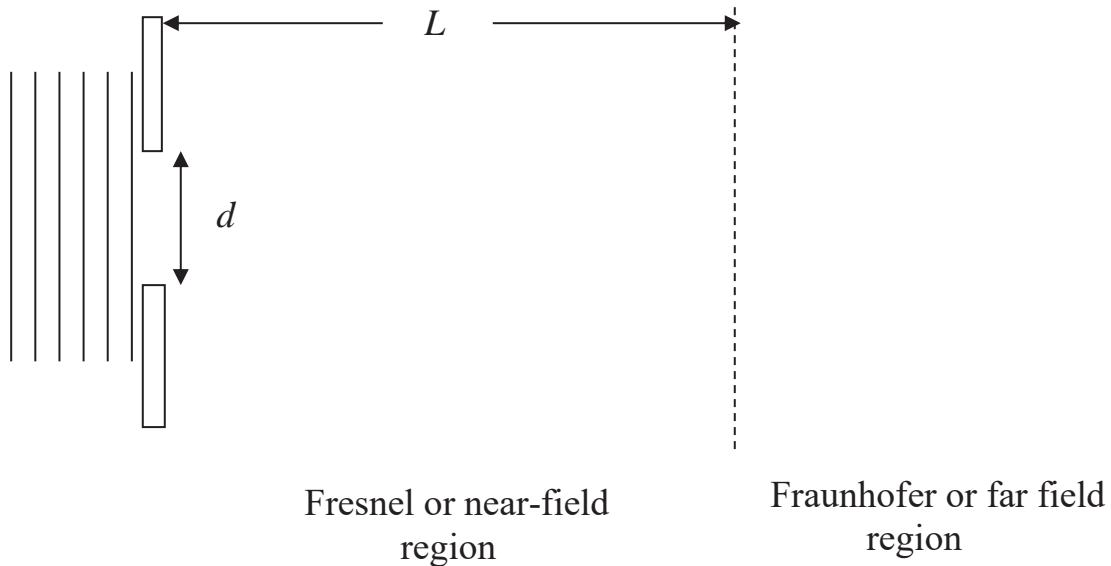


Figure 2 *Near-field and far-field diffraction patterns from a single slit.*
 L is the Rayleigh distance given by d^2/λ .

In the near-field region, the diffraction pattern changes qualitatively as the distance from the object increases - the number of maxima and minima and their relative strengths change.

In the far-field region, the qualitative form does not change - the pattern simply spreads out as the distance increases. These regimes are also referred to as Fresnel and Fraunhofer diffraction, respectively. Basically, Fraunhofer theory is valid when the wavefronts are flat (not curved) and so, strictly speaking for figure 2, is applicable only to observations made at infinite distance. The Fresnel theory of near-field effects is considerably more complicated and at this point we will not discuss it.

In practice the wavefronts become *essentially flat* beyond the, so-called, Rayleigh distance L , from an aperture and simple Fraunhofer theory is an excellent approximation. If the dimension of the aperture is d , then with light of wavelength λ , Rayleigh distance is $L=d^2/\lambda$. Note that there is not a sharp boundary between near and far fields; significantly below L we have near-field and significantly above, far-field.

3. Prelim questions

1. What is the difference between white light and monochromatic light?
Draw a monochromatic wave and indicate its wavelength.
2. When are two sources called coherent? Draw waves emerging from:
 - a) two coherent sources
 - b) two incoherent sources
3. Diffraction
 - a) state the main conditions to observe diffraction
 - b) estimate the value of the Rayleigh distance L for $d = 0.5$ mm and $\lambda = 600$ nm
4. A laser beam is incident on a double slit and an interference pattern is observed on a screen. If the separation between the slits is increased, what happens to the distance between the fringes? Show how you calculated your answer.

4. Materials and methods

The equipment (figure 3) consists of a Helium-Neon laser which produces a narrow highly monochromatic beam of light. The beam passes through a "spatial filter" and a collimating lens so we can regard it as a light wave with plane wave fronts.

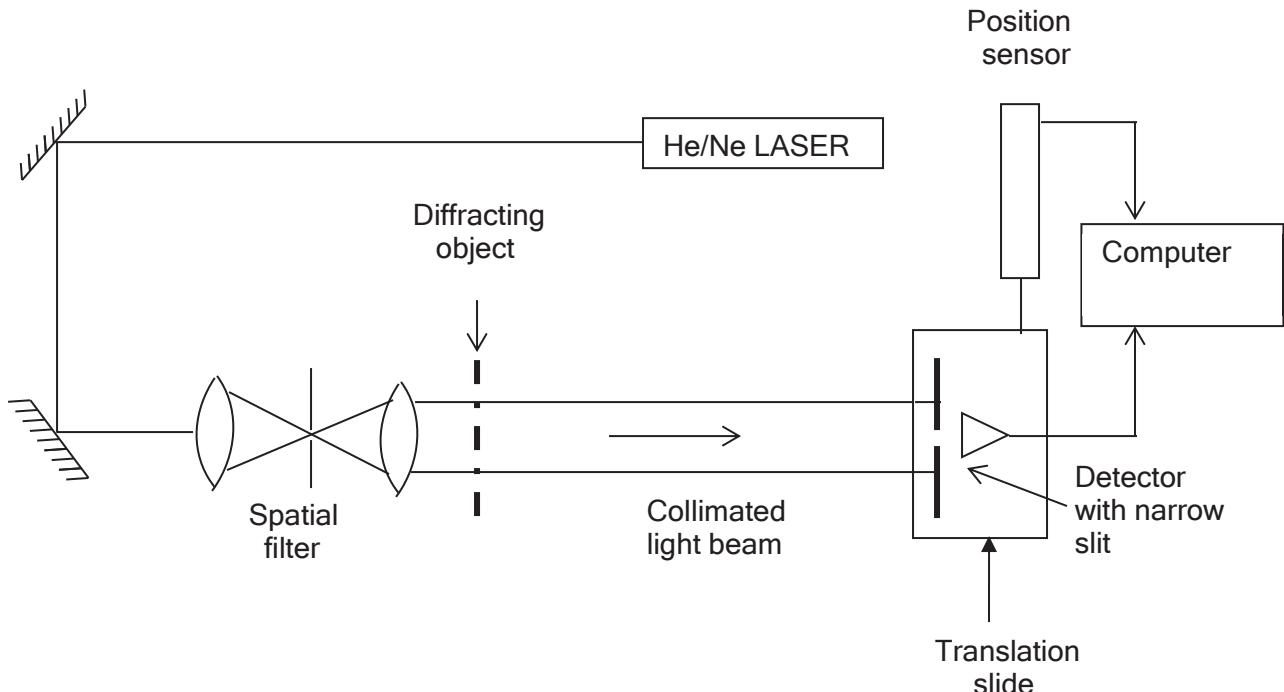


Figure 3 *Schematic of the experimental arrangement.*

The setting of the spatial filter is critical and you should not touch it.

The apertures that will lead to diffraction and interference are placed in the beam just after the collimating lens and the resulting intensity patterns are

recorded on the computer using a photodetector (PIN diode with preamp) with a narrow slit to restrict the sensitive area and allow the study of fine details. The detector can be moved sideways using a translation stage equipped with a position sensor also attached to the computer. Thus, the intensity versus position of any pattern under investigation can be recorded on the computer.

5. Experiments

5.1 Calibration of detector motion.

1. The position sensor is not calibrated, so you will need to determine the relationship between its output voltage and displacement in meters.
2. Translate the detector from one end of its travel to the other and note the change of output voltage from the position sensor. There is a DVM connected up for this purpose and the voltage is simultaneously read by the computer. Now measure the position of the detector as a function of voltage; you are provided with a standard machine-shop dial gauge to do this. A reading every volt should be enough to plot a graph to establish:
 - (a) the linearity of the relationship,
 - (b) the proportionality constant between displacement and voltage
 - (c) that the computer and DVM readings are the same.

5.2 Diffraction by a single slit

1. Position the adjustable single slit in the light beam as far as possible from the detector, i.e. just after the collimating lens. Using a white screen in front of the detector, observe and make sketches of the diffraction pattern produced and how it changes as the width of the slit is varied. Adjust the rotation of the slit so that the diffraction maxima and minima are parallel to the slit in front of the detector.
2. Set the diffracting slit width to about 0.5mm and use a travelling microscope to measure the setting accurately. Position the slit as close to the detector as possible, noting its distance from the detector. Record and save the diffraction pattern on the computer. This may require adjustment of the detector gain and the detector slit in order to give good resolution and avoid saturation of the detector.
3. Using the same settings of detector gain and detector slit, record the diffraction pattern at about three other positions of the diffracting slit spaced between the detector and the collimating lens. Comment on the form of these diffraction patterns.

→ Q: Do the diffraction patterns you recorded confirm the statements made above about the transition from near-field to far-field diffraction region?

4. Adjust the slit width to about 0.2 mm and check the accuracy of that setting using the travelling microscope. Position the slit close to the collimating lens.
5. Record its distance from the detector.
6. Record the diffraction pattern on the computer.
7. Determine the angular distance, in radians, between the central maximum and each of the minima in the pattern.

A simple way to start to understand the diffraction pattern is to think of the slit (width d) as divided into two longitudinal strips of equal width. Now, consider interference between the waves coming from the top and bottom halves of the slit, as shown in figure 4(a); there will be destructive interference when the waves from corresponding positions across these two strips arrive at the detector in antiphase.

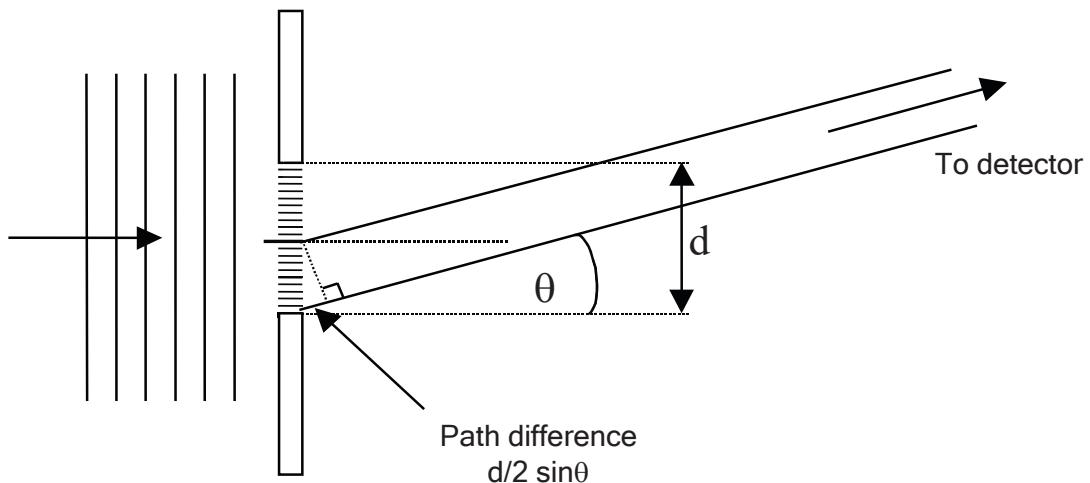


Figure 4a Notional division of a single slit into 2 strips giving destructive interference at the detector when: $d \sin \theta = n\lambda$

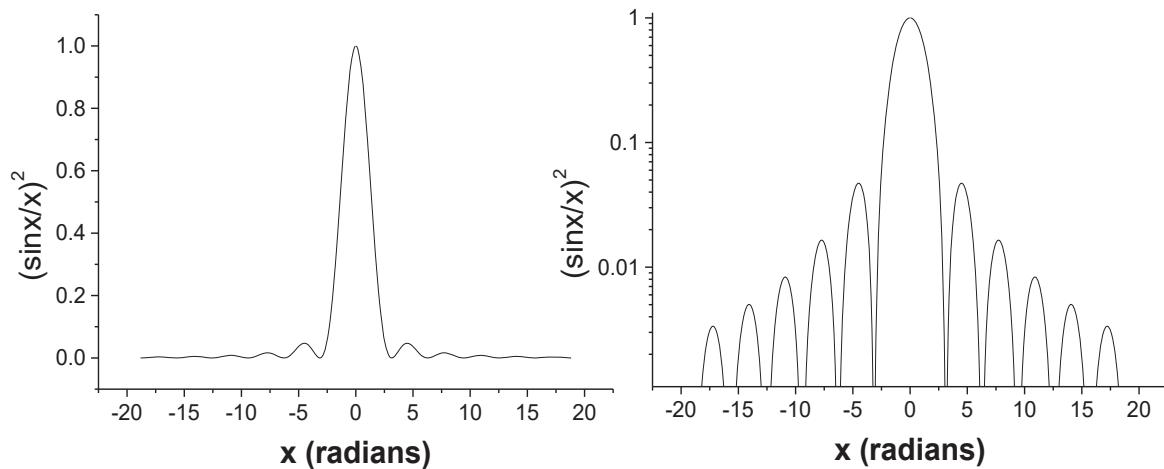


Figure 4b *Diffraction pattern intensity for a single slit plotted against the reduced variable x*

The condition for antiphase of waves from corresponding positions is that the path lengths from them to the detector differ by half a wavelength i.e. $\lambda/2$. Thus, there will be destructive interference when:

$$\frac{d}{2} \sin \theta = \frac{\lambda}{2}$$

In other words

$$d \sin \theta = \lambda$$

or

$$\theta \approx \frac{\lambda}{d}$$

If we imagine the slit divided into four quarters and set the condition for destructive interference of waves from strips in corresponding positions in *adjacent* quarters, we will find

$$\frac{d}{4} \sin \theta \approx \frac{d}{4} \theta = \frac{\lambda}{2}$$

or

$$\theta = \frac{4\lambda}{2d} = \frac{2\lambda}{d}$$

Continuing this line of reasoning we will find the general condition for destructive interference:

$$\theta = \frac{n\lambda}{d}$$

where n is an integer.

- ➔ Q: Check this relationship for the pattern you have just recorded: the angles of the minima should be $\theta = \lambda/d, 2\lambda/d, \dots, n\lambda/d$ where $\lambda = 632.8 \text{ nm}$ and d is the value you have measured for the slit width.

Fraunhofer theory, which carries the idea of the division of the slit into strips a bit further, predicts the intensity of the diffraction pattern to be given by

$$I = I_0 \frac{\sin^2 x}{x^2}$$

where

$$x = \pi \frac{d}{\lambda} \theta$$

and I_0 is the intensity at the centre. This function is plotted in figure 4b.

- Q: How the function from figure 4b compares with the pattern you have recorded?

You could carry out a detailed comparison by calculating the function for your particular slit width and superimposing it on the experimental data, but it will be sufficient, since you should already have found that the angular positions of the minima are correctly predicted, to show that the relative heights of the maxima given by the theory (see figure 4b) are also correct.

5.3 Interference

Replace the single adjustable slit with the painted microscope slide which has slits scratched on it.

First make some measurements of the interference patterns of double slits. Record the patterns, the distance from the detector and the slit separation for two (or more if there is time) pairs of slits.

- Q: Explain the form of the patterns you have recorded.
- Q: How are the sharp interference fringes formed?
- Q: What determines the variation of their intensity across the pattern?
- Q: Compare the expected angular separation of the interference fringes with what you measure from your patterns.

Now investigate the diffraction/interference pattern of the pair of slits which extends only partway across the slide. Then, without altering the detector gain or detector slit width, translate the slide in a vertical direction so that the laser beam passes through just a single slit and record the diffraction pattern.

- Q: Compare the two patterns you have just recorded.
- Q: Explain why the peak intensity transmitted by two slits is greater than double that for a single slit?
- Q: What would you expect the ratio to be?

Normal Modes

Safety

There are the following safety issues for this experiment:

- 1) **The risk is low.** Wires may break and cause injury. To avoid eye injury safety glasses should be worn. If these are not available on the bench ask the laboratory technician to provide them.

Normal Modes

1.0 Introduction

We all know about the possible vibrations of a stretched string or air in an organ pipe. There is a ‘fundamental’ mode and the second etc ‘harmonics’ which have progressively higher frequencies and shorter wavelengths. These are special cases of the normal modes of a system. In general, each normal mode has a particular frequency and a corresponding distribution of amplitudes of the motion at different positions. For example the string vibrating in (say) the second harmonic, has all parts of the string moving with the same frequency while the amplitude varies smoothly from zero at each end, where the string is fixed, to a node at the centre, with the two halves going in antiphase.



Figure 1 Waveform for the second harmonic mode of transverse vibration in a string or wire

We see that a normal mode is specified by a single frequency, and a distribution of amplitudes. These two things can be found mathematically by following the prescription

(Equation of motion + boundary conditions) **normal modes**

For the stretched string (tension, T; length, L; mass per unit length, ρ) the equation of motion is:

$$\frac{\partial^2 y}{\partial t^2} = \frac{T}{\rho} \frac{\partial^2 y}{\partial x^2} \quad (1)$$

where y is the transverse displacement and x the position along the string. The phase velocity of the transverse waves on the string is $v_p = \sqrt{(T/\rho)}$. The boundary conditions are that the string is fixed at each end i.e. $y=0$ for $x=0$ and $x=L$ at all times. The normal modes are derived mathematically in the appendix.

The same principles apply to other cases where the equation of motion and boundary conditions may be more complicated. For example a drum skin (two-dimensional) has:

$$\frac{\partial^2 y}{\partial t^2} = v_p^2 \left(\frac{\partial^2 y}{\partial x^2} + \frac{\partial^2 y}{\partial z^2} \right) \quad (2)$$

and the boundary conditions are $y=0$ all around the edges i.e. $x^2 + z^2 = R^2$ where R is the radius. This will specify all the complicated harmonics or normal modes of the drum which timpanists exploit to change the tone of the drum by drumming and damping the surface at different points.

There are two very important points about the normal modes of any system. First they are a *complete* set – there are no other resonances of the system. Second, any time-dependent pattern of displacements of the system (that is any $y(r,t)$ where r is position in space and t is time) can be expressed as a *linear superposition* (or sum) of the normal modes.

How many normal modes does a system possess? Obviously a continuous system such as the stretched string has an infinite number; but what about a discrete system such as a set of N pendulums coupled together by swinging from the same flexible support, or a set of N weights attached to a stretched spring? A reasonable (and correct) guess would be N normal modes – a finite number. In general it turns out that the number of normal modes is equal to the number of degrees of freedom of the system. The appendix gives the calculations for normal modes in the cases of string with N weights.

The aim of this experiment is to investigate the normal modes of a stretched wire and of a similar wire with weights attached at intervals along its length.

2.0 Safety Issues

Take precautions to protect your eyes in case any of the wires break under tension.

3.0 Experimental Method

The apparatus consists of two identical wires with the same length and stretched to the same tension. One wire has no weights attached, the other has six identical weights positioned at equal intervals along its length. The un-weighted string is driven by passing alternating current electricity directly through it and placing a magnet around it near one end. An electrical vibrator driven by a signal generator and amplifier is used to drive the weighted string into oscillation through a flexible coupling near one end. Each string is equipped with a displacement sensor which sends a signal to an oscilloscope or computer. Figure 2 shows the set-up for experiments on each string. For each case the output of the function generator should be 5 volts peak to peak sine wave, the power amplifier should be set to ‘divide by 10’ and the gain set to give a nice sinusoidal output as seen on the oscilloscope. Note that the sensor for the bare wire is connected directly to the oscilloscope whereas sensor 2 used for the weighted wire is connected to a separate psu which then feeds the PC and the oscilloscope.

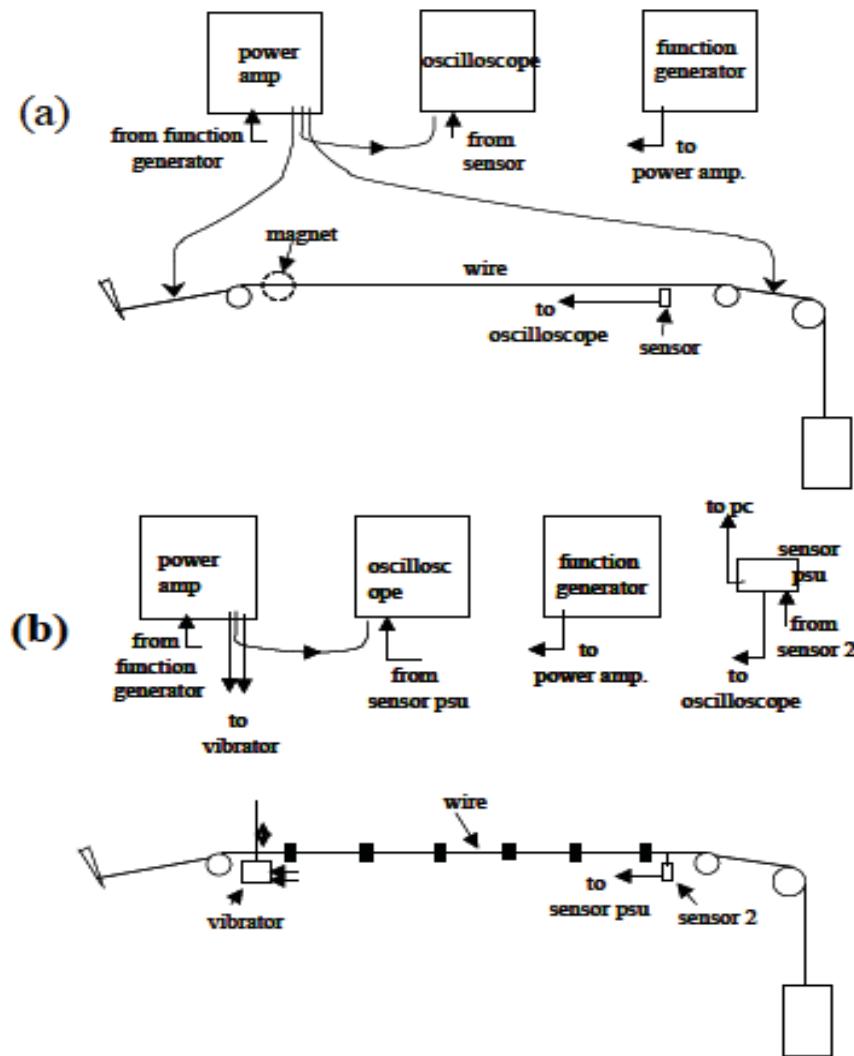


Figure 2 (a)Set-up for study of bare wire (experiment 1).
(b)Set-up for experiments 2 and 3.

Experiment 1: Transverse vibration modes of a bare wire

Excite transverse oscillations in the bare wire and determine the frequency and wavelength of the fundamental and as many harmonics as you can find. The set-up is illustrated in Figure 2(a). If you cannot locate the fundamental frequency by tuning the signal generator, make a guess from the note of the plucked wire.

- Plot a graph of frequency against wave number. Does this give a straight line?
- Using your data, determine and compare the phase velocity, v_p , and the group velocity, v_g , of transverse waves on the wire at your measured frequencies.
- Weigh a short, measured, length of the wire to obtain the mass per unit length, ρ , and hence determine the tension, T, using the formula

$$v_p = \sqrt{\frac{T}{\rho}}$$

Experiment 2: Transverse vibration modes of a weighted wire

Use the experimental configuration shown in figure 2(b). Make a preliminary visual estimate of the fundamental frequency by tapping one of the weights. Carefully adjust the vibrator to excite transverse vibrations in the weighted wire. As before, measure the frequency and wavelength of as many resonances of the system as you can find.

- Plot a graph of frequency against wavenumber. Does this give a straight line?
- Determine and compare the phase and group velocities at each frequency and compare what you have here with what you found in the case of the bare wire.
- Weigh one of the weights and, using the value of T determined in part (1), calculate the frequencies of the normal modes of the weighted wire (see appendix). Compare these calculated values with your measurements. Have you found all the normal modes?

Experiment 3: Impulse response of the weighted wire with frequency response extracted by a Fourier Transform.

What do you expect if you give an impulse to (i.e. tap between the weights) the weighted wire? Will it move with a well-defined frequency? Will its amplitude pattern correspond to a single harmonic? Your answer to both of these questions should be “No, unless I am particularly skilful or lucky with applying the impulse”. According to theory, outlined in the introduction, the motion should be a superposition of all the normal modes with different amplitudes and phases depending on how and where you gave the impulse. So, if the theory is right, when we twang the wire, it should only respond at the **normal mode** frequencies – no others are possible. To test this, give an impulse to the wire and then record the output of the displacement sensor for a suitably long time interval (say 10 or 100 times the period of the lowest frequency vibration you wish to look for) using the handyscope, the small black box connected to the computer. When starting up the computer software to analyse the spectra, you will need to load in a set-up file with digitizing parameters optimized for the frequency ranges you will encounter here. **To do this, click file -> restore instrument setting, and then choose the file N_modes.** Do the experiment by twanging or tapping the wire gently in several places using the mode shapes to select tapping positions. This analysis should contain only the normal mode frequencies. Discuss what you find.

Prelim questions: (write answers down before the prelim session)

1. What is a normal mode? Describe a physical situation where the phenomenon of a normal mode can be observed and point out what special conditions have to be fulfilled.
2. How is the excitation of the oscillation of the bare wire technically realized? What is the physical law behind?
3. How many normal modes can we expect for the 2nd experiment (weighted wire)? Why is the number of normal modes limited?
4. What are phase and group velocity? Give one example for each.

Some helpful and advanced literature: (this is if you are interested to learn more about applications of the concept of normal modes or want to understand the background)

1. Normal modes of a string is discussed in Wallace '*Mathematical analysis of physical problems*', Dover Publications (1984), p 25.
2. Normal modes (of coupled oscillators) are discussed under classical wave equation in any 'Classical Mechanics' textbook: see for instance:
Goldstein et al. 'Classical Mechanics', Addison Wesley 3rd edition (2001). or
Landau Lifshitz 'Theoretical Physics, Vol. 1 - Mechanics', Butterworth Heinemann; 3rd edition (1982). (strong stuff)
3. But also *Wolfsen 'Essential University Physics, Vol I'*, Pearson Int., (2007) p 234 f. has some heuristic remarks on standing waves.
4. Search the www. Nice animations are around to play with. Wikipedia etc.
5. Normal modes are also important in optics, especially in laser resonators (cavities) or for so-called standing light waves: see e.g. *Meschede 'Optics, Light and lasers'*, Wiley, (2004) p.150 ff.
6. Normal modes are also important in solid state systems for instance to describe collective vibrations of coupled atoms in the lattice, which are then called *phonons* , see e.g.: *Ashcroft & Mermin 'Solid state physics'*, Cengage Learning Services (1976). Also smaller systems of coupled oscillators as atoms in molecules show normal mode vibrations.
7. The Fourier transformation (FT) is very important in physics and you can find descriptions in almost all textbooks on classical (continuous FT) or quantum (discrete FT) mechanics or optics. Some more fundamental introduction can be found in Wallace as above on page 150 ff.

Appendix:

Tutorial on normal modes for a stretched spring



Tension T, mass per unit length ρ , length L, fixed at $x=0$ and $x=L$.

Equation of motion:-

$$\rho \frac{\partial^2 \gamma}{\partial t^2} = T \frac{\partial^2 \gamma}{\partial x^2} \quad (1)$$

Look for normal mode solutions in which all parts of the string move with the same frequency but with different amplitudes and phases. Such a solution will separate into a product of two functions containing time and position :-

$$Y(x, t) = V(t)A(x) \quad (2)$$

$V(t)$ is a (time dependent) vibrational function with no x -dependence, while $A(x)$ is the amplitude function containing no t -dependence.

Substitution into the equation of motion gives

$$\rho \frac{\partial^2 V(t)}{\partial t^2} A(x) = T \frac{\partial^2 A(x)}{\partial x^2} V(t) \quad (3)$$

Rearrange: $\frac{\rho}{V(t)} \frac{\partial^2 V(t)}{\partial t^2} = \frac{T}{A(x)} \frac{\partial^2 A(x)}{\partial x^2} \quad (4)$

Now the left hand side contains only time-dependent functions while the right hand side only depends on position x . Therefore, if the equation is to hold for all values of t and of x , each side must equal a constant which does not depend on either x or t which we shall call C.

Now we have:

$$\frac{\rho}{V} \frac{\partial^2 V}{\partial t^2} = C \quad (5)$$

and

$$\frac{T}{A} \frac{\partial^2 A}{\partial x^2} = C \quad (6)$$

The general solutions of these equations are of the form $V = e^{at}$ or $A = e^{bx}$, where a and b are constants which may be real or imaginary. If b were real, we can quickly see that y could only ever be zero at one value of x . But the boundary conditions require it to be zero at $x = 0$ and $x = L$ so we must look at imaginary values of b .

Hence putting $b = ik$, where k is real, try a function

$$\begin{aligned} A(x) &= \alpha e^{ikx} + \beta e^{-ikx} \\ &= (\alpha + \beta) \cos kx + (\alpha - \beta) i \sin kx \end{aligned} \quad (7)$$

This means that $A(x)$ varies sinusoidally with x with wavelength $\lambda = \frac{2\pi}{k}$

Substituting (7) into (6) we find

$$\begin{aligned} -Tk^2 A(x) &= CA(x) \\ \therefore V &= V_0 e^{i\omega t} \end{aligned} \quad (8)$$

where

$$\omega = k \sqrt{\frac{T}{\rho}} \quad (9)$$

Applying the boundary conditions to the function $A(x)$, eq. 7 gives

$$\begin{aligned} (i) \quad \alpha &= -\beta, \\ (ii) \quad \sin kL &= 0 \quad \text{ie} \quad k = \frac{n\pi}{L}, \quad n = 1, 2, 3, \dots \end{aligned}$$

Finally we can specify the normal modes as

$$\begin{aligned} \omega_n &= \frac{n\pi}{L} \sqrt{\frac{T}{\rho}} \\ \text{and } A_n(x) &= A_0 \sin\left(\frac{n\pi x}{L}\right) \end{aligned} \quad (10)$$

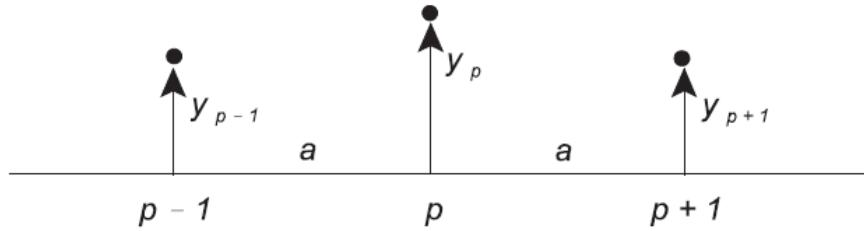
where A_0 is a constant.

The phase velocity of a wave is $v_p \equiv \frac{\omega}{k}$ and the group velocity is $v_g \equiv \frac{\partial \omega}{\partial k}$

Hence, from (9) we have, in this case

$$v_p = v_g = \sqrt{\frac{T}{\rho}}.$$

Tutorial on normal modes for weighted wire



N weights, mass m and spacing a . Wire is assumed to be massless and we consider only motion of the weights.

Consider weight number p . For small displacements, transverse force on it is

$$-T \frac{(y_p - y_{p-1})}{a} + T \frac{(y_{p+1} - y_p)}{a} = \frac{T}{a} [-2y_p + (y_{p-1} + y_{p+1})]$$

Hence equation of motion of p^{th} weight is :-

$$m \frac{\partial^2 y_p}{\partial t^2} = \frac{T}{a} [-2y_p + (y_{p-1} + y_{p+1})] = \frac{T}{a} y_p \left[\frac{(y_{p-1} + y_{p+1})}{y_p} \right] \quad (11)$$

As for the unweighted wire, we are looking for solutions with separate amplitude and vibrating parts:

$$y_p = A_p V(t)$$

The amplitude part is only defined at the weights so has a label p rather than being a function of x .

Substitute into eq. (11)

$$\frac{m}{V} \frac{\partial^2 V(t)}{\partial t^2} = \frac{T}{a} A_p V(t) \left[-2 + \frac{A_{p-1} + A_{p+1}}{A_p} \right].$$

Therefore

$$\frac{m}{V} \frac{\partial^2 V}{\partial t^2} = \frac{T}{a} \left[-2 + \frac{A_{p-1} + A_{p+1}}{A_p} \right] = C \text{ (constant).} \quad (12)$$

This is satisfied if $A_p = \partial e^{ika} + \beta e^{-ika}$ and to satisfy the boundary conditions we must have

$$A_p = 0 \text{ for } p = 0 \text{ and } (N+1)$$

$$\text{Whence } \alpha = -\beta \text{ and } k = \frac{n\pi}{(N+1)a} n = 1, 2, 3, \dots$$

Therefore

$$\partial_p = a(e^{ikpa} - e^{-ikpa}) = 2ia \sin kpa \text{ and } \frac{A_{p+1} + A_{p-1}}{A_p} = 2 \cos ka$$

Substituting into (12) we get:

$$\begin{aligned} C &= \frac{T}{a} \left[-2 + 2 \cos ka \right] \\ &= -\frac{4T}{a} \sin^2 \frac{ka}{2} \end{aligned}$$

And

$$m \frac{\partial^2 V}{\partial t^2} = -\frac{4T}{a} \sin^2 \frac{ka}{2} V$$

And assuming $V \sim e^{-i\omega t}$

$$\begin{aligned} -m\omega^2 V &= -\frac{4T}{a} \sin^2 \frac{ka}{2} V \\ \therefore \omega^2 &= \frac{4T}{ma} \sin^2 \frac{ka}{2} \end{aligned}$$

Hence the normal modes are:

$$A_p = A_o \sin \frac{n\pi p}{(N+1)}, \quad n=1, 2, 3, \dots \text{ where } A_o \text{ is a constant.}$$

With

$$\omega_n = \sqrt{\frac{4T}{ma}} \sin\left(\frac{n\pi}{2(N+1)}\right).$$

A quick glance suggests (incorrectly) that there is a maximum frequency of normal modes given by

$$\omega_{\max} = \sqrt{\frac{4T}{ma}} \text{ which occurs for } \sin\left(\frac{n\pi}{2(N+1)}\right) = 1 \text{ ie when } n=N+1.$$

However the amplitude of the motion in this mode would be

$$A_p = A_0 \sin \pi p \text{ where } p = 1, 2, 3, \dots$$

So actually the weights are all stationary which means the mode does not exist.

Looking with more care we find, for N = 6:

$$\omega_1 = \sqrt{\frac{4T}{ma}} \sin \frac{\pi}{14} = \sqrt{\frac{4T}{ma}} \times 0.223 \quad \omega_2 = \sqrt{\frac{4T}{ma}} \sin \frac{2\pi}{14} = \sqrt{\frac{4T}{ma}} \times 0.434$$

$$\omega_3 = \sqrt{\frac{4T}{ma}} \sin \frac{3\pi}{14} = \sqrt{\frac{4T}{ma}} \times 0.624 \quad \omega_4 = \sqrt{\frac{4T}{ma}} \sin \frac{4\pi}{14} = \sqrt{\frac{4T}{ma}} \times 0.782$$

$$\omega_5 = \sqrt{\frac{4T}{ma}} \sin \frac{5\pi}{14} = \sqrt{\frac{4T}{ma}} \times 0.901 \quad \omega_6 = \sqrt{\frac{4T}{ma}} \sin \frac{6\pi}{14} = \sqrt{\frac{4T}{ma}} \times 0.975$$

And then $\omega_8 = \omega_6$, $\omega_9 = \omega_5$ etc. So there are only 6 different frequencies.

Black Body Radiation

Safety

No special safety issues.

Black Body Radiation

Aims and Objectives

This experiment explores radiation emitted by objects at different temperatures. You will observe electromagnetic radiation emitted by a thermal source, relate these observations to the Planck radiation law for a “black body” and verify the Stefan-Boltzmann law.

The main stages of this practical involve :

- measuring the visible and infrared radiation emitted by an incandescent filament as a function of the temperature of the filament;
- comparing the total radiated power, measured within the bandwidth of the detector, to the Stefan-Boltzmann law of thermal radiation;
- studying the spectral distribution of radiation from the filament, for a number of different temperatures,
- comparing the experimental results with the Planck Radiation law for a “black body”.

1. Introduction

All objects emit radiation. The sun or incandescent lamps are the best examples, but people or buildings also emit radiation. We are able to detect this radiation in the form of thermal radiation (heat) using our sense of touch.

The energy of emitted radiation from objects at room temperature is quite weak and almost completely contained in the far infrared region of spectrum. We can't see it, so special detectors, like a thermopile in this experiment, has to be used.

However, with increasing temperature, the total radiated power increases rapidly. For sufficiently high temperatures, the emitted radiation falls in the visible spectrum, so for example we can see “red hot” objects.

A well-known observation is that dark objects absorb more thermal radiation than white or pale coloured objects. Good absorbers, such as for example, dark leather seats in cars, are also good emitters. An object that absorbs all incident radiation is called an ideal “black body”. It is also a perfect emitter and the power of the emitted radiation (per unit area) is proportional to the fourth power of the absolute temperature, so called **Stefan-Boltzmann Law**:

$$P = \sigma T^4 \quad (1)$$

where $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$ is called Stefan's constant.

The best approximation of an ideal “black body” is a cavity (a box) with a very small hole. It is a perfect absorber, as all radiation entering the cavity is

absorbed by its walls and then re-emitted. One of challenges in the past was to calculate and measure the spectrum of such black body emission. The approach was to calculate the number of modes of oscillation inside the cavity and then taking the energy per mode as $k_B T$. This approach, using classical physics, gave Rayleigh-Jeans law:

$$u(\lambda, T) = \frac{8\pi k_B T}{\lambda^4} \quad (2)$$

where $u(\lambda)$ is the radiated energy per unit area per unit wavelength, λ . This law predicted well the spectrum measured for radiation at long, infrared wavelengths, but failed to predict the experimental observations at shorter wavelengths. It is obviously wrong since the predicted energy density continues to increase with increasing frequency - which is clearly not consistent with common sense and is called the "ultra-violet catastrophe". The distribution of spectrum could be measured and showed a peak at a specific temperature. The position of this maximum is given by Wien's law:

$$\lambda_{max} T = 2897.8 \times 10^{-6} \text{ m} \cdot \text{K} \quad (3)$$

Note that with increasing temperature, the peak in the curve moves to shorter wavelengths.

The breakthrough idea to resolve the "ultraviolet catastrophe" came from Max Planck and this is where the quantum theory comes to the rescue. Planck's inspiration was to postulate that energy of each mode of oscillation in the cavity can only take discrete values rather than continuous spread of values, as postulated by classical physics. A mode can be excited in units of the quantum of energy $\hbar\omega$, where ω is the mode frequency and \hbar is a constant. Thus, the energy in a mode is $E = n\hbar\omega$, where n is an integer. Planck's hypothesis led to the particle description of light: the quantum of electromagnetic radiation is the *photon*. Planck's law gives the following energy density (per unit frequency per unit volume of the cavity):

$$u(\omega, T) = \frac{1}{\pi^2 c^3} \frac{\hbar\omega^3}{\exp(\hbar\omega/k_B T) - 1} \quad (4)$$

This is **Planck's Radiation Law**. We see that in the high frequency limit, the spectrum cuts off because of the exponential factor in the denominator; the "ultra-violet catastrophe" is cured.

Since we will be measuring the *wavelength* of the radiation, rather than the frequency, we should convert (4) from energy in a range of frequency ω to $\omega + d\omega$ into energy in a range of wavelength λ to $\lambda + d\lambda$, using $\omega = ck = 2\pi c/\lambda$. We then get the result for the energy density as a function of wavelength:

$$u(\lambda, T) = \frac{8\pi hc}{\lambda^5} \frac{1}{\exp(hc/\lambda k_B T) - 1} \quad (5)$$

The variation of $u(\lambda, T)$ with wavelength λ is plotted in Fig. 1 for a number of temperatures.

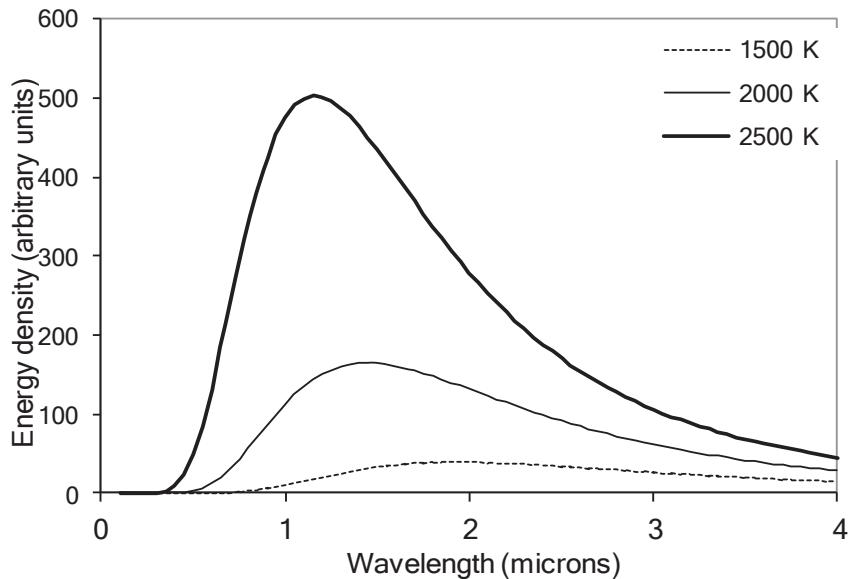


Figure 1. Spectral energy density of black-body radiation as a function of wavelength for three different temperatures.

Of course, real objects are not perfect absorbers or emitters that would, for example, absorb every incident photon. The deviation from black body behaviour is described by the emissivity $\varepsilon(\lambda)$. It means that, at a certain wavelength λ , an object absorbs or emits a fraction ε of the radiation as compared to that emitted by a black body (at the same wavelength and temperature). If we average emissivity ε over all wavelengths, the Stefan-Boltzmann law for the object would be:

$$P(T) = \varepsilon \sigma T^4 \quad (6)$$

Finally, if we take into account the area of the object, then, according to the Stephan-Boltzmann law, the power it radiates into solid angle 2π is:

$$P(T) = \varepsilon \sigma A T^4 \quad (7)$$

Note that the emissivity of a shiny surface can be very small, perhaps just a few percent. For example, the inside walls of thermos flasks are aluminised to reduce radiation losses from the hot contents.

The measurement of spectrum of radiation, in particular from a black body, played a crucial role in the development of modern and quantum physics. This lab practical provides you with the experience in measuring such spectrum and

in applying theoretical predictions from the Stefan-Boltzmann law and the Wien's law.

2. Prelim Questions

1. Define black body radiation.
Do not copy the text from the practical, but use your own words and keep your definition short (aim for not more than three sentences).
2. Look up the temperature of the Sun. Identify the relevant law and calculate the wavelength corresponding to the peak intensity emitted by the Sun. What is the region of spectrum this wavelength belongs to?
3. Show the conversion from equation (4) to equation (5) to verify the factor λ^5 in the denominator of equation (5).
4. Draw the spectral energy density curve versus wavelength for a cool object. Plot or describe the main changes in this curve as the object temperature is increased?
(for a full mark, use a computer program to draw the curve).

3. Apparatus

The apparatus consists of a tungsten filament lamp, a calibrated thermopile and a calibrated prism spectrometer to act as a wavelength filter. The thermopile has essentially constant spectral response from the middle of the visible far into the infrared, so it is an ideal detector for this experiment. The prism spectrometer is not so ideal, since the crystalline quartz prism has an absorption line near 3 microns, which may be apparent in your measurements. It is also necessary to correct the measured spectrum for the variation in the dispersion of the prism with wavelength (see Table 1).

The *thermopile* has three sensitivity ranges; you should choose the most appropriate range for your measurements. It measures only when the black "read" button is depressed. *Note that the reading is power per unit area.* The reading may be zeroed using the pink "offset adjust" knob.

The output of the thermopile tends to drift as it heats up due to absorption of incident radiation; also the thermopile receives radiation from objects other than the hot filament. To minimise both these uncertainties two readings should be taken in quick succession: the first with the thermopile receiving radiation from the black body and its surroundings and secondly with the same geometry but with the lit filament obscured to the thermopile by a small black disc held in front of the bulb. The reading due to the direct radiation from the filament is the difference between these. Much of the indirect radiation comes from the reflected illumination provided by the bulb so the bulb should be on for both readings.

4. Measurements

Experiment 4.1 The total radiant energy from an incandescent lamp.

Set up the thermopile, without the spectrometer, to detect the radiation from the tungsten filament lamp at a distance of about 5 cm. Measure the distance from the filament to the thermopile and make an estimate of the area of the filament as seen from the thermopile (see Fig. 2).

Using the technique above, measure the total radiation from the lamp as a function of the voltage across the filament (say 0.5 V steps up to the maximum voltage of 7.29 V).

As the signal from the thermopile is collected by a voltmeter, you will need to convert voltage to power. If for example, you use a setting of $2.02 \text{ mW cm}^{-2} \text{ V}^{-1}$, each 1 Volt measured corresponds to 2.02 mW/cm^2 of radiant power per unit area.

To find the filament temperature, note the current and voltage readings from the lamp's power supply. Work out the resistance of the filament $R(T)$, then divide this by the resistance of the cold filament $R(300) = 0.286 \text{ ohms}$. Then using the calibration graph in Appendix 1, determine the filament temperature T . A more accurate value may be obtained using the values for resistivity given at <http://www.tungsten.com>

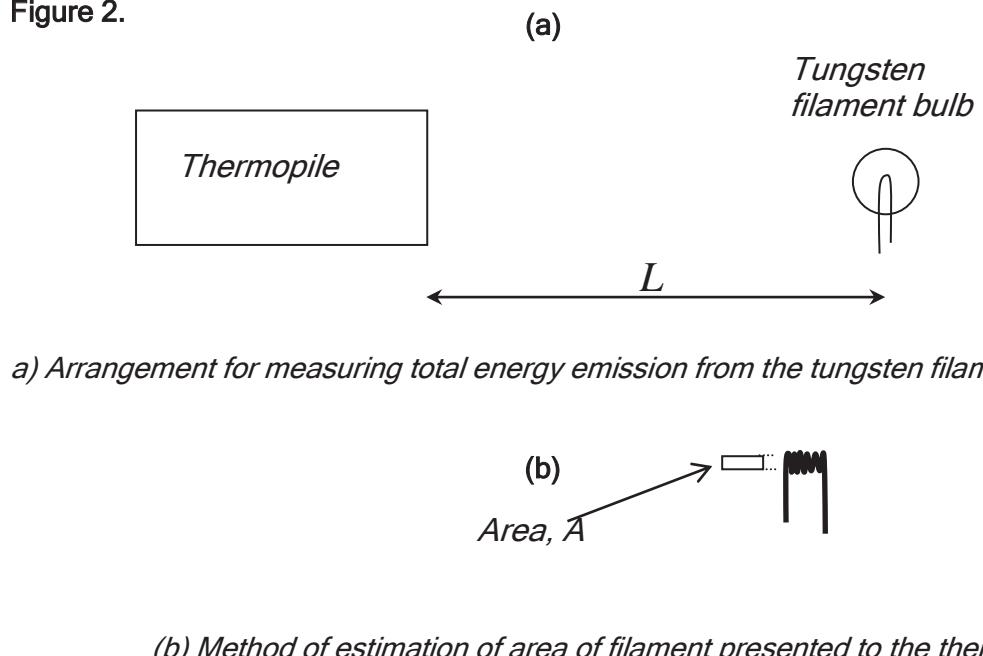
If the filament, with area A , behaves as a perfect black body then the power it radiates into solid angle is given by equation (7) with $\epsilon=1$. If the detector is at a distance L and reads power per unit area, its measurement would correspond to $\sigma AT^4/(2\pi L^2)$. Comparing this formula with your graph will give an estimate of the emissivity.

1. Plot the radiant power versus temperature on a log-log plot. This should confirm the power law relation between radiated power and blackbody temperature
2. Plot the radiant power versus the fourth power of the temperature, as for the Stefan-Boltzmann law (5).
3. Make a linear fit according to the Stefan-Boltzmann law and comment what value of slope you obtained.

→ Q: How this value compares to the actual Stefan's constant?

4. From the slope of your graph estimate the emissivity of the filament.

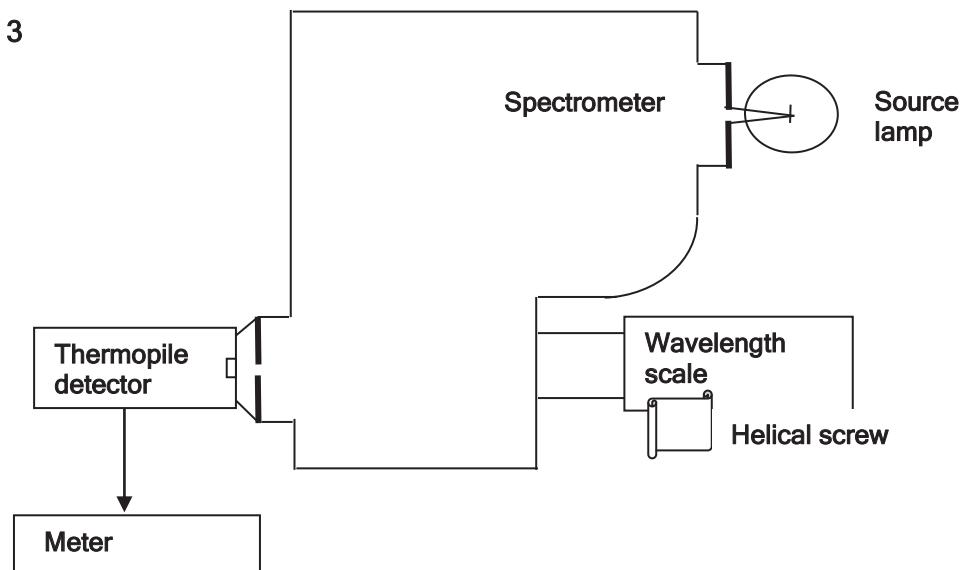
Note: Remember about estimating the errors of the voltage and current measurements

Figure 2.

Experiment 4.2 The spectral distribution of radiation from an incandescent lamp.

The experimental set-up is shown on figure 3.

1. First align the lamp so that the filament is centred on the input slit of the spectrometer. To do this, both input and exit slits should be about 1 mm wide and the power supply to the lamp should be set at maximum. Rotate the helical screw on the spectrometer until you see visible light emerging from the exit slit (e.g. a setting of about 0.6 microns).

Figure 3

Arrangement of lamp, spectrometer and thermopile for measurement of spectral distribution

2. Adjust the position of the lamp to give maximum light output from the spectrometer. Now place the thermopile to receive the radiation from the exit slit and rotate the helical screw to a setting near 1.3 microns (infrared) and adjust the position of the thermopile to give maximum reading.

Note that both slits on the spectrometer have shutters, so set the lever "up" if you want to close them. Make sure that when you read the thermopile signal, you also read the "background" signal by closing one of these shutters. Once the thermopile is aligned, you are ready to take measurements.

3. Select a certain filament temperature by setting the voltage on the lamp power supply; note the current and voltage readings.

There is considerable back-lash on the helical screw that selects the wavelength on the spectrometer. It is designed to be wound clock-wise, i.e. when you are selecting different wavelengths you should always drive from short to long wavelengths.

4. Start a scan near 0.6 microns then measure the thermopile readings for 0.1 micron steps up to 3.5 microns.
5. Repeat the scans for two more values of the filament temperature.

The data should now be corrected for the variation of the dispersive power of the prism with wavelength. This procedure is necessary as the refractive index of crystalline quartz does not vary linearly with wavelength, so the size of the wavelength interval $\delta\lambda$ passing through the slit changes as the wavelength varies. To correct for this effect, divide your thermopile intensity by the values of $d\lambda/dn$ for crystalline quartz given in Table 1.

6. Plot the corrected data against wavelength for the three filament temperatures. Note the values of λ_{max} and use Wien's law to estimate the temperatures.

→ Q: How do these estimated temperatures compare with the temperatures derived from the resistance?

→ Q: Include in your graph the plot of the theoretical black body spectra.

5. References and background material

The theory of the spectral distribution of electromagnetic radiation from a cavity was covered during "Waves, Light and Quanta" lecture course. You will also find it in chapter "Continuous spectra" of "University Physics" (semester 2) and in Wolfson "Essential University Physics", chapter "Blackbody radiation".

Appendix

$\lambda(\mu\text{m})$	0.6	0.7	0.8	0.9	1.0	1.1	1.2	1.3	1.4	1.5
$d\lambda/dn$	0.581	0.853	1.131	1.378	1.570	1.697	1.764	1.782	1.765	1.725

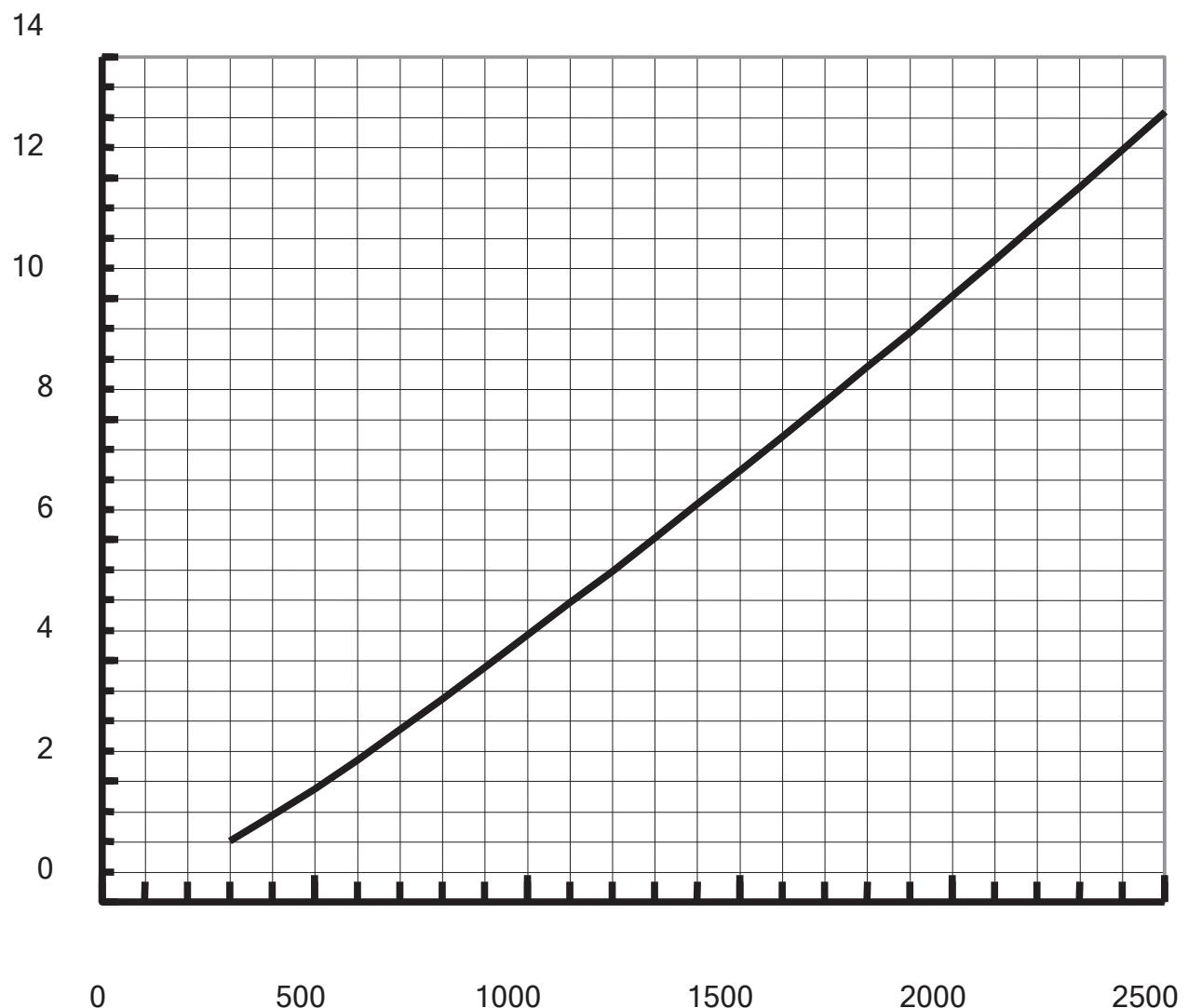
$\lambda(\mu\text{m})$	1.6	1.7	1.8	1.9	2.0	2.1	2.2	2.3	2.4	2.5
$d\lambda/dn$	1.670	1.607	1.541	1.474	1.408	1.343	1.281	1.222	1.166	1.113

$\lambda(\mu\text{m})$	2.6	2.7	2.8	2.9	3.0	3.1	3.2	3.3	3.4	3.5
$d\lambda/dn$	1.063	1.005	0.970	0.927	0.886	0.848	0.811	0.777	0.744	0.712

Table 1: Variation with wavelength of inverse dispersive power $d\lambda/dn$ for crystalline

Resistivity of Tungsten

R_T/R_{300}



Measurement of the Speed of Electromagnetic Waves in Air and in a Dielectric

Safety

There are the following safety issues for this experiment:

- 1) **The risk is moderate.** Risk of temporary damage to vision. The experiment uses a laser with visible (red) beam of power ~ 1 milliwatt. Do not look directly into the laser beam or into reflected or scattered beams. Take precautions to prevent exposure of other people to the beams.

Measurement of the Speed of Electromagnetic Waves in Air and in a Dielectric

Aims and Objectives

This experiment has two parts; both are to be completed in one practical session. The parts may be done in any order.

In Part 1 the speed of light is measured in air using an updated form of Fizeau's method.

In Part 2 the speed of radio-frequency waves is measured in a dielectric coaxial cable, as used in standard test equipment connections. In this case you are encouraged to use your initiative and skill to make the most accurate possible measurement.

Part 1: Speed of Light in Air

Safety issues

A helium-neon laser is part of the apparatus for this experiment. Its beam power, about 1 milliwatt, is high enough to cause serious discomfort if not actual damage if it enters your eye directly. Do not look directly in to the beam.

Assignments

Rather little actual laboratory work is required in this experiment. You are expected to make this up by carrying out a number of assignments set at various points in the text which follows. Your mark will be based partly on these assignments.

1. Introduction

The experiment uses a modern version of Fizeau's "toothed wheel" method (1849) for measuring the velocity of light. This same idea was used by Anderson (1941) and by Bergstrand (1951). The basic principle is that a modulation of intensity is imposed on a light beam and the speed of the crests and troughs of the modulation, which travel at the group velocity of the light, is measured. Fizeau chopped the light beam into pulses at about 10kHz with a rotating toothed wheel, whereas Anderson and Bergstrand used Kerr cell modulators at about 20 MHz to give a sinusoidal modulation. The increase of frequency brought a corresponding increase of accuracy. In our case we shall take advantage of the fact that the output of an ordinary helium-neon (HeNe) laser

automatically has a modulation at several hundred MHz. This means that with quite simple apparatus our accuracy should be about 1-2%. You will separately measure the frequency of the modulation, $\Delta\nu$, and its wavelength, λ_b . The speed of light is then:

$$\Delta\nu \times \lambda_b = c.$$

Today the speed of light is defined to be precisely:

$$c = 299792458 \text{ ms}^{-1},$$

with **no** uncertainty, so that we define the metre in terms of c and the caesium atomic clock frequency. The reason for this is that it has become easier and more accurate to measure the frequency of a signal rather than the wavelength. The implication is that we need no longer maintain a distance standard.

2. Theory

The HeNe laser you are given operates on two different standing waves, or *longitudinal modes* simultaneously. The q th longitudinal mode is an optical standing wave of wavelength λ_q that fits a large integer number q of half-wavelengths into the length of the laser cavity l , so that

$$l = q \frac{\lambda_q}{2}. \quad (1)$$

The frequency of the q th mode is given by

$$\nu_q = \frac{c}{\lambda_q} = q \frac{c}{2l}. \quad (2)$$

thus a laser cavity of length l defines a comb of possible frequencies for laser action, spaced at regular intervals of:

$$\Delta\nu = \frac{c}{2nl}. \quad (3)$$

Suppose that in the HeNe laser the gain covers just enough frequency range for two adjacent longitudinal modes, frequencies ν_1 and $\nu_2 = \nu_1 + \Delta\nu$, to oscillate (lase) simultaneously. The electric field of the light at a distance z from the laser can be represented as the superposition of terms representing the two laser modes (we are assuming that the air has $n=1$):

$$E = E_1 \cos(k_1 z - 2\pi\nu_1 t) + E_2 \cos(k_2 z - 2\pi\nu_2 t + \phi_2), \quad (4)$$

where $k_1 = 2\pi/\lambda_1$ and $k_2 = 2\pi/\lambda_2$ are their wavenumbers. The intensity measured at some fixed position $z = z_0$ will be proportional to:

$$\begin{aligned} |E(z_0, t)|^2 &= E_1^2 \cos^2(k_1 z_0 - 2\pi\nu_1 t) + E_2^2 \cos^2(k_2 z_0 - 2\pi\nu_2 t - \phi_2) \\ &+ E_1 E_2 \cos([k_1 + k_2]z_0 - 2\pi[\nu_1 + \nu_2]t - \phi_2) + E_1 E_2 \cos([k_1 - k_2]z_0 - 2\pi[\nu_1 - \nu_2]t + \phi_2) \end{aligned} \quad (5)$$

The first three terms oscillate at frequencies of $2\nu_1$, $2\nu_2$ and $(\nu_1 + \nu_2)$ respectively and are far too rapid to be picked up using any detector such as a photodiode. Only their averages will be seen, i.e. $1/2(E_1^2 + E_2^2)$. However if a sufficiently fast detector is used the last term may be observed, giving rise to a "beat" signal at the difference frequency $\Delta\nu = \nu_1 - \nu_2$ with amplitude $E_1 E_2$. The total signal seen by a fast detector such as a photodiode will therefore be proportional to:

$$I_1 + I_2 + \sqrt{I_1 I_2} \cos(\Delta k z_0 - 2\pi\Delta\nu t + \phi_2). \quad (6)$$

The output current of a photodiode placed at z_0 will have the form:

$$i(t) = \alpha(I_1 + I_2 + \sqrt{I_1 I_2} \cos(\Delta k z_0 - 2\pi\Delta\nu t + \phi_2)) \quad (7)$$

where α is the response of the diode in mA/mW and I_1 and I_2 are the intensities of the two modes. $\Delta k = k_1 - k_2 = 2\pi/2l$ is the wavenumber difference between the two longitudinal modes of the laser, and defines the wavelength of the amplitude modulation $\lambda_b = 2l$ corresponding to frequency $\Delta\nu$.

Thus by measuring the frequency of the current variation in time we can obtain $\Delta\nu$ directly. By combining this with the length of the laser we obtain a value for c . The problem with this way of estimating λ_b is that it requires an accurate value for l which is not easy to obtain.

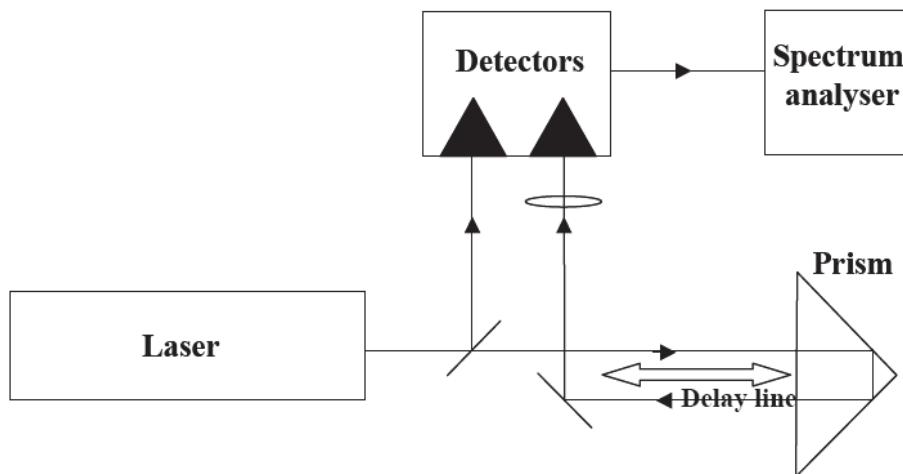


Figure 1. Experimental arrangement for measuring the speed of light.

A more sophisticated approach to determining λ_b uses two fast photodetectors and a delay line as shown in Fig. 1. The transit time of the signal between the two detectors changes the phase of the current seen by the second detector with respect to the phase of the first detector. If the phase change is π then the sum of the two currents oscillating at the beat frequency will be a minimum and can be made equal to zero by adjusting the currents i_1 and i_2 to be equal. To see this mathematically write the currents from the first and second detectors, positioned at z_1 and z_2 respectively, as:

$$i_1(t) = a_1 + b_1 \cos(\Delta k z_1 - 2\pi\Delta\nu t + \phi_1) \quad (8)$$

$$i_2(t) = a_2 + b_2 \cos(\Delta k z_2 - 2\pi\Delta\nu t + \phi_2) \quad (9)$$

where $\Delta k z_2 = \Delta k z_1 + \delta$, and δ is the phase change of the beat due to the path length L between the two detectors, given by:

$$\delta = \frac{2\pi}{\lambda_b} L \quad (10)$$

Add the two currents in (4) to obtain the total current:

$$i = i_1 + i_2 = a_1 + a_2 + 2b \cos(\Delta k(z_1 + z_2)/2 - 2\pi\Delta\nu t + \phi_2) \cos(\delta/2). \quad (11)$$

3. Prelims questions

(write full answers in your lab book before the start of the prelim marking session)

1. A. List the aims of this experiment.
B. In addition to those mentioned in Section 1.0, there are many methods which have been used to measure the speed of light. List the various techniques, *briefly* summarise their principles and indicate the precision achieved by each. A good source for this is Jenkins and White, Fundamentals of Optics, Chapter 19.
2. Make a rough estimate of $\Delta\nu$ for a HeNe laser that is about 20cm long assuming that the speed of light is about $3 \times 10^8 \text{ ms}^{-1}$ and that $n \approx 1$ for the gas in the tube. Find the value of the beat wavelength λ_b that corresponds to this beat frequency.
3. Fill in the steps between Eqs. (8) and (11) Hint: look at your 1st year notes on beat frequencies to find trigonometric identity that you need.
4. In experiment 4.2 you will be moving the prism to and fro along the delay line, changing the value of δ . Sketch a graph showing how the **amplitude of the modulation** in the total current given by Eq. (11) varies with δ for values of δ between 0 and 2π .
5. Aligning delay lines is difficult. Unless the input beam is exactly parallel to the direction of travel of the delay line, and the reflected beam is

exactly antiparallel to the input beam, the corresponding laser spot will move off the detector when the delay is changed. Explain how using a prism, as shown in Fig. 1, rather than mirrors, takes care of one of these problems.

6. By how much does L increase when the prism is moved a distance d to the right?

4. Measurements

Experiment 4.1

The beat frequency is measured by illuminating one of the detectors and using an RF (radio frequency) spectrum analyser to measure the frequency spectrum of the photocurrent.

The spectrum analyser may detect frequencies not associated with the laser. The most likely source of these is TV channels picked up by the photodiode acting as an antenna. You must be sure that the output you choose is in fact due to the laser modulation frequency.

Use the beat frequency $\Delta\nu$, and the approximate length of the laser to estimate c. Comment on your result.

Experiment 4.2

Use the experimental arrangement shown in figure 1 but now with both detectors illuminated, one with the direct input, the second with the delayed light from the delay line. If the prism is translated along the delay line at least two minima should be obtained, providing that the detectors are properly balanced. Measure the separation between minima and hence obtain a figure for the speed of light.

- ➔ Q: The arrangement used in this experiment is actually related to a Michelson interferometer: explain.
- ➔ Q: Discuss advantages and disadvantages of this technique compared to an optical interferometer.
- ➔ Q: How do you think the experiment might be improved?
- ➔ Q: Explain how signal to noise considerations limit the accuracy of the technique.

Part 2: Speed of em waves in a dielectric

Safety issues

There are no special safety issues.

1. Objectives

Your objective is to make the most accurate measurement you can of the speed of electromagnetic waves of frequency of order 100MHz in a coil of coaxial cable of known length. The basic method is to use an oscilloscope to measure the phase difference between waves launched into and transmitted through a coil of cable of known length. It is possible to do this by direct observations of the waveforms displayed separately on the two channels of the oscilloscope, but the same equipment can be reconfigured as a form of interferometer which greatly improves the accuracy.

The apparatus is illustrated in figure 2 it consists of a variable frequency RF signal generator, a frequency meter, a twin channel oscilloscope and a coil of coaxial cable. Note that the channels of the oscilloscope may be displayed as two separate traces or added or subtracted and displayed as one trace. The signal generator drives both channel 1 of the oscilloscope and one end of the cable, the other end of the cable is connected to channel 2 with a 50 ohm terminating load (using a BNC 'T' adaptor).

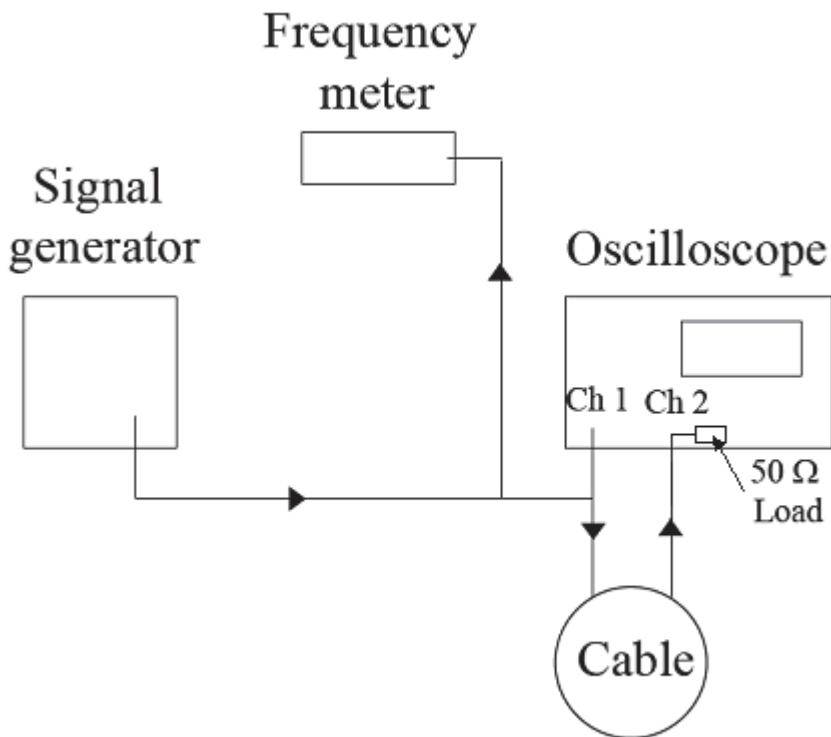


Figure 2. Experimental arrangement for measuring the speed of radiofrequency waves in a dielectric-filled coaxial cable.

Semiconductor *p-n* Junction

Safety

The **optical chopper** used in part 2 of used in the photoconductivity measurement has a fast rotating slotted disc that can cause injury if touched.

Make sure you know where the chopper blade is before turning the chopper on.
Keep your hands well away once it is running.

There is also a risk of damage to the chopper blade.

The lamp used in the photoconductivity measurement gest quite hot, mind your fingers.

The risk is low.

Semiconductor *p-n* Junction

Aims and objectives

This experiment introduces the semiconductor *p-n* junction, demonstrating its properties of electrical rectification and sensitivity to light. You will study two *p-n* junction photodiodes, one from each of the two major semiconductor families.

- Experiment 1: measure the current-voltage characteristic of each diode in the absence of light, and deduce values for the saturation current and ideality factor.
- Experiment 2: measure the response of each *p-n* junction to different incident wavelengths of light, and thereby deduce an estimate for the energy band-gap of the constituent semiconductors.
The detection scheme for this experiment uses a lock-in amplifier.

After completing this practical you should be able to explain in simple terms how a *p-n* junction works, and understand how to use a *p-n* junction photodiode.

1. Introduction: physics of semiconductors

Semiconductors gave us the breakthrough technology that brings cheap powerful electronic devices to the masses.

Computers are formed of switches, and, before the advent of semiconductor transistors in the late 1940s, switching could only be performed by large, slow, power-hungry vacuum tubes.

In that era a simple computer (far simpler than your calculator) took up a space the size of the teaching labs.

Semiconductor structures can now be made with dimensions of tens of nanometres: thus billions can be found in a current microprocessor chip, all powered from a single battery.

The semiconductor *p-n* junction is the fundamental current-rectifying, light-detecting and light-emitting structure used in electronics and optoelectronics.

A current rectifier is a circuit element that only allows current to flow through it in one direction, when the voltage, or ‘bias’ is applied in the forward direction. When the applied voltage is reverse-biased only a small leakage current flows.

A *p-n* junction is a diode: it does not obey Ohm’s law.

In Experiment 1 you will measure the current-voltage characteristic of your diodes and observe this non-Ohmic behaviour.

The current-voltage characteristic of a semiconductor diode changes when light shines on the *p-n* junction. This is the mechanism by which a photodiode detects light.

You will study this phenomenon in Experiment 2. There follows a concise

introduction to the physics of semiconductors, defining some essential terms.

2. Introduction to the physics of semiconductors

2.1 Crystalline silicon

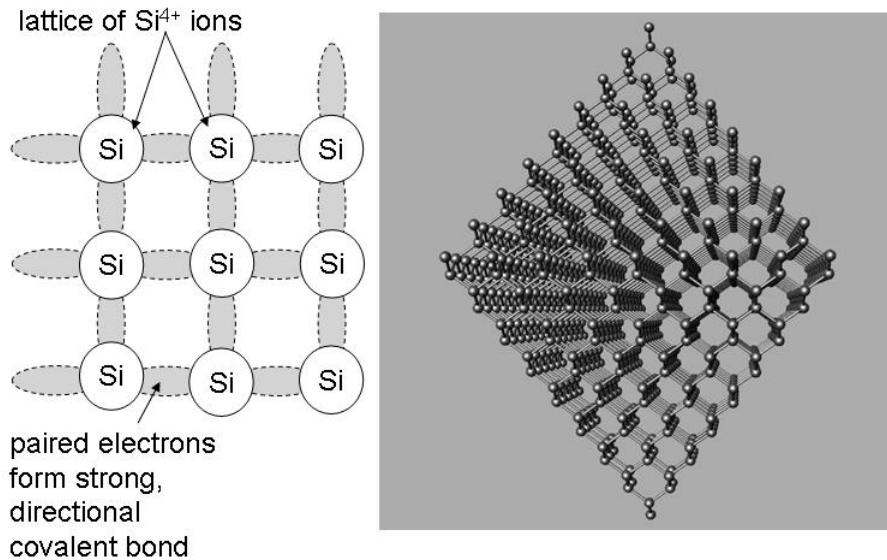


Figure 1: Schematic of Si crystal lattice in 2-D (left); 3-D model of Si lattice (right).

Carbon (C), silicon (Si) and germanium (Ge) occupy Group IV of the periodic table, with 4 valence electrons outside the spherical inner filled shells. These elements form hard crystalline solids with the atomic structure of diamond, in which each atom is linked to 4 nearest neighbours by covalent bonds. Each valence electron is not localised to a particular bond, but free to propagate through the network of bonds linking the entire crystal. Intuitively one would expect such a crystal to conduct electricity; but this is not so. A chemically pure, cold, dark, defect-free Si crystal is insulating, for a quantum-mechanical reason.

2.2 Band theory of solids

The Schrödinger wave function of a valence electron in a crystal of Si has the form of a travelling wave, characterised by wavevector k , and crystal momentum $\hbar k$. Electrons are fermions, with an intrinsic spin of $1/2$, so there are two distinct quantum states corresponding to each value of k ; one with spin up and one with spin down. The Pauli Exclusion Principle of quantum mechanics says that it is not possible for more than one fermion to occupy the same quantum state.

The valence electrons of the Si crystal are therefore distributed over states with a range of different k -values and different energies - they occupy an **energy band**.

Wave mechanics shows that a crystal containing N atoms has N possible values for k . Taking spin into account, there are $2N$ distinct electron quantum states in each energy band. In some crystals successive bands overlap in energy, but in semiconductor crystals they are separated by an energy gap. It is the energy gap, or **band gap**, that gives semiconductors their characteristic properties.

A crystal of Si with N atoms has $4N$ valence electrons. The lowest energy state of this crystal is achieved by filling up the single electron quantum states in order of increasing energy. In this ground state, two bands are completely filled. The highest filled band is called the **valence band**, and the lowest empty band is called the **conduction band**. Between the highest energy filled state in the valence band and the lowest empty state in the conduction band lies the **band gap**; a range of energy within which there are no allowed electron states in the semiconductor. The energy levels are shown schematically in Fig. 2. The band gap energy is the energy needed to pull an electron out of a covalent bond.

A filled band does not conduct electricity. Even if an electron in a filled band is acted on by an E-field, it cannot be accelerated into a state of higher momentum, because all such states are occupied, and thus blocked off by the Pauli exclusion principle. Every energy band contains pairs of states with equal and opposite crystal momentum; if all these states are occupied the net velocity of the electrons is zero and no current can flow.

On the other hand, if a few electrons are excited out of the valence band and into the conduction band, they become able to conduct electrical current because they are surrounded by large numbers of empty states into which they can be accelerated by an applied E-field. Charge carriers can be created by the action of either heat or light, supplying the energy needed to excite electrons across the band gap. The vacant states left behind in the valence band also conduct electricity; they behave like carriers with positive charge, and are called **holes**. Light can be absorbed by a semiconductor if it has a photon energy greater than the band gap; $\hbar\omega > E_G$. The absorption of light creates electrons and holes in equal numbers; these are electron-hole pairs. This is the phenomenon of photoconductivity; the control of electrical conductivity by light.

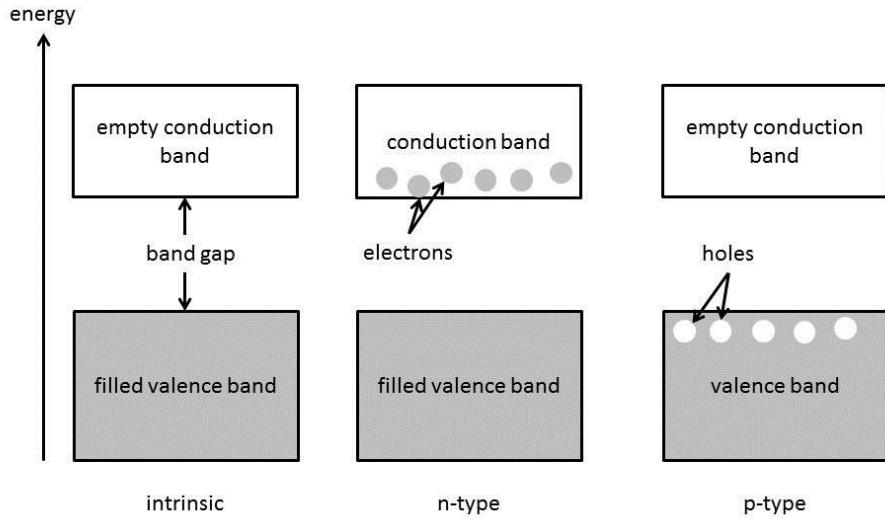


Figure 2: Energy bands in semiconductors.

Additional complication

Semiconductor materials divide into two families with respect to their optical properties; direct band gap and indirect band gap. In direct gap material an electron is readily excited from the top of the valence band to the bottom of the conduction band by light with a wavelength corresponding to the band gap energy. Conversely, if carriers at the band edges recombine, they are very likely to emit photons rather than lattice vibrations (heat). LEDs, or light-emitting diodes, are just forward-biased p-n junctions made from direct semiconductor.

A great tragedy for technology is that silicon, such a fantastic material for large-scale integration of devices in computer processor chips, has an indirect band gap; it can detect light, but it does not emit light efficiently. An indirect gap occurs when the electron states at the top of the valence band have a different momentum from the states at the bottom of the conduction band. Optical transitions at the band gap energy are then forbidden because they do not conserve momentum. LEDs and laser diodes are based on p-n junctions made from the compound semiconductor gallium arsenide, and its alloys, which have a direct band gap.

2.3 Donor and acceptor impurities

The electrical conductivity of a semiconductor increases strongly in response to tiny concentrations of impurities. Consider the effect of introducing a Group 5 atom such as arsenic (As) into a crystal of Si. As has 5 valence electrons; thus it can fit into the diamond lattice, contributing 4 valence electrons to make covalent bonds with its neighbours. The 5th electron has nowhere to go; it remains weakly bound in a large orbit around the As and easily moves into the conduction band. If a Si crystal is doped with As, it has a large excess of electrons over holes, and conducts electricity even in the absence of heat or light: the crystal is said to be **n-type**. In an n-type crystal electrons are the **majority carriers**; the holes which are present due to the effect of light or heat are the **minority carriers**.

If the impurity atoms come from Group 3, as does for example gallium (Ga), then

they fit into the lattice by taking an electron out of the valence band to complete their four covalent bonds. These are **acceptor impurities**, and they make the semiconductor **p-type**, with holes as majority carriers and electrons as minority carriers.

When a hole in the valence band interacts with an electron in the conduction band there is a finite probability that they will mutually annihilate, releasing energy E_G , corresponding to the band gap. This process normally leads either to the emission of a photon, or to the generation of lattice vibrations (heat).

2.4 The *p-n* junction

A *p-n* junction is formed in a piece of semiconductor simply by changing the type of impurity at some point from donor to acceptor so that one end is p-type and the other n-type. Fig. 3 shows schematically what such an abrupt change from p-type to n-type would look like. In practice, the free electrons and holes in close proximity around the junction quickly annihilate, leaving a narrow region with no free carriers called the **depletion layer**, shown in Fig. 3. The annihilation of carriers around the junction breaks the overall charge neutrality of each side of the crystal, leaving uncompensated negatively-charged acceptor ions on the p-side, and positively-charged donor ions on the n-side. Within the insulating depletion region there is a built-in E-field, caused by the difference in potential between the two sides. Outside the depletion layer free carriers screen any E-field to zero.

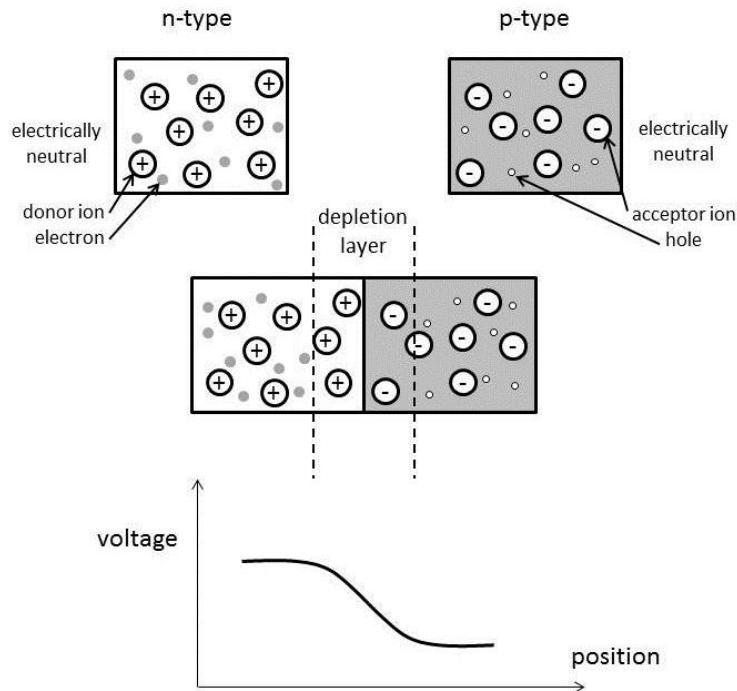


Figure 3: *Structure of a p-n junction.*

The built-in field forms a potential barrier that keeps carriers out of the depletion layer. Electron-hole pairs that are created by heat inside the depletion layer are

pulled apart by the E-field, so that thermally generated holes flow to the p-side, and electrons to the n-side. In equilibrium, with zero voltage, or ‘bias’, applied to the *p-n* junction, no net current flows: the thermal current is balanced by an equal and opposite current due to the annihilation of carriers that still occasionally penetrate the depletion layer.

Consider what happens if we apply an external dc voltage to the material with the positive terminal on the p-type region and the negative terminal on the n-type region. This is called a **forward bias** because it pushes the charge carriers forwards in the direction of the junction. It effectively reduces the potential barrier for transport across the depletion region by the magnitude of the external potential. Once the barrier is low enough, the free electrons and holes continually annihilate at the junction, releasing energy and making way for new holes and electrons to be pushed into their places. Thus, a current can be made to flow quite easily, restricted mainly by the resistance of the semiconducting material. The energy released, E_G , per electron-hole annihilation, may appear as heat, or as photons (light) of energy equal to the band gap.

If the battery is connected the other way, negative to p-type and positive to n-type, the electrons and holes are dragged back from the *p-n* junction, increasing the width of the depletion layer. This is called **reverse bias**. Clearly in this direction it will be much harder to make current flow through the semiconductor, because the current is limited by the rate at which electron-hole pairs are generated in the depletion layer, and this requires energy E_G per electron-hole pair. Any process which can supply this energy will cause a current to flow, for example heating, or the absorption of photons. Since we cannot work at $T = 0$ K, there will always be some thermal excitation and associated finite reverse bias current in any *p-n* junction. Increasing the band gap energy, E_G , reduces this so-called **leakage current**.

To summarise, in forward bias the *p-n* junction readily conducts electricity and can emit photons if the right semiconductor is used, and in reverse bias it will not conduct unless energy is supplied to generate electron-hole pairs. It can be a light emitter, detector and rectifier all in one.

3. Prelims questions

(*write full answers in your lab book before the start of the prelim marking session*)

1. List the aims of this experiment.
2. Explain whether or not a crystalline solid with a half-filled energy band will conduct electricity.
3. We know from the photoelectric effect that the energy of an electromagnetic wave is quantised, and that an optical transition normally involves the absorption of only one quantum, or photon, unless the light is very intense. What condition must the wavelength of light satisfy to generate electron-hole pairs in a) Silicon and b) GaAs? To what regions of EM spectrum of these

wavelengths correspond?

4. What is the Boltzmann distribution? How does the temperature affect the size of the leakage current in a semiconductor *p-n* junction?

4. Measurement of current-voltage characteristics

You are provided with the following apparatus:

- Si photodiode and GaAsP photodiode,
- Function generator,
- Variable amplifier, Differential probe,
- Digital Tektronix oscilloscope,
- USB memory stick.

Use the circuit shown in Fig. 4 to display the current versus voltage characteristic of each diode on the digital oscilloscope. The X-displacement is the voltage applied to the diode and the Y-displacement is proportional to the current flowing. Notice that you can display the input signals either as voltage versus time (Y-t mode; 2 traces), or as Channel 2 versus Channel 1 (X-Y mode). The X-Y mode shows you the I-V characteristic directly. In X-t mode you can see how many periods of the oscillator are included in your record, and check that the offsets are adjusted so that the zero volt position is centred on the display.

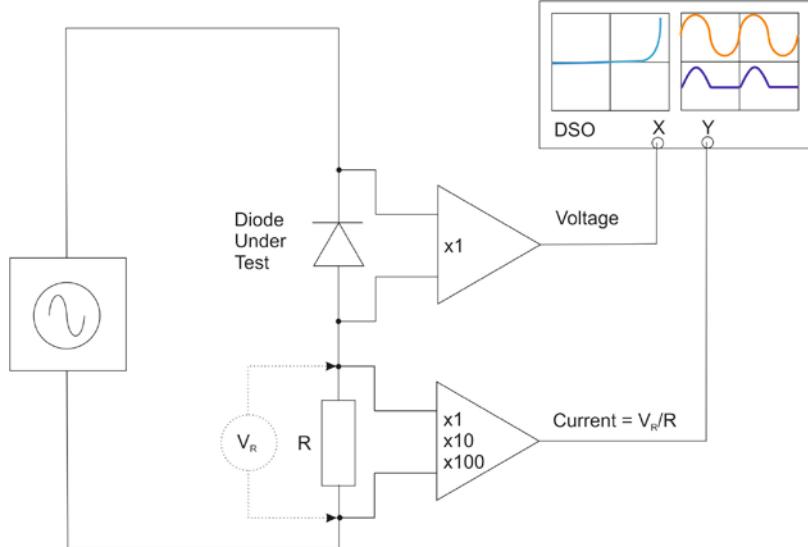


Figure 4: Circuit for measuring the I-V characteristic of a diode.

Sketch the form of the measured I-V characteristic in your notebook, indicating which is the forward and which the reverse bias direction. Record the values of I and V at significant points on the characteristic, as read off the oscilloscope screen. Remember that your current reading is actually the voltage generated by the current across a $10^4\Omega$ resistor. Note the effect produced on the I-V characteristic when light illuminates the active area of the photodiode. Compare and contrast the

characteristics measured for the two different diodes.

Now make a digital record of the dark I-V characteristic for each diode. When you are satisfied with the settings of the oscilloscope, insert the memory stick provided into the USB port on the front of the oscilloscope, put the 'scope into Y-t mode, and press save/recall. After a short delay, the instrument will create a new folder on the USB stick containing 2 data files, one for each channel.

The **Shockley diode equation** expresses a theoretical relationship between I and V for a p-n junction diode:

$$I = I_s \left[\exp\left(\frac{eV}{\eta kT}\right) - 1 \right],$$

where I_s and η are constants characteristic of the diode: I_s is the **reverse bias saturation current** that flows when V is large and negative (reverse bias): η is a parameter called the **ideality factor** ($\eta=1$ for perfect diodes).

Transfer the USB stick to a laboratory PC. The oscilloscope data files will open automatically in Excel. Columns 1 & 2 list instrument settings, column 4 has time-series data that you are not interested in (same for the channel 1 & channel 2 files), and column 5 contains your data. Open Origin from the icon on the desktop, and paste your data for V and I into columns A and B. Under the Analysis menu you will find Non-linear Curve Fit. From the menu of fitting functions select

$$y = y_0 + ae^{bx}.$$

- ➔ Q: Deduce values of I_s and η for each diode.
- ➔ Q: Can you improve the results using a different fitting function?

5. Photoconduction spectrum measurement

The aim of this experiment is to investigate the size of the photocurrent generated in a p-n junction diode as a function of the wavelength of the incident light.

You are provided with the following apparatus:

- Tungsten filament lamp and current supply,
- Grating Monochromator,
- Optical chopper and controller,
- Transimpedance Amplifier,
- Digital Oscilloscope,
- Lock-in Amplifier,
- Digital Multimeter.

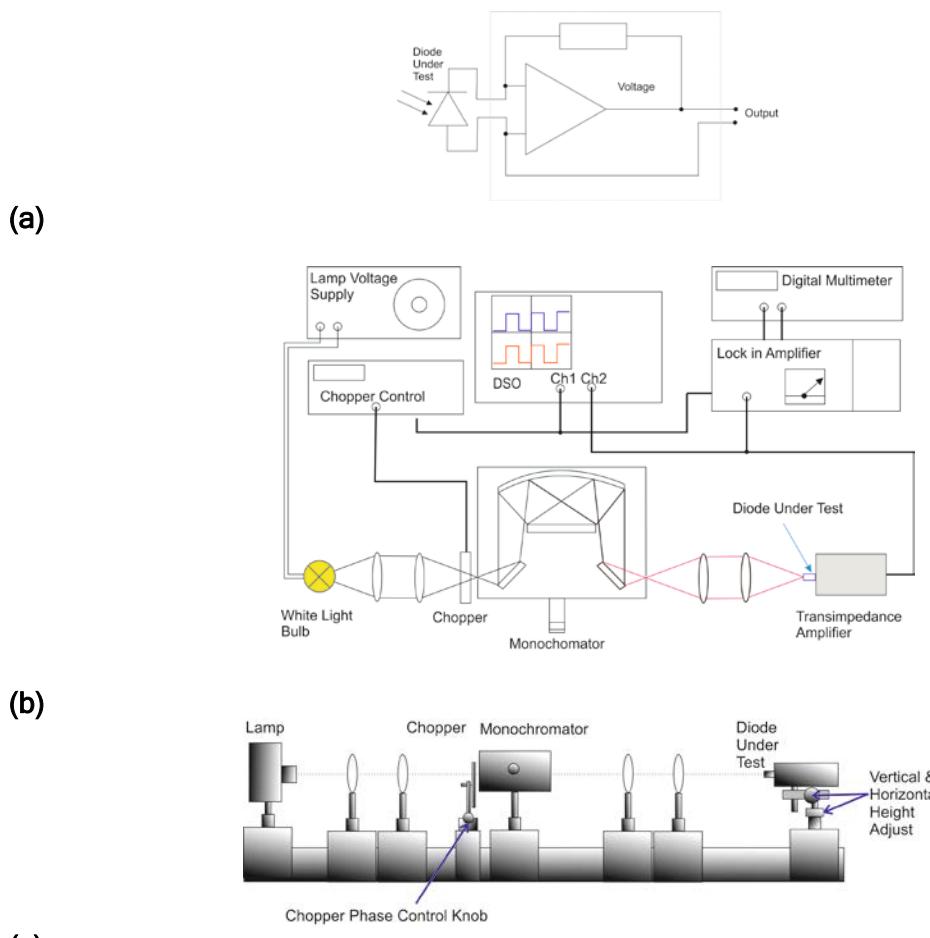


Figure 5:

- (a) Transimpedance amplifier for converting photocurrent to voltage while keeping the terminals of the diode at equal potential.
- (b) Experimental arrangement for measuring photoconduction spectrum of p-n junction.
- (c) Location of Chopper Phase control knob & horizontal and vertical adjust controls

To detect the photo-current from the diode, we use an op-amp circuit contained in a small aluminium box. (see Fig. 5a)

The pn-junction (diode) attaches directly onto the aluminium box via a BNC fitting. The op-amp is arranged in a ‘transimpedance’ mode which presents zero resistance to the *p-n*-junction and so draws a current from it without creating a potential difference.

The output of the op-amp is a voltage proportional to the current flowing at the input.

The gain thus has units of ohms (ie impedance), giving the name *transimpedance amplifier*.

The apparatus is used as shown in Fig. 5b). Illuminate the sensitive area of the *p-n* junction diode with monochromatic light of variable wavelength produced by a halogen lamp and a diffraction grating monochromator. The light is modulated (switched on and off) at an audio frequency by an optical chopper. The signal from the transimpedance amplifier is detected by a lock-in detector and indicated by a meter. The lock-in has two inputs: ‘signal’ and ‘reference’. The signal comes from the *p-n*-junction via the transimpedance amplifier and the reference is a square wave at the same frequency and phase as the chopper. There is an oscilloscope to monitor the waveforms.

Set the chopping frequency to a few hundred Hertz and display the reference waveform on the oscilloscope. Switch on the lamp and observe the light output from the monochromator.

Change reading of the micrometer on the monochromator and observe the change of colour of the output light. Do not make the lamp too bright and overload the LIA.

The wavelength of the light transmitted by the monochromator is given by the formula:

$$\lambda \text{ [nm]} = 100 \times m \text{ [mm]},$$

where *m* is the micrometer reading in mm. (i.e. $0.5\text{mm} \equiv 500\text{nm}$)

The photon energy of light of wavelength λ is given by

$$E = \frac{hc}{e\lambda} \text{ [eV].}$$

Turn off the chopper. Adjust the first two lenses and the monochromator so that the image of the bulb filament is focused on the entry slit of the monochromator.

Set the monochromator to red light (0.65mm) and by use a piece of white card trace the light output from the monochromator. Adjust the position of the last two lenses and the amplifier so that the light focuses on the surface of the diode.

For fine adjustments, the amplifier if mounted on a horizontal and vertical translation stage. Turn on the chopper.

With the amplifier switched on observe the output on the second channel of the

oscilloscope. Both the chopper reference and output signal should be a clean square wave. The room lights may cause a ripple on the signal which may be eliminated by shielding or dimming the room lights.

The lock in Amplifier should eliminate the effect of any slight changes in the room lighting.

Alter the relative phase of the two waveforms by translating the chopper blade across the optical beam by means of the screw adjustment on the chopper mount and set them to be in phase with one another ($\phi=0$).

Record the output of the lock-in detector manually as the wavelength of the incident light is varied.

For each of the two p-n-junctions (diodes), plot a graph of output vs photon energy as you take the readings. Take sufficient points where the signal is changing rapidly to reveal the details of the change - but do not waste effort recording large numbers of points where the variation is slow.

Try not overload the lock-In-Amplifier or signal clipping will occur and you will lose the peak.

Use your data to estimate a value for the band gap in each of the diodes that you have studied, and measure the width in energy of the band edge region.

You will need to choose your own criteria: within reason it does not matter what these criteria are (there is no right or wrong answer here), but use common sense, and note down your method.

This will also enable you to quantify the uncertainty in your measurements.

Compare the band gap you have determined for Si with the official value at 300K.

Now change to the other diode and use the same method to determine a value for the band gap of GaAs/P. You should find that the band gap energy of GaAs/P is considerably greater than that of Si, and that the width of the band edge measured along the energy axis is far greater in Si.

Fig. 6 shows a plot of the band gap of GaAs/P alloys as a function of composition. Use it to estimate a value for the P concentration of the alloy used in this diode.

Physical Constants.

Planck's constant, h:	6.6×10^{-34}	Js
Electron charge, e:	1.6×10^{-19}	C
Velocity of light, c:	3.0×10^8	m/s
Boltzmann's constant, k:	1.4×10^{-23}	J/K

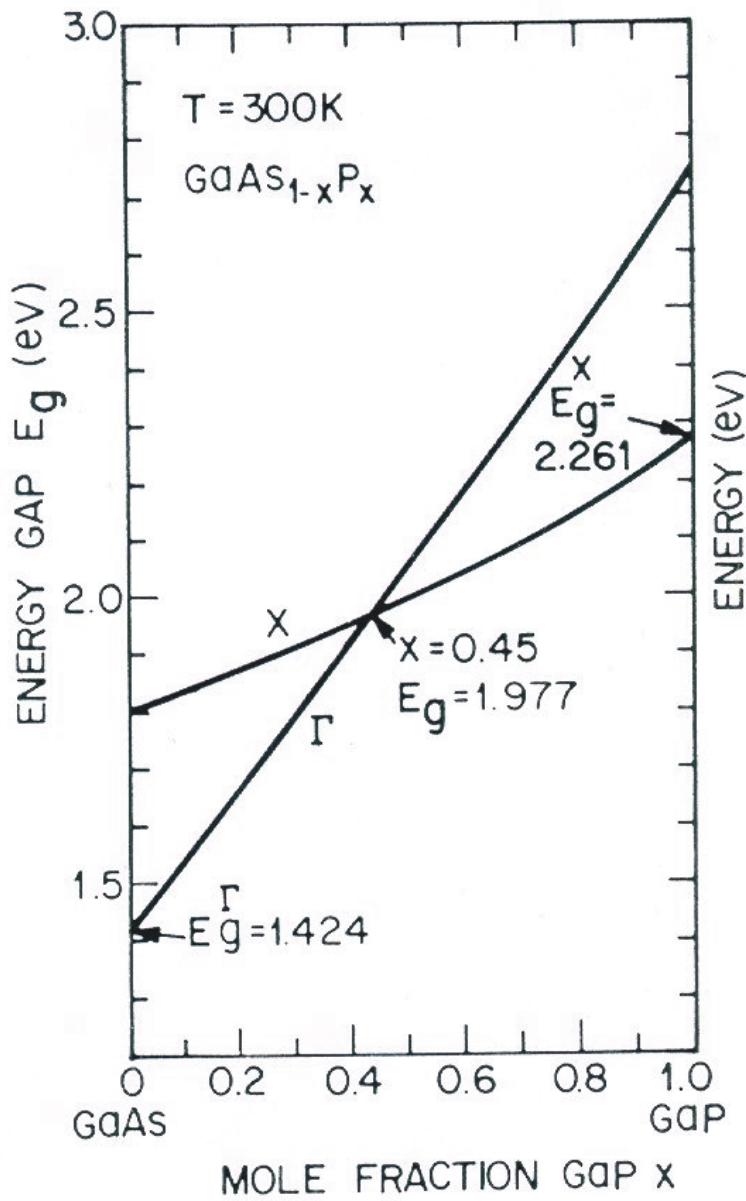


Figure 6: Separation of conduction and valence bands in GaAs/GaP alloys for two extreme values of electron wavevector ('X-point' and 'Gamma-point'), as a function of concentration of P. The band gap at a given concentration is represented by the lower curve.

- ➔ Q: Discuss the ideal requirements for a circuit diode. For example, should it show a response to heat or light?
- ➔ Q: How should a *p-n* junction be used as a linear detector of light? For instance, should it be connected to a voltmeter or an ammeter?
- ➔ Q: How can a *p-n* junction be used as a device to convert the Sun's energy to electricity (ie as a Solar cell)? Can we simply allow the Sun's rays to heat the *p-n* junction?