KUWAIT UNIVERSITY **PHYSICS DEPARTMENT**

MODERN PHYSICS LAB MANUAL

Course ID: Physics 0430306

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INTRODUCTION:

This manual contains the description of 8 experiments in follow up of the modern physics course. The student must read the manual and understand the physics behind each experiment prior to attending the laboratory hours. At the beginning, the physics of the experiment and required tasks will be explained, then under supervision of faculty members, the experiment can be done by the student. The measurements must be recorded and based on the founded results a scientific report must be written and delivered. All reports, graphics and calculations must be generated by using a PC with standard layout (as an international scientific journal) and no handwriting may be used. The report must cover the theoretical part about the general introduction (history of the subject) plus the main physical laws and equations related to the experiment. Then, the experimental procedures must be given about the tools which are used and how the experiment is applied. Finally, all results of the measurement (observations) must be delivered by using a table. The required parameter(s) can be calculated by using physical equations together with founded experimental data. The final conclusions with its error percentage must be expressed numerically and as a graphic when required. At the end of each experiment manual, some questions are available which must be answered as clearly and complete as possible. The final grading of this course is based on practical performance of the student during the laboratory hours, the lab reports, and the final exam.

Instructor:

- ……………………….

TA's:

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CONTENT:

DETERMINATION OF SPEED OF LIGHT

Introduction

The velocity of light in free space is one of the most important and intriguing constants of nature. According to the special theory of relativity, **Einstein** proposed that speed of light **c** is the upper limit at which conventional matter or energy (any signal carrying information) can travel through space. Historically different scientists, like **Galileo, Olaf Romer, Fizeau, Foucault** etc. tried to measure the speed of light with different techniques. The best of these measurements gave a velocity of 2.99774x 10^8m/sec. This may be compared to the presently accepted value of 2.99792458x 10^8m/s. All forms of electromagnetic radiation, including visible light, travel at the speed of light. For many practical purposes, light and other electromagnetic waves will appear to propagate instantaneously, but for long distances and very sensitive measurements, their finite speed has noticeable effects. Starlight viewed on Earth left the stars many years ago, allowing humans to study the history of the universe by viewing distant objects. When communicating with distant space probes, it can take minutes to hours for signals to travel from Earth to the spacecraft and vice versa. In computing, the speed of light fixes the ultimate minimum communication delay between computers, to computer memory, and within a CPU. The speed of light can be used in time of flight measurements to measure large distances to extremely high precision. The speed at which light propagates through transparent materials, such as glass or air, is less than **c**; similarly, the speed of electromagnetic waves in wire cables is slower than c. **The ratio between speed of light in vacuum c and the speed v at which light travels in a material is called the refractive index n of the material:**

$$v = \frac{c}{n} \qquad (m/s) \tag{1}$$

For example, for visible light, the refractive index of glass is typically around 1.5, meaning that light in glass travels at $v = \frac{c}{1.5} = 124000\ m/s$.

Description of Experiment

The Speed of light unit (SLU) is used to measure the speed of light in a polymer optical fiber. The light whose speed is to be determined is produced by a light emitting diode fitted inside SLU. The light from the diode is guided to the SLU through optical fiber. SLU converts the light signal into electrical signals, which are fed to the oscilloscope to measure the time taken by the light through optical fiber. The speed of light is calculated from this data.

Theory

If in an optical fiber with length $d = 20\ m$ the time which light needs to travel through the fiber is T_2 and delay time in SLU (which is measured with optical fiber with length of $d = 15\ cm$) is T_1 , the speed of light through the fiber can be calculated by:

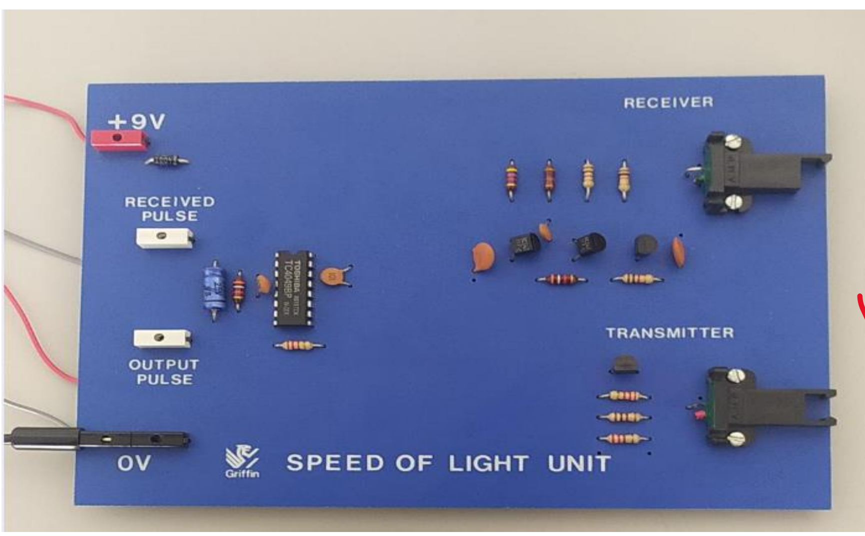
$$v = \frac{d}{T_2 - T_1} \qquad (m/s) \tag{2}$$

The optical fiber used here has a refractive index of $n = 1.6$. We can use equations 1 and 2 and measure experimentally the times $T_1\ and\ T_2$ to calculate the speed of light as follow:

$$v = \frac{c}{n} = \frac{d}{T_2 - T_1} \rightarrow c = \frac{n \times d}{T_2 - T_1} \qquad (m/s) \tag{3}$$

Apparatus

1. Speed of light unit with the following accessories.
2. 15 cm and 20m optical fibers terminated with ‘sweet spot’ connectors.
3. Double-beam CRO with a time-base capability of 0.1 us per division.
4. battery pack (9 volt) or smoothed power supply.



connect

optical fiber

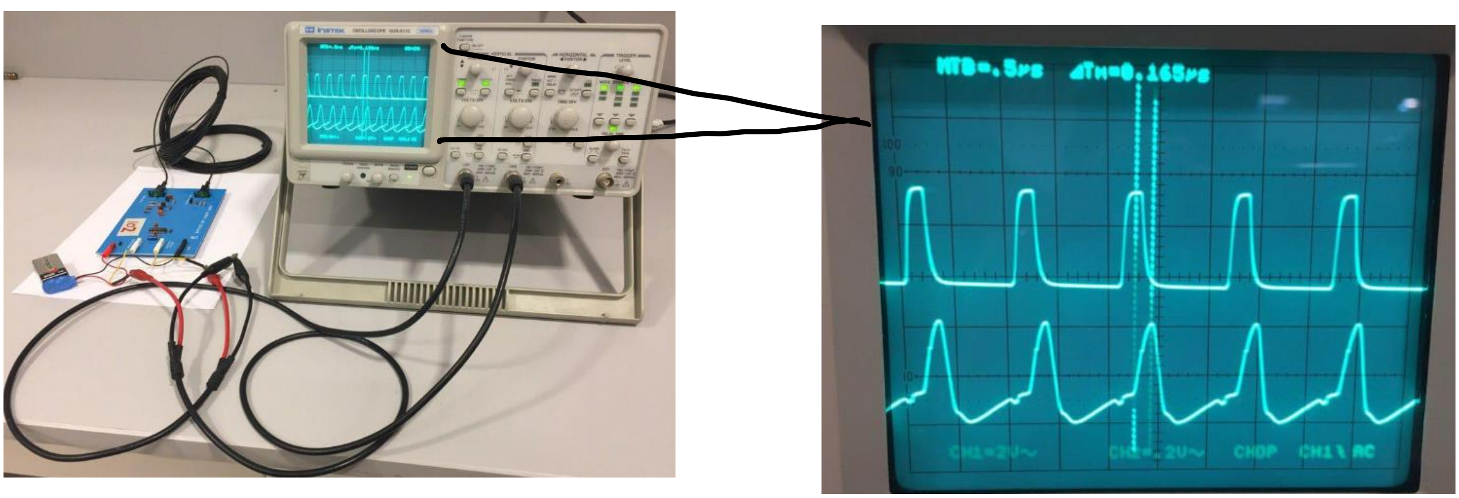
15cm fiber

20m fiber

Speed of Light Unit

Procedure:

1. Connect 9V battery to the speed of light unit.
2. Connect 15cm optical fiber between **RECEIVER** and **TRANSMITTER** housings on the speed of light unit.
3. Switch on CRO. Press AC/DC on CH1 and CH2 to show ac (∼) signal in the display of CRO.
4. If the cursor lines are not present, give a ‘long press’ on ‘CURSOR FUNCTION’ on CRO to show the lines. After that, press it again and again to bring ΔT_M on the CRO display.
5. Connect channel1 (CH1) to OUTPUT PULSE end and Channel2 (CH2) to RECEIVED PULSE end of the Speed of light unit.
6. Turn TIME/DIV on CRO to change MTB on the display through 0.2μs to 2μs. fix MTB as per table.1 for the measurement.
7. Place the cursor lines on the peak of signal1 and signal2 using position knobs under VERTICAL of CRO.
8. Record ΔTM in the Table. (This is the time T_1)
9. Now replace 15cm fiber with 20m optical fiber. Record ΔT_M after carefully fitting the cursor lines on the peak of signal1 and signal2. This is T_2.
10. Repeat the measurement for different MTB as per the table.



measuring speed of light

	T_1 (15cm fiber used)	T_2 (20m fiber used)	$v_{fiber} = \frac{20m}{T_2 - T_1}$	**C = n** v
MTB = 0.2µs Channel 1 = ---- V/div Channel 2 = ---- V/div				
MTB = 0.5µs Channel 1 = ---- V/div Channel 2 = ---- V/div				
MTB = 1µs Channel 1 = ---- V/div Channel 2 = ---- V/div				
MTB = 2µs Channel 1 = ---- V/div Channel 2 = ---- V/div				

Table 1: speed of light

C $_{average}$ = -------

Percentage error in C = $\left(\frac{Ctheory - Cmeasured}{Ctheory}\right) x100$ = ------

Questions

1. What is the value of the speed of light in vacuum?

2. How does the speed of light depend on the refractive index of the medium of propagation of light?

3. From your text find the values of the refractive indices of
   [i] Air
   [ii] Water
   [iii] Glass
4. Light travels in vacuum (refractive index of vacuum is n=1) with a constant speed of c=300 000 km⁄s. When we compare the speed of light through a transparent medium such as glass, optical fiber and so on (with a refractive index n>1) with speed of light in vacuum, which of the following statements is correct:
   a. The speed is decreased, and it is given by $v=c/n$
   b. The speed is increased, and it is given by $v=n\times c$
   c. The speed of light is always the same v=c regardless of refractive index

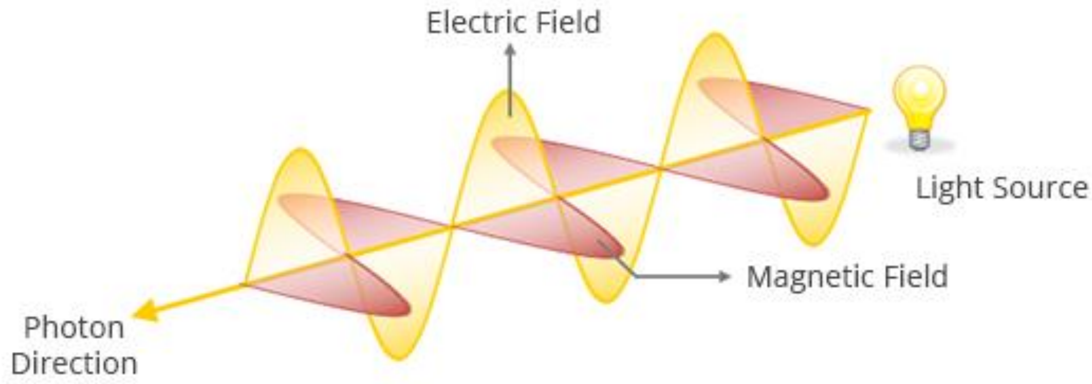
2. When light with different colors (different wavelengths) travels through a medium with refractive index n, which of the following statements is correct:
   d. Red color travels faster than blue color
   e. Blue color travels faster than red color
   f. All colors travel with the same speed

3. When light with different colors (different wavelengths) travels through vacuum, we can say that:
   a. Red color travels faster than blue color
   b. Blue color travels faster than red color
   c. All colors travel with the same speed

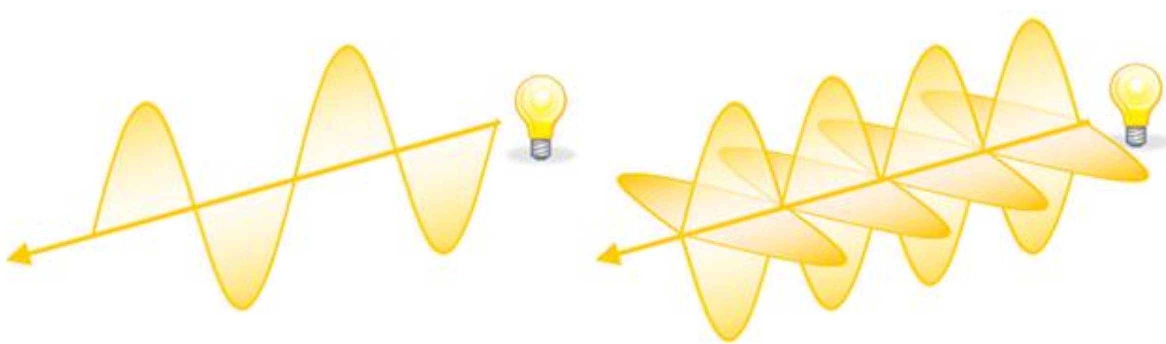
POLARIZATION OF LIGHT

Introduction

The light coming from the Sun, candlelight, and light emitted by a bulb etc. are ordinary light and are known to be un-polarized. In an un-polarized light electric and magnetic field vectors vibrate in all possible directions perpendicular to each other and also perpendicular to the direction of propagation of light.



The unpolarized light can be considered to be composed of two linear orthogonal polarization states with complete incoherence. Certain transparent materials such as Nicol and Tourmaline are capable of filtering and allowing light waves having vibrations in only one plane. Such materials are called Polaroids. This filtering is possible due the structure of the material that is having its cells arranged in a straight-line manner only in one direction (parallel to the pass axis of polarizer). This phenomenon of filtering and producing light waves having vibrations confined to one direction is called polarization. Polarization is a property of a material by which light waves are filtered and made directional.



(a) Polarized light (b) Unpolarized light

Since randomly oriented unpolarized light has as many y-components as z-components, when unpolarized light is incident on an ideal polarizer, the intensity of the transmitted light is one-half of the incident light. Also, if the polarizer is rotated with respect to incident light there is no change in the irradiance of the transmitted light i.e. its intensity remains half of the incident light. This is called One-half rule. If I_0 is the intensity or unpolarized original light (sun light for example) and I_1 is the light intensity transmitted through the polarization sheet, we can say:

$$I_1 = \frac{1}{2} \times I_0 \tag{1}$$

Malus's Law:

When light falls on a polarizer, the transmitted light gets polarized. The polarized light falling on another Polaroid, called analyzer, then transmitted light depending on the orientation of its axis with the polarizer. The intensity of light transmitted through the analyzer is given by Malus' law. The law describes how the intensity of light transmitted by the analyzer varies with the angle that its plane of transmission makes with that of the polarizer. The law can be stated in words as follows:

The intensity of the transmitted light varies as the square of the cosine of the angle between the polarization axes of the two polaroids.

If I_1 is the light intensity transmitted through the first polarization sheet (the polarizer) and θ is the angle between the polarizer sheet and the second polarziation sheet (the analyzer), the light intensity transmitte through the analyzer I_2 is given by Malus's law (also called the cosine-squared law) as follow:

$$I_2 = I_1 \times cos^2\,\theta \tag{2}$$

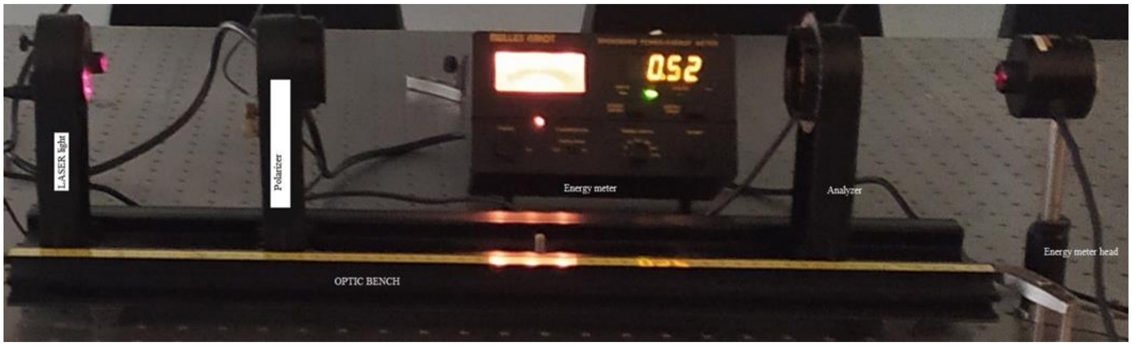
Note the two extreme cases illustrated by this equation:

- If θ is zero, the second polarizer (analyzer) is aligned with the first polarizer, and the value of $\cos^2\theta$ is one. Thus, the intensity transmitted by the second filter is equal to the light intensity that passes through the first filter. This case will allow maximum intensity to pass through.
- If θ is 90°, the second polarizer (analyzer) is oriented perpendicular to the plane of polarization of the first filter, and the $\cos^2(90^\circ)$ gives zero. Thus, no light is transmitted through the second filter. This case will allow minimum (zero) intensity to pass through.

In the first part of this experiment, we are analyzing the polarization of light by transmission through polaroid sheets (polarizer and analyzer sheets). The light intensity is measured by an energy meter. The angles are noted experimentally from the dial fitted to the Polaroids.

Procedure for first part:

1. Set up the laser, Energy meter, the polarizer and analyzer as shown in Figure to test Malus' Law.



2. Make sure the polarizer and analyzer are normal to the laser beam and that the beam passes through a "good" portion of the polarizers – look for minimal scattering, etc.
3. Turn Polarizer and analyzer to 0^0. Use the indicator mark below the dial fitted to the polaroid sheets to fix the angle.
4. SWITCH ON energy meter and press POWER/ENERGY switch to read power and arrange its range to 2mW and make its reading on display to 0 by turning OFFSET.
5. Turn on Laser light.
6. Adjust the energy meter head to read maximum value in the display. Record this as I_1.
7. Rotate the **analyzer** through the angles mentioned in the table and record the light intensity at each angle as $I_2 \equiv I_{measured}$

Table: 1

Angle(θ)	Cos θ	Cos^2 θ	$I_{measured}$	$I_1 = I_{measured}/cos^2\theta$
0				
10				
20				
30				
40				
45				
50				
70				
80				
90				
100				
110				
120				
135				
150				
160				
170				
180				
190				
200				
210				
220				
225				
240				
250				
260				
270				
280				
300				
320				
340				
360				

Graphics:

Use the values mentioned in table 1 for measured light intensity transmitted through the analyzer $I_{measured}$ and plot following three graphics:

1. Plot θ (x-axis) versus $I_{measured}$ (y-axis)
2. Plot $\cos\theta$ (x-axis) versus $I_{measured}$ (y-axis)
3. Plot $cos^2\,\theta$ (x-axis) versus $I_{measured}$ (y-axis)

Questions

1. What is the shape of the plot of light intensity versus angle?

2. What is the shape of the plot of light intensity versus cosine of the angle?

3. What is the shape of the plot of light intensity versus cosine^2 of the angle?

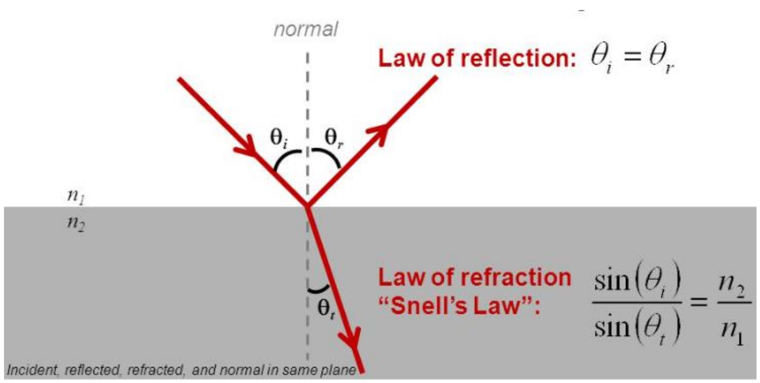
4. Three polarizers are arranged along a line in such a way that their transmission axes are rotated 17 degrees from each other. If the unpolarized light of Intensity I falls on first polarizer, then calculate the transmitted light Intensity by second and third polarizer.

BREWSTER'S ANGLE

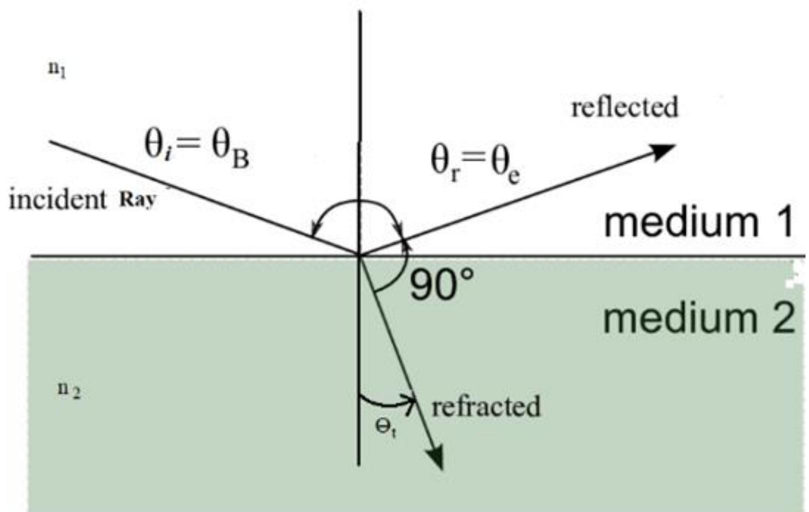
Introduction

Light can be also polarized by reflection from a transparent medium. When light moves between two media of different refractive indices n_1 and n_2, some of the light is reflected from the surface of the denser medium and some transmitted through the medium. The reflected and transmitted (refracted) light angles θ_r and θ_t and their intensities vary with the angle of incidence θ_i . The reflected angle is equal to the angle of incident $\theta_i = \theta_r$ and transmitted (refracted) angle is given by Fresnel's law:

$$n_1\, sin\,\theta_i = n_2\, sin\,\theta_t \qquad (3)$$



At one particular angle of incidence, light with a particular polarization (perpendicular to the surface) is not reflected at all. The angle of incidence at which a particular polarized light is not reflected from a denser medium is called **Brewster's angle $\boldsymbol{\theta_B}$**. This is also called as Polarization angle. Figure shows the conditions of light when angle of incidence is Brewster's angle.



At Brewster's angle, the reflected and refracted rays are perpendicular to each other and the angle 90^0 shows that reflected ray is completely polarized parallel to the interface. Thus, this incident angle is called **Brewster's angle $\boldsymbol{\theta_B}$** and we can say:

$$tan\ \theta_B = \frac{n_2}{n_1} \rightarrow \theta_B = tan^{-1}\left(\frac{n_2}{n_1}\right) \tag{4}$$

Procedure for second part

For the second part of this experiment, the Brewster angle of a D-lens (as a transparent medium) made of glass with refractive index $n_2 = 1.52$ must be measured. For error procentage, the calculated Brewster angle mus be found by using equation 4 and knowing that refractive index of air is $n_1 = 1.0003$.

1. Arrange the laser light, D-lens Assembly with the spectrometer deck, polaroid, and the screen as shown in the figure given below.
2. Fix the polarizer angle on polaroid to 90^0
3. fix the angle on the spectrometer to 0^0
4. Fix the D-lens at the center of the spectrometer platform and make sure the laser light falls on the center of the flat face of the D-lens.
5. Turn the D-lens though 20 to 90 degrees and observe the intensity of the reflected laser light on the screen.
6. As the angle is increased reflected light intensity decreases. Find the angle that gives minimum reflected light intensity. This angle is Brewster's angle and record it.
7. Repeat the process to find Brewster's angle two or three times.

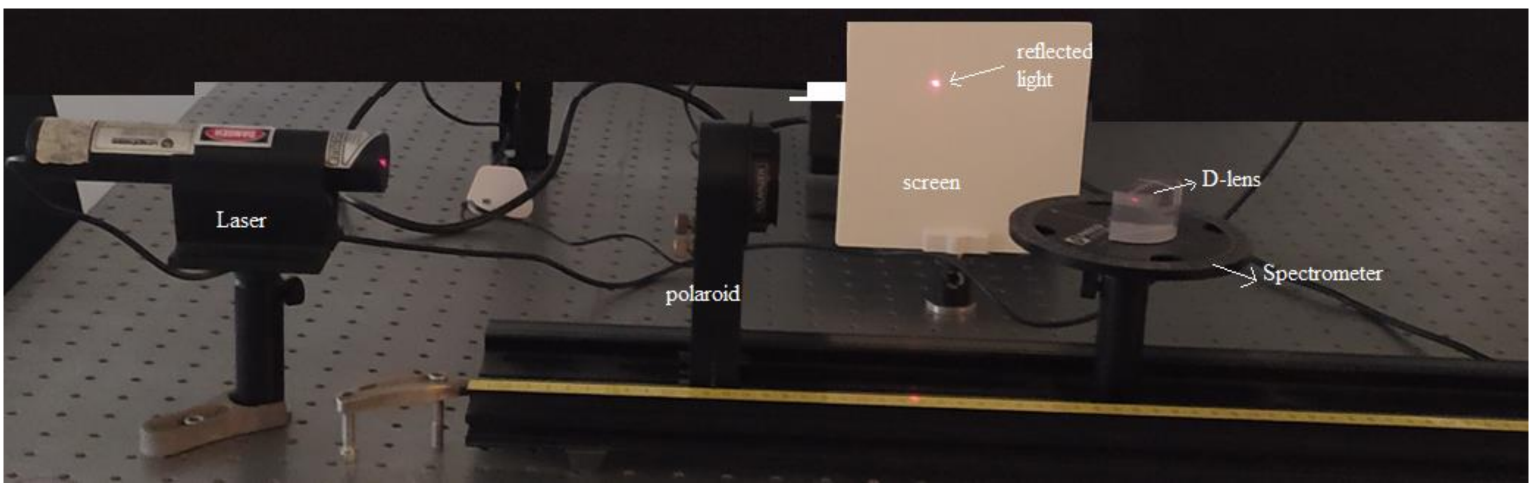


Table 2 : Brewster's angle

	Trial 1	Trial 2	Trial 3
θ_B			

$$\theta_{B_{experimental}} =$$

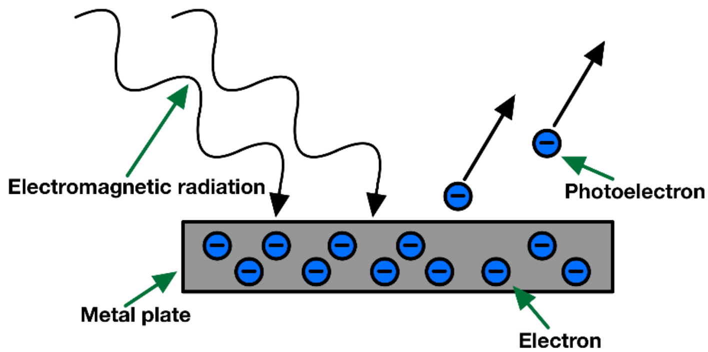
$$\theta_{B\ theory} = tan^{-1}\left(\frac{1.52}{1.0003}\right) = 56.65^{\circ}$$

$$Error\ in\ \theta_B = \left(\frac{\theta_{B_{theory}} - \theta_{B_{experimental}}}{\theta_{B_{theory}}}\right) \times 100 = \cdots\%$$

PHOTOELECTRIC EFFECT

Introduction:

The nature of light is twofold. It can act as a particle (a photon) at times, which explains why light travels in straight lines. It can function like a wave at times, explaining how light bends (or diffracts) around an object. The phenomena such as interference, diffraction and polarization were successfully explained based on wave nature of light. On the other hand, photoelectric effect, Compton effect etc. can be explained based on quantum nature of radiation. Quantum theory describes that matter, and light consists of minute particles that have properties of waves that are associated with them. Light consists of particles known as photons and matter are made up of particles known as protons, electrons, and neutrons. The particle nature of light could explain a phenomenon called photoelectric effect at beginning of 20 century. photoelectric effect, phenomenon in which electrically charged particles are released from or within a material when it absorbs electromagnetic radiation. The effect is often defined as the ejection of electrons from a metal plate when light falls on it.



In photoelectric effect, when a photon of radiation strikes a metal surface, it gives up all its energy to a single electron in an atom and the electron is knocked out of the metal. Ejected electron from metal surface (photoelectron) carries a part of the incident photon energy. This effect appears as if a particle (photon of radiation) is colliding against another particle(electron). Hence it became necessary to assume that in photoelectric effect, radiation exhibits particle nature.

Experimental observation of Photoelectric effect

In 1887, Heinrich Hertz made the observation that when light strikes a metal surface, certain electrons close to the surface can absorb enough energy from the incoming radiation to overcome the attraction of the positive ions in the surface material. Then, Philipp Eduard Anton von Lenard (7 June 1862 – 20 May 1947) as a Hungarian-born German realized experimentally that the energy (speed) of the electrons ejected from a cathode depends only on the wavelength, and not the intensity, of the incident light.

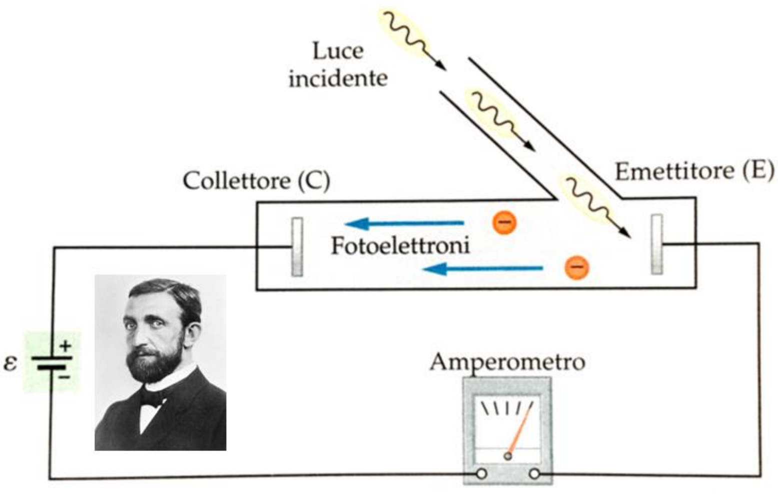


Figure 1: Phillipe Lenard and experimental study of photoelectric effect

The Lenard apparatus consists of an evacuated glass tube fitted with two electrodes. The electrode E is called the emitting electrode, and the other electrode C is called the collecting electrode. A varying potential difference can be applied across the two electrodes. When a suitable radiation is incident on the electrode E, electrons are ejected from it. The electrons, which have sufficient kinetic energy reach electrode C. As the collecting electrode is become more and more negative, fewer, and fewer electrons will reach the cathode and the photo electric current recorded by the ammeter will fall. In case **the retarding potential equals V_0 called the stopping potential**, no electron will reach the cathode and the current will become zero. In such case the work done by stopping potential is equal to the maximum kinetic energy of the photo emitted electrons.

$$eV_0 = \frac{1}{2}mv_{max}^2 \qquad (1)$$

All these experimental observations could not be explained by classical theories and clearly were in contradiction with wave properties of light. Those contradictions can be summarized as follow:

1. ***Dependence of photoelectron kinetic energy on light intensity***

   ***Classical prediction*:** Electrons should absorb energy continuously from the electromagnetic waves. As the light intensity incident on a metal is increased energy should be transferred into metal at a higher rate and the electrons should be ejected with more kinetic energy.

   Experimental result: The maximum kinetic energy of photoelectrons is independent of light intensity. According to equation 1 the maximum kinetic energy is proportional to the stopping potential.

2. ***Time interval between incidence of light and ejection of photoelectrons***

Classical prediction: At low light intensities, a measurable time interval should pass between the instant the light is turned on and the time an electron is ejected from the metal. This time interval is required for the electron to absorb the incident radiation before it acquires enough energy to escape from the metal.

Experimental result: Electrons are emitted from the surface of the metal almost instantaneously (less than 10^{-9}s after the surface is illuminated) even at very low light intensities.

3. ***Dependence of ejection of electrons on light frequency.***
   Classical prediction: Electrons should be ejected from the metal at any incident light frequency, as long as the light intensity is high enough, because energy is transferred to the metal regardless of the incident light frequency.
   Experimental result: No electrons are emitted if the incident light frequency falls below some cut off frequency ν_c whose value is characteristic of the material being illuminated. No electrons are ejected below this cut off frequency regardless of the light intensity.

4. ***Dependance of photoelectron kinetic energy on light frequency.***

   Classical prediction: There should be no relationship between the frequency of the light and the electron kinetic energy. Kinetic energy should be related to the intensity of the light.

   Experimental result: The maximum kinetic energy of the photoelectrons increases with increasing light frequency.

Photoelectric effect explained by Einstein:

Successful explanation of the photoelectric effect was given finally by Einstein in 1905. He stated that just as the atomic oscillators of a blackbody surface can only change energy in discrete jumps, the energy of an electromagnetic field is also quantized and can only take on a set of discrete values proportional to the frequency of the field. The discrete amount or quanta of energy which make up an electromagnetic field is called photon. Each photon has energy $E = h\nu$ where h is Plank's constant and ν is the frequency of the light. The electrons of an illuminated metal surface absorb energy of one photon at a time. If a photon kicks an electron with enough energy to escape the material surface it flies away as photoelectron with kinetic energy equal to the difference between the photon's energy and binding energy of the electron.

$$KE\ (electron) = \frac{1}{2}mv^2 = h\nu - \Phi \qquad (2)$$

The maximum energy of the photoelectron can be obtained for an electron at any frequency is:

$$KE_{max} = eV_0 = h\nu - \Phi_0 \qquad (3)$$

Where Φ_0 is called the work function of the metal which is the minimum binding energy (the minimum energy needed to remove one electron from metal surface with zero kinetic energy) and V_0 is the stopping potential needed to stop the most energetic electron. Albert Einstein's equations could explain the photoelectric effect perfectly as follow:

1. ***Dependence of photoelectron kinetic energy on light intensity.***

   Equation 3 shows that KE_{max} is independent of the light intensity. The maximum kinetic energy depends on frequency of the light and work function of the metal only. If light intensity is increased, the number of photons arriving increases to eject more photo electrons.

2. ***Time interval between incidence of light and ejection of photoelectrons***

   Near instantaneous emission of electrons is consistent with the photon model of light. The incident energy appears in small packets, and there is a one-to-one interaction between photons and electrons with less intensity means less number of photons only. These photons can eject photoelectrons instantly (in $10^{-9}\,s$) from a metal provided their frequency is above cut off frequency.

3. ***Dependence of ejection of electrons on light frequency.***

   If the incident photon energy is less than work function of the metal, then KE of the electron would become negative. This is not possible in a real situation. Therefore equation 3 suggests that no photoelectric effect occur below cut off frequency.

4. ***Dependance of photoelectron kinetic energy on light frequency.***

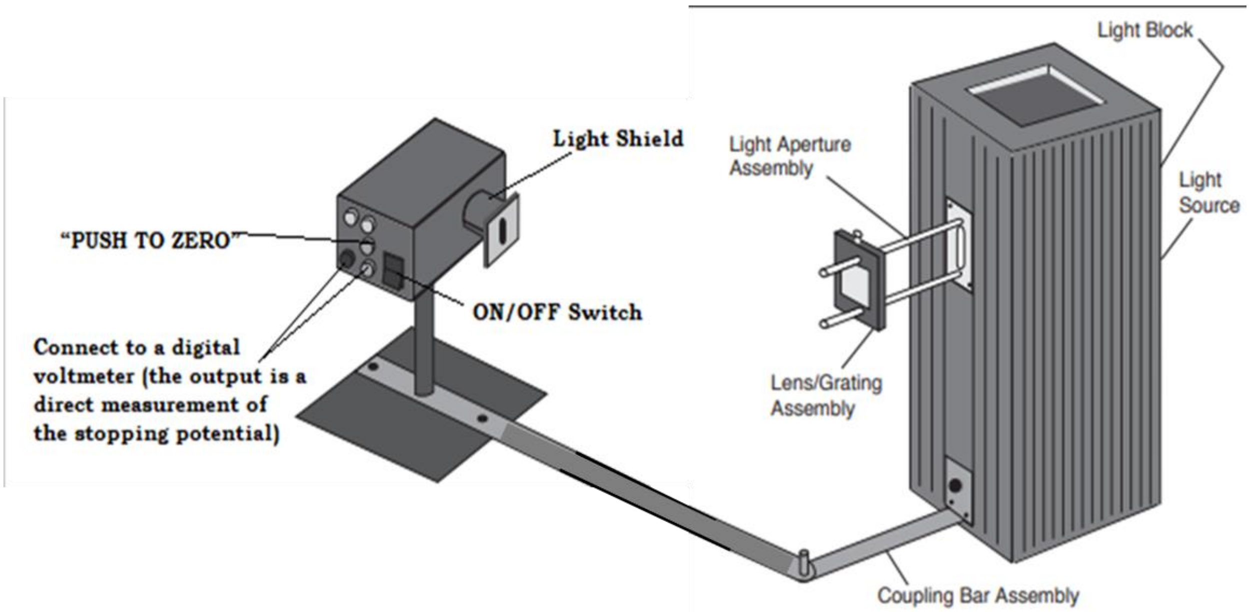
   A photon of higher frequency carries more energy and therefore ejects a photoelectron with more kinetic energy than a photon at lower frequency. Equation 3 shows a linear relationship between frequency and Kinetic energy which was observed in experiment.

EQUIPMENT AND SETUP:

DANGER - THE MERCURY LIGHT SOURCE HAS COMPONENTS IN THE ULTRAVIOLET REGIME WHICH ARE DANGEROUS TO OUR EYES! DO NOT STARE DIRECTLY INTO IT! BY PLACING THE SLIT CLOSE IN FRONT OF IT MOST OF THE LIGHT MAY BE BLOCKED IT MAY ALSO BE HELPFUL TO PLACE A THIN BOOK OR FOLDER ON TOP OF THE LIGHT SOURCE TO BLOCK THE LIGHT FROM VIEW.

The list of equipment:

- h/e Apparatus (Vacuum Photodiode and High Input Impedance Isolation Circuit)
- Mercury Light Source
- Diffraction Grating/Lens assembly
- Light Filters



Procedure:

Set up and use the equipment described above as follows:

1. Switch on the mercury light source.
2. Place the slit directly in front of the source. Again, be careful not to stare into the source directly.
3. Position the lens and grating assembly so that beam is collimated (neither spreading or narrowing.) You will want to adjust it slightly later to focus the image of the slit as sharply as possible upon the photodiode. Swing h/e apparatus to left or right to observe first order diffraction image. Allow the blue light of the spectrum to fall on the photodiode placed inside the h/e apparatus. Adjust the lens-grating assembly to focus the blue light on the photodiode.
4. Close the cylindrical light shield at the front entrance of h/e apparatus to prevent ambient light.
5. Switch on the h/e apparatus.
6. Connect a voltmeter(multimeter) to the output of the h/e apparatus. Make sure the voltmeter is set to read voltages in the range of around 1 Volt.
7. Press '**Push to Zero**' of the h/e apparatus so that the multimeter reads 0.00. Now take the hand off from Zero switch. Wait 2-3 seconds till the voltmeter value stabilizes to a value. This voltmeter reading is the stopping potential for blue light.

8. Place the neutral density filter (intensity variation) in front of the slit of h/e apparatus, so that blue light passes through 100% region marked on it.
9. Press Zero button to make the voltmeter to zero. Then release the switch and record (after 1-2 sec) the stopping potential shown in the voltmeter for 100% light intensity.
10. Repeat the same process for blue light at different intensities (80%, 60%, 40%, and 20%).
11. Swing the h/e apparatus a bit more to focus violet-1 on the photodiode. (Open the light shield and make sure the violet -1 is well focused on the photodiode) Measure the stopping potential for violet-1 at different intensities and record the values in table 1.
12. Swing the h/e apparatus to focus yellow light on the photodiode. Place the yellow filter at the front entrance of the h/e apparatus followed by the filter to vary the intensity (place them one on top of other). Measure the stopping potential for different intensities by proper selection of intensity window on neutral density filter (Intensity filter).
13. Same as above focus green light and violet 2 and measure the stopping potential and record them in table 2. (Please make sure that green filter is used with green light)
14. ***Use colored filters only for green and yellow color.***
15. Plot stopping potential versus frequency graph and measure Planck's constant from the slope of the graph.

Table:1 Frequency and Intensity of light.

Transmission	Blue light	Violet-1 light
%	Stopping potential	Stopping potential
100		
80		
60		
40		
20		

Table 2: Frequency and stopping potential.

Color	Wavelength λ(nm)	Frequency ν (Hz)	Stopping potential (100% intensity)
yellow	580	$5.17x10^{14}$	
green	546	$5.49x10^{14}$	
blue	436	$6.88x10^{14}$	
Violet-1	405	$7.41x10^{14}$	
Violet-2	365	$8.22x10^{14}$	

Analysis of the experimental results:

A): Use two values of stopping potential with their corresponding frequencies mentioned in table 2 and calculate the constant of Planck as follow:

$$h = \frac{V_2 - V_1}{\nu_2 - \nu_1} \times e$$

Calculate the error of Planck constant as well.

$$Error = \frac{h_{th} - h_{exp}}{h_{th}} \times 100 = \cdots \% \qquad h_{th} = 6.62607 \times 10^{-34}\, J.s$$

B): Plot frequency ν (x-axis) versus Stopping potential V_0 (y-axis). Find the slope of the graph and there after planks constant h from it by using as follow:

$$h = e \times slope$$

Where $e = 1.602 \times 10^{-19}\, C$ is the electronic charge and therefore one electron volt is $1\, eV = 1.602 \times 10^{-19}\, J$

C): Use your graph to find the minimum frequency (cut off frequency ν_c) to start photoelectric emission from the metal used for your experiment.

Questions:

Q1: Explain that your experimental results (the photoelectric effect) follow Einstein's equation. Explain the relationship between light intensity and light frequency with the kinetic energy of photoelectron (the stopping potential).

Q2: How much is **the work function of the metal Φ** under the experiment? To do so, use graph to find it.

DIFFRACTION OF LIGHT

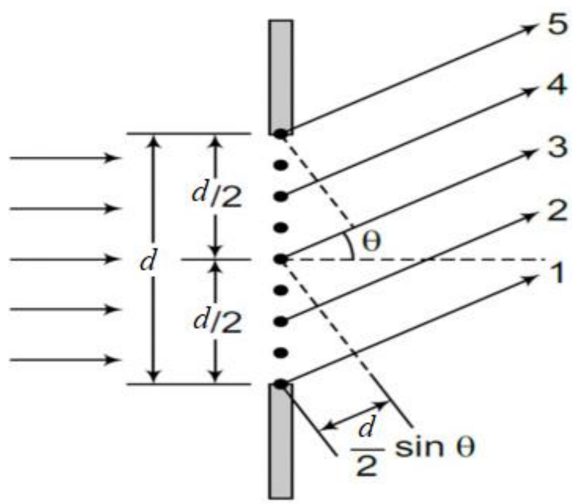
Introduction:

Diffraction is a general characteristic exhibited by all types of waves, such as sound waves, light waves, water waves, or matter waves. When light passes by an obstacle, then it appears to bend around the edges of the obstacle. The phenomenon of bending of light around the corners of small blocks or apertures and its consequent spreading into the regions of the geometrical shadow is termed **Diffraction of light**. If the size of the obstacle is comparable to the wavelength, then the bending of the waves is large. The larger the aperture or obstacle, the smaller is the bending and the less noticeable any diffraction effects. In optics, diffraction, like interference, tends to produce patterns of illumination with bands of bright and dark light. Essential Condition for observation of diffraction is that the source of light should be coherent, and the wavelength of the light used should be comparable to the size of the obstacle.

Diffraction is generally classified as Fresnel diffraction and Fraunhofer diffraction. In Fresnel diffraction the point source and the screen where you observe the diffraction effect are relatively close to the obstacle forming the diffraction pattern. By contrast, in Fraunhofer diffraction, source, obstacle and the screen are far apart so we can consider all lines from the source to the obstacle to be parallel. We are analyzing only Fraunhofer diffraction in this experiment.

Single Slit Diffraction Formula

In this topic, we will see how the finite width of slits is the basis for understanding Fraunhofer diffraction. Figure shows a single slit of width d here. Let us consider waves coming from various portions of the slit in the given figure. Now, according to Huygens's principle, **each portion of the slit acts as a source of light waves.** So that the light from one portion of the slit can interfere with light from another portion of the slit, and the resultant light intensity will depend on the direction θ and it can be obtained on a screen. To analyze the diffraction pattern, first divide the slit into two halves, as shown in figure. Keeping in mind that all the waves are in phase as they leave the slit, now consider rays 1 and 3. As these two rays travel toward a viewing screen far to the right of figure, and ray 1 travels farther than ray 3 by an amount equal to the path difference of $\left(\frac{d}{2}\right)\sin\theta$ where d is the width of the slit. Similarly, the path difference between rays 2 and 4 is the same. The two waves cancel each other if this path difference is exactly half a wavelength (corresponding to a phase difference of 180°). When any two rays originate at points (at phase difference 180°), then it is separated by half the slit width.



Therefore, we can conclude that waves from the upper half of the slit will interfere with waves from the lower half destructively when:

$$\frac{d}{2}\sin\theta = \frac{\lambda}{2} \quad \leftrightarrow \quad \sin\theta = \frac{\lambda}{d} \qquad (1)$$

Again, using a similar reason, if we divide the slit into four equal parts, we will notice that the viewing screen is also dark when:

$$\sin\theta = \frac{2\lambda}{d} \qquad (2)$$

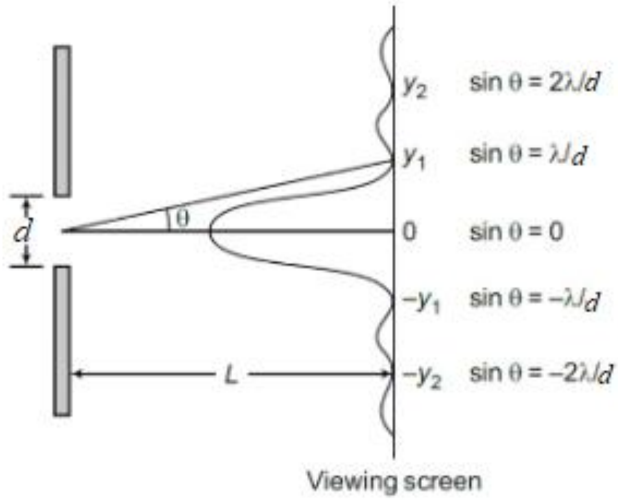
And if we will divide the slit into six equal parts and again, we will notice that darkness occurs on the screen when:

$$\sin\theta = \frac{3\lambda}{d} \qquad (3)$$

Therefore, for **destructive interference**, we can write the general condition as:

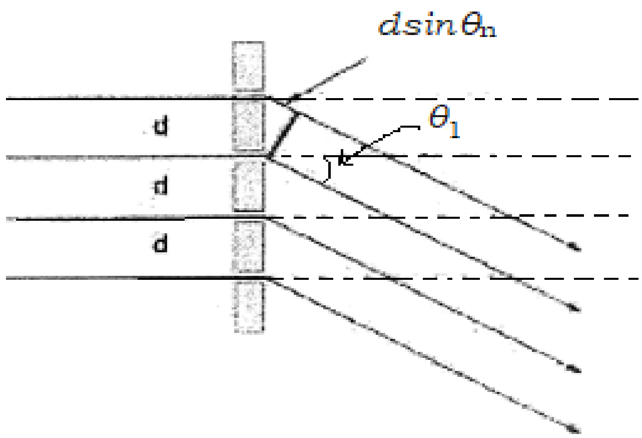
$$\sin\theta = \frac{n\lambda}{d} \quad with\ n = \pm 1, \pm 2, \pm 3, \ldots \qquad (4)$$

This equation gives the values of θ for which the diffraction pattern has zero light intensity—that is, when a dark fringe is formed. The intensity distribution of the fringes is shown in Figure 2. We can observe a broad central bright fringe is flanked by much weaker bright fringes, which alternate with dark fringes. The various dark fringes occur at the values of θ. And each bright fringe peak will lie approximately halfway between its bordering dark fringe minima. The following figure shows the distribution for a Fraunhofer diffraction pattern.



Diffraction grating

A transmission diffraction grating is a piece of transparent material on which many equally spaced parallel lines had been ruled. The distance between the lines is called the grating constant d. The following figure shows a diffraction grating and patch difference equal to $d\sin\theta_n$

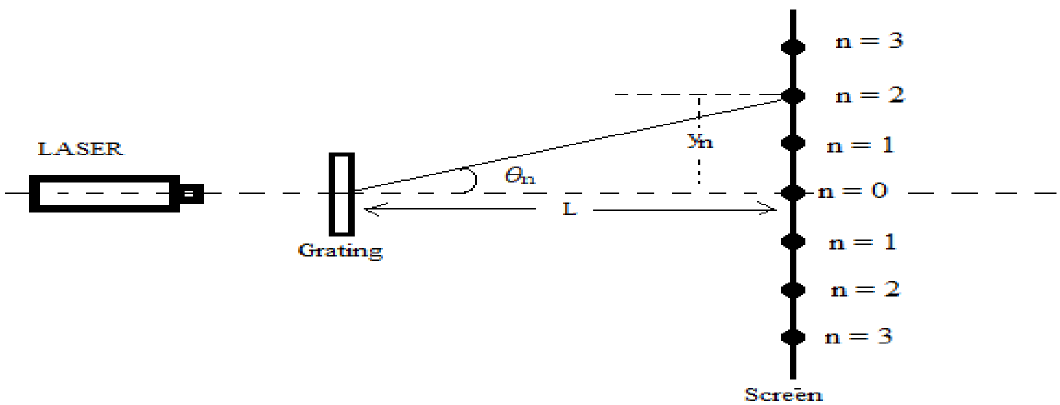


Light rays that strike the transparent portion of the grating between the ruled lines will pass through the grating at all angles with respect to their original path. If the deviated rays from adjacent rulings on the grating are in phase, an image of the source will be formed. This will be true when the adjacent rays differ in path length by an integral number of wavelengths of the light. Thus, for a given wavelength λ, there exists a series of angles at which an image is formed. The first image is formed when the path difference between rays from adjacent ruled lines is exactly equal to one wavelength λ. According to Figure above, that condition will be true at an angle θ_1 such that the equation $d\ sin\theta_1 = \lambda$ is satisfied. At some larger angle

θ_2 when the path difference between rays from adjacent ruled lines is exactly equal to 2λ, then the equation d sin $\theta_2 = 2\lambda$ is satisfied.
In general, an image will be formed at any angle θ_n for which the rays from adjacent rulings have a path difference equal to **nλ where *n* is an integer called the order number**. Thus, the general case is described by the equation:

$$d \sin\theta_n = n\lambda \qquad (5)$$

The image formed along the original path of the light rays is called zeroth order. For each of the higher orders (i.e. n > 1), there are two images formed symmetrically at both sides of the zeroth order image as shown in figure below:



If the linear distance between the center of the zeroth order image and the n^th order image is y_n, then the angle θ_n at which the n^{th} order image formed with respect to the original path of the light rays is given by:

$$\theta_n = tan^{-1}\left(\frac{y_n}{L}\right) \qquad (6)$$

where *L* is the distance from the grating to the screen. If the grating constant is known, the wavelength of the light is then given by:

$$\lambda = \frac{d}{n}\sin\left[tan^{-1}(\frac{y_n}{L})\right] \qquad (7)$$

Using equation 7, the grating element d can be calculated as well by:

$$d = \frac{n\lambda}{\sin\left[tan^{-1}(\frac{y_n}{L})\right]} \qquad (8)$$

Apparatus

- Coarse gratings 1and 3.
- He-Ne laser source.
- Two diffraction gratings (300lines/mm and 600lines/mm) and grating holder.
- Measuring tape
- Screen to View the diffraction pattern.

Experiment PART-A: Determination of the wavelength of He-Ne Laser light.

1. Switch on the laser power supply. Caution: DO NOT look directly into the laser beam! DO NOT shine the laser beam across the room!
2. Aim the laser so its beam is normal to the screen.
3. Place grating 1(300lines/mm) into its holder in front of the laser. Adjust the position of the laser so that the beam is centered on the grating.
4. Adjust the distance (40-50cm) between the screen and the grating so that at least 2nd or 3rd order images are seen clearly on the screen.
5. Measure the distance from the grating to the screen and record the distance as L in the data table1 provided.
6. Measure the distance between image in the center (zero order) and first order on any side of the center image. Record this distance as y_n in table1.
7. Calculate λ using the equation 7.
8. Repeat steps 3-7 for grating-2 (600lines/mm)
9. Find the average of λ.

NOTE: MAKE SURE THAT THE GRATING-TO-SCREEN DISTANCE (L) DOES NOT CHANGE WHEN GRATINGS ARE REPLACED.

Table:1 Wavelength of the laser light used

grating	Grating element $d = \frac{1 \times 10^{-3}}{no.\ of\ lines}$ (m)	Distance between Screen and grating L (m)	Distance between center maxima and n^{th} order maxima y (m)	Order of the fringe measured from center maxima n	$\lambda = \frac{d}{n} \sin(\tan^{-1}(\frac{y}{L}))$ (nm)
300 lines/mm					
600 lines/mm					

$$\lambda_{average} =$$

$$\lambda_{theory} = 632.8\,nm$$

$$Error = \frac{\lambda_{th} - \lambda_{avg}}{\lambda_{th}} \times 100 = \cdots \%$$

Experiment PART-B: Determination of the grating element *d*

1. Switch on the laser power supply and wait for a few seconds for the laser on. Caution: DO NOT look directly into the laser beam! DO NOT shine the laser beam across the room!
2. Aim the laser so its beam is normal to the screen.
3. Place coarse gratings-1 into holder in front of the laser. Adjust the position of the laser so that the beam is centered on the grating.
4. Adjust the distance between screen to grating(2m-3m) so that diffraction images are clearly seen on the screen at measurable distance between different order images. Record the distance(L) between screen and grating in table.2

5. Measure the distance between center image (zero order) and first order on any side of the center image. Record this distance as y_n in the table.2

6. Repeat steps 3 to 6 for the course grating 2. Record your results in data table provided.

7. calculate d with the equation 8.

NOTE: MAKE SURE THAT THE GRATING-TO-SCREEN DISTANCE (*L)* DOES NOT CHANGE WHEN GRATINGS ARE REPLACED.

Table 2: Grating element

grating	λ (nm)	Order of the fringe measured from center maxima n	Distance between center maxima and n^{th} order maxima y (m)	Distance between Screen and grating L (m)	$d = \frac{\lambda \times n}{\sin(\tan^{-1}(\frac{y}{L}))}$
Coarse grating-1					
Coarse grating-3					

Questions

1. A grating is labelled '500 lines per mm'. Calculate the spacing of the slits in the grating.

2. Monochromatic light is aimed straight at the grating and is found to give a first-order maximum at 15°. Calculate the wavelength of the light source.

3. Calculate the position of the first-order maximum when reel light of wavelength 730 nm is shone directly at the grating.

4. A grating is illuminated with a parallel beam of light of wavelength 550 nm. The first-order maximum is in a direction making an angle of 20° with the incident light .Calculate the spacing of the grating slits.

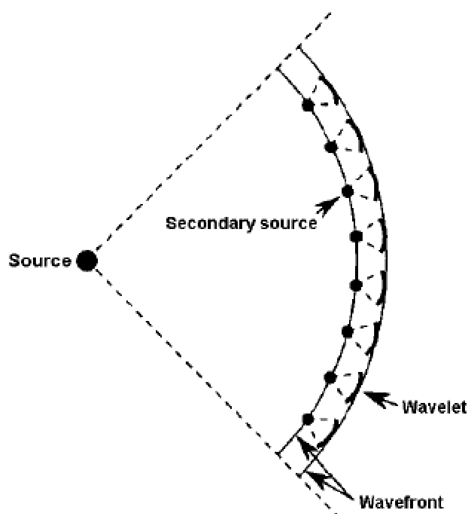
5. What would be the angle of the first-order maximum if a grating of slit spacing of 2.5×10^{-6} m were used with the same light source?

6. Calculate the wavelength of light that would give a second-order maximum at θ = 32°with a grating of slit spacing 2.5×10^{-6} m.

MICHELSON INTERFEROMETER AND ITS APPLICATIONS

Introduction

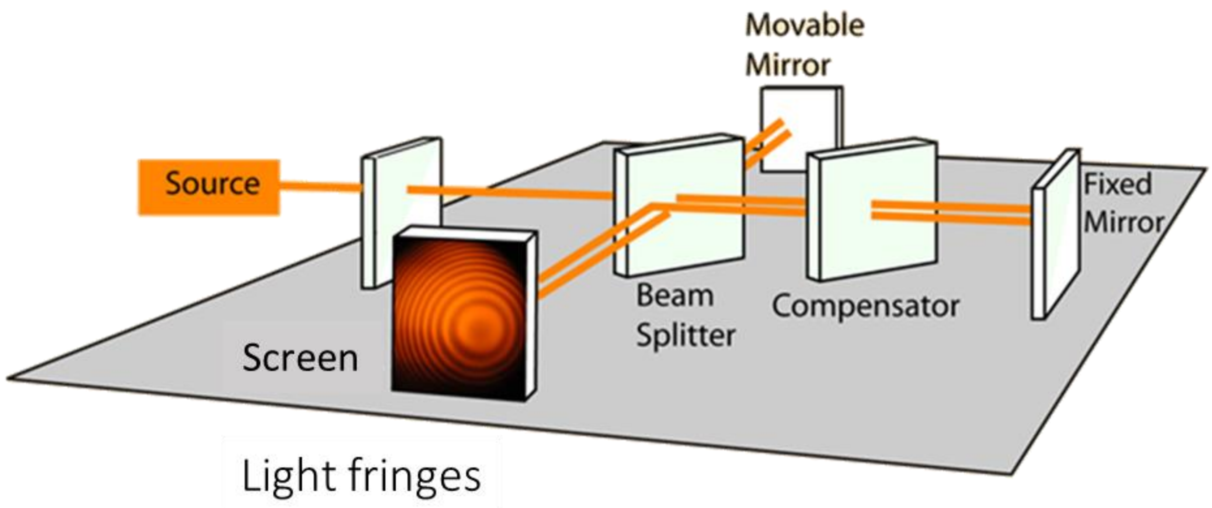
The dual particle-wave properties of light can be demonstrated by different experiments. We saw already that photoelectric effect shows the particle nature of light. Here, the wave property of light is demonstrated in Interference and diffraction phenomenon. The interference of two or more light waves means superposing of them to form a resultant wave. This phenomenon can be analyzed based on Huygens principle and superposition of waves. Huygens' principle, also called Huygens-Fresnel principle, a statement that all points of a wave front of light in a vacuum or transparent medium may be regarded as new sources of wavelets that expand in every direction at a rate depending on their velocities. The Huygens principle is shown here:



Generally, interference effect is produced when two wavelets or two waves from independent and separate sources superimpose each other to redistribute their energy either destructively or constructively. The essential condition for the interference of waves shows that the sources of waves must be monochromatic which means that the waves of light should have the same frequency. The light waves should be propagated in the same direction. The amplitudes of two waves should be equal or nearly equal. When two coherent waves are combined by adding their intensities (or displacements) with due consideration for their phase difference. The resultant wave may have greater intensity (constructive interference) or lower amplitude (destructive interference) if the two waves are in phase or out of phase, respectively. Here in this experiment, interference of light wavers is used to measure the wavelength of the light source producing interference and measurement of the refractive index of the medium by using the Michelson interferometer.

Michelson Interferometer and its working principle

An American physicist A.A. Michelson (1852-1931) invented this interferometer. It is a device that splits a light beam into two parts and then recombines them to form interference pattern after they have traveled over different paths. The device can be used for obtaining accurate measurement of wavelengths or other lengths. Figure here shows a schematic diagram of the interferometer.



A beam of light provided by a monochromatic source (laser) is split into two rays by a partially silvered mirror or beam splitter M inclined at 45^0 relatives to the incident light beam. One ray is reflected towards fixed mirror while the second ray is transmitted toward adjustable (movable) mirror. The two rays travel separate paths and eventually recombine to produce an interference pattern which can be seen on the screen. By changing the position of movable mirror, the optical patch of two rays will be different and the interference condition for the two rays is determined by the difference in their optical path lengths. In this way, the interferometer shows the interference pattern is a series of bright and dark circular rings. If a dark circle appears at the center of the pattern, the two rays interfere destructively. If the movable mirror is then moved a distance of $\lambda/4$, the path difference changes by $\lambda/2$ (twice the separation between two mirrors), the two rays will now interfere constructively, giving a bright circle in the middle. As movable mirror is moved an additional distance of $\lambda/ 4$, a dark circle will appear again. Thus, we see that successive dark and bright circles are formed each time moveable mirror is moved a distance of $\lambda/ 4$. The wavelength of light is then measured by counting the number of fringe shifts for a given displacement of the movable mirror. Conversely, if the wavelength is accurately known, mirror displacements can be measured to within a fraction of the wavelength. By slowly moving the adjustable mirror through a distance d and counting N, the number of times the light fringe pattern is restored to its original state, the wave length of the light is given by:

$$\lambda = \frac{2d}{N} \tag{1}$$

This experiment has two parts. Part one is about measuring the wavelength of light source (the laser). In part two, the interferometer is used to measure the refractive index of air.

Apparatus

• Pasco Interferometer.

• air cell.

• hand vacuum pump.

• He-Ne laser with power supply.

• optical bench.

• Screen to view fringes.

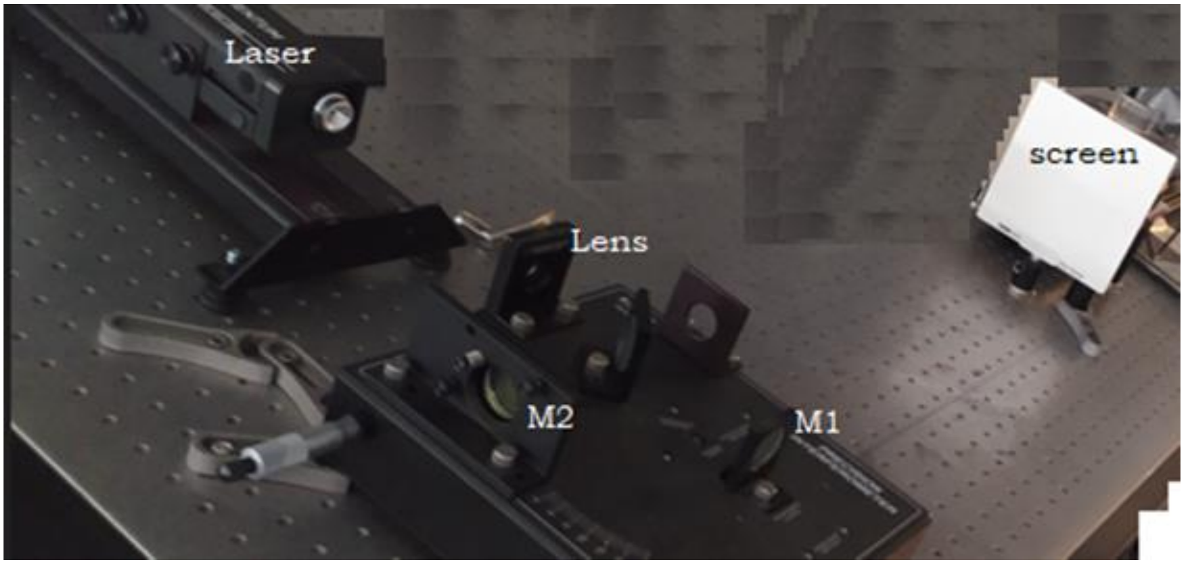
Procedure

PART-I Measuring wavelength of the laser light.

WARNING: *THE INTERFEROMETER GLASS PLATE AND MIRRORS HAVE VERY SENSITIVE SURFACES. PLEASE DO NOT TOUCH THE MIRROR OR THE PLATES. CALL YOUR INSTRUCTOR BEFORE MAKING ANY ADJUSTMENTS THAT REQUIRE YOU TO TOUCH ANY OF THE GLASS SURFACES.*

Aligning the interferometer:

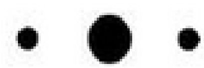
1. The laser, interferometer and screen are set up as shown in Figure below:



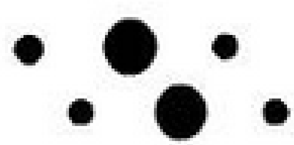
2. Cover the M1 with a sheet of paper. The laser beam should go through the glass plate and strike M2 and return through the plate to the laser.

3. Adjust the location of the laser until the return beam is very close to the exit hole on the face of the laser. (WARNING: Do not look directly into the laser beams!!)

4. A set of three or four dots should now be seen on the screen (see Figure below). Now uncover M1.



5. A second series of dots should now be seen on the screen (see figure below).
   Turn the screws on M2 to superimpose the two sets of dots.



6. When the correct dots are lined up, they should "shimmer," and a slight touch of the interferometer should cause the intensity of the dots to flicker.

7. A small lens (18 mm focal length) will be used to spread the laser beam passing through the interferometer. Place the small lens on the exit hole of the laser.

8. If the interferometer is properly aligned, an interference pattern as light fringes should appear on the screen.

9. If a series of thin circular arcs appear on the screen only a minor adjustment of the three screws on M2 is needed. If the arcs are horizontal carefully turn the top or bottom screw. If the arcs are vertical, try the side screw. In any case, turn the screws to center the pattern of the circular arcs on the screen.

Accurate fringe-counting

1. Select a reference line on the screen and adjust the screen to bring the reference line on any dark fringe.

2. Turn the micrometer on interferometer and count the number of fringes that pass reference line on the screen. Record the micrometer reading for the number of fringes crossing the reference line as per table 1.

Table 1: Measuring Wavelength

No. of fringe shift N	Path length d (μm)	$\lambda = 2d/N$ (nm)
20		
40		
60		

$$\lambda_{average} = \cdots \quad nm$$

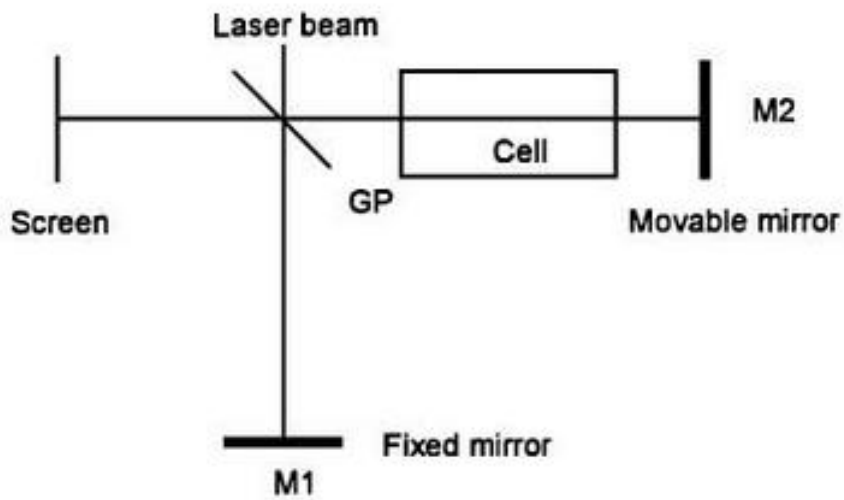
$$\lambda_{theory} = 632.8\, nm$$

$$Error = \left(\frac{\lambda_{theory} - \lambda_{average}}{\lambda_{theory}}\right) \times 100 = \cdots \ \%$$

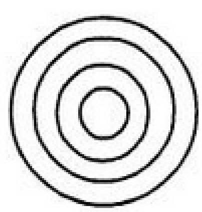
Part 2: Refractive Index n of Air

Introduction

In this experiment you will measure the index of refraction of air by comparing the optical path lengths of two columns of air of equal physical length but at different pressures. The Instrument used to compare optical path lengths is the Michelson Interferometer. In an interferometer (Figure below) a light beam (in this case a helium-neon laser) is incident on a partially silvered glass plate (GP) placed 45^o with respect to the beam. The beam is split, part of it traveling to mirror M_1 at the end of the side arm. This beam is reflected by M_1, returning through GP to strike the screen. The other part of the original beam goes through the glass plate and the cell to mirror M_2. It is reflected by M_2 through the cell to the glass plate where it is reflected to the screen.



The two beams arriving at the screen produce an interference pattern. An interference pattern is normally a series of bright and dark concentric circles (Figure 4), because of the imperfections in the mirrors of our interferometers, the circles may be distorted.



Ideal interference pattern.

In the bright regions of the pattern, the crests of the waves of the two beams arrive together. In the dark areas the crest of one wave arrives at the same time as the trough of the other. If the optical path length of one beam changes by one wavelength, the interference pattern is shifted by one fringe. The optical path length is equal to nL, where n is the Index of refraction and L is the physical path length. The optical path length can be varied by changing either n or L. In our experiment the one beam passes through the cell of length L. Because the beam passes through the cell twice, the optical path length is $2nL$. The air will be removed from this cell, changing the refractive index, n. The other beam passes through the same length of air, but with no cell in that beam, the pressure will remain constant. If the refractive index changes by Δn, the path length changes by $2nL$. As the air is removed, the pattern will shift by one fringe at each time the refraction index changes by an amount $\Delta n = \lambda/2L$. A shift of N fringes will occur when the refractive index changes by an amount:

$$\Delta n = \frac{N\lambda}{2L} \tag{2}$$

The refractive index for most gases is close to 1. For air and other ideal gases, the difference between the refractive index and 1 is proportional to the pressure of the gas. Thus, we define the refractive index of air $n = 1 + KP$, where P is the air pressure and K is an unknown constant. When the pressure is changed, the change in the refraction index is $\Delta n = K\Delta P$. We can therefore relate the number of fringes shifted N, to the change in pressure as follow:

$$\Delta P = \frac{\Delta n}{K} = \frac{N\lambda}{2LK} \rightarrow K = \frac{N\lambda}{2L\Delta P} \tag{3}$$

Thus, if you measure N fringes while the pressure changes by an amount ΔP, you can calculate the refraction index of air at room temperature using:

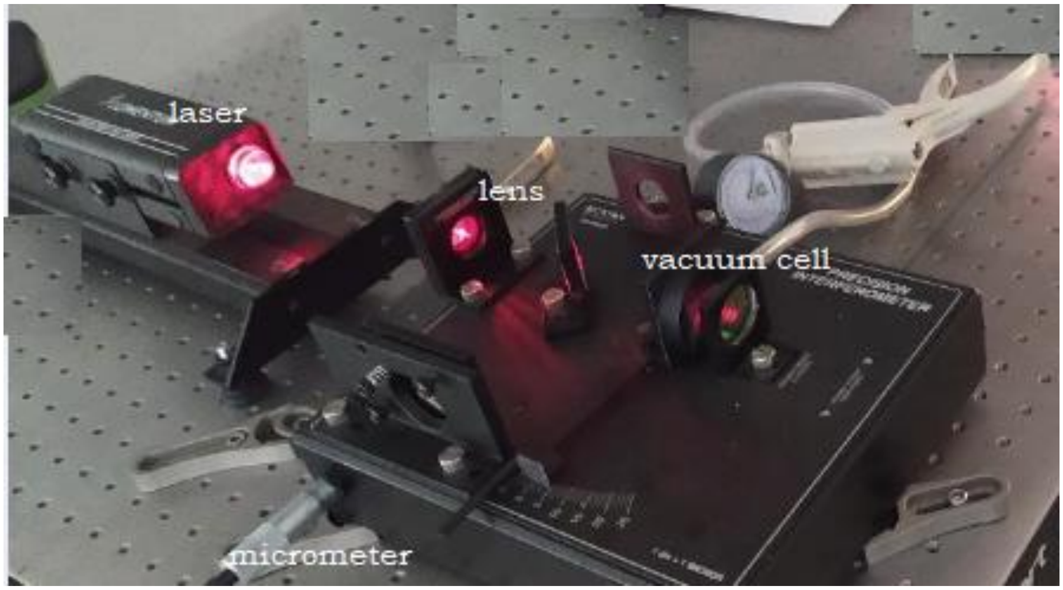
$$n = 1 + \left(\frac{N\lambda P}{2L\Delta P}\right) \tag{4}$$

Experiment

WARNING: *THE INTERFEROMETER GLASS PLATE AND MIRRORS HAVE VERY SENSITIVE SURFACES. PLEASE DO NOT TOUCH THE MIRROR OR THE PLATES. CALL YOUR INSTRUCTOR BEFORE MAKING ANY ADJUSTMENTS THAT REQUIRE YOU TO TOUCH ANY OF THE GLASS SURFACES.*

Aligning the interferometer:

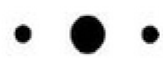
1. The laser, interferometer and screen are set up as shown in Figure below.



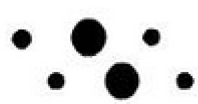
2. Cover the M1 with a sheet of paper. The laser beam should go through the glass plate and cell, strike M2, and return through the cell and the
plate to the laser.

3. Adjust the location of the laser until the return beam is very close to the exit hole on the face of the laser. (WARNING: Do not look directly into the laser beams!!)

4. A set of three or four dots should now be seen on the screen. Now uncover M1.



5. A second series of dots should now be seen on the screen. Turn the screws on M2 to superimpose the two sets of dots.



6. When the correct dots are lined up, they should "shimmer," and a slight touch of the interferometer should cause the intensity of the dots to flicker.

7. A small lens will be used to spread the laser beam passing through the interferometer. Place the small lens on the exit hole of the laser, adjusting the position so that the beam goes through the cell.

8. If the interferometer is properly aligned, an interference pattern similar to Figure 4 should appear on the screen.

9. If a series of thin circular arcs appear on the screen only a minor adjustment of the three screws on M2 is needed. If the arcs are horizontal carefully turn the top or bottom screw. If the arcs are vertical, try the side screw. In any case, turn the screws to center the pattern of the circular arcs on the screen.

Evacuating the cell and making the measurement:

1. Squeeze the handle of the vacuum pump several times to evacuate the cell.

2. When you have evacuated the cell to the lowest pressure you reasonably can, close the valve.

3. Record the reading of the vacuum gauge. This will be the Δp value you will use in Equation (1).

4. Record the room pressure, p, from the barometer in the lab.

5. Concentrate on one point on the screen and open the valve slightly until the fringes move slowly.

6. Count the number of fringes that pass a fixed point on the screen (reference line). Continue counting until room pressure is reached.

A: Refractive index by Calculations

Calculate the refractive index of air by using equation 4 and fill table 2. Use for your calculations the following parameters:

- ✓ The cell length is $L = 3\ cm$.
- ✓ The laser wavelength is $\lambda = 632.8\ nm$.
- ✓ The base air pressure is $P = 30\ inchHg$

Table 2:

No. of fringe shift N	Change in pressure Δp (inchHg)	$\Delta p/p$	Refractive index of air $n = 1 + \left(\frac{N \lambda p}{2L\Delta p}\right)$

$n_{average} = \cdots$

$n_{theory} = 1.0003$

$$Error = \left(\frac{n_{theory} - n_{average}}{n_{theor}}\right) \times 100 = \cdots \quad \%$$

B: Refractive index by Graphic

Plot N (y-axis) versus ΔP (x-axis with inchHg) and calculate the slope of the graphic. Then, use the slope to calculate via graphic the air's refractive index by using the equation:

$$n = 1 + \left(\frac{\lambda P}{2L}\right) \times slope$$

C: Compare the refractive indexes found by calculation and via the graphic.

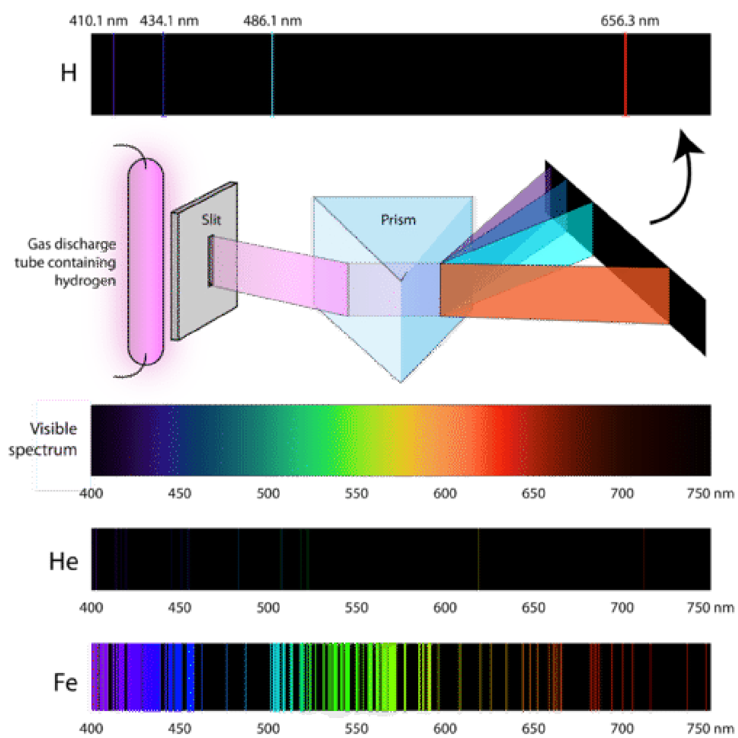
Question:

Can you mention two anther examples which are based on the same physical interference phenomenon? Explain your answer why?

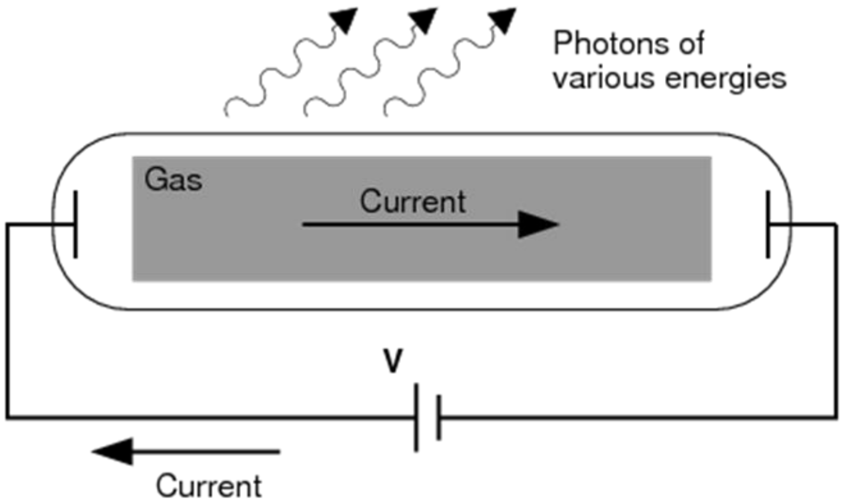
Determination of Rydberg and Planck's constant & Hydrogen Spectrum

Introduction

Atomic spectra are defined as the spectrum of the electromagnetic radiation emitted or absorbed by an electron during transitions between different energy levels within an atom. When an electron gets excited from one energy level to another, it either emits or absorbs light of a specific wavelength. Therefore, the atomic spectra can be seen as the key to the structure of the atoms. Generally, in an atom, electrons have discrete and specified energies. Those discrete energy levels are called energy states and they are nothing but the fixed distances of electrons from the nucleus of an atom. The energy levels are also called electron shells. An electron can move in one energy level or to another energy level, but it cannot stay in between two energy levels. Figure below shows spectrum of some materials.



When light from a hydrogen gas discharge tube passes through a prism, the light is split into four visible lines. Each of these spectral lines corresponds to a different electron transition from a higher energy state to a lower energy state. Every element has a unique atomic emission spectrum, as shown by the examples of helium (He) and iron (Fe). Heated solids, liquids and dens gases emit light with a continuous spectrum of wavelengths due to lot of interaction of each atom (or molecule) with neighboring's atom. In contradiction, applying high voltage to a discharge tube containing gas at low pressure emits light of only certain wavelengths. When this light is analyzed by spectrometer, a line spectrum is seen. For low density gases, the light emitted or absorbed is assumed to be by individual atoms. Therefore, for this experiment, a discharged tube filled with Hydrogen gas at low pressure will be used. In such a discharge gas tube, the electrons of the hydrogen atoms excited from one level t another due to strong electric field and when the relaxed back to their initial energy state, emit light which will be analyzed by the spectrometer. The discharge hydrogen lams is shown here:



In 1913 the Danish physicist Niels Bohr postulated a theory describing the line spectra observed in light emanating from a hydrogen discharge lamp that light emitted only when an electron jumps from a higher (upper) energy level to another lower level. With Albert Einstein's theory for the photoelectric effect, where a photon has energy proportional to its frequency, Bohr postulated the existence of energy levels in the atom. He assumed that the energy associated with the photons of light were the result of transitions in the atom from one level to another, with the energy of the photon being equal to the difference in the internal energies specific to energy levels involved in the transition from an initial state to a final state, so that:

$$E_{Photon} = -(E_{final\ state} - E_{initial\ state}) \rightarrow \Delta E = -(E_f - E_i) = E_i - E_f \qquad (1)$$

The negative sign in the equation shows photons are being emitted instead of being absorbed. In 1905 Albert Einstein worked out the theory for the photoelectric effect using a concept that Max Planck had used to describe black body radiation. In this theory, for which Einstein received his Nobel prize, he postulated that light consists of packets of energy called photons or quanta and that each quantum of light has energy proportional to its frequency. He determined that the energy of a photon, E_{photon} is given by:

$$E_{photon} = h\nu \qquad (2)$$

where ν is the frequency of the photon and h is a constant of proportionality called Planck's constant. Planck's constant is equal to $h = 6.6260755 \times 10^{-34}\ J.s$. From the electromagnetic wave theory of light having relation between frequency ν, wavelength λ and the speed of light c, it become clear that:

$$\nu = \frac{c}{\lambda} \rightarrow E_{photon} = h\nu = \frac{hc}{\lambda} \tag{3}$$

and if we combine the equations 2 and 3, we can say:

$$\Delta E = E_i - E_f = \frac{hc}{\lambda} \tag{4}$$

which relates the wavelength of the emitted light to the difference in energy levels between the final and initial states of the atom. Bohr postulated that an electron could move about the nucleus of an atom in stable orbits, without emitting radiation and losing energy. Thus, its energy would be constant in any single orbit and its energy would change only if it changed orbits and a transition occurred by the electron moving from one stable orbit to another. This postulate was revolutionary in that it contradicted electromagnetic theory, which predicted that the accelerating electron would radiate energy. To have stable orbits, Bohr further postulated that the magnitude of the orbiting electron's angular momentum would be quantized and that it must be an integral multiple of the quantity $h/2\pi$. The definition of angular momentum L for an electron of mass m_e moving in an orbit of radius r with a speed v and Bohr postulate yields:

$$L = m_e\, v\, r \rightarrow m_e\, v_n\, r_n = \frac{nh}{2\pi} \qquad with \quad n = 1, 2, 3, \ldots \tag{5}$$

where v_n is the speed of the electron and r_n is its radius as it orbits with an integral number n of the quantity $h/2\pi$. **The number n is referred to as the "Principal Quantum Number."** Bohr's model for the hydrogen atom was developed using simple classical concepts (except quantization of angular momentum). He assumed that the electron was small in mass compared to the single proton in the nucleus and that it moved about this proton in a circular orbit. He said that the electron was held in an orbit by the electrical force F_E between the electron and proton, that is given by Coulomb's Law,

$$F_E = \frac{1}{4\pi\varepsilon_0} \frac{e^2}{r_n^2} \tag{6}$$

where e is the magnitude of charges of the electron and proton, r_n is the radius of the orbit, and ε_0 is a constant known as the permittivity of free space. The electrical force is the force that supplies the centripetal force F_C , needed to keep the electron in orbit and which is given by:

$$F_C = \frac{m_e\, v_n^2}{r_n} \tag{7}$$

where m_e is the mass of the electron and v_n is the speed of the electron as moves in the circular orbit of radius r_n. Setting Equations (6) and (7) equal gives the relationship:

$$\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_n^2} = \frac{m_e\, v_n^2}{r_n} \tag{8}$$

By using equation 8, it is clear that the Bohr model finds expressions for the radii and speeds of the orbiting electron given as:

$$r_n = \varepsilon_0\ \frac{n^2\, h^2}{\pi\, m_e\, e^2} \tag{9}$$

$$v_n = \frac{1}{\varepsilon_0}\ \frac{e^2}{2\, n\, h} \tag{10}$$

In Bohr's model, the total energy E_n of the electron as it orbits the proton is the sum of the kinetic energy KE_n due to its motion and the electrical potential energy PE_n, so that:

$$E_n = KE_n + PE_n \tag{11}$$

The kinetic energy is given by the classical equation for kinetic energy, KE=½mvn2, and potential energy is given by:

$$PE_n = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_n} \tag{12}$$

The negative sign is a result of the electron being bound to the proton, and the potential is taken to be zero when the electron is infinitely removed from the proton. The total energy is then given by:

$$E_n = PE_n + KE_n = -\frac{1}{4\pi\varepsilon_0}\frac{e^2}{r_n} + \frac{1}{2}\, m_e\, v_n^2 \tag{13}$$

By combination of equations 9, 10 and 13, we can say that:

$$E_n = -\frac{1}{\varepsilon_0^2}\ \frac{m_e\, e^4}{8\, n^2\, h^2} \tag{14}$$

Since the principal quantum number n characterizes the orbit, a change of energy ΔE will occur when it undergoes a transition from an initial value of n_i (upper state) to a final value n_f (lower state) so that the energy changes from an initial value of E_i to a final value of E_f by using equation 14 will be given as:

$$\Delta E = \frac{m_e\, e^4}{8\, \varepsilon_0^2\, h^2}\left[\frac{1}{n_f^2} - \frac{1}{n_i^2}\right] \tag{15}$$

Substituting Equation 15 into equation 4 will gives:

$$\frac{1}{\lambda} = \frac{m_e\, e^4}{8\, \varepsilon_0^2\, h^3\, c} \left[\frac{1}{n_f^2} - \frac{1}{n_i^2}\right] \tag{16}$$

The equation 16 can be written with Rydberg constant R as a physical constant proposed by Johann Balmer and Robert Rydberg used to analyze atomic spectra of atoms. It was first introduced as a fitting parameter to explain hydrogen emission spectra.

$$\frac{1}{\lambda} = R \left[\frac{1}{n_f^2} - \frac{1}{n_i^2}\right] \qquad with\ \ R = \frac{m_e\, e^4}{8\, \varepsilon_0^2\, h^3\, c} = 1.097 \times 10^7 \ \ m^{-1} \tag{17}$$

Generally, by using equation 17 the emission spectrum in classified based on final quantum number n_f. When $n_f = 1$ which means that electron jumps back from upper energy levels to the ground state, the emitted light is in range of invisible ultraviolet (UV) and the series in called Lyman series. If $n_f = 2$ transition of electron from upper states emits visible light and the spectrum is called Balmer series. When electron jump back from upper states to $n_f = 3$, the light emission will be in range if invisible infrared (IR) and it is called Paschen series. In this experiment atomic spectra from a hydrogen discharge tube are studied. The wavelengths of the Balmer series of visible emission lines from hydrogen are calculated. These calculated wavelengths are used to measure experimentally the Rydberg constant (part one of the experiment) and Planck's constant (part two of the experiment). For part one, we can simplify the equation 17 to determine Rydberg constant R from measurements of wavelength λ by knowing that for the visible Balmer series of the Hydrogen atom $n_f = 2$ and initial states $n_i = n = 3, 4, 5, \ldots$ will be matched to the observed spectral pattern. Thus:

$$\frac{1}{\lambda} = R \left(\frac{1}{4} - \frac{1}{n^2}\right) \quad with\, n = 3, 4, 5, \ldots \tag{18}$$

For part two of the experiment to calculate Planck's constant, for the hydrogen atom the expression for the energy states can be written as

$$E_n = 13.6\ eV \ \left(\frac{1}{n^2}\right) \quad with\ 1\ eV = 1.6 \times 10^{-19}\, J \tag{19}$$

Where n is the quantum number of the energy state. Then for energy transition from one state to another, the emitted energy can be written as:

$$\Delta E = h\nu = \ 13.6\ eV \ \left[\frac{1}{n_i^2} - \frac{1}{n_f^2}\right] \tag{20}$$

For Balmer series of hydrogen spectrum, $n_i = 2$ and $n_f = n = 3, 4, 5, \ldots$ so that we can simplify the equation 20 as:

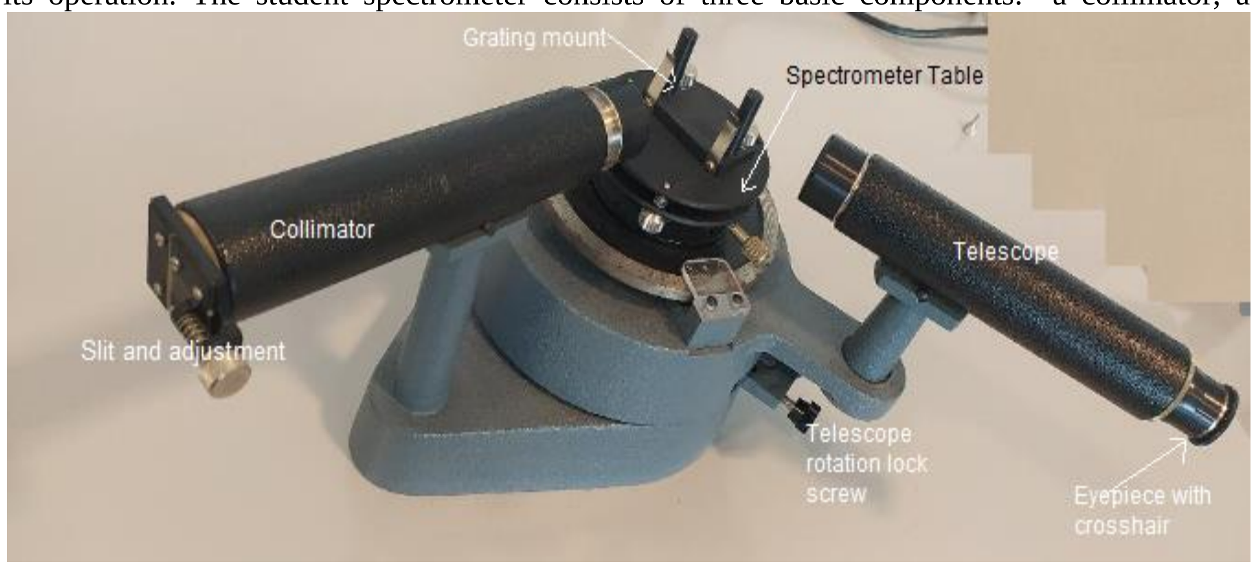
$$h\nu = \frac{hc}{\lambda} = 13.6\ eV\ \left(\frac{1}{4} - \frac{1}{n^2}\right) \rightarrow h = 13.6\ eV\ \left(\frac{1}{4} - \frac{1}{n^2}\right) \frac{\lambda}{c}$$

$$with\ c = 3 \times 10^8\ m/s \quad and \quad eV = 1.6 \times 10^{-19}\ J \tag{21}$$

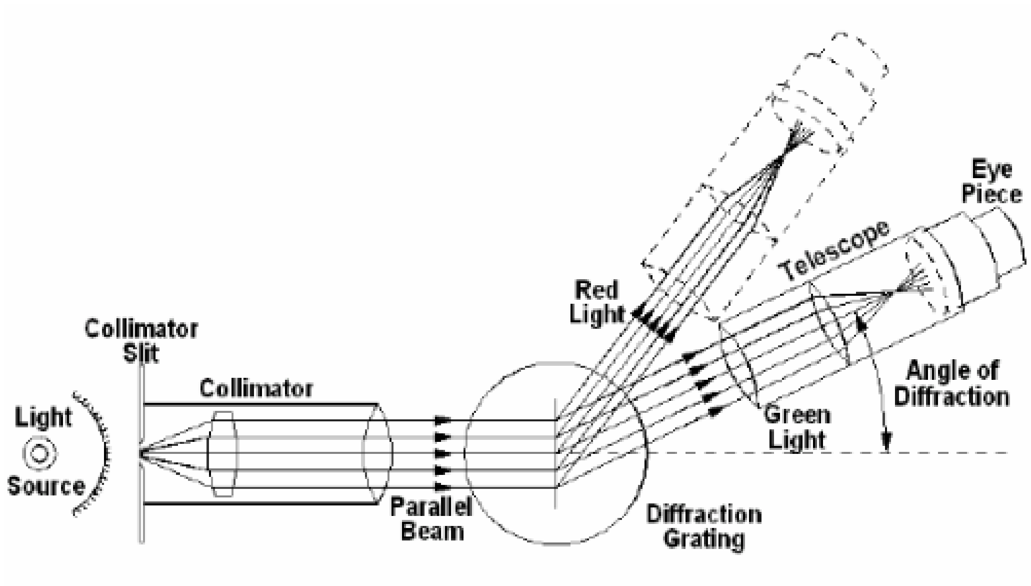
Apparatus

The experimental setup consists of: (1) a Pasco Model SP-9268 precision student spectrometer, (2) a grating with 300 lines/mm (3) a hydrogen discharge lamp and power supply, (4) a magnifying glass, (5) a small night light, and (6) a black cloth to block out stray light. The spectrometer is a precision instrument and is shown in Figure 1 with the important parts labeled. The student spectrometer is shown here:

Figure below is a schematic diagram of the student spectrometer which illustrates the principles of its operation. The student spectrometer consists of three basic components: a collimator, a



diffraction grating, and a telescope. The light to be analyzed enters the spectrometer through an adjustable slit, which forms a narrow, well-defined line source of light. This slit is located at the focal point of the collimator, which transforms the light into a parallel, collimated beam of light. The beam uniformly illuminates the grating so that all light rays strike the grating at the same angle of incidence. A parallel beam of light is necessary to illuminate the grating so that a sharp image of the slit can be formed when viewed with the telescope.



The diffraction grating disperses the light so that the diffraction angle θ depends on the wavelength of light λ and the grating spacing d according to the grating equation:

$$d \sin\theta = m\lambda \qquad with\, m = 0, 1, 2, 3, \ldots \tag{22}$$

The integer m is referred to as the diffraction order. Light of a given color will be diffracted at a specific angle for a given order. Light of a different color is diffracted at a different angle. The telescope is attached to a rotating arm whose angle of rotation can be precisely and accurately measured. This device, often referred to as a goniometer, measures the diffraction angles of the spectra of colors of light. By rotating the telescope arm, images of the slit of various colors can be viewed and magnified with the eyepiece and their respective angles of diffraction measured. The eyepiece has a graticule with an orthogonal set of crosshairs, which help align and reference the viewed images of the slit. From the grating spacing and measurements of the diffraction angles, the wavelength of the observed light can be determined from the grating equation, Equation 22. The apparatus and setup for the Balmer series experiment is shown here:

Procedure

1.Switch on the hydrogen discharge tube light source and place it about 1 cm from the collimator slit. Adjust the slit so that it is barely open.

2. Look through the eyepiece of the telescope and view the crosshairs of the graticule. This should be done preferably without your glasses if you wear them. The eyepiece is adjustable so that you can correct for your eyesight.

Slide the eyepiece in and out until the crosshairs come into sharp focus. By rotating the graticule alignment ring adjusts the orientation of the crosshairs so that they are aligned vertically and horizontally. You may need to refocus your crosshairs.

3. The telescope should be focused for an object located at infinity. Loosen the telescope rotation lock-screw (see Figure 1) and rotate the telescope arm to view a distant object on a wall across the room, or a building outside. Adjust the telescope focus knob so that the viewed image of the distant object is clearly in focus.

4. Rotate the telescope arm so that it is directly across and aligned with the collimator. The telescope focus should remain unchanged, kept focused on infinity, during this step and at all times following.

5. View the slit of the collimator through the telescope. The grating should not be in its mount. Adjust the light source to observe most intense illumination of the slit.

CAUTION: *THE HYDROGEN DISCHARGE LAMP IS POWERED BY HIGH VOLTAGE AND THE TUBE GETS HOT. DO NOT TOUCH THE TUBE ANYWHERE, ESPECIALLY NEAR THE ENDS WHERE THE ELECTRICAL CONTACTS ARE MADE.*

NOTE: *SIMPLE HYDROGEN DISCHARGE TUBES CAN LOSE THEIR HYDROGEN BY REACTING WITH IMPURITIES INSIDE THE TUBE AND BY SMALL LEAKS FROM THE OUTSIDE. A GOOD TUBE WILL HAVE A BRIGHT RED COLOR NEAR ITS CENTER, AND A POOR TUBE WILL BE MORE PINKISH NEAR THE CENTER. FOR BEST RESULTS, IT IS IMPORTANT TO HAVE A GOOD TUBE.*

6. Use the focus knob to adjust the collimator focus for the clearest, sharpest image of the slit. If needed, re-adjust the light source to provide the best illumination of the slit and to give the sharpest images.

7. The diffraction grating (grating with 300lines/mm) should now be placed in the grating mount with the grating side of the glass mount against the vertical posts. The grating itself should not be touched and the glass mount should be handled only by its edges. Loosen the spectrometer table lock-screw and align the plane of the grating so that it is perpendicular to the optical axis formed by the collimator and telescope when they are directly opposite one another. There is a line inscribed on the spectrometer table to assist with the orientation. This adjustment does not have to be precise, but in your best judgment, it should appear to be perpendicular. The image you see with the telescope directly in line with the collimator is the undiffracted, central image. Now with the black cloth over the apparatus to shield out stray light, rotate the telescope arm to the left and right to survey the different lines and colors of diffracted light. Moving away from the central image, you should see the first order diffraction lines of violet, blue violet, blue green and red light followed by the second order diffraction pattern of lines of the same colors. These visible lines are three of the Balmer lines corresponding to $n_f = n = 6, 5, 4, and\ 3$

NOTE: *THERE ARE BANDS OF VERY WEAK TRANSITIONS DUE TO MOLECULAR HYDROGEN THAT CAN SOMETIMES BE OBSERVED BETWEEN THE BLUE, GREEN, AND RED LINES. THE EMISSIONS FROM THESE BANDS GROW STRONGER AS A TUBE AGES, AND AT THE SAME TIME, THE HYDROGEN LINES GROW WEAKER.*

10. Rotate the telescope arm back to the position where it is directly opposite and in line with the optical axis of the collimator and where the central, undiffracted image can be observed. Adjust the arm so that the undiffracted image is at the center of the crosshair. Note down this position from the spectrometer vernier scale as θ_{direct} in your table.

13. The general procedure for measuring the angles of the various diffraction lines is to un-tighten the telescope arm rotation lock-screw, rotate the telescope to view the diffraction line of interest, center the image of the line near the vertical cross-hair, tighten the lock-screw, use the telescope rotation fine adjust knob to align the vertical cross-hair with the left edge of the slit image, and then read the angular scale. Repeat this step for all the other lines and record the angular position in table.1. These are θ_{read} for each colored line.

14. After the first order diffraction lines, swing the telescope a little more to observe the second order diffraction lines (m= 2). Bring each colored line to the cross hair by adjusting telescope and measure the angular position of each color and record them in table1.These are θ_{read} for each colored lines in second order diffraction.

Experiment Part-1: The Rydberg constant.

A): Use the spectrometer and read the values for angles θ_{direct} and $\theta_{measured}$ and calculate the angle which θ which must be used in equation 22 for calculating the wavelengths as follow:

$$\theta = \theta_{measured} \pm \theta_{direct}$$

The grating line spacing d of your experiment (grating element with 300 $lines/mm$) can be calculated as:

$$grating\ with\ 300\ lines/mm \rightarrow d = \frac{10^{-3}}{300} = 3.333 \times 10^{-6}\ m$$

Then, calculate for two orders of the spectrum $m = 1$ and $m = 2$ by using equation 22, the wavelength λ for each colored lines. Calculate the Rydberg constant by using equation 18 and write all your results in table 1.

Table 1: Rydberg Constant

Color	quantum number n	spectrum order m	θ (°)	wavelength λ (nm)	Rydberg constant R (m^{-1})
Violet	6	1			
Blue-violet	5	1			
Blue-green	4	1			
Red	3	1			
Violet	6	2			
Blue-violet	5	2			
Blue-green	4	2			
Red	3	2			

B): Plot a graphic of $1/\lambda$ on y-axis versus $(1/4 - 1/n^2)$ on x-axis and measure its slope. This slope gives the experimental value of Rydberg constant (R).

C): Calculate the error percentage of founded experimental value of Rydberg constant in part B by using:

$$error = \left(\frac{R_{theory} - R_{experimental}}{R_{theory}}\right) \times 100 = \cdots \quad \%$$

$$R_{theroy} = 1.097 \times 10^{7}\ \ m^{-1}$$

Experiment Part-2: Planck's constant.

D): Use the wavelength values of table 1 for each color (quantum numbers $n = 3, 4, 5, and\ 6$) and spectrum order $m = 1$ only to calculate the Planck's constant by using equation 21. Write your results in table 2.

Table 2: Planck constant

Color	n	m	λ (nm)	h (eV)	h ($J \cdot s$)
Red	3	1			
Blue-green	4	1			
Blue-violet	5	1			
Violet	6	1			

E): Calculate the error percentage of average value of Planck's constant in table 2 by using:

$$error = \left(\frac{h_{theory} - h_{average}}{h_{theory}} \right) \times 100 = \cdots \quad \%$$

$$h_{theroy} = 6.62607 \times 10^{-34} \quad J \cdot s$$

Questions

1. Show that the SI units for Planck's constant h are equal to the SI units of angular momentum.

2. Calculate the magnitude of the Bohr radius.

3. Calculate the speed of the electron moving in an orbit whose radius is equivalent to the Bohr radius.

4. Using your value for the Rydberg constant, calculate the wavelength of an ultraviolet transition in the Lyman series from the n = 2 level and to the n = 1 level.

5. Using your value for the Rydberg constant, calculate the wavelength of an infrared transition in the Paschen series from the n = 4 level and to the n = 3 level.

6. How much energy does it take to ionize a hydrogen atom in its ground state? That is how much energy has to be supplied to move an electron from the n = 1 level to the n = ∞ level?

DISPERSION OF LIGHT

Introduction:

Dispersion is the phenomena which leads to the separation of colors in a prism. Generally, the law of reflection states that for a light ray travelling in air and incident on a smooth surface, the angle of reflection $\boldsymbol{\theta_1'}$ equals the angle of incidence $\boldsymbol{\theta_1}$:

$$\theta_1' = \theta_1 \qquad (1)$$

In addition, when light crossing a boundary as it travels from medium 1 with light speed $\boldsymbol{v_1}$ to medium 2 with light speed $\boldsymbol{v_2}$, is refracted or bent. The angle of refraction $\boldsymbol{\theta_2}$ is defined by the relationship:

$$\frac{sin\theta_2}{sin\theta_1} = \frac{v_2}{v_1} \qquad (2)$$

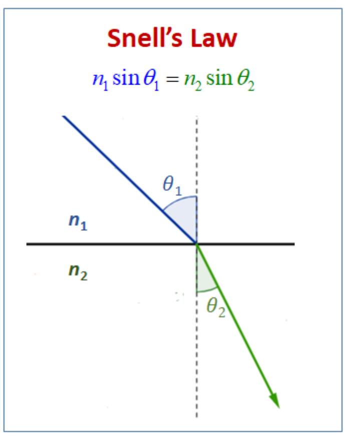
From this equation we can infer that when light moves from a material in which its speed is high to a material in which its speed is lower, the ray is bent toward the normal and vice versa. If we take $\boldsymbol{c}$ as speed of light in vacuum and $\boldsymbol{v}$ the speed of light in a medium, we can define the index of refraction $\boldsymbol{n}$ which is a property of the medium and given as:

$$n = \frac{c}{v} = \frac{\lambda}{\lambda_n} \qquad (3)$$

where $\boldsymbol{\lambda}$ is the wavelength of light in vacuum and $\boldsymbol{\lambda_n}$ is the wavelength of light travelling in the medium. Note that as light travels from one medium to another its frequency remains the same. **The Snell's law of refraction** states that:

$$\frac{sin\theta_2}{sin\theta_1} = \frac{v_2}{v_1} = \frac{n_1}{n_2} \qquad (4)$$

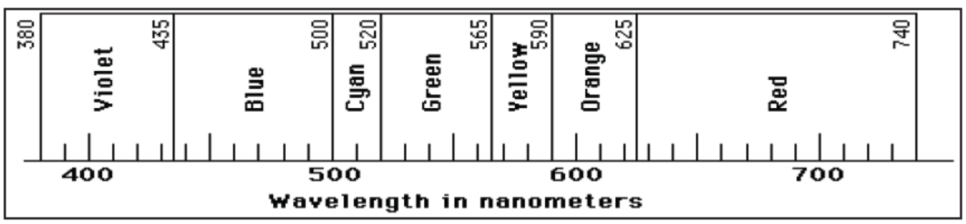
where $\boldsymbol{n_1}$ and $\boldsymbol{n_2}$ are the indices of refraction for the two media. The incident ray, the reflected ray, the refracted ray and the normal to the surface all lie in the same plane.



For a given material, the index of refraction varies with the wavelength of the light passing through the material. The relation between the refractive index and wavelength of light for a particular transparent material is given by ***Cauchy's equation***.

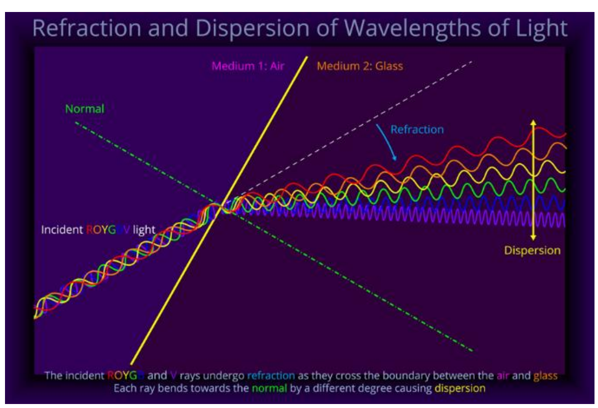
$$n(\lambda) = A + \frac{B}{\lambda^2} \qquad (5)$$

where **A** and **B** are material-dependent constants. Note that the larger the value of **B**, the more dispersive the medium. Because refractive index **n** is a function of wavelength, light of different wavelengths is bent at different angles when incident on a refracting material. The index of refraction generally decreases with increasing wavelength (for visible light). This means that violet light bends more than red light does when passing into a refracting material. Therefore, white light can be separated by a dispersive medium like a prism. Even more effective separation can be achieved with a diffraction grating. The separation of colors by a prism we see the continuous range of spectral colors (the visible spectrum) a phenomenon that is called dispersion of light. A spectral color is composed of a single wavelength and can be correlated with wavelength as shown in the chart below:



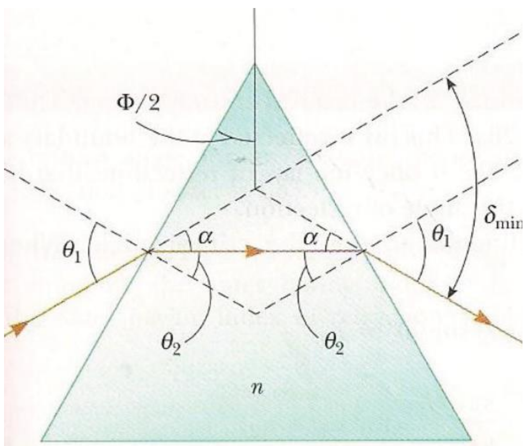
This progression from right to left is from long wavelength to short wavelength, and from low frequency to high frequency light.

Thus, the refractive index determines how much the path of light is bent, or refracted, when entering a material. This causes white light to split into constituent colors when refracted. This is called dispersion.



A refracting prism

It is a convenient geometry to illustrate dispersion. When a ray of single wavelength light incident on a prism from the left it emerges refracted from its original direction of travel by an angle, called the angle of deviation $\boldsymbol{\delta}$. However, optical prisms are typically characterized by their ***angle of minimum deviation*** $\boldsymbol{\delta_{min}}$. The minimum deviation angle $\boldsymbol{\delta_{min}}$ can be achieved by adjusting the incident ray perpendicular to one of the prism's sides which leads that the ray passing through the prism to be parallel to the bottom of the prism. In this condition, the incident angle $\boldsymbol{\theta_1}$ is equal to the refracting angle as demonstrated in figure for a prism with *refractive index* $\boldsymbol{n}$ *and* $\boldsymbol{\Phi}$ *as the apex angle of the prism*.



Using the geometry in the figure above, we find that:

$$\theta_2 = \frac{\Phi}{2} \rightarrow \theta_1 = \theta_2 + \alpha = \frac{\Phi}{2} + \frac{\delta_{min}}{2} = \frac{\Phi + \delta_{min}}{2} \qquad (6)$$

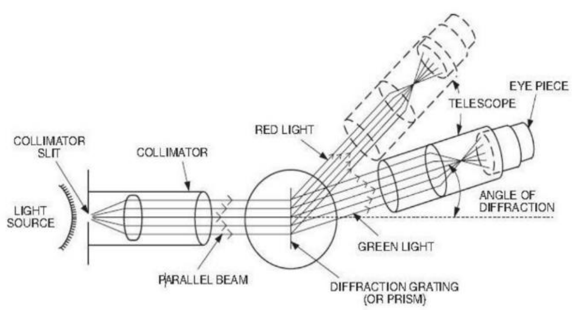
From Snell's law of refraction, with $n_1 = 1$ because medium 1 is air, we obtain:

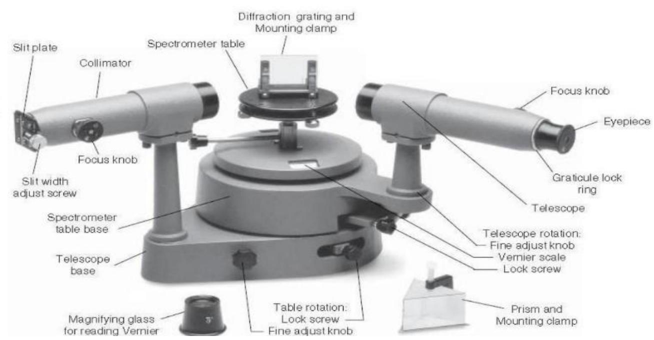
$$sin\theta_1 = nsin\theta_2 \rightarrow \sin\left(\frac{\Phi+\delta_{min}}{2}\right) = n \,.\sin\left(\frac{\Phi}{2}\right) \rightarrow n = \frac{\sin\left(\frac{\Phi+\delta_{min}}{2}\right)}{\sin\left(\frac{\Phi}{2}\right)} \qquad (7)$$

This means that knowing the apex angle of the prism Φ and measuring the angle of minimum deviation δ_{min} we can calculate the index of refraction of the prism material.

A prism spectrometer

It is an optical instrument for producing and analyzing spectra. The importance of the spectrometer as a scientific instrument is based on a simple but crucial fact. Light is emitted or absorbed when an electron changes its orbit within an individual atom. Because of this, the spectrometer is a powerful tool for investigating the structure of atoms. It is also a powerful tool for determining which atoms are present in a substance. Chemists use it to determine the constituents of molecules, and astronomers use it to determine the constituents of stars that are millions of light years away. A spectrometer consists of three basic components, a collimator, a diffracting element which can be a prism or diffraction grating and a telescope. The light to be analyzed enters the collimator through a narrow slit positioned at the focal point of the collimator lens. The light leaving the collimator is therefore a thin, parallel beam, which ensures that all the light from the slit strikes the diffracting element at the same angle of incidence. This is necessary if a sharp image is to be formed. The diffracting element bends the beam of light. If the beam is composed of many different colors, each color is diffracted to a different angle. The telescope can be rotated to collect the diffracted light at very precisely measured angles. With the telescope focused on infinity and positioned at an angle to collect the light of a particular color, a precise image of the collimator slit can be seen.





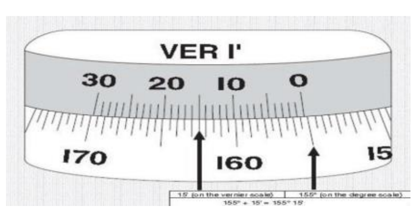
The experiment

The dispersion of light experiment consists of two parts:

1. Measure the refractive index of prism material and corresponding light speeds for each color.

2. Find the refractive index of prism material by using Cauchy formula.

A prism spectrometer and a hydrogen discharge lamp are used for this experiment. After dispersion of white light generated by a hydrogen discharged lamp, clear separated colored lines (the spectrum lines) will be visible. The spectrometer collimator is fitted with a 6 mm long slit of adjustable width. The telescope has an eyepiece with a glass, crosshair. The telescope and the spectrometer table are mounted on independently rotating bases. Vernier scales provide measurements of the relative positions of these bases to within one minute of arc.



The rotation of each base is controlled with a lock-screw and fine adjust knob. With the lock-screw released, the base is easily rotated by hand. With the lock-screw tight, the fine adjust knob can be used for more precise positioning. The spectrometer table is fixed to its rotating base with a thumbscrew, so table height is adjustable. Three leveling screws on the underside of the table are used to adjust the optical alignment. Thumbscrews are used to attach the prism clamp and the grating mount to the table, and reference lines are etched in the table for easy alignment.

1. To measure refractive index of the prism and light speeds of each color through the prism medium

The angle of minimum deviation $\boldsymbol{\delta_{min}}$ for different color lines (the spectrum lines of the Hydrogen lamp) must be measured with the spectrometer. Set up the spectrometer to view light from the hydrogen lamp. Estimate the direction the dispersed light from the collimator will exit the prism. With your bare eye, look at the prism along this direction to find the image of the collimator's slit. You should see a series of brightly colored lines. If the prism is in exactly the right orientation to provide the angle of minimum deviation, the series of colored lines move to the right as a whole, whether you rotate the table clockwise or counterclockwise. rotate the table until you are satisfied that the orientation is where the lines bounce or change direction. Since the position of the prism for minimum deviation is a slowly varying function of the wavelength, it is not necessary to reset the minimum deviation for each line (color). Once the prism is set, this orientation should not be changed for the duration of the experiment. Therefore, lightly tighten the prism holder. Then, loosen the telescope rotation lock screw and rotate the telescope so that its cross hairs are near the fixed-edge side of the slit's image. Lightly tighten the telescope rotation lock screw and finally find (read) the value of $\boldsymbol{\delta_{min}}$ for this color using the vernier scale and fill your results in table 1. Use for the apex angle of prism the value $\boldsymbol{\Phi = 60^\circ}$ and calculate the refractive indexes $\boldsymbol{n}$ and light speeds $\boldsymbol{v}$ by using the equations 3 and 7 for different colors and write your results in table 1. Calculate the average value of the refractive index $\boldsymbol{n}$ for the prism based on found refractive indexes for different colors.

Table 1:

Color	λ (Å)	$1/\lambda^2(10^{12}m^{-2})$	$\delta_{min}(°)$	n	$v\ (\times 10^8\ m/s)$
Violet	4387	5.196			
Indigo	4471	5.0025			
Blue	4713	4.502			
Bluegreen	4921	4.1295			
Green	5047	3.926			
Yellow	5875	2.8972			
Bright Red	6678	2.2424			
Dark Red	7065	2.0034			

2. To measure refractive index of the prism by the Cauchy relation

Plot a graphic of refractive indexes for each color along the y-axis against $1/\lambda^2$ along the x-axis where λ is the wavelength of corresponding colors (see table 1). The cross-section of the graphic with the y-axis is the **constant A** and the slope of the graphic is the **constant B** in Cauchy formula. After finding constants A and B from the graphic, calculate the refractive index $\boldsymbol{n}$ of the prism. Compare the average refractive index found in table 1 with the refractive index calculated from the graphic.

Questions:

1. Explain the speed of light with different color through a medium with refractive index larger than vacuum.

2. What is the relation of speed of light with different colors through space? Which color travels faster?

3. Explain how rainbow related to your experiment?

4. What could happen if for this experiment another light source such as a normal lamp was used?

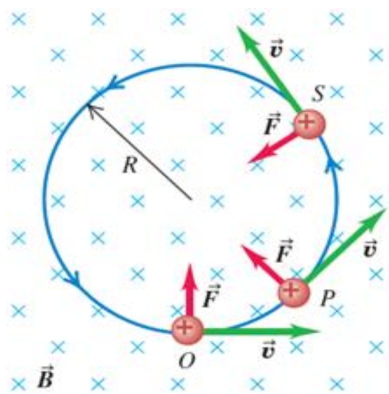
5. When white light bent by travelling through glass with refractive index n=1.5, which color diffracts most, and which color has lowest diffraction angle?

6. The dispersion of light can be explained based on the particle nature of light (photons) or electromagnetic wave properties of light?

E/M OF ELECTRON

Introduction:

When a charged particle moves in a magnetic field, it is acted on by the magnetic force and the motion is determined by Newton's laws. For example, the force applied by an electric field on a particle with **positive charge q** which is at point O and moving with velocity $\vec{\boldsymbol{v}}$ in a uniform magnetic field $\vec{\boldsymbol{B}}$ directed into the plane is shown in figure below.



The force will be given by:

$$\vec{F} = q(\vec{v} \times \vec{B}) \qquad (1)$$

The vectors $\vec{v}$ and $\vec{B}$ are perpendicular, so the magnetic force $\vec{F}$ has magnitude:

$$|\vec{F}| = q|\vec{v}||\vec{B}|sin90^{\circ} \rightarrow F = qvB \qquad (2)$$

The force is always perpendicular to velocity of the charge $\vec{v}$, so it cannot change the magnitude of the velocity, only its direction. Therefore, the electron path become a circular motion and the force F acts as a radial force F_R and we can say that:

$$F = F_R = \frac{mv^2}{r} \;\; and \;\; F = qvB \;\; \rightarrow \frac{mv^2}{r} = qvB \rightarrow v = \frac{eBr}{m} \qquad (3)$$

To put it differently, the magnetic force never has a component parallel to the particle's motion, so the magnetic force can never do work on the particle. This is true even if the magnetic field is not uniform. Note that the direction of the applied force on a positive charge in magnetic field follows the right-hand rule (the cross-product of two vectors).

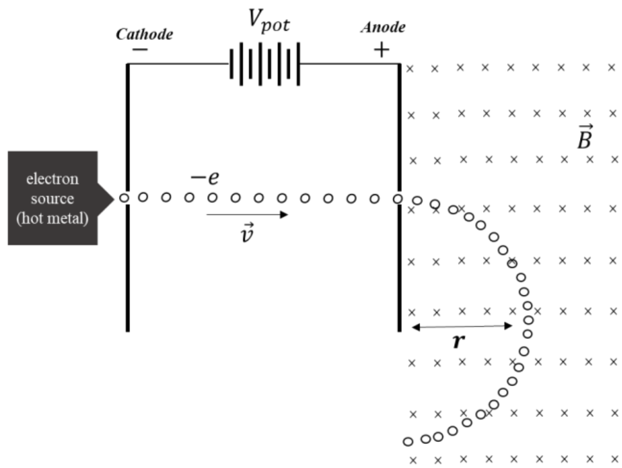
In addition, hot metal is usually used as a source for electron. If electron, then enter an electric field created between two oppositely charged plates with electric potential difference $\boldsymbol{V_{pot}}$ its velocity can be accelerated, and electron kinetic energy will be increased acting as an electron gun. The relationship between the electric potential $\boldsymbol{V_{pot}}$ and kinetic energy KE of electron can be given by:

$$KE\ (electron) = \frac{1}{2}mv^2 = eV_{pot} \qquad (4)$$

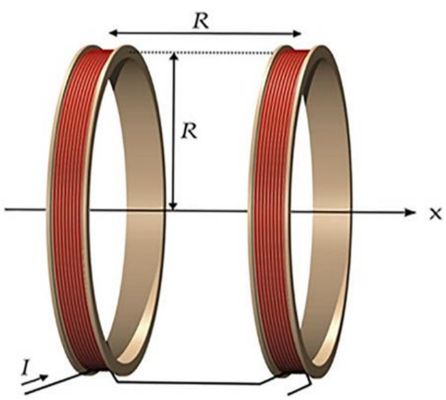
When we combine equations 3 and 4, we obtain a universal relationship for **e/m ratio** of electron with the electric potential $\boldsymbol{V_{pot}}$, magnetic field $\boldsymbol{B}$ and radius of the electron circular motion $\boldsymbol{r}$ as follow:

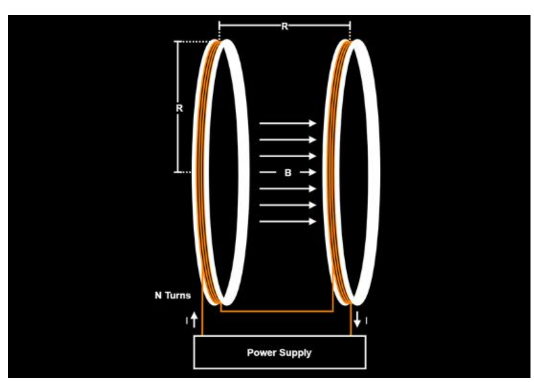
$$\frac{e}{m} = \frac{2V_{pot}}{B^2r^2} \qquad (5)$$

In figure the above-mentioned situation is demonstrated. First, a hot metal source is used for generation of electrons acting as an electron gun. The electron beam is then accelerated to high speed between two oppositely charged plates and finally electron enters a magnetic field where its patch is bent. In this way, by knowing the electric potential, magnetic field strength and radius of the electron path, e/m ratio can be calculated.



To create a uniform magnetic field for the experiment, a Helmholtz coil is used. A Helmholtz coil is a device for producing a region of nearly uniform magnetic field (named after the German physicist Hermann von Helmholtz). A Helmholtz pair consists of two identical circular magnetic coils that are placed symmetrically along a common axis, one on each side of the experimental area, and separated by a distance **R** equal to the radius **R** of the coil. Each coil carries an equal electric current (**I)** in the same direction.





The formula below gives the exact value of the magnetic field at the center point. If the radius of each coil is **R**, the number of turns in each coil is **N** and the current through each coil is **I**, then the magnetic field **B** at the midpoint between the coils will be given by:

$$B = \mu_0 \left(\frac{4}{5}\right)^{\frac{3}{2}} \frac{NI}{R} \qquad (6)$$

Here the experimental setup has $\boldsymbol{N = 130}$ and $\boldsymbol{R = 15\ cm = 0.15\ m}$ and magnetic permeability of free space is $\boldsymbol{\mu_0 = 4\pi \times 10^{-7}\ H/m}$. This means that for calculation of the magnetic field **B** for any used current I of the coils, we can use the relation:

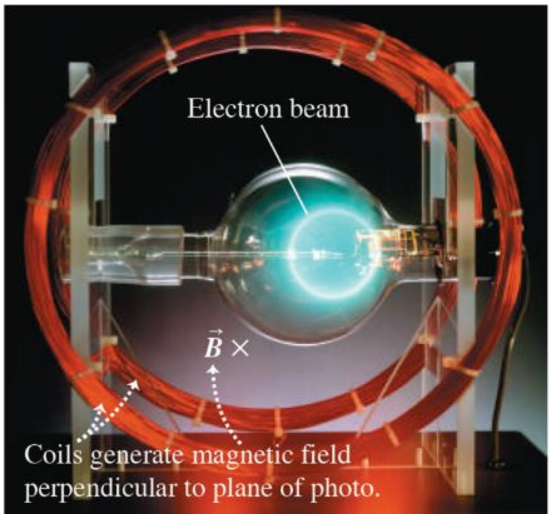
$$B = C \cdot I \qquad with\ \ C = 7.8 \times 10^{-4} \qquad (7)$$

By combining two equation 5, 6 and 7 we can obtain the relationship between ***e/m ratio*** of electron ($\frac{C}{kg}$) and electric potential $\boldsymbol{V_{pot}}$ ($Volt$), current of the coils **I** ($Ampere$) and the radius of electron circular path **r** (m) for this experiment as follow:

$$\frac{e}{m} = \frac{2\,V_{pot}}{C^2\, I^2\, r^2} \qquad with\ \ C = 7.8 \times 10^{-4} \qquad (8)$$

e/m of electron experiment-Part I:

The current used through the coils will be fixed at **constant value** $\boldsymbol{I = 1.4\ A}$. Then, different values for the electric potential $\boldsymbol{V_{pot}}$ must be used (changing the velocity of electrons entering the magnetic field). **For each electric potential, the radius of electron circular path r must be measured**.



Knowing the radius r and by using equation 8, **the e/m of electron must be calculated**, and the results must be written in table 1. Make an average value for the e/m of electron and calculate the **error percentage** of your results.

Table 1:

V_{pot} (Volt)	r (m)	e/m (C/kg)
180		
210		
240		
270		
300		

$$Error = \frac{(e/m)_{th} - (e/m)_{average}}{(e/m)_{th}} \times 100 = \cdots \% \qquad with\ (e/m)_{th} = 1.76 \times 10^{11}\ {}^{C}/_{kg}$$

Plot the graphic V_{pot} along the y-axis versus r^2 along the x-axis for this condition in which the current of each coil is constant at $I = 1.4\ A$. Note that the value for magnetic field **B** for this current must be calculated by using equation 7 first. Then, the relationship between the slope of the graphic and e/m of electron is:

$$(\frac{e}{m})_{graphic} = (\frac{2}{B^2}) \times\ slope \qquad (9)$$

e/m of electron experiment-Part II:

Now, the electric potential used will be fixed at **constant value $V_{pot} = 200\ Volt$**. Then, different values for the current of the coils must be used (changing strength of the magnetic field). For each current, the radius of electron circular path **r** must be measured again. Knowing the radius **r** and by using equation 8, **the e/m of electron must be calculated**, and the results must be written in table 2. Make an average value for the e/m of electron and calculate the **error percentage** of your results.

Table 2:

I (A)	r (m)	e/m (C/kg)
1.2		
1.4		
1.6		
1.8		
2.0		

$$Error = \frac{(e/m)_{th} - (e/m)_{average}}{(e/m)_{th}} \times 100 = \cdots \% \qquad with\ (e/m)_{th} = 1.76 \times 10^{11}\ {}^{C}/_{kg}$$

Plot the graphic I^2 along the y-axis versus $\frac{1}{r^2}$ along the x-axis for this condition in which the electric potential used is constant at $V_{pot} = 200\ Volt$. Note that here $C = 7.8 \times 10^{-4}$ as before. Then, the relationship between the slope of the graphic and e/m of electron is:

$$(\frac{e}{m})_{graphic} = \frac{2\,V_{pot}}{C^2 \times slope} \qquad (10)$$

Questions:

1. Why are the electrons visible in the apparatus?

2. Calculate the speed of the electron entering the magnetic field for electric potentials $V_{pot} = 180\ V$ and $V_{pot} = 300\ V$. What is the ratio of corresponding kinetic energies of the electron for those electric potentials?

3. If direction of the current through the Helmholtz coils is reversed, what change it causes to the electron motion and its path?

4. If in Helmholtz setup each coil is connected separately with the same current but with opposite directions, what will happen with electron path?