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Course Design Committee

Prof. A. K. Ghatak, *Retd.*
IIT Delhi, New Delhi

Prof. Suresh Garg, *Retd.*
School of Sciences
IGNOU, New Delhi
Vice Chancellor,
Usha Martin University

Prof. R.M. Mehra, *Retd.*
Dept. of Electronics,
South Campus,
University of Delhi, Delhi

Dr. Ashok Goyal, *Retd.*
Dept. of Physics, Hansraj College
University of Delhi, Delhi

Dr. Parthasarathy
Dept. of Physics,
Maharaja Agrasen College,
University of Delhi, Delhi

Prof. M.S. Nathawat
Former Director,
School of Sciences,
IGNOU, New Delhi

Prof. Vijayshri
School of Sciences
IGNOU, New Delhi

Prof. Sudip Ranjan Jha
School of Sciences
IGNOU, New Delhi

Prof. S. Gokhale
School of Sciences
IGNOU, New Delhi

Dr. Sanjay Gupta
School of Sciences
IGNOU, New Delhi

Dr. Subhalakshmi Lamba
School of Sciences
IGNOU, New Delhi

Course Preparation Team

Dr. Divya Haridas
(Experiments 1, 2,5)
Keshava Mahavidyalaya,
University of Delhi, Delhi

Dr. Rakesh Malik
(Experiments 6, 10)
A.R.S.D. College,
University of Delhi, Delhi

Dr. Raksha Sharma
(Experiment 7)
Kirorimal College,
University of Delhi, Delhi

Dr. M. B. Newmai,
(Experiments 3,4,8,9)
School of Sciences
IGNOU, New Delhi

Course Coordinators: Dr. M.B. Newmai and Dr. Subhalakshmi Lamba

Course Production

AR (P), IGNOU

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ELEMENTS OF MODERN PHYSICS: LABORATORY COURSE INTRODUCTION

In Unit 4 of the course BPHET -141, you have studied about the important experiments which laid the foundation for the development of quantum mechanics. To explain these experiments, new concepts were required which were totally different from classical ideas. Today these ideas form an intrinsic part of our understanding of the physical world. They also form the basis of several advanced experimental tools and devices. In this laboratory course, you will carry out experiments based on the fundamental postulates of quantum mechanics that you have studied in Block 2. You will determine important fundamental constants, verify the quantum model of an atom and the quantum nature of radiation. We hope that this course will help you understand better the concepts of quantum physics and why they are essential for explaining experimental observations. Experiments on special relativity and nuclear physics, which you have studied in Blocks 1 and 4 of BPHET-141 are outside the scope of this course at UG level.

As in your earlier laboratory courses, the study material for this course will state clear objectives for each experiment, provide the relevant theoretical back ground and also a step-by-step guide to carrying out the experiment. By now you are familiar with a lot of the instruments being used in a Physics laboratory. If any new apparatus is used, a brief introduction to it is given in the study material. Please read the write-up for each experiment carefully before performing the experiment.

In Experiments 1 and 2 of this course, you will determine the value of two important fundamental constants, namely the Boltzmann constant and Planck's constant. You have already studied the I - V characteristics of a p - n junction diode in Experiment 9 of BPHCL-134. In Experiment 1 of this course, you will determine the value of Boltzmann constant from the I - V characteristics of the p - n junction diode using the Shockley Diode Equation. In Experiment 2, you will determine the value of Planck's constant by using different coloured LEDs and determining their I - V characteristics. LEDs are an important semiconductor device and we have included a brief description of their working.

In Experiment 3, you will determine the value of the ionization potential of mercury. This experiment is an extension of the famous 1914 experiment of James Franck and Gustav Hertz, which was the first electrical measurement that clearly demonstrated the quantum nature of atoms and was consistent with the Bohr model. In this experiment, you will use a mercury filled diode to determine the ionization potential of mercury which is defined as the minimum energy required to remove an electron from an atom.

In Experiment 4, you will study the emission spectra of the hydrogen atom. When a hydrogen atom is excited by an electrical discharge, it emits a series of lines in the visible region which is called the Balmer series. You will be using the empirical relation proposed by Balmer for determining the wavelength of the lines of the Balmer series. The H -alpha emission line is produced by the transition of the electron between two discrete energy levels ($n = 3 \rightarrow n = 2$). The lines in the emission spectrum are produced by the transition of the electron between the quantized energy levels in the atom. So this experiment is also a verification of Bohr's atomic model.

In Experiment 5, you will study the absorption spectrum of iodine vapour. Iodine is a diatomic molecule. As you will study in this experiment, like atoms, molecules, also have discrete energy levels. Molecular energy levels are more complicated than atomic energy levels since molecules have several degrees of freedom because of their rotational/vibrational motion. The absorption spectrum of the molecule is also created by the transition of electrons between discrete energy levels. You will determine the wavelength of various absorption lines using a diffraction grating, which you have also used in BPHCL-138.

In Experiment 6, you will set up the diffraction pattern for a single and a double slit, using a laser source and determine the wavelength of the laser from the diffraction pattern. In Experiment 7, you will study the different characteristics of photoelectric effect. You will verify the tenets of the quantum theory of photoelectric effect and understand how this experiment establishes the quantum nature of electromagnetic radiation.

In Experiments 8, 9, and 10 you will determine two more important physical constants, the value of the charge to mass ratio of the electron (e/m) and the value of the electronic charge(e). In Experiment 8, the value of e/m is determined using the method of magnetic focusing. You will learn how a current carrying solenoid is used as a magnetic lens to focus a beam of electrons in a cathode ray tube (CRT). In Experiment 9, you will determine the charge of an electron using the Millikan oil drop apparatus, by studying the motion of an oil droplet between metal electrodes under the action of an electric field. This simple and elegant experiment gives a surprisingly accurate value of the charge of an electron. In Experiment 10, the value of e/m is determined by studying the deflection of a beam of electrons from a CRT by a bar magnet.

We hope that these experiments will help you develop the required skills to pursue further courses in physics and also help you understand how experimental and theoretical knowledge go hand in hand in establishing an accurate understanding of physical phenomena.

We wish you success!

EXPERIMENT 1

DETERMINATION OF BOLTZMANN CONSTANT USING $V-I$ CHARACTERISTICS OF $p-n$ DIODE

Structure

- | | | | |
|-----|---|-----|---|
| 1.1 | Introduction
Expected Skills | 1.3 | Measurement of Boltzmann
Constant using Semiconductor
Diode |
| 1.2 | Theoretical Concepts
Shockley Diode Equation
Boltzmann Constant from Shockley
Diode Equation | 1.4 | Determination of Boltzmann
Constant |
| | | 1.5 | Precautions and Sources of Errors |

1.1 INTRODUCTION

In our day to day life we work with different kinds of materials. Some of these are conducting in nature and others do not conduct at all. Electrical wires used in the household are conducting materials like copper and aluminium. Such materials are classified as good conductors or simply conductors. Some materials like rubber, plastic and cotton do not conduct electricity and are classified as insulators. There is another group of materials which have a conductivity lying between that of conductor and that of an insulator. They are known as semiconductors. Semiconductors behave as an insulator at absolute zero temperature. At room temperature these materials have conductivities considerably lower than that of a conductor but much higher than that of insulators. It is for this reason that these materials are classified as semiconductors. In Experiment 9 of BPHEL-134 you have studied the basic concepts of semiconductors and also learnt how to obtain the $V-I$ characteristics of a $p-n$ junction diode. In this experiment you will learn how to determine the Boltzmann constant from the $I-V$ characteristics of a $p-n$ junction diode.

Expected Skills

After performing this experiment, you should be able to:

- ❖ set up the apparatus to obtain the V - I characteristics of a p - n junction diode; and
- ❖ calculate the Boltzmann constant from the V - I characteristics.

You will require the following apparatus to perform this experiment.

Apparatus Required

A p - n junction diode, a DC power supply, a rheostat, milliammeter (0–20 mA), a digital voltmeter (least count of 0.05 V) and connecting wires.

Before beginning the experiment, let us briefly discuss the basic underlying concepts.

1.2 THEORETICAL CONCEPTS

1.2.1 Shockley Diode Equation

In Experiment 9 of your Laboratory course BPHEL-134, you have studied the basic concepts of semiconductors and p - n diodes. You have also obtained the V - I characteristics of the p - n diode under forward and reverse bias conditions. The general V - I characteristics of a semiconductor diode in forward and reverse bias is described by the following Shockley diode equation (named after the co-inventor of the transistor William Shockley, of Bell Telephone Laboratories):

$$I_D = I_S (e^{V_D/\eta V_T} - 1) \quad (1.1)$$

where

I_D is the diode current

I_S is the reverse saturation current

V_D is the applied voltage across the diode

V_T is the thermal voltage

η is an ideality factor, which is a function of operating condition and physical construction; it has a range between 1 and 2 depending upon a variety of factors.

$\eta = 1$ (for Ge) and $\eta = 2$ (for Si).

For $\eta = 1$, Eq. (1.1) is called the Shockley ideal diode equation. The thermal voltage V_T is defined by :

$$V_T = \frac{k_B T}{e} \quad (1.2)$$

where

k_B is the Boltzmann constant ($= 1.38 \times 10^{-23} \text{ JK}^{-1}$)

T is the absolute temperature in Kelvin ($= \text{temperature in } ^\circ\text{C} + 273$)

e is the magnitude of electronic charge ($= 1.6 \times 10^{-19} \text{ C}$)

A typical plot of Eq. 1.1 is shown in Fig. 1.1.

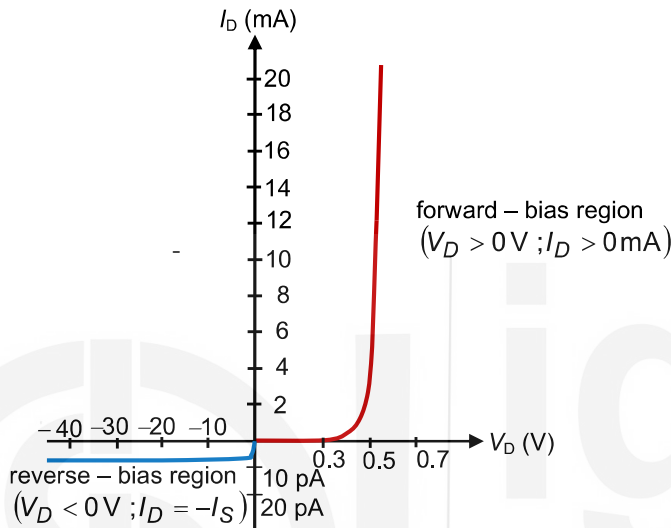


Fig. 1.1: Typical plot of the Shockley diode equation.

For positive values of V_D , (forward bias), the first term of Eq.(1.1) i.e.

$I_D = I_S e^{V_D/\eta V_T}$ will grow very quickly and is much larger than the second term i.e. I_S , so the second term can be easily neglected in comparison the first term thus reducing Eq.(1.1) to

$$I_D \cong I_S e^{V_D/\eta V_T} \tag{1.3}$$

With negative values of V_D , (reverse bias), the first term (exponential term) dies off very quickly, giving the following equation

$$I_D \cong -I_S \tag{1.4}$$

1.2.2 Boltzmann constant from Shockley Diode Equation

Substituting for V_T from Eq. (1.2) into Eq. (1.1) we get

$$I_D = I_S \left(e^{V_D e / \eta k_B T} - 1 \right) \tag{1.5}$$

Taking log on both the sides of Eq. (1.5) we get

$$\log_{10} I_D = \log_{10} I_S + \frac{V_D e}{2.303 \eta k_B T} \tag{1.6}$$

A graph between $\log_{10} I_D$ versus V_D gives $\frac{e}{2.303\eta k_B T}$ as the slope from which the Boltzmann constant k_B can be evaluated:

$$\text{Slope} = \frac{e}{2.303\eta k_B T} \Rightarrow k_B = \frac{e}{2.303\eta T(\text{Slope})} \quad (1.7)$$

With this preliminary knowledge you can now perform the experiment.

1.3 MEASUREMENT OF BOLTZMANN CONSTANT USING A SEMICONDUCTOR DIODE

Follow the procedure described below to perform the experiment.

1. Make the connections as per the Fig. 1.2. Connect the p - n diode in the forward bias mode. Connect the voltmeter across the diode and a milliammeter in series with the circuit.

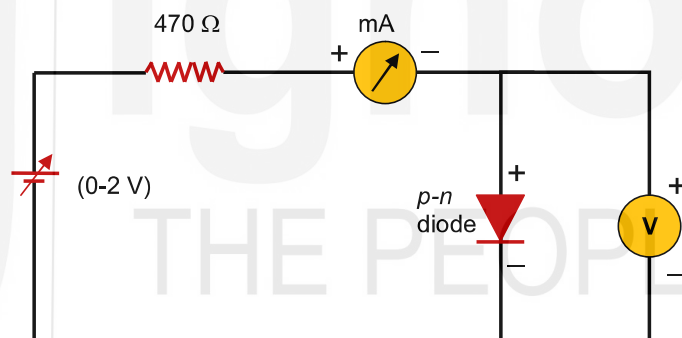


Fig. 1.2: Circuit diagram for the determining Boltzmann constant from the V - I characteristics of a p - n diode

2. Increase the input voltage from 0 V in small steps. The voltmeter will measure the voltage (V) across the diode and the ammeter will measure the current (I) flowing in the circuit.
3. Note down the reading of the voltage and current in Observation Table 1.1. A digital voltmeter and ammeter, preferably with low least count will ensure maximum number of readings and also reduce the possibility of error.
4. Take the readings till the current reaches a value of say 20mA. Note the room temperature.
5. Draw a graph with the voltage along the x-axis and $\log_{10} I$ along the y-axis. A typical graph is shown in Fig. 1.3 Since the values of $\log_{10} I$ are negative so the graph is plotted in the fourth quadrant. A straight line is obtained.

Observation Table 1.1: Variation of current with voltage

Temperature, T =K
 Least count of Voltmeter, V = V
 Least count of Ammeter, I = A

S.No.	Voltage V (Volts)	Current I (mA)	Current I (A)	Log ₁₀ I
1.				
2.				
3.				
4.				
5.				
6.				
7.				
8.				
9.				
10.				
11.				
12.				
13.				
14.				
15.				
16.				
17.				
18.				

1.4 DETERMINATION OF BOLTZMANN'S CONSTANT

Calculate the slope of the straight line as shown in Fig. 1.3 (the slope is positive):

$$\text{Slope} = \frac{AB}{BC}$$

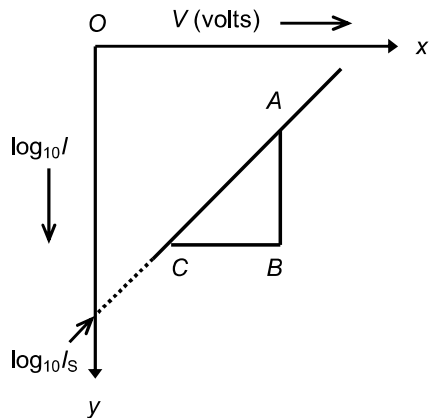


Fig. 1.3: Plot of V versus log₁₀ I.

Boltzmann's constant k is calculated as

$$k_B = \frac{e}{2.303\eta T} \times \frac{1}{\text{Slope}}$$

Using the values of e and T , and inserting the value of η (At 300 K, for a Silicon diode the value of η is 2) we can calculate k_B as

$$k_B = \frac{11.59 \times 10^{-23}}{\text{Slope}} = \dots\dots \text{JK}^{-1}$$

Result:

Boltzmann Constant = $\dots\dots \text{JK}^{-1}$

Standard Value = $1.38 \times 10^{-23} \text{JK}^{-1}$

Percentage error = $\dots\dots\dots\%$

1.5 PRECAUTIONS AND SOURCES OF ERRORS

- The value of ideality factor η is equal to 1 for germanium diode and is equal to 2 for Silicon diode. The values are taken as per the p-n junction diode used in the experiment.
- p - n junction diode is connected in forward bias condition.
- The supply voltage is to be increased slowly and should not be increased to high value else it may damage the diode.

EXPERIMENT 2

DETERMINATION OF PLANCK'S CONSTANT USING LEDs OF AT LEAST FOUR DIFFERENT COLOURS

Structure

- | | | | |
|-----|--|-----|---|
| 2.1 | Introduction
Expected Skills | 2.3 | Measurement of Planck's Constant
using Different Coloured LEDs |
| 2.2 | Light Emitting Diode (LED)
Working of an LED
<i>I-V</i> Characteristics of an LED
Planck's Constant using LED | 2.4 | Calculation of Planck's Constant |
| | | 2.5 | Precautions and Sources of Errors |

2.1 INTRODUCTION

Planck's constant, h , is a fundamental physical constant which describes the behaviour of particles and waves on the atomic scale and helps in explaining the particle aspect of light. You have studied about the relevance of the Planck's constant in Block 2 of the course BPHET-141. In this experiment we determine the value of Planck's constant using a Light Emitting Diode (LED).

To determine Planck's constant experimentally, you need to know the energy of the photon of a known frequency ν , which is $h\nu$. This can be done in two ways: i) by determining the energy gained by the material when a photon is incident on it, or ii) by determining the energy lost by the material when a photon is released. In determining Planck's constant using photoelectric effect we use the first concept. In this experiment we use the second method where emission of the photon is studied using LEDs of different colors.

Expected Skills

After performing this experiment, you should be able to:

- ❖ understand the working of an LED;
- ❖ set up the apparatus to study Planck's constant;
- ❖ draw the I - V characteristics of the LEDs at room temperature;
- ❖ understand the variation of threshold voltage with the wavelength of the light; and
- ❖ calculate Planck's constant.

You will require the following apparatus to perform this experiment.

Apparatus Required

Five different colored LEDs, a DC power supply, a rheostat, milliammeter (0–20 mA), a digital voltmeter (least count of 0.05 V) and connecting wires.

Before beginning the experiment, let us briefly discuss the basic underlying concepts.

2.2 LIGHT EMITTING DIODE (LED)

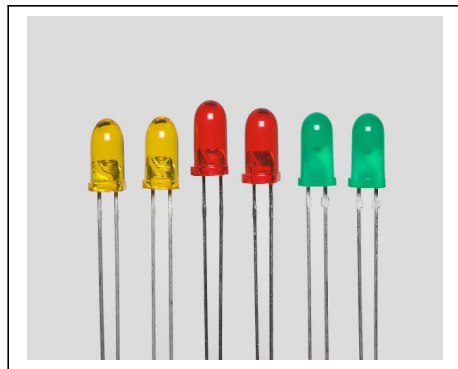
Let us now study about the working and properties of the LED

2.2.1 Working of an LED

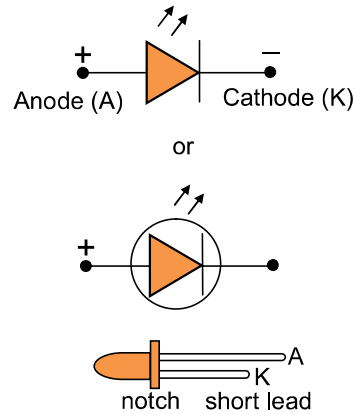
Light emitting diodes are a special category of p - n junction diodes which emit radiation in the visible as well as in infrared and ultraviolet region when a suitable forward bias (voltage) is applied across them. LEDs are now widely used in electronic industry due to their low energy consumption, smaller size and longer lifetime. LEDs are fast replacing incandescence lamps. Typically Light Emitting Diodes are made up of semiconductors such as Gallium Arsenide (GaAs), Gallium Phosphide (GaP), Gallium Arsenide Phosphide (GaAsP), Silicon Carbide (SiC) or Gallium Indium Nitride (GaInN) or other compound semiconductors which are mixed together in different ratios to produce light of a distinct color (wavelength). The color of light emitted by the LED depends on the semiconductor of which it is made. For example, a GaAsP LED emits red light (630 to 660 nm) and SiC LEDs emit blue light (430 – 505 nm).

LED operates only in the forward bias condition like any normal p - n junction diode. To work with the LED, the n -type material of the semiconductor should be connected to the negative terminal of the battery and p -type material should be connected to the positive terminal of the battery.

A typical LED is shown in Fig. 2.1(a). The schematic symbol and the conventional current flow is shown in Fig. 2.1(b).



(a)



(b)

Fig. 2.1: a) LEDs of different colors (Afrank99, CC BY-SA 2.0 <<https://creativecommons.org/licenses/by-sa/2.0/>>, via Wikimedia Commons);
b) symbolic representation of an LED.

Note that the symbol for an LED is the **standard symbol for a diode with two small arrows added denoting emission (of light)**. "A" is the anode, or plus (+) connection, and "C" is the cathode, or minus (–) connection. In Fig. 2.1(a), also note that the two terminals (leads) of the LED are of uneven length. The longer lead is the anode and the shorter lead is the cathode.

If V_0 is the minimum voltage (also called the turn-on voltage or threshold voltage) required for the emission of light of frequency ν when an LED is connected in forward bias, we can write:

$$eV_0 = h\nu \quad (2.1)$$

The energy of the photon emitted by the LED is

$$E = h\nu = h\frac{c}{\lambda} \quad (2.2)$$

Where ν is the frequency and λ , the corresponding wavelength of the emitted radiation. From Eqs. (2.1 and 2.2) we get

$$eV_0 = h\left(\frac{c}{\lambda}\right) \Rightarrow V_0 = \frac{hc}{e}\left(\frac{1}{\lambda}\right) \quad (2.3)$$

From Eq. (2.3) note that, if a graph is plotted between V_0 (along the y-axis) and $1/\lambda$ (along the x-axis) a straight line would be obtained, which has a slope hc/e . Thus Planck's constant can be determined from the slope of the graph.

So Planck's constant h can be evaluated from Eq. (2.3) if V_0 and λ are known. For this the I - V characteristics of the LED are to be obtained.

2.2.2 I-V Characteristics of an LED

To study the I - V characteristics of an LED, it is connected in forward bias, with the p -type (anode) connected to positive terminal of the battery and the n -type

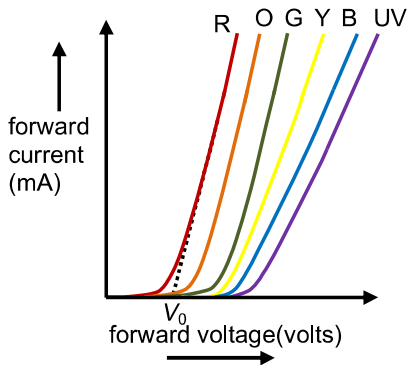


Fig. 2.2: I - V characteristics of different coloured LEDs.

(cathode) connected to the negative terminal of the battery. Care must be taken that the LED is correctly connected in the circuit otherwise it will not glow. An LED when connected in a forward bias configuration should be “**current limited**”, which means that the forward current should have a safe value, from say 5 mA for a simple LED to 30 mA or more where a high brightness light output is needed. This is achieved by using a resistor connected in series in the circuit to protect it from the excess current flow. The LED should not be connected directly to the battery or power supply because excess amounts of current will flow through it and the LED may get damaged. Fig. 2.2 shows the typical I - V characteristics for different coloured LEDs.

With this preliminary knowledge you can now perform the experiment.

2.3 MEASUREMENT OF PLANCK'S CONSTANT USING DIFFERENT COLOURED LEDs

Follow the procedure described below to perform the experiment.

1. Make the connections as shown in Fig. 2.3. A variable power supply can be used or a rheostat can be used as a potential divider across a fixed supply of 5V DC, to change the voltage across the LED in required small steps. Connect the voltmeter across the LED and a milliammeter in series with the circuit.

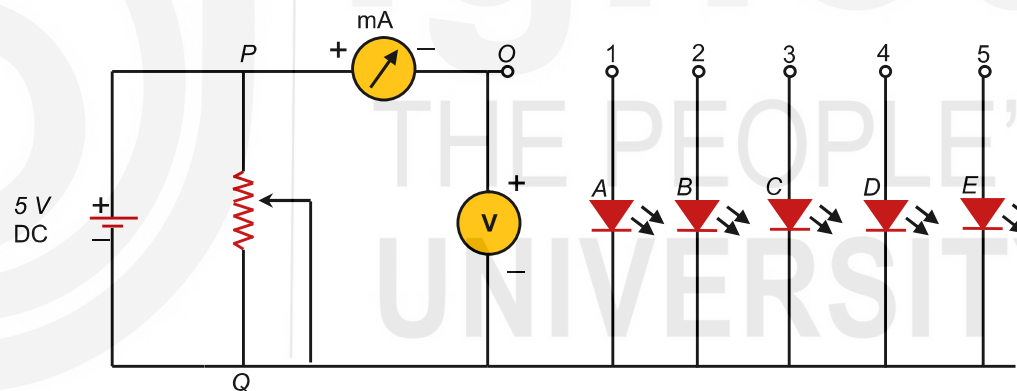


Fig. 2.3: Circuit Diagram for the measurement of Planck's constant using different colored LEDs.

2. Different colored LEDs (indicated by A, B, C, D and E in Fig. 2.3) are to be connected in the circuit as shown in the figure 2.3. To take the observation for each LED, point O is connected one by one to terminals 1, 2, 3, 4 and 5 respectively.
3. Increase the input voltage from 0 V in small steps. The voltmeter will measure the voltage (V) across the diode and the ammeter will measure the current (I) flowing in the circuit.
4. Note down the reading of the voltage and current. Write down the same in Observation Table 2.1. A digital voltmeter and ammeter preferably with low least count will ensure maximum number of readings and reduces the possibility of error.

Observation Table 2.1: Variation of current with voltage

Temperature, T =K
 Least count of Voltmeter = V
 Least count of Ammeter = A

S.No.	Voltage V (Volts)	Current I (mA)
1.		
2.		
3.		
4.		
5.		
6.		
7.		
8.		
9.		
10.		
...		

- Draw a graph with the voltage (in V) along the x-axis and current (in mA) along the y-axis.
- V_0 is determined by extrapolating the linear portion of the curve as shown in Fig. 2.2. Note the color of the light emitted.
- Repeat steps 4, 5 and 6 for each different coloured LED and note down the turn on voltage for each colour of LED.
- Note the color of each LED along with the corresponding wavelength maximum wavelength of the light emitted by it by using the datasheet of respective LED. An approximate value of wavelength of each LED is given in Observation Table 2.2.

Note down V_0 and the corresponding wavelength λ for each LED in Observation Table 2.2. Calculate $1/\lambda$ (m^{-1}) for each value of V_0 .

Observation Table 2.2: V_0 and λ for different LEDs

S.No.	Colour of light emitted	λ (nm)	$1/\lambda$ (m^{-1})	V_0 (Volt)
1.	Violet	432		
2.	Blue	472		
3.	Green	540		
4.	Yellow	590		
5.	Red	695		

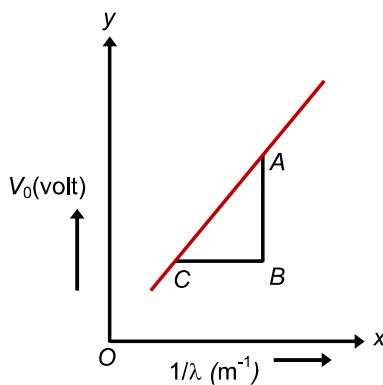


Fig. 2.4: Graph showing the variation between V_0 and $1/\lambda$.

9. Plot a graph with $1/\lambda$ along the x-axis and the turn-on voltage V_0 along the y-axis. A straight line is observed as shown in Fig. 2.4.

10. The slope of the above graph is equal to hc/e , where c is the speed of light and e is the electronic charge. Calculate h from the slope.

2.4 CALCULATION OF PLANCK'S CONSTANT

The value of Planck's constant is calculated from the slope (which is positive) of the graph in Fig. 2.4:

$$\text{Slope} = \frac{AB}{BC}$$

We also know from Eq.(2.3) that:

$$\text{Slope} = \frac{hc}{e}$$

Therefore Planck's constant h is:

$$h = \frac{e}{c} \times \text{Slope} = \dots\dots\dots \text{Js}$$

where,

$$e = 1.6022 \times 10^{-19} \text{ C}$$

$$c = 2.998 \times 10^8 \text{ ms}^{-1}$$

Result:

The experimentally determined value of

Planck's Constant = $\dots\dots\dots$ Js

Standard Value = 6.626×10^{-34} Js

Percentage error = $\dots\dots\dots$ %

2.5 PRECAUTIONS AND SOURCES OF ERRORS

- The LED should be connected in forward bias configuration.
- The supply voltage is to be increased slowly and should not be increased to high values else it may damage the LED.
- The exact value of wavelength of the light emitted by the LED is essential. An accurate measurement can be done by studying the emitted radiation using a spectrometer.
- One can use LASER LED to get the exact value of the wavelength emitted by the LED.
- The turn on voltage should be noted carefully. Manual error creeps in while finding the exact value of turn-on voltage.

EXPERIMENT 3

DETERMINATION OF IONIZATION POTENTIAL OF MERCURY

Structure

- | | | | |
|-----|--|-----|---|
| 3.1 | Introduction
Expected Skills | 3.4 | Experimental Procedure |
| 3.2 | Gas Filled Tubes
Mercury Filled Diode | 3.5 | Determination of the Ionization
Potential of Mercury |
| 3.3 | Theoretical Concepts | 3.6 | Precautions and Sources of Errors |

3.1 INTRODUCTION

In 1914, James Frank and Gustav Hertz performed an experiment that showed the existence of excited states in mercury atoms. This experiment proves that the electrons in an atom occupy discrete energy states (levels), which also confirms the quantum model of an atom. For their novel work they were awarded the Noble Prize in 1925. This experiment that you are going to perform, is, in some sense, an extension of Frank-Hertz experiment. While the aim of the Frank-Hertz experiment was to study the discrete energy levels using the absorption and emission of energy by atoms, here, you will find the minimum energy required to remove an electron from an atom. You will determine the ionization potential of mercury which is defined as the minimum energy required to remove an electron from an atom, such that the atom is ionized. The electron is removed from the outermost shell or the valence shell.

Expected Skills

After performing this experiment, you should be able to:

- ❖ explain the basic concept of ionization potential;
- ❖ understand the working of gas filled tube;
- ❖ set up the apparatus to study ionization potential;
- ❖ draw the $V-I$ graph at room temperature; and
- ❖ determine the ionization potential of mercury.

You will require the following apparatus to perform this experiment.

Apparatus Required

A gas filled diode, DC power supply, a voltmeter, milliammeter, rheostat and connecting wires.

Before beginning the experiment, let us briefly discuss understand the working of gas filled tubes and the basic underlying theoretical concepts.

3.2 GAS FILLED TUBES

A gas filled tubes (Fig. 3.1a) is a glass tube, usually consisting of two electrodes between which a potential is applied. The tube is filled with a gas such as argon, neon, nitrogen or mercury, at low pressure. There are two types of gas filled tubes: a) hot cathode gas filled diode known as **phanotron**, and b) hot cathode gas filled triode known as **thyatron**. In this experiment you will be using a gas filled diode tube to find the ionization potential of the gas. A gas filled diode is symbolically represented as shown in Fig. (3.1b).

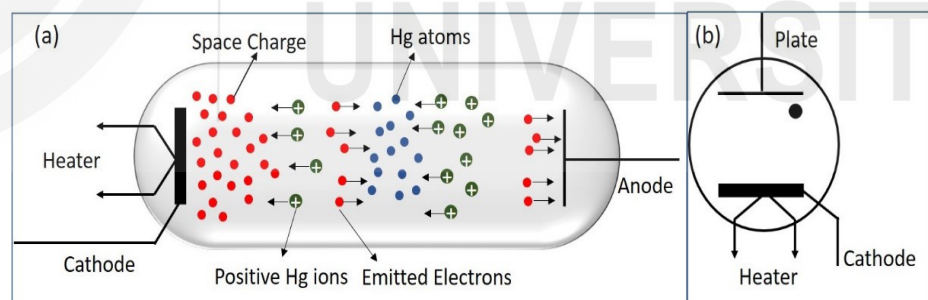


Fig. 3.1: a) Gas filled tube, filled with mercury atoms, showing the ionization of mercury atoms due to collision with emitted electrons; b) symbolic representation of a gas filled tube.

The electrons emitted from the cathode are attracted towards the positively charged plate, and as the electrons move through the tube, they collide with the gas present in the tube. The heavy positive ions slowly drift towards the cathode in such a way that the space between the plate and the cathode is filled with large number of positive ions, this in a way neutralizes the effect of space charge and makes the thermionic emission available as plate current.

It is important you understand what is a space charge. The electrons emitted from the cathode may not reach the positively charged plate, due to repulsion among these electrons, but rather they may form an electron cloud around the cathode. Thus, any new electron emitted by the cathode is repelled by the cloud and the thermionic electron may no longer be able to reach the positive plate. This cloud of electrons is called **space charge**, and the neutralization of the attraction of the positive plate due to electron cloud is known as **space charge effect**. Space charge effect is largely observed in vacuum tubes, however in gas filled tubes, the presence of positive ions allows the steady flow of the thermionic electrons. Hence, gas filled tubes can carry several times the current carried by vacuum tubes.

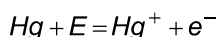
From previous experiments as well from the experiments in previous laboratory courses you are already familiar with most of the apparatus being used for this experiment such as a milliammeter, voltmeter, rheostat, etc. Here we describe the mercury filled diode which you use in this experiment.

3.2.1 Mercury Filled Diode

A mercury (Hg) filled diode is an evacuated glass tube filled with mercury vapour at a low pressure of about 10-50 mm of mercury. A filament, a cathode and an anode are fitted inside the tube. The filament is placed below the cathode, which glows and heats up to the cathode. As a result, electrons are emitted from the surface of the cathode. The emitted electrons will move towards the anode/positive plate if it is connected to the positive terminal of the battery. As the emitted electrons move towards the anode, they collide with the mercury atoms present in the tube. The collision of a sufficiently high energy electron with the mercury atom removes an electron from the 6s shell of the mercury atom and in the process mercury is ionized (Hg^+).

3.3 THEORETICAL CONCEPTS

In this experiment, you have to study the ionization of mercury due to removal of an electron from its valence shell. When the term ionization is used, it usually implies removal of a single electron from the atom (A^0) and the atom is in ionized state of A^+ , unless stated otherwise. If a second electron is removed from the same atom, the atom becomes A^{2+} and this is called the 2nd ionization and so on. So, the 1st ionization is in general simply termed as the ionization of an atom. In the present experiment for mercury,



where $E = 10.437 \text{ V}$ is the ionization energy required to remove an electron from the Hg atom.

As the anode potential or the plate potential is increased steadily, the corresponding plate current also increases, indicating that the number of emitted electrons from the cathode, reaching the positive plate is also increasing. Now, as the plate potential is increased continuously, the kinetic

energy of the emitted electrons also increases continuously. At a critical potential, the kinetic energy of the emitted electrons will be able to remove an electron from the valence shell of the mercury atom. The electrons removed from the mercury atoms are also known as *secondary electrons* and this potential is known as *ionization potential*. Beyond the ionization potential, the plate current will increase drastically since the number of electrons reaching the positive plate has increased, the electrons are now a combination of emitted electrons and the secondary electrons. Thus, further increase in the plate potential will lead to a huge increase in the plate current. If you plot a graph between plate current and plate voltage, you will observe that at a particular potential there will be a discontinuity in the increase in the plate current, after which the rate of increase in current with respect to potential will become very large when compare to rate of increase of current below the ionization potential.

With this preliminary knowledge you can now perform the experiment.

3.4 EXPERIMENTAL PROCEDURE

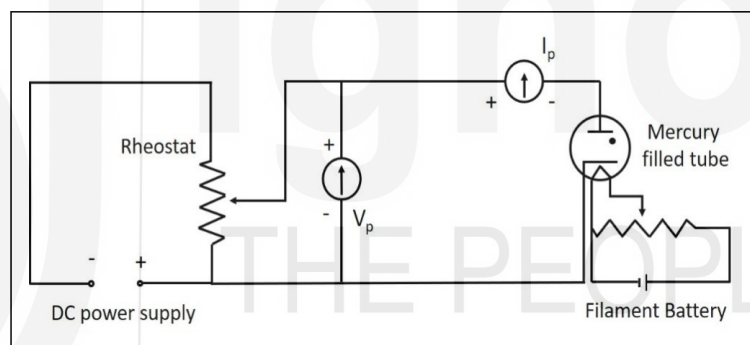


Fig. 3.2: Circuit diagram to determine ionization potential of mercury.

Follow the procedure described below to perform the experiment.

1. Make the connection as shown in Fig. 3.2 and turn on the power supply.
2. Apply suitable potential to the heating filament by the adjusting the rheostat connected to filament battery and note down the filament current (I_f).
3. Turn on the DC power supply and adjust the plate voltage using the rheostat such that the milliammeter gives no deflection.
4. Slowly vary the plate voltage (V_p) using the rheostat, say in steps of 1V, upto 20 V, and take the reading of the milliammeter (I_p) for each case.
5. Draw a graph of V_p versus I_p with V_p along the x-axis and I_p along the y-axis.

Observation Table 3.1: Variation of current with voltageLeast count of Voltmeter, V_p =VLeast count of Ammeter, I_p =A

Sl. No.	Plate Potential V_p (V)	Plate Current I_p (A)
1.		
2.		
3.		
4.		
5.		
6.		
.....		

3.5 DETERMINATION OF THE IONIZATION POTENTIAL OF MERCURY

To obtain the value of ionization potential of mercury a graph between I_p and V_p is plotted as shown in the Fig. 3.3. From the graph you can see that at a critical potential, the current increases abruptly. This potential where the current increases abruptly is the ionization potential.

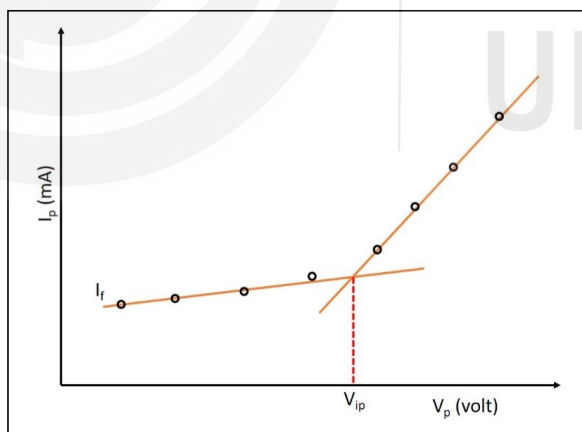


Fig. 3.3: A graph between the plate voltage and the plate current. The potential where the plate current begins to increase abruptly is the ionization potential.

At the ionization potential, electrons are removed from the mercury atoms and as a result more electrons (emitted electrons and secondary electrons) reach the positive plate, hence there is an abrupt increase in the plate current. This point in the I_p versus V_p graph is used to determine the ionization potential.

Result:

The experimentally determined value of ionization potential of mercury

= V

Standard Value = 10.437 V

Percentage error = %

3.6 PRECAUTIONS AND SOURCES OF ERRORS

- Use sand paper to clean the copper wires before connecting the apparatus to remove oxidation and other impurities.
- The plate potential should not be increase beyond 20 V.
- The supply voltage is to be increased steadily.
- The specification given by the manufacturer should be followed strictly.



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EXPERIMENT 4

DETERMINATION OF THE WAVELENGTH OF H-ALPHA EMISSION LINE OF HYDROGEN ATOM

Structure

4.1	Introduction Expected Skills	4.3	Description of the Apparatus Hydrogen discharge tube
4.2	Theoretical Concepts Balmer Series Determination of Wavelength using Diffraction Grating	4.4	Experimental Procedure
		4.5	Determination of the Wavelength of the H-Alpha Emission Line
		4.6	Precautions and Sources of Errors

4.1 INTRODUCTION

In the previous experiment you have learned how to determine the ionization potential of mercury. In the 19th century, physicists devoted considerable in studying the spectra of atoms and molecules. Spectra are formed by the absorption and emission of electro-magnetic radiation by atoms and molecules. Many spectra have been studied in great detail, however, the hydrogen emission spectrum is the most intensely analyzed. When a Hydrogen atom is excited by an electrical discharge, it emits a series of lines in the visible region. This series is called the Balmer series after the name of a Swiss teacher Johan Balmer, who proposed an empirical relation to describe the wavelength of these spectra.

Expected Skills

After performing this experiment, you should be able to:

- ❖ identify the various spectral lines in a hydrogen atom;
- ❖ set up the apparatus to obtain diffraction pattern using a grating on a spectrometer; and
- ❖ determine wavelength of the H-alpha emission in hydrogen atom.

You will require the following apparatus to perform this experiment.

Apparatus Required

Spectrometer, diffraction grating and hydrogen discharge lamp.

Before beginning the experiment, let us briefly discuss the basic theory underlying the experiment.

4.2 THEORETICAL CONCEPTS

Atomic or molecular interaction with an electromagnetic radiation results in the absorption or emission of electromagnetic radiation, which may be classified as absorption or emission spectra, respectively. Such a spectrum may be a (a) continuous or a (b) discontinuous spectrum. A continuous spectrum consists of a wide range of unseparated wavelengths, while a discontinuous spectrum is a line spectra or a band spectra.

You have calculated the value of this constant in Example 4.4 of Unit 4 of BPHE-141:

$$R = \frac{R_H}{hc}$$

where

$$R_H = 13.6 \text{ eV} \\ = 2.18 \times 10^{-18} \text{ J}$$

When an atom absorbs some energy, electrons may be excited to a higher energy level depending on the absorbed energy. This excited electron comes back to its initial state by emitting energy, where the emitted energy is the energy difference between the higher energy state and the (initial) lower energy state. This emitted energy may lie within a large spectrum of wavelengths and hence the study and analysis of emission spectra is very complicated, especially for large atoms. It is in this context that the emission spectra of hydrogen atom becomes very important since it is the simplest possible atom that we can study.

4.2.1 Balmer Series

In 1885, Balmer discovered that the wavelength of the spectral lines in a hydrogen spectrum in the visible region can be described using the following relation:

$$\frac{1}{\lambda} = R \left(\frac{1}{2^2} - \frac{1}{n^2} \right) \quad (4.1)$$

where λ is the wavelength of the radiation, $R = 1.097 \times 10^7 \text{ m}^{-1}$, is a constant known as the Rydberg constant (see margin remark) and n is an integer greater than 2. The Balmer lines for various values of n are given in Table 4.1. Here you can see that for $n=3$, the spectral line is known as the H-alpha line.

The generalized expression given by Rydberg is:

$$\frac{1}{\lambda} = R \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \quad (4.2)$$

Here n_f and n_i are integers with $n_i > n_f$.

If a transition occurs from n_i to $n_f=1$, the series is called Lyman series, if $n_f=2$, then it is part of Balmer series, and if $n_f=3$, then it forms the Paschen series. The formation of Balmer series in hydrogen spectrum is shown by the energy level diagram in Fig. 4.1.

Table 4.1

Line	Value of n
H _α	3
H _β	4
H _γ	5
H _δ	6

4.2.2 Determination of Wavelength using Diffraction Grating

The wavelengths of the spectral lines in the hydrogen emission spectra are spectrally resolved using diffraction grating. In Experiment 6 of BPHCL-138, you already know how to determine the wavelength of light using a diffraction grating. Let N be the number of parallel slits in a plane diffraction grating, each of width ' a ' and an opaque spacing ' b ' between them, then the distance between the center of two adjacent slits is $d = a + b$, where $(a+b)$ is known as grating element. The maxima condition for diffraction grating is given as:

$$m\lambda = (a + b)\sin\theta \quad (4.3)$$

Where m is the order of the spectrum and θ is the angle of diffraction.

The spectrum of a source (monochromatic or white light) is obtained using a grating as shown in Fig. 4.2. The diffraction pattern is then observed using a spectrometer to determine the wavelength. The diffraction pattern observed through the spectrometer for hydrogen emission spectra may consist of various colours such as red, blue, violet and emissions in the ultra-violet region. In the present experiment, your primary objective is to determine the wavelength of H_α emission, however, you can also determine the wavelength of the H_β or H_γ emission using Eq. (4.3). The experimental procedure for the different emission lines will be more or less the same.

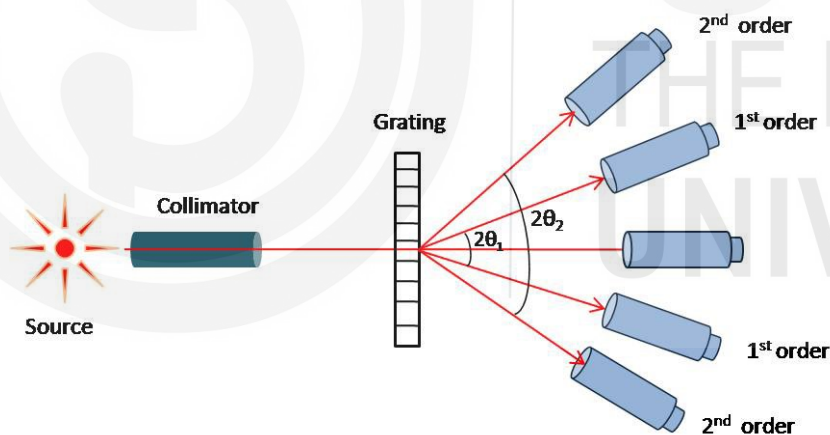


Fig. 4.2: Diffraction pattern obtained using diffraction grating as observed through a telescope for 1st order and 2nd order spectra.

4.3 DESCRIPTION OF THE APPARATUS

The spectrum of hydrogen atom is obtained with the help of a hydrogen discharge lamp and a diffraction grating. The spectral lines of Hydrogen are studied using a spectrometer which you have already learnt about in BPHCL-138. Before you start with the experiment, it is important that you familiarize yourself with the apparatus that you will be using.

A schematic diagram of the experimental set up is shown in Fig. 4.3.

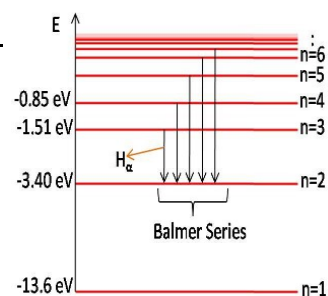


Fig. 4.1: The energy spectrum for the Balmer series indicating the transition of electrons from $n = 3$ to $n = 2$ leading to emission of H_α spectral line.

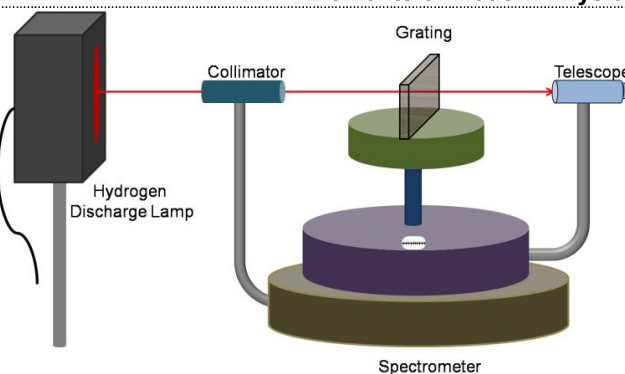


Fig. 4.3: Schematic diagram of the experimental set up.

Let us discuss one important component that you have not studied about before, which is the hydrogen discharge tube.

4.3.1 Hydrogen Discharge Tube

Hydrogen discharge tube is a part of broader class of tubes known as cold cathode discharge tube. They are also called Geissler tubes and are used to study spectra of various gases such as neon, argon, hydrogen or helium at low pressure. Geissler tube consists of two glass tubes connected by a capillary tube. The electrodes at the extreme ends of the two glass tubes are usually made of aluminium or platinum. A schematic diagram of a Geissler tube is shown in Fig. 4.4.



Fig. 4.4: Simplified schematic diagram of a hydrogen discharge tube emitting intense red light.

A hydrogen discharge tube is a tube filled with hydrogen at a low pressure of about 1 or 2 mm of mercury. The operating potential is about 5000 volts. Highly accelerated electrons are discharged from the cathode and collide with the hydrogen atoms present in the tube. This collision excites the hydrogen atoms to higher energy levels ($n = 3, 4$ and so on). These excited atoms then de-excite due to collision with the wall of the tube and come back to lower energy levels thereby emitting radiation. The emitted radiation is usually intense red and is used for experimental purposes.

4.4 EXPERIMENTAL PROCEDURE

Follow the steps described below to perform the experiment.

1. Setting up the spectrometer: Prior to using the spectrometer for measure, it is essential to do the following:
 - a) *Levelling*: The apparatus is levelled using a spirit level. The spirit level should be placed on the prism table and the three equidistant screws should be adjusted till the bubble in the spirit level is at the center. Similar adjustment should also be done for the telescope and the collimator so their axes are horizontal.

- b) *Adjustment of telescope:* Turn the telescope towards the white wall and adjust the eyepiece till the crosswire become distinct. Now turn the telescope towards a distant object and adjust the telescope till the object becomes sharp and distinct.
- c) *Adjustment of the collimator:* The collimator and the telescope are aligned and the parallel beam coming from the collimator is viewed using the eyepiece of the telescope. The slit of the collimator should be adjusted such that the image is sharp and bright and about 1 mm wide. If the image does not appear vertical, you should turn the slit along its plane so that the image becomes vertical.

Take readings on the spectrometer as you have learnt in your Optics laboratory (Experiments 1 and 3, BPHCL 138)

2. Setting the grating at a normal incidence position.
 - a) Set the telescope to receive direct light from the collimator. Align the crosswire of the telescope to coincide exactly with the image from the slit and take reading of one vernier scale.
 - b) Rotate the telescope such that it is at 90° with respect to incident light. Say if the reading taken in one vernier scale in step (a) is 120° , you should rotate to the left or to the right depending on your convenience and make sure that the reading of the same vernier scale is either 30° or 210° .
 - c) Place the grating on the prism table and slowly turn the prism table until an image is formed on the crosswire of the telescope, as shown in the Fig. 4.5. Once the image of the slit coincides with the crosswire of the telescope, note the reading of the prism table, it is at this position of the grating that the light is incident at 45° on the grating.
 - d) Rotate the prism table by 45° so that the ruled side faces the telescope, in this position the light from the collimator is incident normally on the surface of the grating. Clamp the grating in this position.

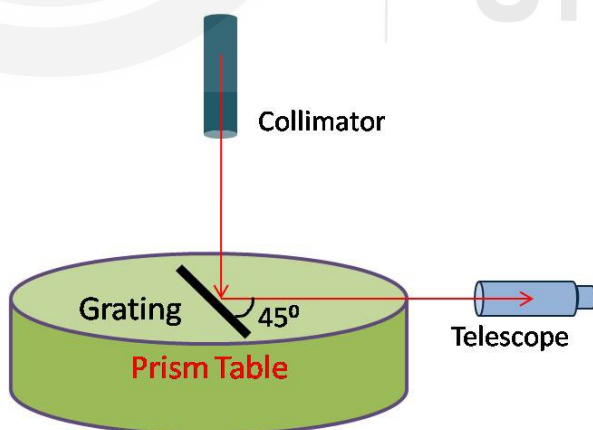


Fig. 4.5: Adjustment of prism table to achieve normal incidence on the surface of grating.

Follow the procedure described below to perform the experiment.

3. Move the telescope to the center and observe the direct image. Diffraction patterns are observed on either side of the direct image.

4. Rotate the telescope to the left of the direct image. Coincide the crosswire with the first image.
5. Note down the reading of vernier 1 and vernier 2 in Observation Table 4.1.
6. Rotate the telescope to the right of the direct image, coincide the crosswire to the first image on the right.

Note down the reading of vernier 1 and vernier 2 in Observation Table 4.1.
Repeat the observations for the second order spectrum.

4.5 DETERMINATION OF THE WAVELENGTH OF H-ALPHA EMISSION LINE

Least count of the spectrometer =

Number of lines per inch, $N = \dots$

Grating constant, $(a+b) = 2.54 / N = \dots\text{cm}$

Observation Table 4.2

Order of Spectrum	Vernier	Telescope Reading						Angle of Diffraction		
		Left			Right			2θ	θ	Mean
		MSR	VSR	Total	MSR	VSR	Total			
1 st ($m = 1$)	V ₁									θ_1
	V ₂									
2 nd ($m = 2$)	V ₁									θ_2
	V ₂									

From Eq. (4.3) we have

$$m\lambda = (a + b)\sin\theta$$

Here m is the order of the spectrum.

For 1st order spectrum ($m=1$), the relation can be written as

$$\lambda = (a + b)\sin\theta_1$$

$$\lambda = \dots\text{cm} = \dots\text{m}$$

For 2nd order spectrum ($m = 2$), the relation can be written as

$$2\lambda = (a + b)\sin\theta_2$$

$$\lambda = \dots\text{cm} = \dots\text{m}$$

Result: Mean wavelength (λ) for H $_{\alpha}$ line =cm =m.

4.6 PRECATUIONS AND SOURCES OF ERRORS

1. The hydrogen discharge lamp is powered by very high voltage and the tube gets hot. Do not touch the tube or the parts where electrical contacts are made.
2. Always touch the grating from the side, do not touch the grating on its surface.
3. Do not change the position of the spectrometer throughout the experiment.

EXPERIMENT 5

STUDY OF THE ABSORPTION LINES IN THE SPECTRUM OF IODINE VAPOUR

Structure

- | | | | |
|-----|---------------------------------|-----|-----------------------------------|
| 5.1 | Introduction
Expected Skills | 5.4 | Experimental Procedure |
| 5.2 | Absorption Spectrum of Iodine | 5.5 | Precautions and Sources of Errors |
| 5.3 | Description of the Apparatus | | |

5.1 INTRODUCTION

You have studied about the emission spectrum of elements in Unit 4 of BPHET-141. As you know an element has a characteristic atomic emission spectrum which shows up as a set of colourful lines on a dark background corresponding to certain discrete wavelengths.

Elements also have a characteristic absorption spectrum. In the absorption spectra portions of a continuous spectrum are missing, appearing as dark lines or gaps. An **absorption spectrum** of an element has dark lines in the same position as the bright lines in the **emission spectrum** of an element. The characteristic atomic spectra of elements is explained on the basis of Bohr's Atomic Model, which you have also studied in Sec. 4.6 of BPHET141. When the electron in an atom makes a transition between energy states, energy is emitted or absorbed. The energy of the emitted or absorbed radiation is equal to the difference of energy between the two energy levels. Since the energy levels are discrete, the emitted or absorbed energy corresponds only to specific frequencies (or wavelengths).

Just like an atom, a molecule is also characterized by a set of discrete energy levels. Transitions between these quantized energy levels due to the absorption or emission of electromagnetic radiations, gives rise to the characteristic absorption and emission spectrum of molecules. In this Experiment, you will study the absorption spectrum of Iodine vapour. Iodine, as you may have studied, is a diatomic molecule.

Expected Skills

The spectrum of each element is like its distinctive finger print which is unique. It is often used to provide information about the structure and the composition of a substance or an object. For example, spectra can be used to identify elements in distant light sources. Joseph von Fraunhofer studied the spectrum of sun's electromagnetic radiation which appeared to be a continuous spectrum. He observed that the spectrum is not a continuous one but rather a series of dark lines are present in the spectrum. These dark lines, sometimes called Fraunhofer lines are formed due to absorption of specific wavelengths of light by cooler atoms in the outer atmosphere of the sun. It was through the study of this spectrum that we came to know that the sun contains large amounts of hydrogen, iron, and carbon, along with smaller amounts of other elements.

After performing this experiment, you should be able to:

- ❖ explain qualitatively the origin of the absorption spectrum of Iodine; origin of spectra and thus able to differentiate absorption spectra and emission spectra;
- ❖ set up the apparatus to study absorption spectra;
- ❖ observe the absorption spectrum of Iodine; and
- ❖ determine the wavelength of various absorption lines.

You will require the following apparatus to perform this experiment.

Apparatus Required

Iodine vapour tube, a steel bench with mounts to hold the iodine tube, a power supply, a straight filament lamp, optical diffraction grating (with 15000 lines per inch), spectrometer, reading lamp and iodine crystals.

Before beginning the experiment, let us briefly discuss the basic theory about the molecular absorption spectrum of Iodine.

5.2 ABSORPTION SPECTRUM OF IODINE

Absorption or emission of radiation takes place due to the transition between the energy levels. Molecular energy levels are more complicated than atomic energy levels. This is because, molecules, as you have studied in BPHCT-135, have several degrees of freedom corresponding to their rotational/vibrational motion. Assuming that the electrons within a molecule are moving much faster than the heavier nuclei, it is possible to separate the electronic motion from the rotational and vibrational motion. So the typical energy in an electronic state of the molecule is $E = E_{\text{elec}} + E_{\text{vib}} + E_{\text{rot}}$. The energy scales are different such that $E_{\text{elec}} \gg E_{\text{vib}} \gg E_{\text{rot}}$ holds. Therefore each electronic energy level of a molecule consists of vibrational sub-levels and each vibrational level consists of rotational sub-levels. Molecular electronic transitions from one electronic state to another could be due to transitions within different vibrational or rotational sub-levels. Thus a transition between two electronic levels results in band (or close spaced collection of energy levels) consisting of many lines giving a band of many transitions close to the same frequency.

Iodine is non-metallic and solid at room temperature. The molecular lattice contains discrete diatomic molecules. Now if light having a continuous emission spectrum (Fig. 5.1a) is made to pass through the iodine vapours, then a few wavelengths of the emission spectrum are found to be missing and appear as dark lines (Fig. 5.1b). These dark lines appear exactly at those wavelengths which are absorbed while travelling through the iodine vapours making a transition between the ground state to the first excited state.

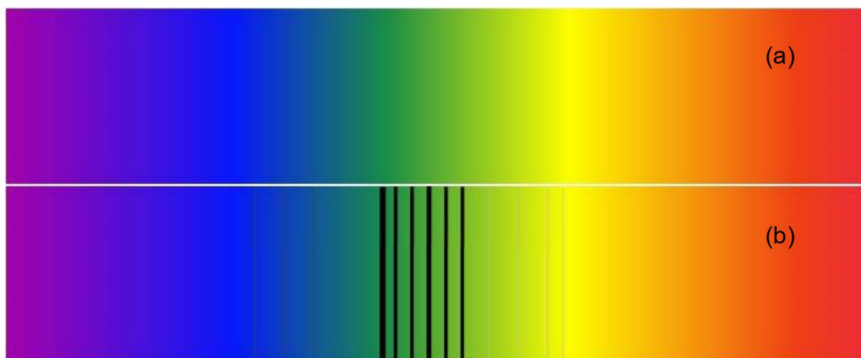


Fig. 5.1: Schematics of visible light spectrum a) continuous spectra as observed using spectrometer, b) dark lines or bands observed when iodine vapour lamp is placed between the visible light source and the spectrometer.

In the present experiment a high power lamp emitting a visible continuous radiation is used so that light from the lamp passes through the iodine vapour. As the light passes through iodine vapour, absorption or emission of radiation can occur due to change in the rotational, vibrational and electronic energies of the iodine molecules. In the process of absorption of visible light by the iodine molecules, iodine molecules in the gaseous form are excited from their ground electronic state to various vibrational levels of the first excited electronic state. As a result of the absorption by iodine molecules, series of dark lines or bands will be observed in visible spectrum. Since the rotational energy levels are sub-levels within each vibrational energy level, some of the dark lines may consist of several weak lines originating from rotational energy levels. Thus, essentially some of the dark lines observed may be considered as dark bands, however, they may be far too weak to resolve at room temperature.

A grating can be used to find the wavelength corresponding to absorption bands in the absorption spectrum of the iodine vapour by using the following relation

$$(a + b)\sin\theta = n\lambda \quad (5.1)$$

where $(a+b)$ is the grating element, θ is the angle of diffraction and n is the order of spectrum.

$$\lambda = \frac{(a + b)\sin\theta}{n} = \frac{\sin\theta}{nN} \quad (5.2)$$

N is the number of lines per cm of the grating and is given by:

$$N = \frac{\text{Number of lines per inch}}{2.54} \quad (5.3)$$

5.3 DESCRIPTION OF THE APPARATUS

In this experiment you will use iodine vapour tube, a steel bench with mounts to hold the iodine tube, a power supply, a straight filament lamp as a source of white light, optical diffraction grating (with 15000 lines per inch), spectrometer, reading lamp and iodine crystals. Let us now describe the Iodine Vapour Tube which you will be using for the first time.

5.3.1 Iodine Vapour Tube

It is a glass tube of length around 1 metre having a uniform diameter of 3 cm. To introduce Iodine in the tube a small inlet is provided which is closed by a glass stopper. A plane glass plate of 4 cm diameter is mounted at one end of the tube while a condenser lens of short focal length is placed at the other end of the tube. The glass tube is fitted in an aluminium casting. The entire system is airtight so that no Iodine vapors escapes out in the atmosphere while performing the experiment. A power supply to heat the tube with two outputs 30 V and 20 V are also provided. 30 V supply is provided initially to vaporize the iodine and later on 20 V supply is selected to maintain the vapors inside the tube while performing the experiment. The Iodine tube is placed on a mild steel bench using V mounts.

With this preliminary knowledge you can now perform the experiment.

5.4 EXPERIMENTAL PROCEDURE

Follow the procedure described below to perform the experiment.

1. Set up the spectrometer and focus the cross lines of the telescope by moving the eyepiece in or out.
2. Place the diffraction grating on the prism table normal to the incident light.
3. Setup the iodine tube on the steel bench on the V mounts provided to hold the iodine tube.
4. Place the electric lamp in front of it.
5. The iodine tube should be placed in such a way that the end having the condenser lens should be towards the lamp and the opposite end of the tube having the glass disc should be placed towards the slit of the spectrometer. The experimental setup is shown in the Fig. 5.2 .

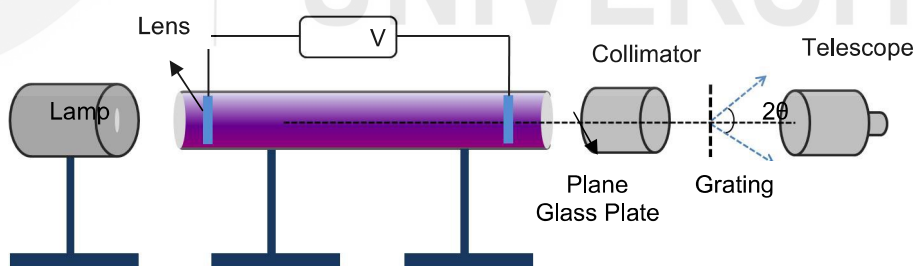


Fig. 5.2: Experimental setup to study the absorption lines of Iodine vapor.

6. Now remove the rubber stopper provided on the tube and put few globules of Iodine in the tube.
7. Switch on the power supply provided for this purpose and start heating the tube. Apply 30 V initially for vaporizing iodine and then reduce the voltage to 20 V to maintain the iodine vapors in the tube.
8. Switch on the lamp and observe the first order absorption spectrum through the telescope of the spectrometer. One can observe a series of dark lines/band in a background of continuous emission spectrum.

9. First note the direct slit reading in both the verniers. Then rotate the telescope towards right of the direct slit and set the cross wires on successive dark lines/bands. Record the readings on both verniers of the spectrometer.
10. Take 10-15 readings of the dark lines in the green region of the spectrum (approximately in the region of 510 nm - 560 nm). The dark lines or bands are most intense in the green region and they are known to originate from $v = 0$ vibrational level in the ground electronic energy state to various values of vibrational levels in the excited state.
11. Now rotate the telescope towards left of the direct slit and set the cross wires on successive dark lines/bands. Record the readings on both verniers of the spectrometer.
12. Find the difference between readings for line to line for both the verniers for first order on two sides of the direct reading.
13. The difference between both sides give 2θ , where θ gives the angle of diffraction.
14. Calculate the wavelength λ corresponding to each value of θ for $n=1$ (1st order) using the relation $\lambda = \frac{\sin \theta}{N}$ where N is the number of lines per cm of grating.

Observation Table 5.1

Main scale division of the spectrometer =

Number of divisions on the vernier =

Least count of the spectrometer =

Number of lines in the grating (per inch) =

Number of lines per cm, $N =$

Order of spectrum	Colour of spectral Band	Position of Telescope				Difference between the readings 2θ		Mean 2θ	θ	Wavelength λ (nm)
		Right Side		Left Side		V_1	V_2			
		Vernier V_1	Vernier V_2	Vernier V_1	Vernier V_2					

Result:

The absorption spectrum of Iodine vapor is studied. The value of various absorption wavelengths were determined at room temperature.

5.5 PRECAUTIONS AND SOURCES OF ERRORS

In principle, various spectroscopic constants such as, fundamental vibrational energy, the dissociation energy, the convergence limit, the force constant of the bond and the anharmonicity constant can be obtained from the same experiment. However, keeping in mind the scope of the syllabus, the present experiment is to introduce to the learners about the absorption lines in Iodine molecules.

1. The Iodine globules should be stored in glass bottles and not in a plastic bottle as they are corrosive in nature.
2. The Iodine globules should not be touched with bare hands.
3. The rubber stopper provided in the Iodine tube must be fitted tightly.
4. The iodine tube should be placed in such a way that the end having the condenser lens should be towards the lamp and the opposite end of the tube having the glass disc should be placed towards the slit of the spectrometer.
5. The axis of the tube must coincide with the axis of collimator.
6. The temperature of the tube must be brought down once the iodine vaporizes by selecting 20 V provided in the power supply.

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EXPERIMENT 6

STUDY OF THE DIFFRACTION PATTERNS OF SINGLE AND DOUBLE SLITS USING LASER SOURCE AND DETERMINATION OF ITS WAVELENGTH

Structure

- | | | | |
|-----|--|-----|--|
| 6.1 | Introduction
Expected Skills | 6.3 | Experimental Procedure
Measuring the Diffraction Pattern using
Single Slit |
| 6.2 | Diffraction of Light
Diffraction of Light from a Single Slit
Diffraction of Light from a Double Slit | 6.4 | Calculation of Wavelength of Laser Light |
| | | 6.5 | Precautions and Sources of Errors |

6.1 INTRODUCTION

The phenomenon of bending of waves when they pass through an opening or around an obstacle in a geometrical shadow is called the diffraction. Diffraction occurs when the size of the opening or obstacle is comparable with the wavelength of the wave. You have studied about the phenomenon of diffraction of light in detail in Unit 10 of BPHCL-138. The diffraction of light is observed by using slit or pinhole, etc. with a size dimension comparable to the wavelength of light. In this experiment, you will use a monochromatic laser light source to illuminate a slit of known width. A diffraction pattern will be observed at screen placed at a distance of few meters from the slit. You have obtained such a diffraction pattern for a single slit in Experiment 10 of BPHCL-138. In this experiment you determine the wavelength of laser light used from the single slit and double slit diffraction pattern.

Expected Skills

After performing this experiment, you should be able to:

- ❖ explain the steps involved in the process of finding the wavelength of a laser light from the single slit and double slit diffraction pattern;
- ❖ set up the apparatus to obtain the diffraction pattern;
- ❖ draw the diffraction pattern for given single and double slit;
- ❖ measure the distance of different minima from central maxima; and
- ❖ calculate the wavelength of given laser light.

You will require the following apparatus to perform this experiment.

Apparatus Required

Laser light Source, single slit, double slit, slit holder, sliding upright, optical bench, display screen, travelling microscope and a meter scale or measuring tape.

6.2 DIFFRACTION OF LIGHT

Before beginning the experiment, let us briefly discuss the concepts required for carrying out this experiment. You may refer to Unit 10, Sec. 10.3 of BPHCT-137 for detailed derivations for the single slit diffraction pattern and Sec. 10.4 of BPHCT-137 for the double slit diffraction pattern.

6.2.1 Diffraction of Light from a Single Slit

Let a parallel beam of monochromatic laser light having wavelength (λ), be incident perpendicular to the single slit of width b as shown in Fig. 6.1. The light beam gets diffracted by the slit and the diffraction pattern is formed on the screen S placed at distance D from the slit. The diffraction pattern is observed in the form of alternative dark and bright fringes, which correspond to the minima and maxima of the diffraction pattern respectively. The intensity of light is maximum at the center of the diffraction pattern and this is known as the principal maxima. The alternate dark and bright fringes are symmetrically spread around the principal maxima. The intensity of the diffraction pattern at any point P on the screen, is given by the following relation (Eq. 10.8 of Unit 10, BPHCT-137):

$$I_{\theta} = I_0 \left[\frac{\sin\left(\frac{\pi b \sin \theta}{\lambda}\right)}{\left(\frac{\pi b \sin \theta}{\lambda}\right)} \right]^2 \quad (6.1)$$

where I_0 is the intensity at the centre, i.e. for $\theta = 0$.

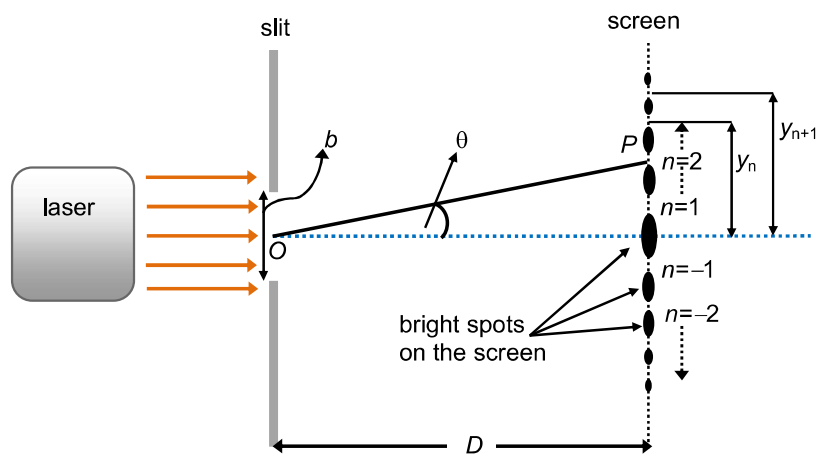


Fig. 6.1: Diffraction from a single slit, due to a laser source.

The condition for the minima can be expressed in terms of the slit width b and the angle θ (Eq. 10.11 of BPHCT-137) is:

$$b \sin \theta = n \lambda, \quad n = \pm 1, \pm 2, \pm 3, \pm 4, \dots \quad (6.2)$$

For small values of θ ; $\sin \theta \approx \theta$ and from Fig. 6.1 we can write

$$\tan \theta = \sin \theta \approx \theta = \frac{y_n}{D} \quad (6.3)$$

where y_n is the distance of n^{th} minima from the centre of central maxima. From Eqs. (6.2 and 6.3), for small values of θ , we get:

$$n \lambda = b \frac{y_n}{D} \Rightarrow y_n = n \lambda \frac{D}{b} \quad (6.4)$$

Using Eq. (6.4), for any two consecutive minima (say the n^{th} minima and the $(n+1)^{\text{th}}$ minima), we can write:

$$y_n = n \lambda \frac{D}{b} ; \quad y_{n+1} = (n+1) \lambda \frac{D}{b} \quad (6.5)$$

and

$$y_{n+1} - y_n = [(n+1) - n] \lambda \frac{D}{b} \Rightarrow \lambda = \frac{b}{D} \left[\frac{y_{n+1} - y_n}{(n+1) - n} \right] \quad (6.6)$$

From Eq. (6.4), note that if we plot y_n (along the y -axis) with n (along the x -axis), we will get a straight line and the slope of the straight line is:

$$\text{Slope} = \left[\frac{y_{n+1} - y_n}{(n+1) - n} \right] \quad (6.7)$$

And so, we can write:

$$\lambda = \frac{b}{D} \times \text{Slope} \quad (6.8)$$

6.2.2 Diffraction of Light from a Double Slit

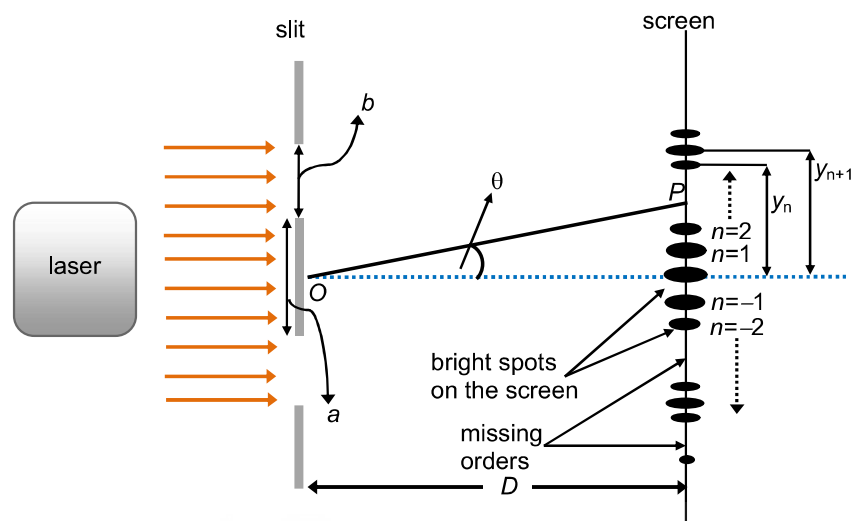


Fig. 6.2: Diffraction from a double slit.

In order to get the diffraction pattern from a double slit, you have to replace the single slit by a double slit in Fig. 6.1. Fig. 6.2 shows the diffraction pattern from the double slit consisting of two slits of width b separated by a distance a . The separation d between two similar points in the slit is $a+b$. The diffraction pattern is formed on a screen placed at a distance D from the slit. The intensity of the light is at any point P on the screen is given by (Eq. 10.19 of Unit 10, BPHCT-137):

$$I_{\theta} = 4I_0 \left[\frac{\sin \beta}{\beta} \right]^2 \cos^2 \gamma \quad (6.9)$$

where $\beta = \frac{\pi b \sin \theta}{\lambda}$ and $\gamma = \frac{\pi d \sin \theta}{\lambda}$ and $4I_0$ is the intensity at the centre, i.e.

for $\theta = 0$. Within the central maximum you will have equally spaced bright and dark fringes. On either side of the central maximum you will have symmetrical alternate dark and bright fringes. All maxima will have equally spaced dark fringes, which will decrease with increasing θ . The condition for the n^{th} maxima at a distance of y_n is given by (Eq.10.23 of Unit 10 of BPHCT-137);

$$d \sin \theta = n\lambda, \text{ for } n = 0, \pm 1, \pm 2, \pm 3, \dots, n = 0, \pm 1, \pm 2, \pm 3, \pm 4 \dots \quad (6.10)$$

For small values of θ ; $\sin \theta \approx \theta, \cos \theta \approx 1$. Therefore,

$$\tan \theta = \sin \theta \approx \theta = \frac{y_n}{D} \quad (6.11)$$

From Eqs. (6.10 and 6.11), for small values of θ we get;

$$n\lambda = d \frac{y_n}{D} \Rightarrow \lambda = \frac{d}{D} \times \frac{y_n}{n} \quad (6.12)$$

For two consecutive maxima we get (Fig. 6.2)

$$y_n = n\lambda \frac{D}{d}; y_{n+1} = (n+1)\lambda \frac{D}{d} \quad (6.13)$$

And
$$\lambda = \frac{d}{D} \left[\frac{y_{n+1} - y_n}{(n+1) - n} \right]$$

Once again the slope of the plot between y_n and n is:

$$\text{Slope} = \left[\frac{y_{n+1} - y_n}{(n+1) - n} \right]$$

Therefore

$$\lambda = \frac{d}{D} \times \text{Slope} = \frac{(a+b)}{D} \times \text{Slope} \quad (6.14)$$

Eqs. (6.8) and (6.14) are used to determine the wavelength of the laser light.

6.3 EXPERIMENTAL PROCEDURE

Follow the procedure described below to perform the experiment to record the diffraction pattern for a single and double slit using a laser source.

1. Fix the laser light source at one end of the optical bench and screen on the other end of the optical bench. Mount the slit in between the laser light source and screen with the help of stand on the optical bench.
2. If the length of the optical bench is not enough to mount all the components onto it and you do not mount the laser source or the screen on the bench, it is necessary to level the optical bench with the help of screws provided for levelling. The laser light should be perpendicular to both the slit and the screen.
3. Align the laser light source such that light falls at the centre of the slit. Place the screen at a distance of few meters from the slit to get a sharp diffraction pattern. If the distance between the slit and screen is sufficiently large (more than 1m), screen can be replaced with the graph paper to observe the diffraction pattern. This will help in measuring the distance from the central maxima.
4. Mark the diffraction pattern on the screen carefully. Encircle the position of the bright spots (maxima) of diffraction pattern. Measure the distance of minima and maxima from the centre of central maxima for single slit and double slit respectively.
5. In case the diffraction pattern is not symmetrical (distance of maxima or minima of same order) it indicates that either the slit or the screen is not exactly perpendicular to the direction of light. Adjust the slit or screen to get a symmetrical diffraction pattern.

6.3.1 Measuring the Diffraction Pattern using Single Slit

You will observe a bright central maxima along with alternate symmetrically spaced dark and bright diffraction spots. Encircle the bright spots only as

shown in the Fig.6.1. Measure the distance from the centre of the central maxima to the centre of minima. Record the distance for different order of minima (n) in the Observation Table 6.1 given below.

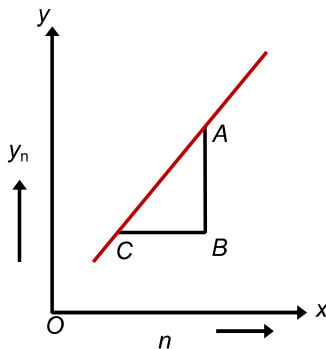


Fig. 6.3: Plot between the order of minima, n (on x -axis) and distance of minima, y_n (on y -axis).

Observation Table 6.1: Position of Minima in the Single Slit Diffraction Pattern

S.No.	Order of Minima (n)	Distance of minima y_n (mm)
1	.	.
2	.	(Negative distance)
3	-3	.
4	-2	.
.	-1	.
.	0	0 (Centre of Central Maxima)
.	1	.
.	2	.
.	3	.
.	.	.
.	.	(Positive distance)
.	.	.

Plot a graph of y_n with n as shown in Fig. 6.3 and measure the slope of the straight line.

$$\text{Slope} = \frac{AB}{BC} \quad (6.14)$$

6.3.2 Measuring the Diffraction Pattern using Double Slit

In case you are using a double slit in the above mentioned experimental setup, you will observe bright central maxima along with alternate symmetrically spaced dark and bright diffraction spots which are equidistant.

1. Encircle the bright spots only as shown in the Fig. 6.2.
2. Measure the distance from the centre of the central maxima to the centre of each maxima.
3. Record the distance for different order of maxima (n) in Observation Table 6.2 given below.

Observation Table 6.2: Position of Maxima in the Double slit Diffraction Pattern

S. No.	Order of Maxima, n	Distance of maxima (mm), y _n
1	.	.
2	.	(Negative distance)
3	-3	.
4	-2	.
.	-1	.
.	0	0 (Center of Central Maxima)
.	1	.
.	2	.
.	3	.
.	.	(Positive distance)

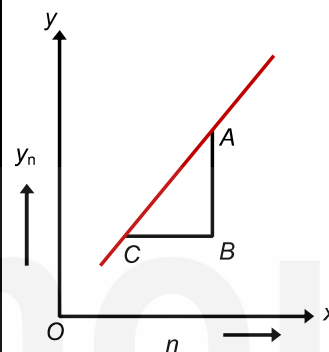


Fig. 6.4: Plot between order of maxima, n (on x-axis) and distance of maxima, y_n (on y-axis).

4. Plot a graph of y_n with n as shown in Figure 6.4 and measure the slope of the straight line.

$$Slope = \frac{AB}{BC} = \dots \text{mm} \tag{6.15}$$

6.4 CALCULATION OF THE WAVELENGTH OF LASER LIGHT

To obtain the wavelength of laser light, measure the distance, D, between the slit and the screen using meter scale. Measure the slit width directly if the micrometer screw is provided with the slit or using a travelling microscope.

1. For single slight

$$b = \dots \text{mm}; \quad D = \dots \text{mm}$$

Using the value of the slope calculated from Fig. 6.4 in Eq. (6.8), you calculate the wavelength of light as:

$$\lambda = \frac{b}{D} \times Slope = \dots \text{mm} = \dots \text{nm}$$

2. For double slit

$$d = (a+b) = \dots \text{mm}; \quad D = \dots \text{mm}$$

Using the value of the slope calculated from Fig. 6.5 in Eq. (6.14), you can calculate the wavelength of light as:

$$\lambda = \frac{a+b}{D} \times \text{Slope} = \dots\dots \text{mm} = \dots\dots \text{nm}$$

6.5 PRECATUIONS AND SOURCES OF ERRORS

1. Before you turn the laser on, make sure that it is facing away from you.
2. Never look directly into the laser pointer nor point it at another person.
3. Laser should be 'ON' for at least 10 minutes before the start of the experiment.
4. Keep the laser off when not in use.



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EXPERIMENT 7

STUDY OF PHOTOELECTRIC EFFECT

Structure

7.1	Introduction Expected Skills	Variation of Photocurrent with Frequency for a Fixed Intensity of Light
7.2	Photoelectric Effect	Effect of the Potential on the Photoelectric Current
7.3	Experimental Procedure Variation of the Kinetic Energy of the Photoelectrons with Frequency of Light Variation of the Photocurrent with the Intensity of Light	Variation of Stopping Potential with the Frequency of Light
7.4	Calculations and Results	
7.5	Precautions and Sources of Errors	

7.1 INTRODUCTION

Photoelectric effect is the phenomenon in which electrons are emitted from a metal surface when light of sufficiently high frequency falls upon it. You have studied about photoelectric effect in Unit 4 of BPHET-141.

In this experiment you will study the characteristics of photoelectric effect and understand how Einstein's theory of photoelectric effect explains the observed characteristics.

Expected Skills

After performing this experiment, you should be able to:

- ❖ list the important characteristics of photoelectric effect;
- ❖ explain the variation of the kinetic energy of the photoelectrons with frequency of light;
- ❖ plot and explain the variation of photocurrent with the intensity of incident light;
- ❖ plot and explain the variation of photocurrent with frequency for a fixed intensity of light;
- ❖ calculate Planck's constant from the kinetic energy versus frequency graph;
- ❖ plot a graph connecting photocurrent and applied potential; and

- ❖ determine stopping potential from the photocurrent versus applied potential graph.

You will require the following components and apparatus for this experiment.

Apparatus Required

Source of light (with variable Intensity, voltage), Spectrometer, metal plate, Filters- blue, Green, Yellow, Orange, Red(to obtain light of different frequency), metallic cathode, metallic anode, quartz window (W), ammeter, voltmeter, rheostat, and power supply.

Let us briefly recapitulate the important characteristics of the photoelectric effect.

7.2 PHOTOELECTRIC EFFECT

As you know from Sec. 4.4 of BPHE 141, the minimum amount of energy required for an electron to escape the metal surface is called **work function** of the metal (ϕ) and the corresponding frequency of the incident radiation is called **threshold frequency** (ν_0), with $\phi = h\nu_0$. Electrons emitted in this manner are called **photoelectrons**. The current constituted by photoelectrons is known as **photoelectric current**. Most solids emit electrons when this value is in ultraviolet region of the spectrum, although some metals like potassium (K), rubidium (Rb), caesium (Cs) and sodium (Na) etc. emit electrons in the visible and near ultraviolet region.

Alkali metals have a low ionization potential therefore electrons are easily ejected when exposed to light. All alkali metals except lithium show photoelectric effect. Lithium does not emit photoelectrons due to the high value of its ionization energy. Among alkali metals, Cs has lowest ionization potential and hence it can show photoelectric current to maximum extent. Ultraviolet radiation has a low wavelength (or high frequency) and hence the energy of the photons is high as compared to visible light. Hence UV radiation is able to eject the electrons from most metallic surfaces, even other than alkali metals (see Fig. 7.1).

You have studied the quantum theory of photoelectric effect in Sec. 4.4.2 of BPHE-141. The maximum kinetic energy (K_{max}) of the photoelectrons emitted from the surface the metal is related to the frequency of the incident radiation (ν) by the relation (Eqs. 4.16 and 4.17 of BPHE-141):

$$K_{max} = h\nu - \phi = h\nu - h\nu_0 \quad (7.1)$$

In an experimental set-up (Fig. 4.4 of Unit 4, BPHE-141), the maximum kinetic energy of the photoelectrons is measured by applying a retarding potential between the electrodes. The stopping potential is the value of the retarding potential V_S at which the photocurrent in the circuit reduces to zero. Therefore (Eq. 4.20a of Unit 4, BPHE-141):

$$K_{max} = eV_S = h\nu - h\nu_0 \Rightarrow V_S = \frac{h}{e}(\nu - \nu_0) \quad (7.2)$$

From Eq. (7.2) it is clear that maximum kinetic energy K_{max} (stopping potential V_S) is independent of the intensity of the incident light and depends only on

the frequency and the work function of the metal. However, the photocurrent increases with the intensity of the incident radiation (Fig. 4.4 of BPHET-141) , since the **number of photons** incident on unit area of the surface **increases** with the intensity of the incident radiation. And provided the frequency of the incident radiation is beyond the threshold frequency, for a fixed intensity, the magnitude of the photocurrent will not change with frequency.

We can also write K_{max} in terms of the wavelength of the incident radiation ($v = c/\lambda$ and $v_0 = c/\lambda_0$) as:

$$K_{max} = eV_S = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) \Rightarrow V_S = \frac{hc}{e}\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right) \quad (7.3)$$

Eq. (7.2) and (7.3) can be used to experimentally obtain the value of Planck's constant h .

7.3 EXPERIMENTAL PROCEDURE

The experimental set up to study the photoelectric effect consists of a metallic cathode (C) which serves as the collector of photoelectrons, metallic anode (A) which serves as the photoelectrode, a quartz window (W), micro ammeter, voltmeter, rheostat, and a power supply connected as shown in Fig. 7.2.

When light of suitable frequency falls on the photoelectrode, photoelectrons are emitted which move towards the cathode and constitute a photocurrent. The magnitude of the potential difference as well as the polarity of the two electrodes can be reversed using the polarity reversing switch (K). Note that the quartz window is preferred because it transmits all UV, visible and infra-red light, whereas a glass window would transmit only visible and infra-red lights but not UV light.

If light sources of different frequencies are not available, filters can be used for obtaining light of different frequencies. For example a red filter in front of white light will allow only red light to pass through it, so we can say that the light falling on the metal surface is red light, and we can note down the frequency of red light for calculations. Similarly, we can get light of different frequencies using filters of different colours.

With this arrangement we now study the different properties of photoelectric effect.

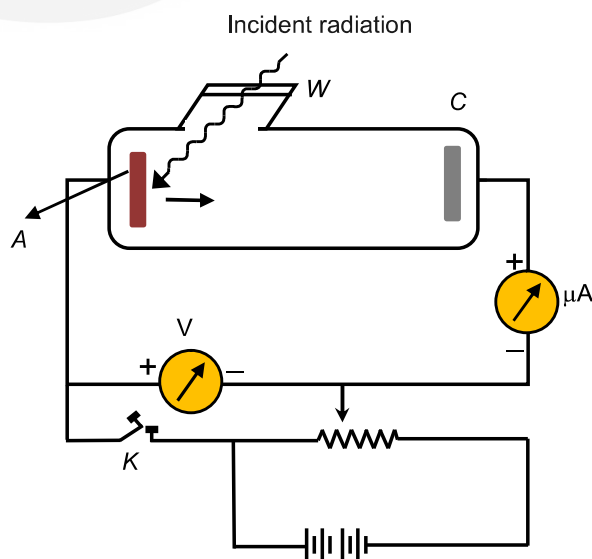


Fig. 7.2: Experimental set up to study the photoelectric effect of a metal.

7.3.1 Variation of the Kinetic Energy of the Photoelectrons with Frequency of Light

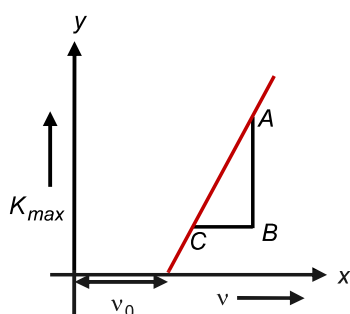


Fig. 7.3: Variation of the maximum kinetic energy of the photoelectrons with frequency for a given metal.

1. For a given photoelectrode and a particular frequency of radiation ν (a particular colour of filter) adjust the intensity of light to get a sufficient amount of photocurrent. Once the intensity is fixed, do not change it for this part of the experiment.
2. Initially the cathode is kept at zero potential. Then its retarding potential is gradually increased.
3. As the value of retarding potential increases, the photocurrent will decrease. At a certain value of the negative potential the photocurrent will become zero in the circuit, this value of negative potential is the stopping potential, V_s . The maximum kinetic energy of the electrons can be then determined using this value of V_s (Eq. 7.1). Enter your readings in Observation Table 7.1.
4. Repeat the steps 1-3 for different frequencies of the incident radiation (Blue, green, yellow, orange) and enter your readings in Observation Table 7.1

Observation Table 7.1: Variation of kinetic energy with frequency

Colour	Frequency (ν in Hertz)	Stopping Potential (V_s in V)	Maximum Kinetic Energy ($K_{\max} = eV_s$ in J)
Blue			
Green			
Yellow			
Orange			
Red			
...			

4. Plot the graph of frequency (ν) versus maximum kinetic energy K_{\max} , along the x and y axes respectively using the data of Observation Table 7.1. You will see that the graph is a straight line (Fig. 7.3).
5. From Eq. (7.1), note that the slope of this graph will give us the value of Planck's constant and the work function of the metal ϕ can be calculated from the intercept on the x-axis.

7.3.2 Variation of the Photocurrent with the Intensity of Light

1. For a fixed frequency/wavelength of incident radiation, adjust the cathode potential to a positive value. (The frequency of the radiation should be above the threshold frequency).
2. Increase the intensity of light slowly starting from zero, in steps of 10 % and note down the photoelectric current in the circuit. Enter your readings in Observation Table 7.2.

- Repeat Step 2 till the light intensity is 100%

Wavelength of incident radiation =m

Cathode potential=.....V

Observation Table 7.2: Variation of photocurrent with intensity

Sl.No	Intensity (L)	Photocurrent (μA)
1	0	0
2	10%	...
3	20%	...
..
..

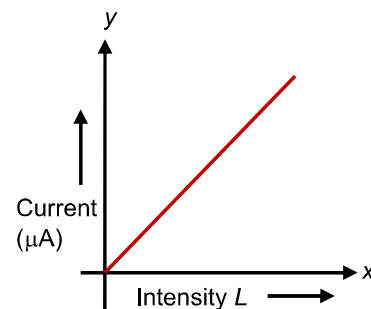


Fig. 7.4: For a given frequency or a given wavelength of light, the photoelectric current increases linearly with intensity of light.

- Plot the data of Observation Table 7.2 as shown in Fig. 7.4. For a fixed frequency (above threshold frequency), the photoelectric current increases linearly with increase in intensity of incident light.

7.3.3 Variation of Photocurrent with Frequency for a Fixed Intensity of Light

- Adjust the intensity of light to a maximum value.
- Vary the frequency/wavelength of the incident radiation. Choose frequencies above the threshold frequency.
- Note the photoelectric current for each frequency in Observation Table 7.3.

Observation Table 7.3: Variation of photocurrent with frequency

S.No.	Wavelength (nm)	Frequency	Photoelectric current (μA)
1	580 nm (red)	
2	545 nm (green)	
3	440 (blue)		
	...		

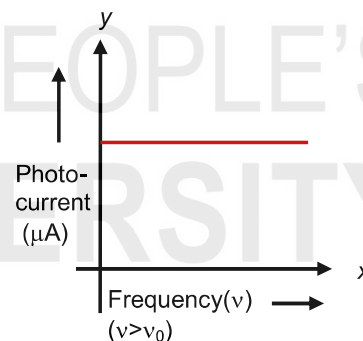


Fig. 7.5: Variation of photocurrent with the frequency of incident light. The photoelectric current remains does not change with the frequency.

- Plot the data of Observation Table 7.3 as shown in Figure 7.5. For a fixed intensity of the incident light, the photoelectric current does not depend on the frequency of the incident light. This is because the photocurrent simply depends on the number of photoelectrons emitted and in turn on the number of photons incident and not on the energy of the photons.

7.3.4 Effect of the Potential on Photoelectric Current

In this part of the experiment we will plot a graph between applied potential and the photocurrent for a fixed intensity of light and for a fixed colour of light.

- Start with a particular frequency (for example the red colour filter). Note down the frequency of light used then set the intensity of light to a value such that you have sufficient current in meter.

2. Now the anode voltage is adjusted to zero. Then increase the negative/ reverse voltage and note down the corresponding photocurrent. Enter the values in Observation Table 7.4. We need a large number of data points to plot the graph, so you need to take at least 15-20 readings to have proper graph.
3. Continue to increase the applied negative potential until the ammeter reading becomes zero, which means that the photocurrent in the circuit becomes zero.
4. Now increase the potential back to zero again and increase the positive potential and note the corresponding photocurrent.
5. Take the readings till the values of photoelectric current becomes constant, this constant value of photocurrent is known as saturation current. The saturation current is the maximum current that is obtained for a given intensity (L_1) of light.
6. To take second set of readings we need to change the intensity (L_2). And again, adjust the voltage to zero and repeat the same steps from 1-5 again.

Observation Table 7.4: Voltage and photocurrent for two different intensities

Intensity L_1			Intensity L_2		
S. No.	Applied Cathode Potential(V)	Photocurrent (μA)	S. No.	Applied Cathode Potential(V)	Photocurrent (μA)
1	0		1.		
2	-0.01		2.		
3	-0.02		3.		
4	-0.03		4.		
5			5.		
6		6.		
7	+0.01 (positive potential)		7.		
8	+0.02		8.		
		
	...	Saturation current (I_0)			Saturation current (I_0)
	...	(I_0)			

7. Plot the data of Observation Table 7.4 for the two different intensities of light as shown in Fig. 7.6. For a fixed frequency and intensity of incident light, the photoelectric current increases with an increase in the potential applied to cathode. When all the photoelectrons reach the plate C, the current becomes maximum and is called the saturation current (I_0).

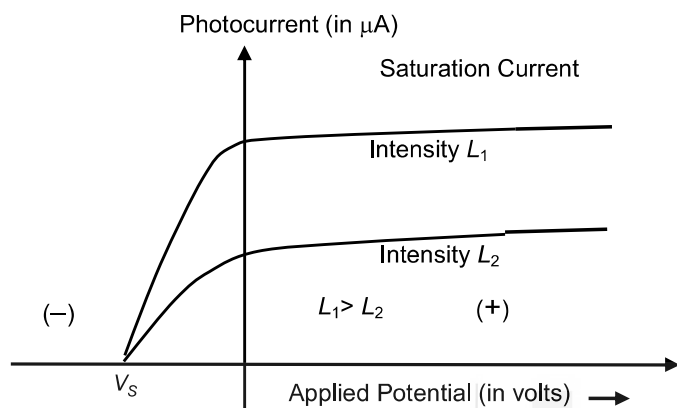


Fig. 7.6: Effect of photocurrent with potential. Here L_1 and L_2 are two known intensities, V_s is the stopping potential.

Note that the current is not zero at zero potential. This shows that even in absence of accelerating potential, a few photoelectrons manage to reach the plate on their own due to their kinetic energy.

Note also that the intensity of the incident light does not affect the stopping potential V_s . The stopping potential (which is a measure of the maximum kinetic energy of the photoelectrons) depends only on the frequency of the incident radiation.

Recall Fig. 4.7 of Unit 4 of BPHET-141. The graph between stopping potential and frequency does not pass through the origin. It shows that there is a minimum value of frequency called threshold frequency below which photoelectric emission is not possible however high the intensity of incident light may be. It depends on the nature of the metal emitting photoelectrons. In the next part of the experiment we study the variation of stopping potential with frequency.

7.3.5 Variation of Stopping Potential with the Frequency of Light

1. In this part of the experiment you will calculate the stopping potential for two different frequencies of light. Choose a particular frequency of radiation (for example use red filter) and fix the intensity of incident radiation to maximum.
2. Repeat steps 2-5 of Sec 7.3.3 and enter the readings in Observation Table 7.5. Note the value of the negative potential at which photoelectric current becomes zero. This is called stopping potential. Mark it as V_{s1} .
3. Now vary the frequency (for example use blue filter) and repeat the steps from 1 and note down the value of stopping potential (V_{s2} ) for this frequency.

Observation Table 7.5: Stopping potential for different frequencies

Frequency ν_1			Frequency ν_2		
S. No.	Applied Cathode Potential(V)	Photocurrent (μA)	S. No.	Applied Cathode Potential(V)	Photocurrent (μA)
1	0		1.		
2	-0.01		2.		
3	-0.02		3.		
4	-0.03		4.		
5			5.		
6		6.		
7	+0.01 (positive potential)		7.		
8	+0.02		8.		
		
	...	Stopping Potential (V_{S1})			Stopping Potential (V_{S2})

4. Plot the data of Observation table 7.5 as shown in Fig. 7.7.

7.4 CALCULATIONS AND RESULTS

From the graphs plotted in above experiment we can conclude that

1. The threshold frequency for the given metal as obtained from Fig. 7.3 isHz.
2. The value of Planck's constant as obtained from the slope of kinetic energy versus frequency graph (Fig. 7.3) is:

$$h = \text{Slope} = \frac{AB}{BC} = \dots\dots \text{Js}$$

The standard value of the Planck's constant is 6.626×10^{-34} Js

Percentage error

$$= (\text{Experimental value} - \text{standard value}) / \text{standard value} \times 100$$

$$= \dots\dots \%$$

3. The work function of the metal, ϕ , is calculated using the values of h and ν_0 :

$$\phi = h\nu_0 = \dots\dots \text{J} = \dots\dots \text{eV}$$

4. The stopping potential of the given metal iseV for the incident radiation of frequency.... Hz,eV for the incident radiation of frequency.... Hz, etc.
5. The maximum kinetic energy of the emitted electrons isJoules for the incident radiation of frequency ...Hz,Joules for the incident radiation of frequency ...Hz , etc.

7.5 PRECATUIONS AND SOURCES OF ERRORS

1. The position of the light source should not be changed during the experiment.
2. Care should be taken that when no light is falling on the cathode the current should be zero.
3. While noting down the stopping potential, the voltage across the photocell should be varied very slowly.

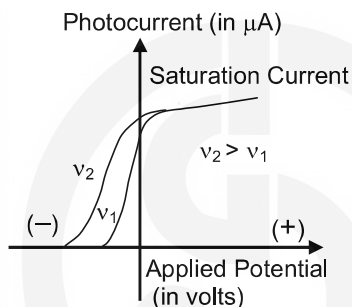


Fig. 7.7: Variation of photocurrent with potential for two different frequencies of light ν_1 and ν_2 .

EXPERIMENT 8

DETERMINATION OF e/m BY MAGNETIC FOCUSING

Structure

- | | | | |
|-----|---------------------------------|-----|-----------------------------------|
| 8.1 | Introduction
Expected Skills | 8.4 | Calculations of e/m |
| 8.2 | Charge / Mass (e/m) Ratio | 8.5 | Precautions and Sources of Errors |
| 8.3 | Description of the Apparatus | | |

8.1 INTRODUCTION

British physicist Sir J.J. Thomson is credited with discovery of the first subatomic particle, the electron, in 1897 in his experiments with cathode ray tubes. He also measured the charge-to-mass ratio of the electron in these experiments. It is difficult to measure the electric charge e and the rest mass m of an electron separately, because both these quantities are extremely small. However the ratio of these two fundamental constants (e/m) has a fairly large value (1.758820×10^{11} C/kg) and a precise value of e/m can be determined easily from the radius of curvature of an electron beam traveling in a known magnetic field. The charge of an electron was determined for the first time by Millikan in his oil-drop experiment much later, in 1909, which you will read about in Experiment 9. In this experiment you use a magnetic lens to determine the e/m ratio. In Experiment 10 you will use a bar magnet to determine the value of e/m .

Expected Skills

After performing this experiment, you will be able to:

- ❖ explain magnetic focusing of an electron;
- ❖ set up the apparatus to obtain magnetic focusing;
- ❖ effect of solenoid on the path of a moving charge; and
- ❖ calculate the e/m ratio of an electron using magnetic lens.

You will require the following apparatus to perform this experiment.

Apparatus Required

Cathode ray tube (CRT), power supply, a circular coil (C) capable of sliding along the axis of CRT, a voltmeter (0 - 1500 V), ammeter (0 - 3 A) and a wooden stand.

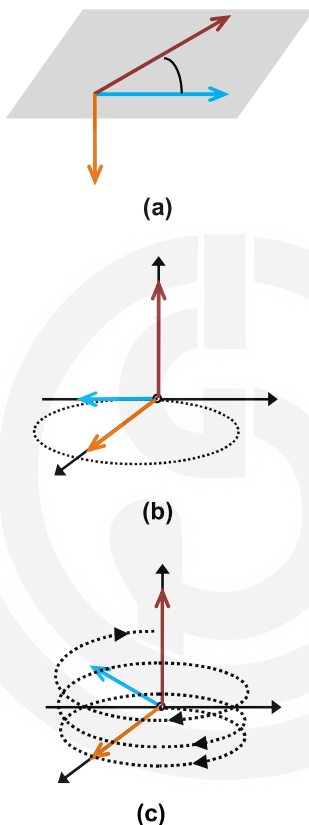


Fig. 8.1: A moving electron in a magnetic field.

Before beginning the experiment, let us briefly discuss the theoretical concepts.

8.2 CHARGE / MASS (e/m) RATIO

In this experiment, you will use a cathode ray tube (CRT) and a solenoid to determine the e/m ratio of an electron. Here, the solenoid behaves as a **magnetic lens**. The magnetic lens is a device in which the magnetic Lorentz force is used for focusing or deflecting a moving charged particle like an electron. A magnetic lens bends a beam of moving charged particles, in the same way as an optical lens bends a beam of light.

Recollect that the focus of a lens may be simply defined as a point where all rays of radiation (heat, light, etc) converge after being reflected or refracted. Hence, focusing is the process in which rays are made to focus at a particular point. In this experiment the magnetic lens is used to focus a stream of moving electrons at a particular point. This process is called **magnetic focusing**. The focal length of the lens can be changed by changing the current in the solenoid.

From BPHCT-133, you know that the force on an electron moving in a magnetic field \vec{B} with a velocity \vec{v} is just $\vec{F} = -e(\vec{v} \times \vec{B}) = -evB \sin \theta \hat{n}$ (Fig. 8.1a). The direction of this force is perpendicular to the direction of motion of electron and the magnetic field and θ is the angle between \vec{v} and \vec{B} . If the velocity of the particle and the magnetic field are at right angles to each other, the electron moves in a circular path in a plane perpendicular to the plane containing \vec{v} and \vec{B} as shown in Fig. 8.1(b).

Let us assume that the magnetic field lies along the z-direction ($\vec{B} = B_z \hat{k}$) and the plane containing \vec{v} and \vec{B} lies in the yz-plane. We can write $\vec{v} = v_y \hat{j} + v_z \hat{k}$. From the expression for the Lorentz force you can see that the force on the moving charge due to the magnetic field is $\vec{F} = -ev_y B \hat{i}$. If $v_z = 0$,

the electron moves in a circular path in a plane perpendicular to the plane containing \vec{v} and \vec{B} as shown in Fig. 8.1(b).

If $v_z \neq 0$ the electron undergoes circular motion in the xy -plane due to the Lorentz force. However the electron also continues to move in along the z -direction with a constant speed v_z , since there is no force along the z -direction. So the resultant path of the charged particle is a helix as shown in Fig. 8.1(c).

Now consider the electron to be moving inside a CRT with the solenoid creating a magnetic field as shown in Fig. 8.2. The electron will follow a helical trajectory as shown. If the electron traces out one complete circle, by the time it reaches the screen, the electron reaches the point X on the screen, exactly opposite to the point of the electron gun from where it was emitted, along the axis of the tube. Electrons are emitted from the electron gun with different initial velocities (v) and at varying angles (θ) relative to the axis of the tube. **The time required by the electron to complete one cycle of depends on the magnetic field and the charge to mass ratio of the electron. Since the charge to mass ratio is the same for all electrons, the electrons complete one cycle at the same time for a given magnetic field.** Hence, magnetic focusing occurs when the electrons complete the cycle synchronously on the screen of the CRT.

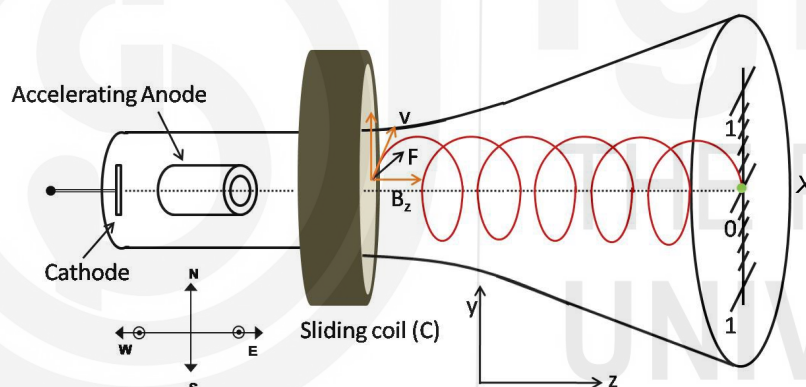


Fig. 8.2: Schematic diagram of the CRT placed along W-E direction and the sliding coil (C) placed on the wooden stand along the CRT. The Lorentz force on the electron arising out of the applied magnetic field (B_z) due to the coil and the initial velocity (v) of the electron causes the electron to travel in a helical path as shown.

The CRT is placed on a wooden stand and the current carrying circular coil is mounted on the wooden stand such that it can slide along the axis of CRT as shown in Fig. 8.1. The wooden stand is fitted with a scale to measure the position of the sliding coil. As the power supply is given to the CRT, a bright spot is observed on the screen of the CRT. When the coil slides along the CRT, a sharp bright spot will be obtained for two positions of the coil (C_1 and C_2), as shown in Fig. 8.3.

The focal length of the magnetic lens is given by the relation:

$$\frac{1}{f} = \frac{1}{P} + \frac{1}{Q} \quad (8.1)$$

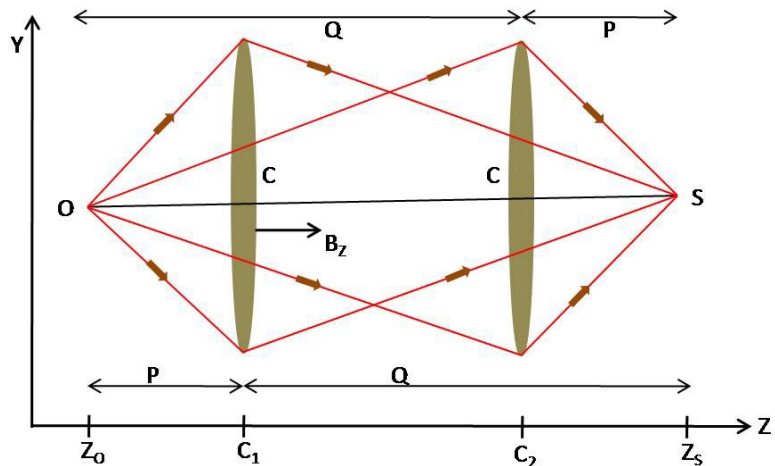


Fig. 8.3: Schematic diagram showing the two positions (C_1 and C_2) of sliding coil (C) which gives a sharp focus at S on the screen. B_z is the magnetic field due to the current carrying coil (C), P and Q are the distances/position of the coil (C) as measured from the scale on the wooden stand with respect to O .

If V is the applied voltage, ' n ' the number of turns in the sliding coil, ' a ' the radius of the sliding coil and ' i ' the current along the coil, then the focal length of the magnetic lens relation is:

$$\frac{1}{f} = \frac{e}{m} \times \frac{i^2}{V} \times \frac{3}{16} \times \frac{n^2 \pi^3}{a} \times 10^{-14}$$

$$\therefore \frac{e}{m} = \frac{16a}{3\pi^3 n^2} \left(\frac{V}{i^2 f} \right) \times 10^{14} \text{ C/kg} \quad (8.2)$$

Eq. (8.2) is used to calculate the ratio e/m . The proof of this equation is beyond the scope of the syllabus.

8.3 EXPERIMENTAL PROCEDURE

1. Draw the North-South line using compass needle and the East-West line perpendicular to the N-S line. Now place the wooden stand along with CRT and the circular coil along the East-West line such that the CRT is perpendicular to N-S line. The earth's magnetic field will contribute to the circular path of the electron. The circular coil should be able to slide along the wooden stand.
2. Initially the circular coil should be placed at the end of the CRT. Check that the scale on the wooden stand is visible.
3. Switch on the power supply. The CRT should be connected to a high voltage supply (say 700 - 800 V) and the circular coil to a low voltage supply.
4. A bright spot will appear on the screen of the CRT. Now let us see what happens if we slide the circular coil along the wooden stand. First let us fix the current in the coil, to say 1 Amp, and then slowly slide the circular coil along the wooden stand. As the coil slides along the wooden stand,

you will observe that the spot on the screen becomes very sharp and bright.

5. The position of the sliding coil where the spot on the screen becomes sharp and bright is one of the foci of the magnetic lens for a given current. Mark the position of the coil (C_2) and note the distance of this position from one end of the CRT, using the scale on the wooden stand. Enter this distance as P in Observation table 8.1.
6. As you slide the coil further beyond P , you will observe that the spot becomes blurred. However, as you continue to slide the coil, the bright spot will become sharp and bright and focussed at another position C_1 . Using the scale, note the distance of this position from the same end of CRT as Q . If, for some reason if you are not able to find the two foci (P and Q), you may vary the current or the accelerating voltage.
7. Note down the accelerating voltage.
8. Keeping the voltage constant, vary the current by about 0.1 Amp and repeat steps 4 -6. Take 4 sets of readings by varying the current.
9. Using Eq. (8.1), calculate the value of f for each value of current and calculate i^2f as given in Observation Table 8.1.
10. Now vary the accelerating voltage by steps of 50-100 V and repeat steps 5 -11. You may take such readings five to six different accelerating voltages.

Observation Table 8.1: Variation of i^2f with V

S. No.	V (volts)	i (Amp)	P (cm)	Q (cm)	$f = PQ/$ $(P+Q)$ (cm)	f (metre)	i^2f (SI unit)
1		i)					
		ii)					
		iii)					
		iv)					
							mean i^2f
2							
3							

11. Plot a graph between V and i^2f as shown in Fig. (8.4), you will find that it is a straight line.

Determine the slope:

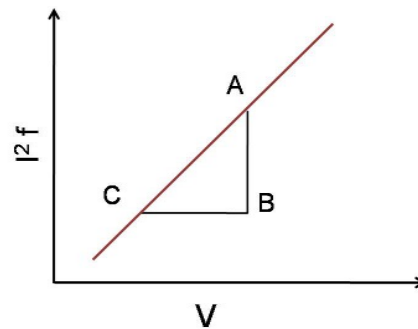


Fig. 8.4: Plot between V and $i^2 f$.

8.4 CALCULATION OF e/m

From Fig. 8.4, we can calculate the slope of the graph as:

$$\text{Slope} = \frac{AB}{BC}$$

Replacing $\frac{V}{i^2 f}$ by the slope of the graph in Eq. (8.2) we can write:

$$\frac{e}{m} = \frac{16a}{3\pi^3 n^2} \times \frac{1}{\text{Slope}} \times 10^{14} \text{ C/kg}$$

Inserting the values of a , n and the slope of the graph, we can calculate:

$$\frac{e}{m} = \dots\dots\dots \text{ C/kg}$$

Result: The value of e/m determined by magnetic focussing method is

$$= \dots\dots \text{ C/Kg}$$

The standard value of $e/m = \dots\dots \text{ C/Kg}$

$$\text{Error (\%)} = \dots\dots$$

8.5 PRECATUIONS AND SOURCES OF ERRORS

1. Make sure that the connections are tight.
2. There should not be any external magnetic field near the instrument.
3. Since we are using high voltage source, the beam on the CRT screen should not be focussed for long time as it may damage the screen.
4. The sliding of the coil should be smooth and slow.

EXPERIMENT 9

SETTING UP THE MILLIKAN OIL DROP APPARATUS AND DETERMINING THE CHARGE OF AN ELECTRON

Structure

- | | | | |
|-----|---------------------------------|-----|-----------------------------------|
| 9.1 | Introduction
Expected Skills | 9.4 | Experimental Procedure |
| 9.2 | Theoretical Concepts | 9.5 | Precautions and Sources of Errors |
| 9.3 | Description of the Apparatus | | |

9.1 INTRODUCTION

In this experiment you will determine the charge of an electron using the Millikan oil drop apparatus. In 1909, Robert Millikan and Harvey Fletcher conducted the oil drop experiment to determine the charge of an electron. They suspended tiny charged droplets of oil between two closely spaced metal electrodes by balancing the downward gravitational force with the upward drag and electric forces. Millikan and Fletcher then determined the charge on the oil droplets in mechanical equilibrium by using the applied electric field, the density and viscosity of the medium between the electrodes and the density of oil. They were able to confirm that the charges on the droplets were all multiples of some fundamental value.

They calculated this value to be 1.5924×10^{-19} Coulombs (C), which is within 1%

of the currently accepted value of $1.602176487 \times 10^{-19}$ C. They proposed that

this was the charge of a single electron.

Expected Skills

After performing this experiment, you should be able to:

- ❖ outline the steps involved in the process of determination of charge of the electron;
- ❖ set up the apparatus to perform Millikan oil drop experiment; and
- ❖ determine the charge of the electron.

You will require following apparatus to perform this experiment.

Apparatus Required

Millikan's oil drop apparatus, oil, DC supply, atomizer.

Before beginning the experiment, let us briefly discuss the basic theory underlying the experiment.

9.2 THEORETICAL CONCEPTS

Consider a charged spherical oil droplet of radius r falling in a chamber between two metal electrodes with a speed v . If the density of oil is ρ , the mass m of the droplet is:

$$m = (\text{volume of the oil droplet}) \times \text{density} = \frac{4}{3} \pi r^3 \rho \quad (9.1)$$

In the absence of an electric field the forces acting on the droplet are the following:

- i) The **gravitational** force acting downwards:

$$F_g = mg = \frac{4}{3} \pi r^3 \rho g \quad (9.2)$$

- ii) The **upward buoyant** force (F_b) exerted on the oil drop due to the medium (air):

$$F_b = \frac{4}{3} \pi r^3 g \rho_{air} \quad (9.3)$$

where ρ_{air} is the density of the air in the chamber.

- iii) The **drag force** (F_v) in the upward direction due to the oil drop moving in the viscous medium:

$$F_v = 6 \eta \pi r v \quad (9.4)$$

where η is the coefficient of viscosity of the medium (air).

As you have studied in school, the droplet would initially accelerate due to the effective downward force ($F_g - F_b - F_v$) and eventually reach a constant terminal velocity (v_t) when the net force acting on the particle becomes zero.

Using Eqs.(9.2) , (9.3) and (9.4) with $v = v_t$, we can write, for zero net force acting on the particle:

$$\begin{aligned} F_g &= F_v + F_b \\ \Rightarrow \frac{4}{3} \pi r^3 \rho g &= 6 \eta \pi r v_t + \frac{4}{3} \pi r^3 g \rho_{air} \\ \Rightarrow r &= 3 \sqrt{\frac{\eta v_t}{2 g (\rho - \rho_{air})}} \end{aligned} \quad (9.5)$$

If the droplet travels a distance l in time t_1 with the speed v_t , we can write:

$$v_t = \frac{l_1}{t_1} \quad (9.6)$$

Using Eqs.(9.5) and (9.6), the radius and mass of the oil drop can be determined if ρ , ρ_{air} and η are known. Now consider that a potential difference of V is applied between the two electrodes, thereby creating an electric field E as shown in Fig. 9.1(b). If the distance between the electrodes is d , the electric field is:

$$E = \frac{V}{d} \quad (9.7)$$

If the charge on the droplet is q , the force acting on the droplet due to the electric field E , F_E is:

$$F_E = qE = \frac{qV}{d} \quad (9.8)$$

By adjusting the applied voltage between the two metal plates, we can cause the charged oil droplets to fall, stop falling or rise. Suppose the potential difference is adjusted in such a way that the droplet remains suspended in space (Fig 9.1b), let this value of the potential be V_0 . In this situation, the net upward force due to the electric field must be balanced by the net downward force. Since the speed of the droplet is zero ($v=0$) we can write:

$$F_E = F_g - F_b \Rightarrow \frac{qV_0}{d} = \frac{4}{3} \pi r^3 g (\rho - \rho_{air}) \quad (9.9)$$

or
$$q = \frac{4\pi r^3 g d}{3V_0} (\rho - \rho_{air}) = \frac{9\pi d}{V_0} \left(\frac{2\eta^3 v_t^3}{g (\rho - \rho_{air})^3} \right)^{1/2} \quad (9.10)$$

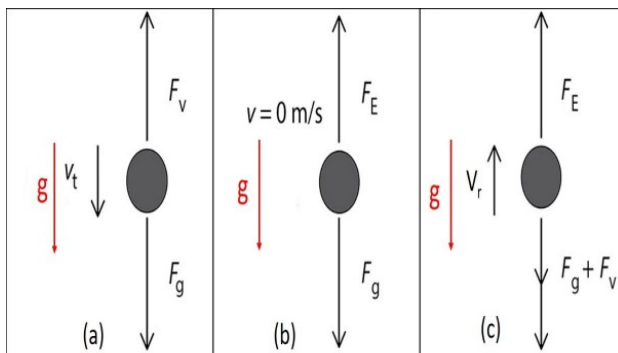


Fig. 9.1: a) Oil droplet in free fall; b) oil droplet suspended due to applied electric field; c) oil droplet rising due to applied electric field.

Let us now adjust the value of V such that the charged droplet begins to rise with a constant velocity v_r . Since the net force acting on the oil droplet must be zero, the net force due to the electric field in the upward direction should be balanced by the net downward force, therefore:

$$F_E = F_g - F_b + F_v \Rightarrow \frac{qV}{d} = \frac{4}{3} \pi r^3 \rho g - \frac{4}{3} \pi r^3 g \rho_{air} + 6\eta\pi r v_r \quad (9.11)$$

Note that since the droplet is moving upwards, the drag force, F_v , in this case, is in the downward direction.

From Eq. (9.5) we can write:

$$\frac{4}{3} \pi r^3 \rho g - \frac{4}{3} \pi r^3 g \rho_{air} = 6\eta\pi r v_t \quad (9.12)$$

Therefore Eq. (9.11) reduces to:

$$\begin{aligned} \frac{qV}{d} &= 6\eta\pi r v_t + 6\eta\pi r v_r \\ \Rightarrow q &= \frac{6\eta\pi r d}{V} (v_t + v_r) = \frac{18\eta\pi d}{V} (v_t + v_r) \sqrt{\frac{\eta v_t}{2g(\rho - \rho_{air})}} \quad (9.13) \end{aligned}$$

The charge on the oil drop can also be determined using Eq. (9.10) and / or Eq. (9.13). It can be shown in this experiment that the charge on the droplets is always an integer multiple of a **minimum charge**, which is the charge of an electron. This experiment is considered to be one of the most beautiful experiments of all time, because the charge of the electron can be determined with great precision by this simple and ingenious method.

9.3 DESCRIPTION OF THE APPARATUS

The experimental set up consists of two metal plates, an X-ray source and an atomizer as shown in Fig. 9.2. The atomizer helps to spray tiny droplets of oil, which falls, due to the gravitational pull of the Earth. As the droplets falls, some of them may filter through the hole of the plate as shown in the Fig. 9.2. The behaviour of the droplets as they fall are analysed through the viewing chamber. The two metal plates are arranged in such a way that the positive plate is at the top and the negative plate, is at the bottom. X-Rays are used to ionize the air in the lower part of the chamber. As the droplets traverse through the air, electrons accumulate over them and they acquire negative charge. A DC voltage is applied using a power supply. The speed of the droplet can be changed by varying the DC voltage. By adjusting the voltage applied, an oil drop can be suspended in air or even made to rise upwards. The charge on the droplet can be measured by each of these methods.

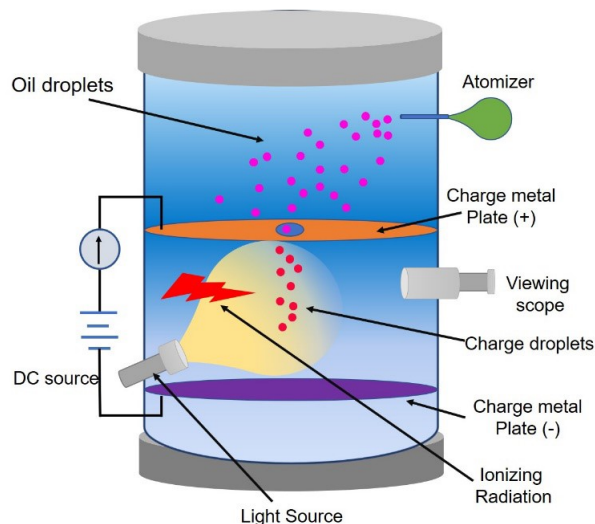


Fig. 9.2: Schematic diagram for the Millikan oil drop experiment.

9.4 EXPERIMENTAL PROCEDURE

Follow the procedure described below to perform the experiment and determine q using Eq. 9.13.

- Put non-volatile oil (olive oil, glycerine) of known density into the atomizer.
- Place the tip of the atomizer into the hole of the droplet viewing chamber
- While observing through the viewing scope, squeeze the atomizer bulb.
- Select a droplet that falls slowly. When you find an appropriately sized and charged oil droplet, fine-tune the focus of the viewing scope. The oil droplet is in best focus for accurate data collection when it appears as a pinpoint of bright light.
- Measure the time (t_1) taken by a droplet to travel a certain distance, say l_1 , in absence of any applied electric field. Enter your readings in Observation Table 9.1.
- Turn on the X-ray to ionize the droplets. Now turn on the power supply and adjust the voltage such that the droplet comes to rest. This gives us the value of the balancing voltage V_0 . A slight increase in the potential difference will make the drop rise upwards.
- The speed and motion of the droplet can be controlled as needed using the plate voltage switch. Fix the voltage to a value V and observe the time (t_2) taken to travel a distance (l_2) upwards and enter your readings in Observation Table 9.1.
- Calculate the charge on the droplet using Eq. (9.13). **If the charge on the droplet is greater than $5e$, you should repeat the procedure for slower moving droplets (Explain why?)**
- Repeat step 5 to 8 for droplets of different sizes and calculate the charge on the droplet in each case.
- Calculate the number of electrons, $n = q/e$, on each oil drop using the standard value of the electronic charge e .

Observation Table 9.1: Determination of v_t , v_r and q Viscosity of air $\eta = \dots\dots\dots$ kg/msDensity of oil $\rho = \dots\dots\dots$ kg/m³Density of air $\rho_{\text{air}} = \dots\dots\dots$ kg/m³Distance between the electrodes $d = \dots\dots\dots$ m

S. No.	l_1 (cm)	t_1 (s)	l_2 (cm)	t_2 (s)	Velocity		Potential (V)		Charge on the droplet q (in Coulombs)		No. of electronic charges on each droplet $n = q/e$
					$v_t = l_1/t_1$ (ms ⁻¹)	$v_r = l_2/t_2$ (ms ⁻¹)	V_0	V	Using Eq. (9.10)	Using Eq. (9.13)	
1.											
2.											
3.											
4.											
5.											
...											

Result:

The charge on each droplet is a multiple of the fundamental chargeC which is the charge of the electron.

9.5 PRECAUTIONS AND SOURCES OF ERRORS

1. The time calculated for rise and fall of the oil drop should be measured carefully.
2. The balancing voltage should be measured carefully, it should be the exact voltage where the drop is suspended in air.

EXPERIMENT 10

DETERMINATION OF e/m BY BAR MAGNET

Structure

- | | | | |
|------|--------------------------------|------|-----------------------------------|
| 10.1 | Introduction | 10.4 | Calculation of e/m |
| | Expected Skills | 10.5 | Precautions and Sources of Errors |
| 10.2 | Charge to Mass (e/m) Ratio | | |
| 10.3 | Experimental Procedure | | |

10.1 INTRODUCTION

You must have seen old television (TV) and computer monitors of huge sizes. The larger the size of the screen, the greater is the depth of the television or computer monitor. The reason for their depth is the size of one of the main components, that is, picture tube. A picture tube is nothing but the cathode ray tube (CRT). The CRT is also the main component of an instrument – the cathode ray oscilloscope (CRO) which is used in Physics and Electronics Laboratories. The CRO is used to observe the shape of the waveform and to measure the frequency, phase shift and amplitude of an electric signal. You have used the CRO in your first semester laboratory course (Experiment 10, BPHCL-132). The main component of a CRO is a CRT. In this experiment, you will use the CRT to determine the e/m ratio.

Expected Skills

After performing this experiment, you will be able to:

- ❖ explain the steps involved in the process of determination of e/m ratio;
- ❖ set up the apparatus to obtain the e/m ;
- ❖ study the effect of electric and magnetic field on the path of a moving charge; and
- ❖ calculate the e/m ratio.

You will require following apparatus to perform this experiment.

Apparatus Required

Cathode ray tube (CRT) and its power supply, a magnetometer, a set of bar magnets, a wooden stand.

Before beginning the experiment, let us briefly describe the basic theoretical concepts required to calculate the charge to mass ratio using a cathode ray tube.

10.2 CHARGE TO MASS (e/m) RATIO

As you have studied in Experiment 10 of BPHCL 132, in a cathode ray tube, the electrons emitted by the electron gun can be focussed at different points on a fluorescent screen with the help of electric fields. Suppose a potential difference V is applied between the two horizontally placed plates D_1 and D_2 inside the CRT as shown in Fig. 10.1. The plates have the same length l , and are separated by a distance d . A uniform electric field $= E = \left(\frac{V}{d}\right)$ is set up in between the plates as shown in Fig. 10.1.

Consider that the electrons emitted by the electron gun inside the CRT are initially moving with a velocity v along the x -axis. When an electron passes through the region of uniform electric field \vec{E} , it is deflected vertically.

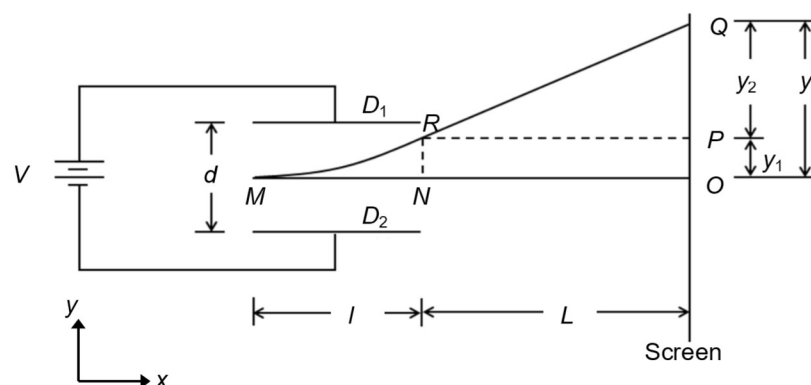


Fig. 10.1: Schematic Diagram of the path of the electron in the CRT.

Let us now calculate the vertical deflection of the electron travelling due to the electric field E . The force acting on the electron when it is in the region of the uniform electric field is: $\vec{F} = eE \hat{j} = e \left(\frac{V}{d} \right) \hat{j}$, the velocity is $\vec{v} = v_x \hat{i} + v_y \hat{j}$. Let

the initial velocity of the electron be $\vec{v} = v \hat{i}$ or. The equation of motion for the electron is:

$$m \frac{d\vec{v}}{dt} = \vec{F}$$

$$\Rightarrow m \frac{dv_x}{dt} = 0; \quad m \frac{dv_y}{dt^2} = eE \quad (10.1)$$

These differential equations can be solved using the techniques you have learnt in Unit 4 of BPHCT-131 (see the margin remark for the complete solution). The initial conditions for the solution are $v_x(t=0) = v; v_y(t=0) = 0$.

Suppose the electron takes a time t_1 to reach the point R shown in Fig. 10.1. At that point the deflection of the electron along the y direction $NR = y_1$. On solving the equations of motion we get

$$y_1 = \frac{EeI^2}{2mv^2} \quad (10.2)$$

The electrons experience a force only when they pass through the region of uniform electrostatic field, which is confined in between the plates. On leaving this region the electron has a component of velocity both along the x and y axes. However since no force act on the electron in this region, the velocity remains constant and is equal to the velocity of the electron at R which is (see margin remark):

$$\vec{v} = v \hat{i} + \frac{eEI}{mv} \hat{j} \quad (10.3)$$

Now the electron will move in a straight line with the constant velocity of Eq. (10.3) till it hits the screen at the point Q . Suppose that the time taken by the electron in reaching the point Q on the screen is t_2 . In this time the electron moves a distance L along the x -axis and has a further deflection y_2 along the y -axis.

The vertical deflection y_2 is then (see margin remark):

$$y_2 = \frac{Ee}{m} \frac{IL}{v^2} \quad (10.4)$$

The total deflection on the screen is $OQ = y = y_1 + y_2$

$$y = \frac{Ee}{m} \frac{I}{v^2} \left(\frac{I}{2} + L \right) \quad (10.5)$$

Form Eq. (10.5) we can also write:

$$eE = \frac{y}{I} \frac{mv^2}{\left(\frac{I}{2} + L \right)} \quad (10.6)$$

$$m \frac{dv_x}{dt} = 0$$

$$\Rightarrow v_x = \text{constant} = v \quad (i)$$

$$\Rightarrow \frac{dx}{dt} = v \Rightarrow x = vt + c$$

$$\because x = 0 \text{ at } t = 0, c = 0$$

$$x = vt \quad (ii)$$

Further we can write:

$$m \frac{dv_y}{dt} = eE \Rightarrow \frac{dv_y}{dt} = \frac{eE}{m}$$

$$\Rightarrow v_y = \left(\frac{eE}{m} \right) t + c$$

$$\because v_y = 0 \text{ at } t = 0$$

$$v_y = \left(\frac{eE}{m} \right) t \quad (iii)$$

$$\frac{dy}{dt} = \left(\frac{eE}{m} \right) t$$

$$\Rightarrow y = \left(\frac{eE}{2m} \right) t^2 + c_1$$

$$\because y = 0 \text{ at } t = 0, c_1 = 0$$

So we get:

$$y = \left(\frac{eE}{2m} \right) t^2 \quad (iv)$$

We know that at:

$$t = t_1, x = l \text{ and } y = y_1$$

So from Eq. (ii):

$$t_1 = l/v \quad (v)$$

Using Eq.(v) in Eqs. (iii)

and (iv) we get that at $t=t_1$:

$$v_y = \left(\frac{eE}{m} \right) t_1$$

$$= \frac{eEI}{mv} \quad (vi)$$

$$y_2 = \left(\frac{eE}{2m} \right) t_1^2$$

$$= \left(\frac{eE}{2m} \right) \left(\frac{l}{v} \right)^2 \quad (vii)$$

$$t_2 = L/v$$

and

$$y_2 = t_2 \left(\frac{eEI}{mv} \right) = \frac{eEIL}{mv^2}$$

y is the total deflection on the screen due to \vec{E} only. Now suppose an external magnetic field \vec{H} is applied perpendicular to the direction of motion of the beam of electrons such that the net deflection on the screen is zero. This will happen only when the two fields exert an equal and opposite force. Therefore, we must have:

$$eE = eHv \quad (10.7)$$

Using Eq. (10.6) we can write

$$\frac{y}{l} \frac{mv^2}{\left(\frac{l}{2} + L\right)} = eHv \Rightarrow \frac{e}{m} = \frac{y}{H} \frac{v}{l \left(\frac{l}{2} + L\right)} \quad (10.8)$$

The external applied magnetic field is produced using a bar magnet using bar magnet. The value of H can be determined using a deflection magnetometer. You have learnt how to use the deflection magnetometer in Experiment 2 of BPHCL-134. You know that if the magnetic compass needle of the magnetometer attains an equilibrium position at an angle θ with the magnetic meridian, the magnetic field H is just:

$$H = H_E \tan \theta \quad (10.9)$$

where H_E is the horizontal component of magnetic field of Earth. Using Eq. (10.9) in Eq. (10.8) we get

$$\frac{e}{m} = \frac{yV}{\tan^2 \theta} \left[\frac{1}{H_E^2 l \left(\frac{l}{2} + L\right) d} \right] \quad (10.10)$$

Eq. (10.10) is used to calculate the value of e/m for the electron

10.3 EXPERIMENTAL PROCEDURE

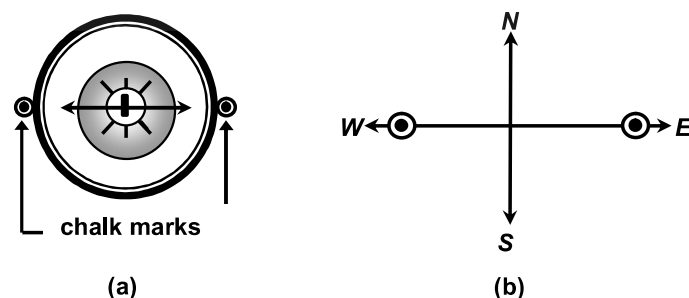


Fig. 10.2: Marking the magnetic meridian: a) Chalk marks corresponding to the ends of the pointer depicts the east-west direction; b) the magnetic meridian is normal to the east-west line.

Follow the steps outlined below to perform the experiment.

1. Remove all magnets (if there are any) and put the deflection magnetometer on the working table. Mark the positions corresponding to

the ends of the pointer on the table using a chalk as shown in Fig. 10.2a. Remove the magnetometer and join the chalk marks by a straight line and extrapolate it as shown in Fig. 10.2b. This defines the magnetic east-west line in the laboratory. A line drawn perpendicular to it will represent the magnetic meridian.

- Place the wooden stand with the arms parallel to east-west line and place the cathode ray tube parallel to north-south line mark as shown in Fig. 10.3. Placing the CRT parallel to north-south direction will ensure that the horizontal component of earth magnetic field will not affect the direction of the beam of electrons.

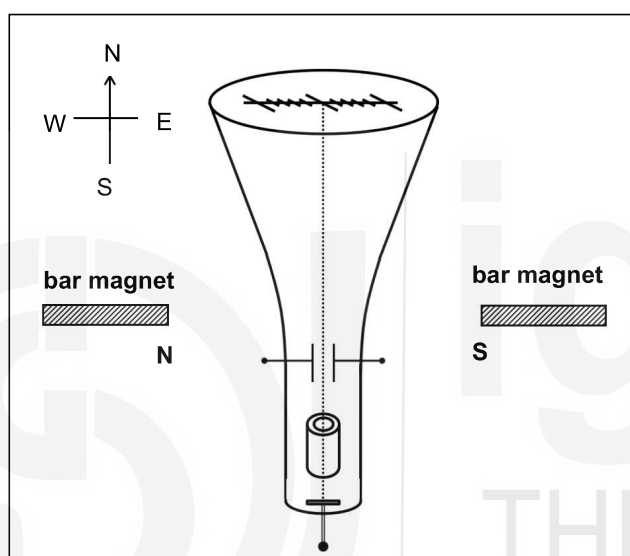


Fig. 10.3: Schematic diagram showing the placement of the CRT (N-S direction) and the Bar magnet (W-E direction).

- Switch on the power supply of the CRT. Adjust the deflecting voltage to zero. To get a bright focused spot at the middle of CRT, make necessary adjustments with the help of a knob provided for the purpose. Note the position of focused bright spot on the screen, with the help of a scale marking given on the CRT screen.
- Now apply the deflection voltage V and note down the vertical deflection of bright spot on the screen as y cm (convert into meters) from the initial position (corresponding to zero applied deflection voltage). Enter the values of V and y in Observation Table 10.1.
- Place the bar magnet on the arms of wooden stand facing opposite poles on the either sides of CRT. Slowly move both the bar magnets, towards the CRT, till the spot reaches its initial position (zero deflection voltage position). Record this position of bar magnets with the help of scale provided on arms of wooden stand as x cm and enter the value in Observation table 10.1. Make sure that the distances of both the bar magnets are exactly symmetrical on the scale.

Note: If the bright spot moves away from the initial position on moving the bar magnets toward CRT, change the polarity of bar magnets.

6. After taking the measurements, switch off the power supply of CRT. Carefully remove the bar magnets and CRT from the wooden stand, leaving the wooden stand position unchanged. Don't move the wooden stand from its position.
7. Place the magnetometer on the centre of wooden stand. In this position aluminium pointers *AB* is pointing at an angle θ zero degree (0°) on the circular scale of magnetometer.
8. To measure the magnetic field strength, place the bar magnets at a distance x cm on either side of the magnetometer on the arms of wooden stand facing opposite poles (as in step 5). Note down the deflection angle θ_1 and θ_2 corresponding to the two ends (*A* and *B*) of the pointer in the magnetometer in Observation table 10.1.
9. Repeat steps 4 to 8 for different values of V .
10. Measure the values of l , d , L and H_E and enter the values in Observation Table 10.1

Observation Table 10.1: Determination of y and θ for different applied deflection voltage

Length of deflection plate : $l = \dots\dots\dots$ cm = $\dots\dots\dots$ m

Distance of separation between the deflection plates:
 $d = \dots\dots\dots$ cm = $\dots\dots\dots$ m

Distance between screen and plate:
 $L = \dots\dots\dots$ cm = $\dots\dots\dots$ m

Horizontal component of earth magnetic field:
 $H_E = \dots\dots\dots$ Wb/m³

S. No.	Applied deflection voltage V (volts)	Spot position y (m)	Distance of bar magnets x (cm)	θ_1 (deg)	θ_2 (deg)	Mean θ (deg) $\left(\theta = \frac{\theta_1 + \theta_2}{2} \right)$	Vy (Vm)	$\tan \theta$	$\tan^2 \theta$
1.									
2.									
3.									
4.									
5.									
...									

11. Plot a graph of $\tan^2\theta$ versus V_y (Fig. 10.4) for the data obtained in Observation Table 10.1

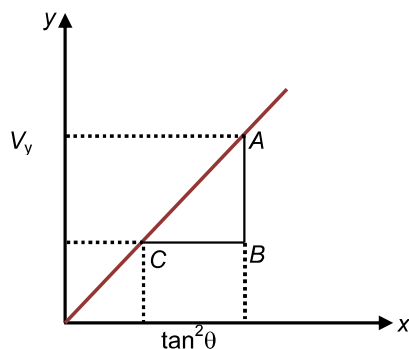


Fig. 10.4: Plot $\tan^2\theta$ along x-axis and v_y along y-axis.

10.4 CALCULATION OF e/m

Calculate the slope of the graph as shown in Fig. 10.4 .

$$\text{Slope} = \frac{AB}{BC} = \dots Vm \tag{10.11}$$

The value of the slope is equal to $\frac{V_y}{\tan^2\theta}$. Substituting $\text{Slope} = \frac{V_y}{\tan^2\theta}$ in

Eq. (10.10) we get :

$$\frac{e}{m} = \frac{\text{Slope}}{H_E^2} \frac{1}{l\left(\frac{l}{2}+L\right)d} \tag{10.12}$$

Using the values of the Slope, l , L , d and H_E in Eq. (10.12) we can calculate the value of e/m .

Result: The value of $e/m = \dots\dots\dots$ C/Kg

Standard Value (i.e. $e/m = 1.76 \times 10^{11}$ C/Kg).

Percentage error = $\dots\dots\%$ (see margin remark)

10.5 PRECATUIONS AND SOURCES OF ERRORS

1. There should not be any nearby external magnetic field that can affect the motion of the electron beam inside the CRT.
2. The axis of the CRT and the bar magnetic should be perpendicular to each other.
3. The axis of CRT should be in north-south direction of the earth's magnetic field.

In order to increase the accuracy the above experiment can be repeated for reverse applied deflection voltage using the reverse switch given on CRT power supply and the value of e/m can be calculated in the same way. The average of the two values of e/m obtained for direct field and reverse field can be taken.

4. The luminous spot on the screen should be sharp and bright. The spot should not remain at a given position for a long time.
5. Remember to note θ_1 and θ_2 from both ends separately.



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