BS 192: Undergraduate Science Laboratory (Physics)

A
Laboratory Report
on

Planck's Constant

by

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Experiment No. 1

Planck's Constant

I. Aim:

To determine Planck's Constant h by photocell and demonstrate inverse square law of radiation.

II. Theory:

The emission of electrons from the surface of metal under the influence of incident radiation is termed as the Photoelectric Effect. The main experimental facts of this phenomenon are as follows:

1. Emission process depends on the frequency of incident radiation.
2. There exists a critical frequency for each metal such that any light of lower frequency is unable to liberate electrons, while light of higher frequency is always able to do so.
3. The electrons are emitted almost instantaneously after the arrival of incident radiation and number of electrons emitted is strictly proportional to the intensity of the incident radiation.

These experimental facts strongly suggest that light is quantized, and the electromagnetic field consists of packets or quanta of energy $E = h\nu$ where ν is the frequency of the radiation and h is the Planck's constant. These quanta are called photons.

Above the critical frequency, the maximum photoelectron energy KE_{max}, increases linearly with increasing frequency.

$$KE_{max} = h\,(\nu - \nu_0) = h\nu - h\nu_0$$

Where ν_0 is the critical or threshold frequency below which no photoemission occurs. The value of h is always the same, whereas ν_0 varies with the particular metal being illuminated. The quantity $h\nu_0$ is equal to $e\phi$, where e is the magnitude of electronic charge and ϕ is the work function of the metal, which is defined as the minimum energy required to remove an electron from the metal surface being illuminated.

$$\frac{1}{2}mv^2 = h\nu - e\phi$$

The kinetic energy of photoelectrons is determined by the retarding potential technique and the potential at which the photocurrent drops below zero is termed as stopping potential.

$$\frac{1}{2}mv^2 = eV_s$$

$$V_s = \frac{h}{e}\nu - \phi$$

When we plot stopping potential against the frequency, we get a straight line. The slope yields the value of h and the intercept on y-axis gives the work function.

If L is the luminous intensity of an electric lamp and E is the intensity of illumination at point r from it, then according to inverse square law,

$$E \propto \frac{1}{r^2}$$

If this light is allowed to fall on the cathode of photoelectric cell, then the photocurrent I will be proportional to E

$$E = \frac{L}{r^2} = K.I$$

Hence a graph between $\frac{1}{r^2}$ and I is a straight line, which verifies the inverse square law of radiation.

III. Apparatus:

Optical bench of length 40 cm with a halogen tungsten lamp (12V/35W) on it, which includes a display meter (current or voltage), knobs for varying the light intensity, voltage, and five colour filters with different wavelengths (635 nm, 500 nm, 540 nm, 570 nm, 460 nm).

IV. Procedure:

Part I: To determine Planck s constant (h).

1. While the instrument is off, remove the cover from the phototube and insert a colour filter into it.
2. Set the voltage direction to negative.
3. Ensure that the distance between the filter and light is 25 cm and tighten the knob so that light does not move.
4. Turn on the instrument and keep the intensity between minimum and maximum.
5. Increase the deaccelerating voltage in fixed intervals and note down the reading of the photoelectric current. Take 18-20 readings till it reaches zero.
6. For checking the stopping potential, set the current multiplier to 0.1x, increase the deaccelerating voltage till the display shows zero current. Then set the current multiplier to 0.01x, and increase the deaccelerating voltage till the display shows zero current. Do the same after setting the current multiplier to 0.001x.
7. For the remaining filters, block the light with a book or an opaque object, change the filter, and repeat steps 5 and 6.

Part II: To demonstrate inverse square law of radiation.

1. Remove the cover from the phototube, insert the red filter, place the light source 40 cm away from the filter.
2. Set the voltage direction to positive at +0.1V and turn it on.
3. Keep the intensity around the same as for part 1. Note down the reading of photocurrent.

4. Now move the light source 2 cm closer, and after each move, note down the reading of photocurrent.
5. Continue this till the distance between the filter and light source is 20 cm.

V. Results:

- Observation Tables and Graphs:

635nm	
Voltage (V)	Photocurrent (A)
0.00	0.190
0.02	0.152
0.04	0.120
0.06	0.090
0.08	0.065
0.10	0.049
0.12	0.033
0.14	0.022
0.16	0.014
0.18	0.008
0.20	0.004
0.22	0.002
0.23	0.000
0.26	-0.002

570nm	
Voltage (V)	Photocurrent (A)
0.00	0.580
0.02	0.486
0.04	0.440
0.06	0.374
0.08	0.320
0.10	0.264
0.12	0.226
0.14	0.155
0.16	0.141
0.18	0.119
0.20	0.090
0.22	0.068
0.24	0.051
0.26	0.036
0.28	0.025
0.30	0.015
0.32	0.009
0.34	0.004
0.36	0.000
0.38	-0.003

540nm	
Voltage (V)	Photocurrent (A)
0.00	1.044
0.03	0.893
0.06	0.794
0.09	0.625
0.12	0.565
0.15	0.470
0.18	0.380
0.21	0.313
0.24	0.297
0.27	0.197
0.30	0.140
0.33	0.097
0.36	0.069
0.39	0.047
0.42	0.029
0.45	0.014
0.48	0.004
0.50	0.000
0.51	-0.002

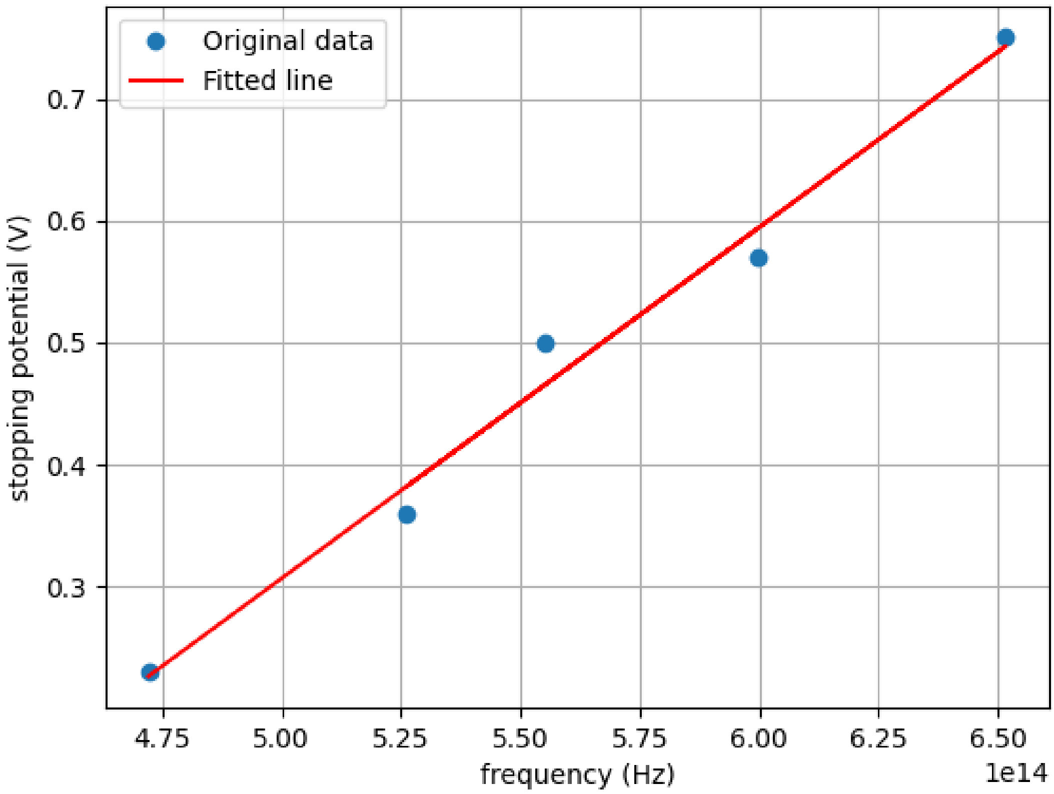
500nm	
Voltage (V)	Photocurrent (A)
0.00	1.060
0.04	0.882
0.08	0.744
0.12	0.606
0.16	0.482
0.20	0.377
0.24	0.286
0.28	0.211
0.32	0.152
0.36	0.098
0.40	0.066
0.44	0.041
0.48	0.023
0.52	0.010
0.56	0.002
0.57	0.000
0.60	-0.004

460nm	
Voltage (V)	Photocurrent (A)
0.00	1.290
0.05	1.100
0.10	0.910
0.15	0.750
0.20	0.610
0.25	0.475
0.30	0.369
0.35	0.275
0.40	0.205
0.45	0.142
0.50	0.100
0.55	0.084
0.60	0.041
0.65	0.024
0.70	0.010
0.75	0.000
0.80	-0.050

(Images of these readings are in Section VIII)

- Graph between stopping potential (V_s) and frequency (ν):

Wavelength (nm)	Frequency (Hz)	Stopping Potential (V)
460	6.52×10^{14}	0.75
500	6.00×10^{14}	0.57
540	5.55×10^{14}	0.50
570	5.26×10^{14}	0.36
635	4.72×10^{14}	0.23



By using the Least Square Fitting method, we get the above red line, with slope,

$$\frac{h}{e} = 2.874 \times 10^{-15}\, JsC^{-1}$$

and y-intercept,

$$\phi = |-1.13|\, V$$

or

$$\phi = 1.13\, V$$

Hence, we get the value of h as,

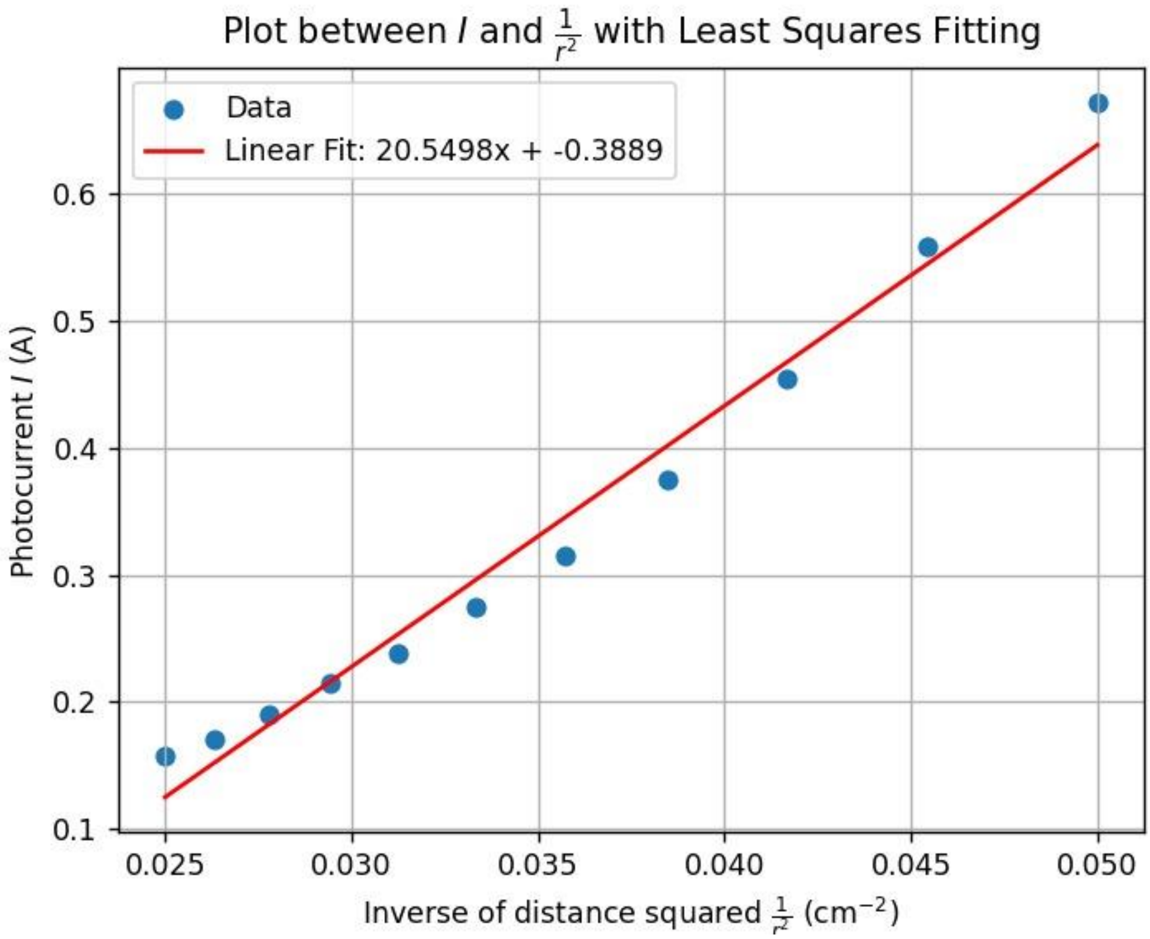
$$h = 2.875 \times 10^{-15} \times 1.602 \times 10^{-19}\,Js$$

or

$$h = 4.605 \times 10^{-34}\,Js$$

- Plot between photocurrent (I) and $\frac{1}{r^2}$:

Distance (cm)	Photocurrent (A)
40	0.158
38	0.170
36	0.190
34	0.215
32	0.238
30	0.274
28	0.315
26	0.375
24	0.455
22	0.559
20	0.672



VI. Discussion and Error Analysis:

For Part 1 of the experiment, we obtained values of stopping potential for different values of wavelengths. In theory, on plotting stopping potential vs frequency, we should get a straight line. So, to estimate that line, we used Least Square Fitting method, and found out the value of the slope and the y-intercept. From there h can be calculated as,

$$h = \text{slope} \times 1.602 \times 10^{-19}\, Js$$

and ϕ is the absolute value of the y-intercept.

Another way we could have estimated the value of h and ϕ is as follows:

1. We have five datapoints, hence we can formulate five equations in h and ϕ.
2. Choose any two of them and get the values of h and ϕ (We get 5 choose 2 = 10 systems of equations, hence 10 pairs of values of h and ϕ).
3. Compute mean values of h and ϕ.
4. Compute deviation from mean for all values of h and ϕ.
5. Compute their average to get the average error in deviation from mean.

h (Js)	ϕ (V)	h - h0 (Js)	|h-h0| (Js)	ϕ-ϕ0 (V)	|ϕ-ϕ0| (V)
4.639E-34	1.137	-1.022E-35	1.022E-35	-3.957E-02	3.957E-02
3.869E-34	0.910	-8.721E-35	8.721E-35	-2.664E-01	2.664E-01
5.208E-34	1.305	4.675E-35	4.675E-35	1.283E-01	1.283E-01
4.273E-34	1.029	-4.674E-35	4.674E-35	-1.472E-01	1.472E-01
4.968E-34	1.271	2.273E-35	2.273E-35	9.448E-02	9.448E-02
4.149E-34	0.938	-5.923E-35	5.923E-35	-2.389E-01	2.389E-01
5.531E-34	1.500	7.905E-35	7.905E-35	3.236E-01	3.236E-01
7.677E-34	2.160	2.936E-34	2.936E-34	9.836E-01	9.836E-01
4.569E-34	1.140	-1.715E-35	1.715E-35	-3.643E-02	3.643E-02
2.525E-34	0.375	-2.216E-34	2.216E-34	-8.014E-01	8.014E-01
Mean h = h0 (Js)	4.741E-34				
Mean ϕ = ϕ0 (V)	1.176				
Mean error in h (Js)	8.842E-35				
Mean error in ϕ (V)	0.306				

The value of h comes out to be,

$$h = 4.741 \times 10^{-34} \pm 8.842 \times 10^{-35} Js$$

The error % is,

$$\frac{\Delta h}{h} \times 100 = \frac{8.842 \times 10^{-35}}{4.741 \times 10^{-34}} \times 100 = 18.65\ \%$$

The value of ϕ comes out to be,

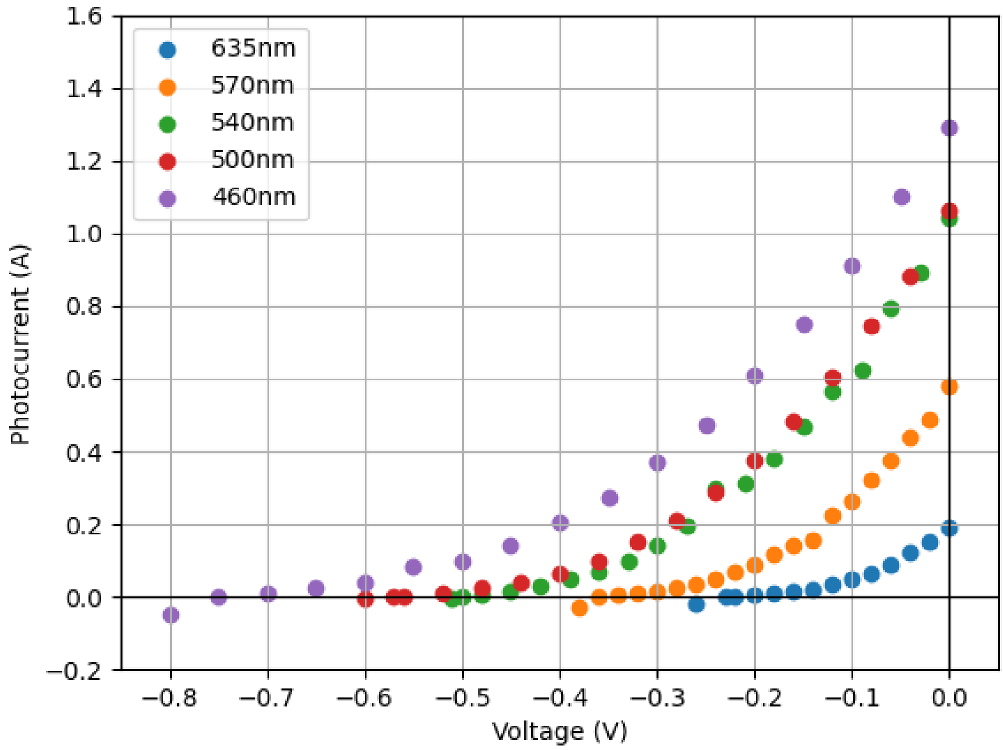
$$\phi = 1.176 \pm 0.306\, V$$

The error % is,

$$\frac{\Delta\phi}{\phi} \times 100 = \frac{0.306}{1.176} \times 100 = 26.02\ \%$$

The above procedure can also be visualised as drawing all possible lines joining two points in the dataset and calculating their average slope.

Alternatively, if we plot photocurrent vs voltage, we can also come to the same conclusion that, as frequency increases (or, wavelength decreases), the magnitude of stopping potential increases.



For Part 2 of the experiment, we fixed the light intensity and found out the value of the photocurrent as we varied the distance between the light source and the filter. We gathered 11 datapoints and plotted photocurrent vs one over distance squared. As the distance between the light source and colour filter decreases, number of photons hitting the metal increases, hence, photocurrent increases. And since the light source emits radiation in all directions, the number of photons vary linearly with one over distance from the source squared. This is verified by viewing the plot, which is approximately a straight line.

- Possible sources of errors for both parts:

We are getting the value of Planck's constant which is less than the expected value, that is, the slope of stopping potential and frequency curve is smaller than expected, which means, for a given frequency of incident light, the stopping potential is lower than expected, which might be due to erroneously high resistance in the photocell circuit. Unexpectedly high resistance in the circuit might be due to damage to internal wires, loose connections, and due to old age of the device. While taking readings, we should wait till the photocurrent value settles down, as, initially it might fluctuate as light source will heat up. The filters used might be imperfect, allowing a band of frequencies to pass through, instead of a discrete value, which would slightly increase or decrease the value of stopping potential.

$$V_s = \frac{h}{e}(\nu \pm \Delta\nu) - \phi$$

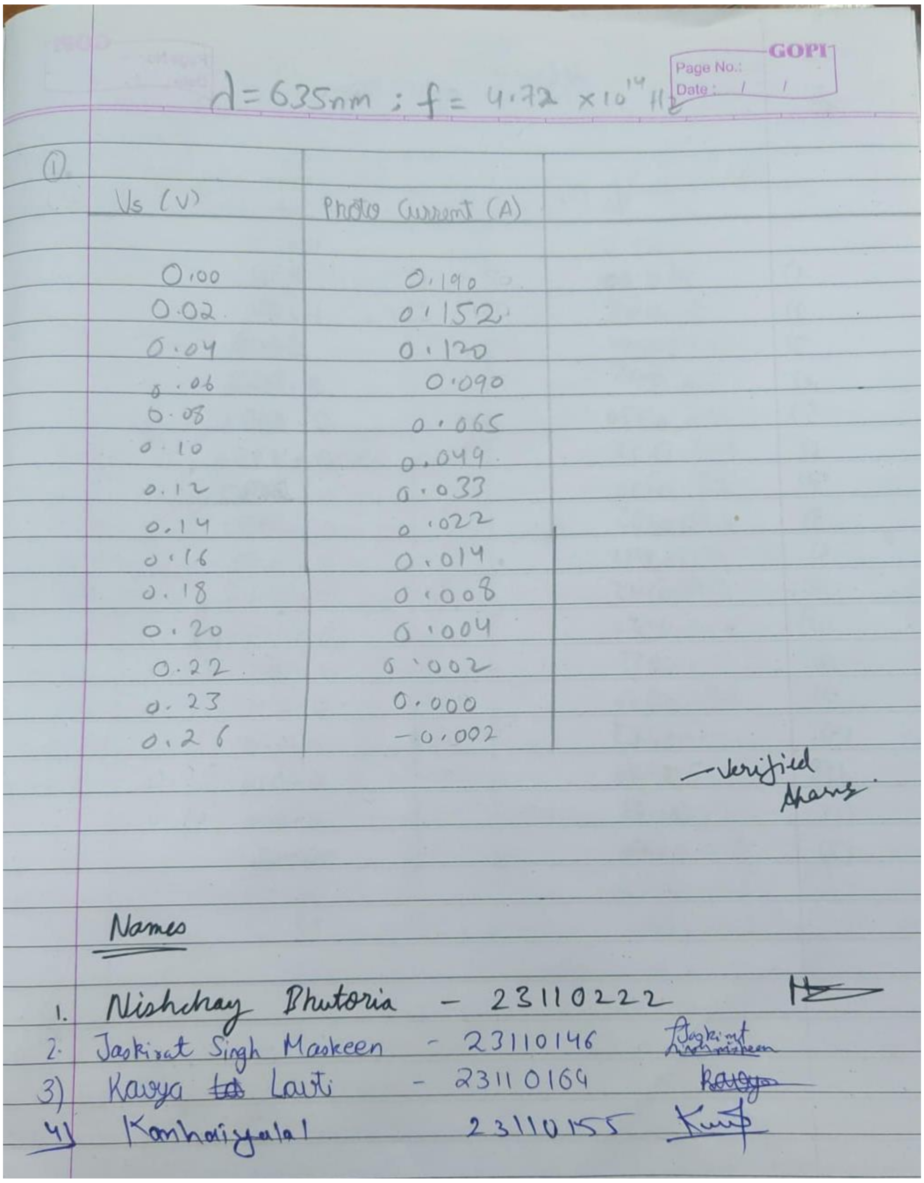
Other random errors might have crept in: for example, parallax error for the part 2. We must look from the top of the apparatus, so that parallax can be avoided.

VII. Conclusion:

We conducted this experiment to determine the value of the Planck's constant and the work function of the metal and figure out the relation between photocurrent and distance of light source from metal. We found out that as frequency increases, the stopping potential for a given metal increases. Then from the relation between the above quantities we get the values of the Planck's constant as well as the work function. This experiment proves that light behaves as a particle in its interaction with matter. Through this experiment, we demonstrated that the energy of photons is independent of intensity and linearly dependent on wavelength, we determined the constant of proportionality with some degree of accuracy. The actual value of Planck's constant, $6.626 \times 10^{-34}\,Js$ fell outside the error bounds, but the error associated is reasonable (roughly 31%). Reducing the error can be accomplished by repeating the experiment on different apparatus at different times. Waiting for a long period of time between readings would help as well. Further, a brighter photon source such as a LASER, would offer much greater resolution and will produce a better estimate for the stopping potential.

From Part 2 of the experiment, we verified that as the distance between light source and metal decreases, the photocurrent increases. For the future, we can conduct multiple sets of the same experiment to determine the value of the Planck's constant more accurately, or we can switch to more thorough experiments like modern photoemission spectroscopy. We can also change the work function and repeat the same experiment to have a better estimate of the value of the Planck's constant.

VIII. Readings Images:



$\lambda = 635nm$; $f = 4.72 \times 10^{14}$ Hz

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(1)

Vs (V)	Photo Current (A)
0.00	0.190
0.02	0.152
0.04	0.120
0.06	0.090
0.08	0.065
0.10	0.049
0.12	0.033
0.14	0.022
0.16	0.014
0.18	0.008
0.20	0.004
0.22	0.002
0.23	0.000
0.26	-0.002

— Verified

Names

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540 nm

	Vs (V)	I (A)
1)	0.00	1.044
	0.03	0.893
	0.06	.794
	0.09	.625
	0.12	.565
	0.15	.470
	0.18	.380
	0.21	.313
	0.24	.297
	0.27	.197
	0.30	.140
	0.33	0.097
	0.36	0.064
	0.39	0.047
	0.42	0.029
	0.45	0.014
	0.48	0.004
	0.50	0.000
	0.51	-0.002

460 nm

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4)	0.15	0.750
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635 nm

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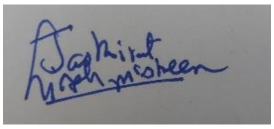
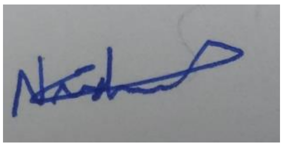
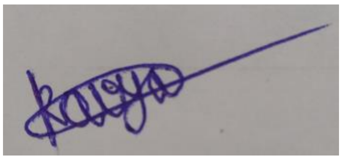
20	0.672

IX. Author Contribution:

Name	Roll Number	Contribution	Signature
Jaskirat Singh Maskeen	23110146	Theory, Generating graphs for Part 1 along with observation tables [Matplotlib + NumPy], Conclusion and sources of error, Document structure, Index.	
Nishchay Bhutoria	23110222	Taking readings in lab, Error analysis and computation, Generating graphs for Part 2 along with observation tables [Matplotlib + NumPy], Author contribution, Document formatting, Cover page.	
Kavya Lavti	23110164	Document structure, Taking readings in lab, Procedure.	
Kanhaiyalal	23110155	Noting readings.