Determination of Planck's Constant

Under-Graduate Science Laboratory – BS 192 (Group - 7)

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1 Objective

The objective of this experiment is to determine Planck's constant (h) using a photoelectric setup and to validate the inverse square law of radiation. Specifically, the experiment aims to measure the stopping potential of photoelectrons as a function of light frequency to calculate Planck's constant. Additionally, it seeks to confirm the inverse square relationship between light intensity and distance from a point source. This dual focus will provide practical insights into these fundamental principles and evaluate their consistency with theoretical models.

2 Apparatus Description

The apparatus used for measuring Planck's constant consists of the following components:

- **Halogen Tungsten Lamp**: A 12V/35W halogen tungsten lamp provides the light source for the experiment. Its intensity can be continuously adjusted, which is essential for studying how varying light intensities affect the photoelectric effect.
- **Vacuum Phototube**: This device contains a photocathode and is mounted inside a closed chamber. The vacuum inside the phototube ensures that no external light interferes with the experiment, allowing for accurate measurements of the photoelectric effect.

- **Drawtube**: Attached to the front of the closed chamber, the drawtube holds color filters at one end and a lens at the other. The color filters enable the selection of specific wavelengths of light, while the lens focuses the light onto the photocathode.

- **Color Filters**: Five color filters are included, each with a known central frequency. These filters allow for precise control over the wavelength of light hitting the photocathode, facilitating the investigation of the photoelectric effect across different light frequencies.

- **Voltage Control**: The experiment features a ±15V multi-turn potentiometer that adjusts the voltage between the anode and cathode of the phototube. This allows for precise control of the stopping potential. A switch button is provided to change the polarity of the voltage as needed.

- **Digital Nano-Ammeter**: This instrument measures the photocurrent generated by the ejected photoelectrons. Its high sensitivity is crucial for detecting and recording small currents accurately.

- **Optical Bench**: The setup is mounted on a 40 cm optical bench. The lamp and phototube are positioned along this bench, with the lamp adjustable to vary the distance between it and the phototube. This feature allows for the study of the effect of distance on light intensity and photocurrent.

Figure 1: Apparatus for Planck's constant experiment.

3 Theory

3.1 Historical Background

The story of the **photoelectric effect** starts back in 1887 with Heinrich Hertz, who was experimenting with radio waves. During his experiments, he noticed something unusual: when ultraviolet light was shined on metal, it helped spark a gap between two electrodes. Even though this was an interesting observation, it didn't get much attention at the time. The real breakthrough came in 1905 when Albert Einstein, inspired by Max Planck's quantum hypothesis, proposed an audacious explanation. Einstein suggested that light, long considered purely a wave, could also be thought of as consisting of particles, or "quanta" of energy, now known as photons. He theorized that when a photon strikes a metal surface, it imparts its energy to an electron in the metal. If the photon's energy exceeds the work function—the minimum energy required to eject an electron—the electron is emitted from the surface. This radical idea not only explained the photoelectric effect but also implied that light's energy was quantized, leading to the concept of wave-particle duality.

Einstein's theory was revolutionary because it contradicted the classical wave theory of light, which couldn't explain why the energy of ejected electrons depended on the frequency rather than the intensity of the light. This work earned Einstein the Nobel Prize in Physics in 1921, and it provided one of the first concrete validations of quantum theory, reshaping our understanding of the physical world.

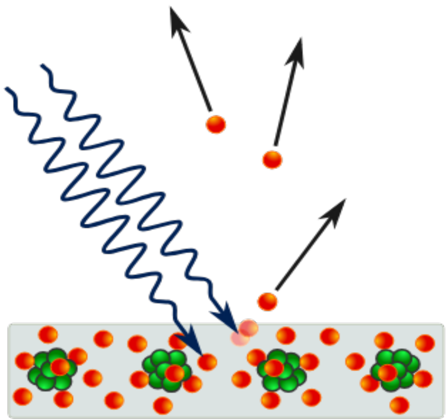


Figure 2: Illustration of the photoelectric effect.

3.2 Photoelectric Effect

When light of a certain frequency, ν, shines on a metal surface, it can cause the ejection of electrons, provided the frequency of the light exceeds the material's threshold frequency, ν_0. The maximum kinetic energy ($KE_{\max}$) of these photoelectrons is described by the equation:

$$KE_{\max} = h(\nu - \nu_0) \tag{1}$$

In this equation:

- h is Planck's constant, which is a fundamental constant in quantum mechanics.
- ν represents the frequency of the incoming light.
- ν_0 is the threshold frequency, below which no photoelectrons are emitted.
- $h\nu_0$ corresponds to the work function (ϕ), which is the minimum energy required to eject an electron from the metal.

The relationship between the kinetic energy of the ejected electrons and the stopping potential V_s is given by:

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

Where:

- e is the elementary charge of an electron.
- V_s is the stopping potential, which is the voltage needed to reduce the photocurrent to zero by halting the movement of the most energetic photoelectrons.

This stopping potential V_s can also be expressed in terms of the frequency ν of the incident light as:

$$V_s = \frac{h}{e}\nu - \phi \tag{3}$$

From this relationship, when V_s is plotted against ν, the slope of the resulting straight line provides the ratio $\frac{h}{e}$, and the y-intercept gives the value of the work function ϕ.

Additional Points:

- The photoelectric effect not only provides a direct method to measure Planck's constant but also gives experimental evidence of the quantum nature of light, reinforcing the idea that light can exhibit both wave-like and particle-like properties.
- The linear relationship between the stopping potential and the frequency of light is a critical aspect that disproved the classical wave theory of light, which could not account for the dependency of kinetic energy on frequency.
- The threshold frequency ν_0 is specific to each material, depending on its atomic structure, which determines the work function ϕ.

3.3 Inverse Square Law of Radiation

The **inverse square law of radiation** describes how the intensity of light, denoted by E, diminishes as the distance r from a point source increases. Specifically, the intensity is inversely proportional to the square of the distance from the source, and this relationship is mathematically expressed as:

$$E = \frac{L}{r^2} \tag{4}$$

In this equation:

- L represents the luminous intensity of the source, which is a measure of the light emitted per unit solid angle.
- r is the distance from the light source to the point where the intensity is being measured.

Since the photocurrent I generated in a photoelectric effect experiment is directly proportional to the intensity of the incident light E, we can establish the following relationship:

$$I \propto \frac{1}{r^2} \tag{5}$$

This means that as the distance from the light source increases, the photocurrent decreases following the inverse square law. To experimentally verify this law, a plot of the photocurrent I against $\frac{1}{r^2}$ should produce a straight line, indicating that the intensity of light (and thus the photocurrent) indeed follows the inverse square relationship.

4 Experimental Procedure

4.1 Part I – Determination of Planck's Constant

1. Insert the chosen color filter into the drawtube.
2. Adjust the light intensity to its maximum setting.
3. Position the photocathode at a distance of 25 cm from the light source.
4. Set the voltage polarity switch to "negative" and switch the display mode to current measurement in microamperes (μA).
5. Gradually increase the de-accelerating voltage until the photocurrent is reduced to zero.
6. Record the value of the stopping potential at which the photocurrent ceases.
7. Repeat the above steps for each of the color filters provided.
8. Plot the recorded data on a graph and determine the slope and intercept to calculate Planck's constant and the work function of the material.

4.2 Part II – Verification of the Inverse Square Law of Radiation

1. Insert the chosen filter (e.g., Red – 670 nm).
2. Set the voltage direction to "+ve" V and the voltage to +0.1 V.
3. Place the light source at 40 cm from the detector.
4. Record the photocurrent as the source is moved closer to the detector in 2 cm increments, down to 20 cm.
5. Plot the graph of photocurrent vs $1/(\text{distance})^2$.

5 Results and Discussion

5.1 Stopping Potential vs Frequency

Colour	Wavelength (m)	Stopping Voltage (V)	Frequency (Hz)
Blue	4.80×10^{-7}	-1.03	6.25×10^{14}
Green	5.20×10^{-7}	-0.83	5.77×10^{14}
Yellow	5.65×10^{-7}	-0.71	5.31×10^{14}
Orange	5.90×10^{-7}	-0.53	5.08×10^{14}
Red	6.70×10^{-7}	-0.32	4.48×10^{14}

Table 1: Stopping Potential vs Frequency

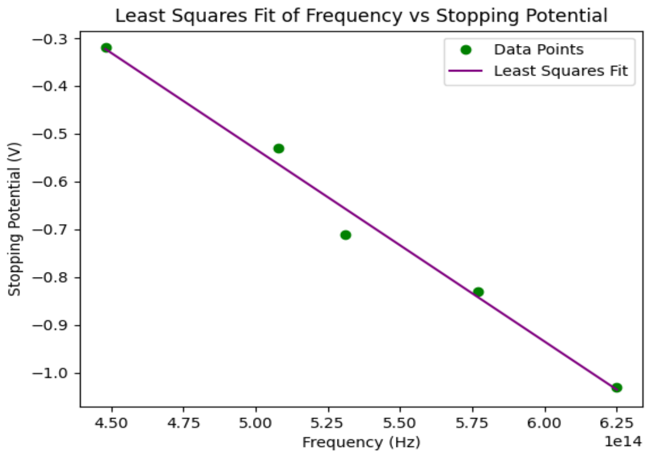


Figure 3: Plot of Stopping Potential vs Frequency

By plotting the stopping potential V_s against the light frequency, a linear graph was obtained (Figure 3). The experimental data used to create this plot is summarized in Table 1. According to Equation (3), the slope of the graph was -4.024×10^{-15}, and the intercept was 1.480. The Planck's constant, derived from the slope, is 6.446×10^{-34} Js. The intercept value represents the work function of the photocathode material. The plot shown in Figure 3 was generated using Python, demonstrating the linear relationship between the stopping potential and the light frequency based on the data presented in Table 1.

5.2 Photocurrent vs $1/r^2$ for Red Light

Distance (cm)	Photocurrent (μA)
40	0.568
38	0.618
36	0.670
34	0.738
32	0.819
30	0.979
28	1.015
26	1.146
24	1.194
22	1.508
20	1.830

Table 2: Photocurrent vs $1/r^2$

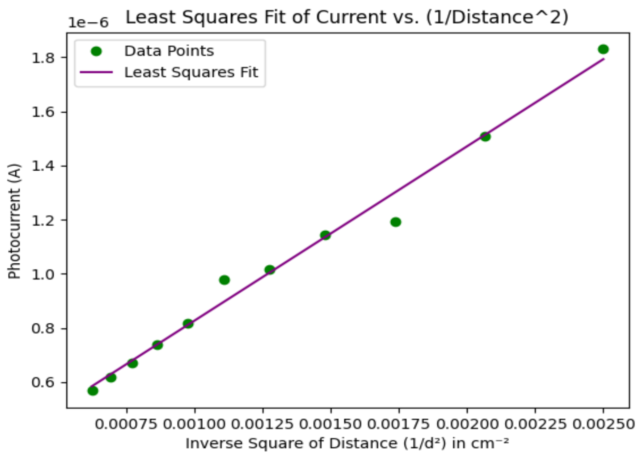


Figure 4: Plot of Photocurrent vs $1/\mathrm{r}^2$

A plot of photocurrent I versus $\frac{1}{r^2}$ resulted in a straight line (Figure 4). The data collected during the experiment, as shown in Table 2, was used to generate this plot. This linear relationship confirms the inverse square law of radiation, described by Equation (5). The plot was created using Python, based on the experimental data presented in Table 2.

6 Conclusions

The objective of the experiment was to determine Planck's constant and to verify the inverse square law of radiation. The findings from the experiment are summarized below:

6.1 Determination of Planck's Constant

The analysis of the stopping potential (V_s) as a function of the light frequency revealed a linear relationship. From the graph, Planck's constant was determined to be 6.446×10^{-34} Js. The intercept value of 1.480 V corresponded to the work function of the photocathode material.

The known theoretical value of Planck's constant is approximately 6.626×10^{-34} Js. The experimental value obtained is slightly lower, and this discrepancy could be due to several factors:

- **Instrumental Errors:** Minor inaccuracies in voltage measurements or calibration issues with the phototube and ammeter could lead to deviations from the expected value.
- **Environmental Factors:** Fluctuations in temperature or ambient light conditions may influence the performance of the phototube, thereby affecting the accuracy of the measurements.
- **Filter Accuracy:** The actual central wavelengths of the color filters may deviate from their specified values, resulting in errors in frequency determination.
- **Measurement Precision:** The precision of the equipment used, including the digital nanometer and the phototube, could impact the accuracy of the results.
- **Experimental Setup:** Any misalignment or imperfections in the experimental setup, such as improper focusing of light or inconsistencies in light intensity, could also affect the outcomes.

Overall, while the experimental value for Planck's constant is close to the theoretical value, these potential sources of error highlight areas where the experimental accuracy could be improved.

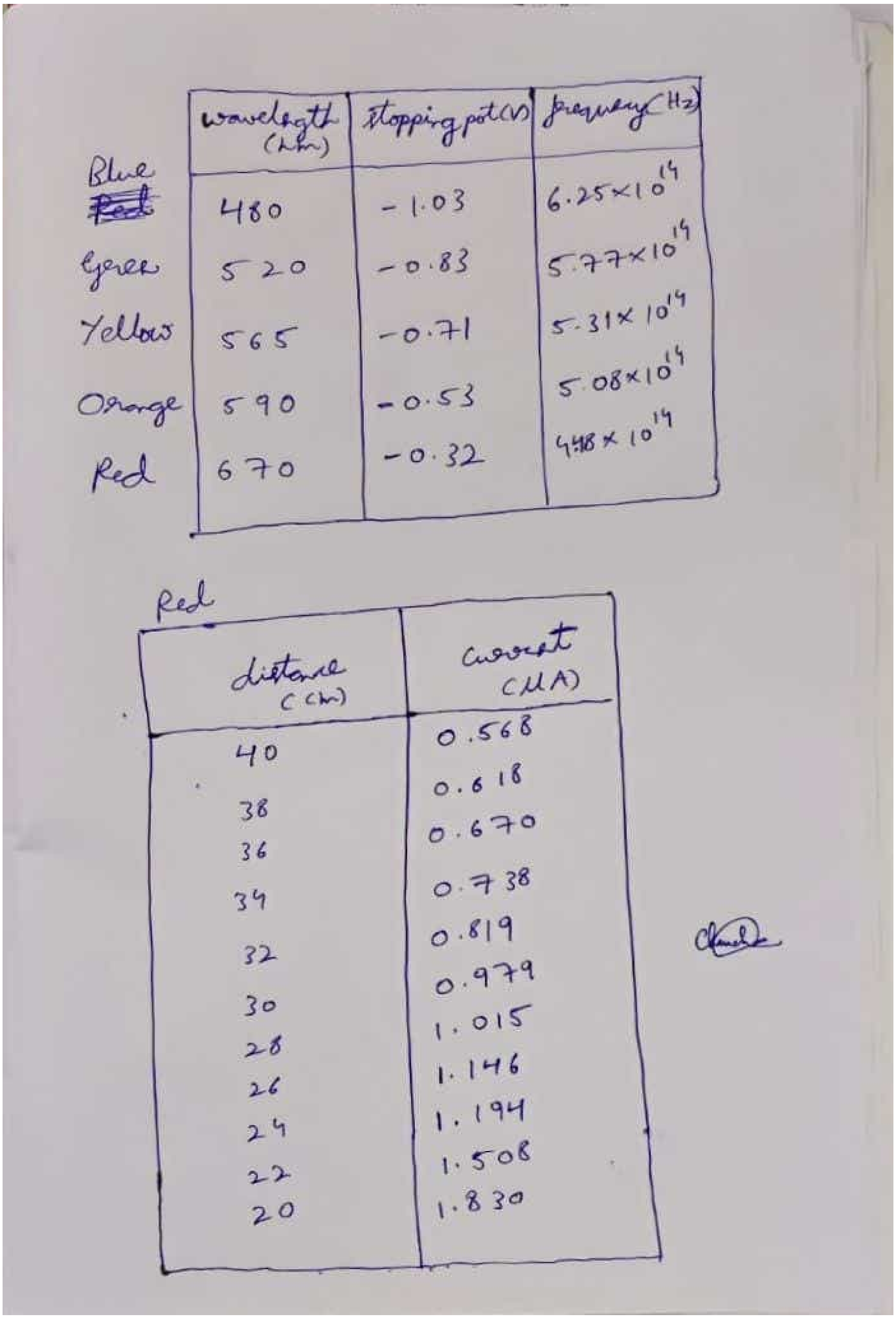
6.2 Verification of the Inverse Square Law

The plot of photocurrent (I) versus $\frac{1}{r^2}$ yielded a straight-line graph, as shown in Figure 4. This linear relationship supports the inverse square law of radiation, demonstrating that the intensity of light decreases in proportion to the square of the distance from the source. This result is consistent with theoretical predictions.

The experiment successfully verified the photoelectric effect and validated the inverse square law. Although the observed results confirmed the theoretical expectations for the inverse square law, the value of Planck's constant derived from the experiment differed slightly from the accepted value. Identifying and addressing potential sources of error could improve the accuracy of future measurements and ensure closer alignment with theoretical values.

7 Author Contributions

- **Birudugadda Srivibhav**
  - Collected and recorded the experimental data.
  - Generated plots using Python based on the experimental data.
  - Created and formatted the tables and figures used in the report.
  - Reviewed and edited the entire report for clarity and coherence.
- **Vubbani Bharath Chandra**
  - Collected and recorded the experimental data.
  - Formatted and finalized the report, including the preparation of the title page and author contributions.
- **Ankeshwar Ruthesha**
  - Analyzed the data and performed the calculations for Planck's constant and work function.
  - Compiled the results and discussion sections, including interpreting the data and comparing observed values with theoretical ones.
- **Kirtankumar Patel**
  - Drafted the conclusion section, addressing the accuracy of the experimental results and potential sources of error.
  - Reviewed and edited the entire report for clarity and coherence.



	wavelength (nm)	stopping pot (V)	frequency (Hz)
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Figure 5: Lab Recordings