Determination of Planck's Constant through the photoelectric effect

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***Abstract*—Planck's constant, $\boldsymbol{h}$ is an prominent constant within Physics and appears in important theories such as Black Body radiation. The report aims to measure the value of Planck's constant experimentally through the photoelectric effect. It was concluded that Planck's constant had a value of $(\mathbf{6.15 \pm 0.09}) \times \mathbf{10^{-34}} \boldsymbol{Js}$, close to the accepted value of $\mathbf{6.63} \times \mathbf{10^{-34}} \boldsymbol{Js}(\mathbf{3.s.f})$.**

I. Introduction

Planck's constant shows up in theories which describe behaviors of particles. Finding its value will allow us to both describe quantum physics and its subsequent real world application.

Planck's constant stems from the idea that light could be seen not as a wave but rather particles known as 'photons'. Each photon has energy

$$E = hf \tag{1}$$

Where E is the energy of the photon, f is the frequency of the light and h is Planck's constant [1]. This idea then becomes a key concept in the "photoelectric effect". The photoelectric effect is a phenomena where light shone incident on a material, causes the surface to emit electrons.

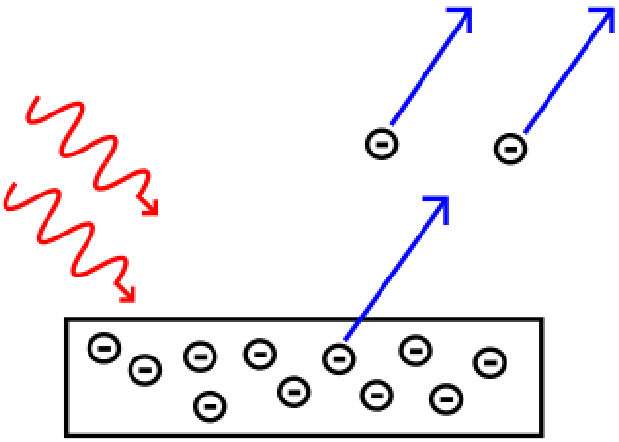

Fig. 1. Photoelectric effect – photons (red lines) absorbed and electrons emitted [3]

This effect is explained by the quantization of light into particles. Assuming light is made of photons, each photon with energy $E = hf$ gives the energy required for each electron to be emitted. This then proposes the equation

$$hf = KE + \phi \tag{2}$$

Where KE is the kinetic energy which the emitted electron escapes with and ϕ is the 'work function' which describes the energy required for the electron to escape the surface. The equation describes how photon energy is transferred to the electron, which overcomes the work function to escape the surface of the material with some kinetic energy. This idea will be used to determine Planck's constant.

If a plate(cathode) emitting electrons faces an anode which collects the electrons, a current can then be formed by the moving electrons and measured with a circuit. If a potential opposing motion of electrons is created between the cathode and anode, then the potential can be raised to the point called the 'stopping potential', V where electrons stop collecting on the plate and current becomes 0. The kinetic energy becomes the potential energy of the electrons as a result of the potential field. This is given by

$$KE = Ve \tag{3}$$

Where e is the charge of an electron. Substituting Equation 3 into Equation 2, we end up with

$$hf = Ve + \phi \tag{4.1}$$

$$V = \frac{h}{e}f - \frac{\phi}{e} \tag{4.2}$$

We can measure the stopping potential experimentally and plot how it varies with different frequencies of light shone incident on surface to then get the gradient of Equation 4.2, which can then tell us a value of Planck's Constant by multiplying by a factor of e [1].

$$h = em \tag{4.3}$$

Where m is the gradient of Equation 4.2. We are also able to see the work function, ϕ can be expressed by

$$\phi = -Ce \tag{4.4}$$

Where C is the y-intercept of Equation 4.2. Finally within the experiment we must calculate the frequency of light, f, from wavelength, λ. For electromagnetic waves, the relation between frequency and wavelength is

$$f = \frac{c}{\lambda} \tag{5}$$

Where c is the speed of light. As a hypothesis, we should see linear relationship between stopping potential and frequency of light incident. As stopping potential is independent of intensity, changing intensity should not change stopping potential.

II. Equipment and Method

The equipment used was

- PASCO scientific h/e apparatus Model AP-9368
- 20W Tungsten Halogen lamp
- Focusing Lenses
- Optical Rail
- Selected narrow band interference filters
- Digital voltmeter
- Selected neutral density filters

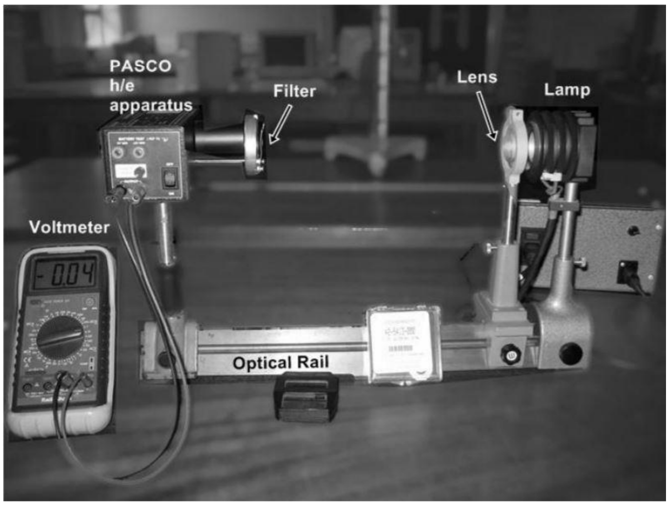

Fig. 2. Apparatus setup – A lamp shining on h/e apparatus connected to a voltmeter through a filter. [1, p. 7]

The apparatus was set up as seen in Fig. 2. The h/e apparatus served as the cathode-anode plates which contained the photoelectric effect but also applied the reversing potential. The tungsten halogen lamp was turned on which sent light through a focusing lens, which concentrated the intensity of light onto a narrow band interference filter and sent the light of a specific wavelength through the h/e apparatus. The h/e apparatus when turned on created a stopping potential, using a battery of 10V. A digital voltmeter was then connected to the h/e apparatus which could be able to measure this potential when the h/e apparatus was turned on. After 30 seconds the potential would level out. The stopping potential for a given wavelength of light was then recorded. This was repeated for different various wavelengths between 400 – 670nm.

A second part of the experiment looked at the effect of intensity of light on the stopping potential. The selected neutral density filters were slotted with a band interference filter with a fixed wavelength (546nm). One neutral density filter changed the intensity of light to 80% and the other changed intensity to 40%. The stopping voltage was recorded for each intensity of light. Repeat measurements for each interference filter and density filters were done 3 times.

III. Results, Uncertainties and Analysis

Table 1: Initial Measurements

Wavelength, λ ($\pm$5 nm)	Stopping Potential ($\pm$0.01 V)
670	0.39
	0.39
	0.39
546	0.77
	0.77
	0.77
440	1.30
	1.30
	1.30
430	1.33
	1.33
	1.34
410	1.50
	1.49
	1.49
400	1.55
	1.54
	1.54

Through Equation 5, we obtain frequency and stopping potential

Table 2: Calculated frequency and stopping potential

Frequency, f (10^{14} Hz)	Stopping Potential (V)
4.48 ± 0.03	0.39 ± 0.01
5.49 ± 0.05	0.77 ± 0.01
6.82 ± 0.08	1.30 ± 0.01
6.98 ± 0.08	1.33 ± 0.01
7.31 ± 0.09	1.49 ± 0.01
7.50 ± 0.09	1.54 ± 0.01

The data from Table 2 is plotted to show the relationship between stopping potential and the frequency of the light.

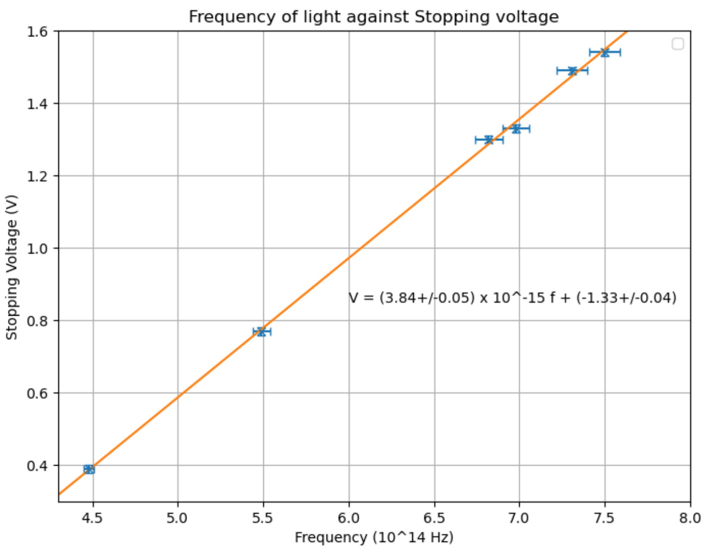

Fig. 3. Graph of frequency of light incident against stopping voltage

A line of best fit was also graphed on Fig 3. and was found through least squares regression. The data follows a straight line graph which is in line with the hypothesis - the stopping potential will vary with the frequency linearly. The gradient was then used with the charge of an electron to find the value of Planck's constant through Equation 4.2. The charge of an electron was taken to be approximately $1.60 \times 10^{-19}\ C$ [4]. The error of Planck's constant was found through the propagation of uncertainty through Equation 4.3. Uncertainty in electron charge was assumed to be negligible (NIST uncertainty is much smaller than 3 sig fig). This gives the final value of Planck's constant to be

$$h = (6.15 \pm 0.09) \times 10^{-34}\ Js$$

The work function is found through Equation 4.4. Its value is found to be

$$\phi = (2.14 \pm 0.06) \times 10^{-19}\ J$$

h has deviation from the accepted value of approximately $6.63 \times 10^{-34}\ Js$ [5]. This gives it an error of 7.2%. The value of 6.63 is not within the uncertainties which have been derived, suggesting that errors affected the accuracy of data. Furthermore, the actual value of ϕ is approximately $2.26 \times 10^{-19}\ J$ [2]. The work function from our data has an error of 5.3%. Likewise, the uncertainty propagated from the results do not cover this deviation from the expected result. It is likely the uncertainty comes from a form of systematic error.

A reduced chi-squared test on the measurements gives ${\chi^2}_{reduced} = 2.09$. The value of ${\chi^2}_{reduced} > 1$ is an indication that the uncertainty in the stopping potential is underestimated. From observing Fig 3, the line of best fit does not pass through some error bars which means the line of best fit is not justified by the data points. The larger chi-squared reduced value and observation of Fig 3. can be fixed if we assume the uncertainty in the stopping potential is larger than what is being used (0.01V). Inaccurate h and ϕ values suggest the experiment is being affected by systematic error that is not being accounted for by the stopping potential reading.

A possible source of systematic error is the circuit and voltmeter used for reading the stopping potential value. Energy could have been lost through the wires and power for the voltmeter to work. This would reduce the value of the stopping potential to lower than it should be. This can explain the value of h being lower than expected.

IV. Conclusion

Overall the value of Planck's constant was found to be $(6.15 \pm 0.09) \times 10^{-34} Js$. The stopping potential was observed to vary with frequency of light incident on the surface linearly and changing the intensity of light did not change stopping potential which confirms the hypothesis. The experiment was able to complete the objective of finding a value of Planck's constant.

There were certain strengths to the experiment. For instance, there was low amount of random error created by instruments within the apparatus such as the voltmeter and bandwidth filters.

However, inaccuracy of the value of h and ϕ implied there was systematic error which is the major weakness to this experiment. To improve the experiment moving forward, Multiple voltmeters could be attached to the h/e apparatus if possible, which could ensure there is no systematic error to due to voltmeter fault. Or an experiment can be done to figure how much the voltage is being shifted as a result of energy lost through the circuit and voltmeter to compensate the values measured. As previous discussed, the uncertainty of the voltmeter seems to be underestimated, thus methods to eliminate random error can be improved. Doing many trials of measuring stopping potential for a given wavelength will allow a calculation of standard error of mean instead which would produce a more correct estimation of the stopping potential uncertainty.

References

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