Determining Planck's Constant From Photodiode Responses to LEDs of Differing Wavelengths

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Abstract

This experiment set out to measure Planck's Constant by recording the result of threshold voltages from a photodiode when light from different LED's was incident on it. The result of this experiment was a Planck's constant of h = 8.8x10^{-34} ± 0.1x10^{-34}J/s, a difference of 25% from the current accepted value, h = 6.63×10^{-34}J/s [1], measured using a Kibble balance. In an alike experiment measuring responses of LEDs, a result of h = 9.5x10^{-34} was found [2]. This will prove important for the discussion in the last section of this paper.

1 Introduction

Planck's constant provides the fundamental framework for quantum mechanics, being found in most equations in the field. It inherently acts as a multiplying constant used to determine the energy of a 'packet' of light known as a photon. Due to its incredibly small scale of x10^{-34}, there proves to be great difficulty in measuring the constant to a high degree of accuracy. However, as before its importance can not be overstated and therefore finding ways of calculating this constant has provided great successes, such as, in 2019, being used to redefine the kilogram [3] with no dependence on a physical reference.

As aforementioned, Planck's constant has been recently used to redefine the kilogram. This was taken further by physicist P.R. Bunker and Sergei N. Yurchenko [4] who induced voltage in a coil by moving it through a magnetic field at constant velocity. This voltage was measured and from which the Planck constant was calculated to the highest degree of accuracy ever recorded; due to the precision of the Kibble balance used. A kibble balance equates electrical and mechanical power generated by the current produced from an objects mass. Their experiment resulted in a measure of h = 6.62607015×10^{-34}J/s. A key difference in this experiment is that Bunker and Yurchenko used a magnetic field to avoid errors like parallax error in calculating threshold voltages, or the assumption that the environment was completely light-less so the photodiode response was independent of background light. This is due to the fact that the fields produced have no dependence on light. However, while this experiment provides an incredibly accurate result, a Kibble balance is typically unaffordable at the cost of hundreds of thousands of pounds. To perform this experiment, a person would have to have access to a high quality facility which is unlikely for an undergraduate physicist. Instead, this experiment was performed without the use of high-end, expensive equipment.

Here in this investigation, it aimed to provide a precise and accurate measure of Planck's constant without use of high grade equipment. The experiment consists of measuring a photodiode's response to different LED's of 5 wavelengths, ranging 430nm - 660nm, as input voltage varies. The response could then be used to predict when the photoelectric effect begins occurring and as such can be used to calculate Planck's constant - see section 3.

Throughout this paper, section 2 will discuss the theory behind the experiment and the methodology will be discussed in section 3. Section 4 will then outline the results and analysis, while section 5 will discuss the results and conclude the investigation.

2 Theory

Max Planck discovered the aptly names 'Planck's constant' in an attempt to 'fix' the ultraviolet catastrophe, an issue which had challenged classical physics. Rayleigh-Jean's law predicted a continuous spectrum of radiation led to infinite energy being produced at high frequencies which didn't abide by the laws of physics [5]. This led to Planck theorising that radiation is not continuous, but rather can be quantised in discrete packets of energy. This was because a wave can be thought of as having a frequency, f, and wavelength, λ, where (for EM-Waves):

$$f = \frac{c}{\lambda} \tag{1}$$

As frequency is proportional to velocity, a constant of proportionality can convert from hertz to joules and therefore:

$$f = \frac{E}{h} = \frac{c}{\lambda} \tag{2}$$

and as such:

$$E = \frac{hc}{\lambda} \tag{3}$$

This only accounts for the energy of some photon of light at specific wavelengths. Therefore, as Einstein proposed particles and photons interact one-to-one, some term for the remaining energy of the particle is needed:

$$\frac{hc}{\lambda} = \phi + T \tag{4}$$

Where ϕ is the minimum energy required to liberate an electron, and T is the remaining kinetic energy, also calculated as $T = eV$. It is assumed from this that any energy losses are accounted for in the work function, ϕ. Finally, for this experiment the result:

$$h = \frac{eV\lambda}{c} = gradient \tag{5}$$

Is found.

3 Methods

For this investigation, the method used was as follows: setting up a LabView circuit as shown in Figure 1 to flow into the circuit shown in Figure 2 from the A0 and A1 arms attached to the MyDAQ - multifunction I/O. The LabView circuit was then used to control the input voltage by turning a dial, and is set up in such a way to record the response of the Photodiode as each LED was replaced with by another, with wavelengths: 430nm, 465nm, 525nm, 615nm, and 660nm. Data was then downloaded into a text file from LabView and was exported into csv files containing initial measurements and repeat measurements in a table. Rows not contained in the table were flooded with nan values to avoid shape errors when analysing, however these were later masked to avoid complications in calculations. This data was then used to produce figures 3 and 4 found in section 4.

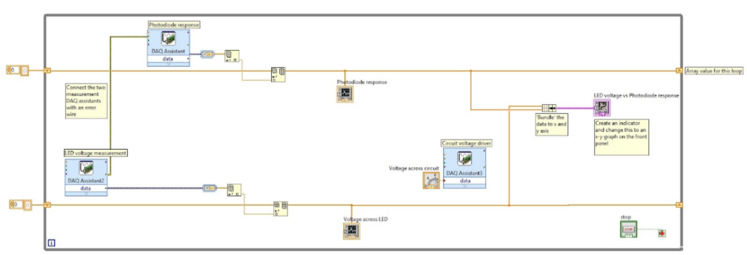

Figure 1: The setup presented as needed to vary the voltage across the LEDs from dials in the front panel which control a MyDAQ. Data acquisition is also taken this way

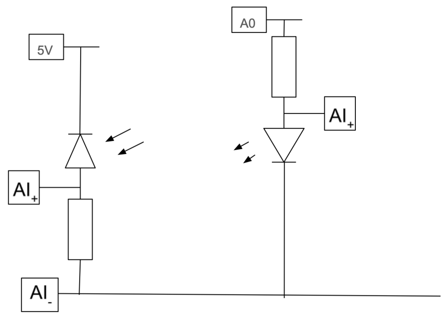

Figure 2: Circuits powering the LEDs and Photodiode through a MyDAQ. The MyDAQ is attached at the arms A0 and A1 as well as grounded between the components. Resistors of value 220Ω and 1kΩ were also used and the LED was replaced by differing wavelengths: 430nm, 465nm, 525nm, 615nm, and 660nm.

Errors and limitations in the method were limited. The largest limitation came from environmental light having an effect on the photodiode and varying results. To prevent this a box was placed above the circuit, however it is unlikely that this removed all effects on the results. Error also came from the speed at which the dial was turned. Measurements were only taken every half a second and therefore varying the speed of the dial resulted in a variance in the amount of results to work with and as such a higher error between data sets. This also meant that varying speed would vary the amount of data at each point of the curve which might have also limited the linear regression to be skewed around these regions as shown in Figure 3 and mentioned in sections 4 and 5.

4 Analysis & Results

This experiment required measuring an output voltage of a photodiode as a result of varying input voltage to different LEDs. This was repeated once for each of the LEDs, and the data was plotted as shown in Figure 3. From this, estimates of threshold voltage were taken, and the data was sliced around these to perform a linear regression in order to calculate exact values. An example of this is shown in Figure 3 where error is calculated halving the smallest precision and is therefore too small to be seen. The final result, shown in Figure 4, shows a strong positive correlation between threshold voltage and inverse wavelength, as expected from equation 5. The error bars shown in this final figure represent the error on the mean of the threshold voltages. They were produced by halving the range between repeat measurements.

For this experiment, the hypothesis was that Planck's constant can be accurately measured by performing a linear regression of threshold voltages

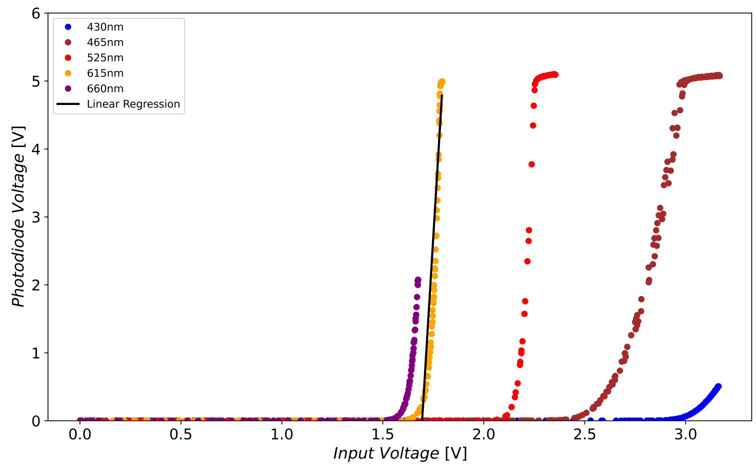

Figure 3: Measurements of changes in photodiode output voltage as an input voltage from a MyDAQ power source is varied to differing LEDs. A linear regression using the least squares method was than performed on each set of data to calculate an accurate measurement of threshold voltage. An example of this is presented on the data for the 615nm photodiode. Repeats of data are also shown on the graph. Errorbars are too small to be shown.

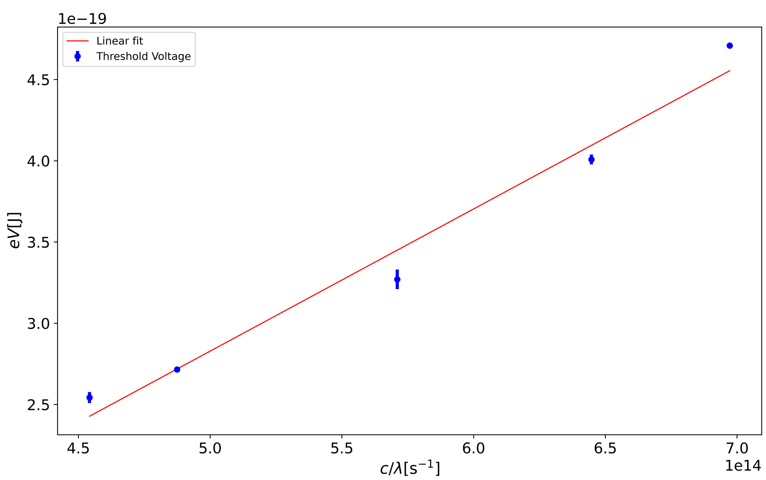

Figure 4: Measurements of threshold voltages plotted against inverse wavelengths. Measurements were those calculated from the linear regressions alike shown in Figure 3. Error bars are shown and have been calculated by halving the range of results. For a larger data set, a weighted mean may have been used instead.

against the inverse of their associated wavelength. The gradient of this could then be used to determine Planck's constant as shown in equation 5. This linear regression is shown in Figure 4.

The correlation coefficient for the graph shown in Figure 4 is $r^2 = 0.977$. The intercept of the graph was calculated as (-1.5 ± 0.1)x10^{-19}J. From this analysis, a gradient and as such a value of h = 8.8x10^{-34} ± 0.1x10^{-34}J/s was calculated.

5 Discussion & Conclusion

This experiment set out to measure an experimental value of Planck's constant, h. The results presented in Figure 4 follow a strong positive correlation as is seen by the large value of correlation coefficient. The intercept can be interpreted as a change in energy due to resistive factors in the LED. Uncertainty in the intercept was very small, which is perhaps related to the minimal amount of data recorded. A larger data set may have produced a larger variance in data. The background light intensity in the room may have also affected readings from the photodiode as it was only assumed all light had been reduced when taking readings. Overall, this means that the data followed the trend outlined by equation 5 to a high degree, with slight complications arising from the assumptions discussed.

The main finding of this experiment was the result h = 8.8x10^{-34} ± 0.1x10^{-34}J/s. A result of this manner falls within three standard deviations of the accepted result h = 6.62607015×10^{-34}J/s [1]. This would typically be considered a poor result and is highly likely to have been caused by the limited number of data taken, however, this makes sense in light in the face of the many unquantified assumptions made. Taking more sets would've produced a larger range of results and as such a larger standard deviation due to the lack of restraints on the current data from the assumptions made. This would've led to the raw uncertainty on the result being underestimated which might explain why it was so far from the accepted. While the measured results were precise, they were inaccurate compared to the universal value of Planck's constant. A far more accurate result can be found using the previously mentioned experiment laid out by P. Bunker in his article "The Planck Constant of Action and the Kibble Balance" [4]. The more accurate measure is made due to the accuracy and precision of the Kibble balance used. In the future, re-performing this experiment with this equipment should provide stronger results; taking a far greater number of repeats to provide a much larger range of data would minimise uncertainty. If this were not possible, to minimise the light dependence in the calculation, performing the experiment in a dark room specifically designed to remove light as a factor would be advisable.

In an experiment similar to that of measuring LED repose, performed by 'MrsPhysics' [2], a result of h = 9.5x10^{-34} was found. Unlike the accepted value of Planck's constant, this value is much closer to that which we measured lying within 2 standard deviations. As MrsPhysics result also lies within 3 standard deviations of the accepted value, it seems that the problem lies within the experiment itself. MrsPhysics publishes all results for each LED and it shows that between infrared and yellow-green a much better result of h can be found (h = 6.4x10^{-34}). In a future repeat of this experiment, I might look to compare individual results of LEDs such as has been done here to prove the validity of this argument.

In conclusion, this experiment produced the result h = 8.8x10^{-34} $\pm$ 0.1x10^{-34}J/s. This result lay outside of two standard deviations from the universally accepted result h = 6.62607015×10^{-34}J/s [1] and so is typically considered a poor result. This was potentially due to environmental light interacting with the photodiode, or the sheer lack of data recorded. To fix this in the future, more datasets can be taken and the experiment can be performed elsewhere in a darker environment. More accurate measurements can also be taken from equipment such as a Kibble balance.

References

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