**PHOTOELECTRIC EFFECT**

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**Introduction**

James Clark Maxwell was the legendary physicist who is known as the father of theory of electromagnetic radiation. His bringing the concepts of light, magnetism and electricity together have been the second great unification in physics[[1]](#footnote-1). According to Maxwell electric and magnetic fields are the waves that travel at the speed of light[1]. Although his theory had a immerse effect on physics and led to further discoveries some phenomena related to light one of which is the photoelectric effect couldn’t be explained with this theory. The photoelectric effect is the emission of the electrons from a material when the light is shone onto it. According to the classical wave theory when we shine light on a metal, the intensity of light should provide the energy needed for emission and the higher intensity must result in higher kinetic energy of the electrons. Additionally, as the energy of the light is spread over its wave fronts it was expected that there had to be a time delay between the shining and the emission as the electrons must accumulate the energy to break free. On the contrary, the emission of the electron depended only on the frequency of the light and depending on the material the light had to have the frequency above certain threshold to cause the emission. Increasing the frequency of the light caused the increase in kinetic energy of the electrons. Moreover, there was no observable delay between the time that the light was incident and the light was emitted. The explanation for this phenomenon came in 1905 from Albert Einstein who advanced on the idea of electromagnetic waves releasing energy in packets. Einstein thought if energy comes in packets so can light, therefore he hypothesised that light consists of discrete quantized packets which are called photons. Einstein received a Nobel prize for his discovery[[2]](#footnote-2) of the law that governs the photoelectric effect which is mathematically stated as

(1)

Where is the kinetic energy of the emitted electrons, is the frequency of the incident light, h is the Planck’s constant and is the work function of the metal which is the minimum energy required to free the electron [2]. Work function of a metal doesn’t depend on the frequnecy of the light that’s falling on it and is specific to each metal itself. When we incident light causes electron emissions the reverse potential that needs to be applied for stopping these electrons can also be calculated by rewriting as

(2)

Where is caled the stopping potential. The stopping potential depends on the energy of the incident light since the workfunction is constant for the same metal and higher energy of the inciden light means higher kinetic energy of the electrons which requires more potential to stop them.

Based on this theoretical background one can test which of these theories hold true with the proper equipment that enables the possibility of manipulating the intensity and the frequency of the light and observing the activity of the emitted electrons as current in a circuit. This can be done by the help of an illuminated cathode which emits electrons and an anode that attracts them and with a few other elements that measures the current in the circuit, manipulates the potential between anode and the cathode.

**Experimental Details**

For observing photoelectric effect Phototube is used. The phototube has a cathode photoemissive which is sensitive to light and a ring shaped anode which allows the light to go through it without affecting it while illuminating the cathode. The light source used is a mercury lamp as its spectral lines are of a wide range. The light coming from the source is collimated by the help of a collimator so that it hits the cathode directly without spreading. The provision of necessary varying voltage and measurement of voltage and the current across the phototube is done by The Photoelectric Effect Apparatus. The apparatus takes its power from the power supply instead of an electric socket which provides 120V of AC current because we need 30V of DC current and the error that the source can contribute is clear to us.

The experiment consists of 2 parts in which we test both of the theories stated about light by Maxwell and Einstein. In the first part of the experiment we test Maxwell’s theory who claimed the increasing intensity must result in higher kinetic energy of the electrons. Therefore, we keep the frequency of the light constant and change the aperture sizes. In the second part of the experiment, we test Einstein’s theory to see if the kinetic energy of the electrons depends on the frequency by keeping the aperture size constant and changing the frequency of the light that’s falling on the metal.

**Measurement & Data Analysis**

*Data:*

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| 436 nm | | | | | |
| Aperture size = 2 mm | | Aperture size = 4 mm | | Aperture size = 8 mm | |
| V | I(10-13 A) | V | I(10-13 A) | V | I(10-13 A) |
| -1.3(14) | 0 | -1.3(01) | 0 | -1.3(57) | 0 |
| -2.0 | -3.5 | -2.0 | -12.3 | -2.0 | -27.2 |
| -1.5 | -2.2 | -1.5 | -8.7 | -1.5 | -16.1 |
| -1.0 | 19.4 | -1.0 | 71.3 | -1.0 | 383.0 |
| 0.0 | 101.0 | 0.0 | 375.0 | 0.0 | 1702.0 |
| 5.0 | 587.0 | 5.0 | 2150.0 | 5.0 | 8620.0 |
| 10.0 | 978.0 | 10.0 | 3630.0 | 10.0 | 14810.0 |
| 20.0 | 1535.0 | 20.0 | 5760.0 | 20.0 | 23400.0 |
| 30.0 | 1934.0 | 30.0 | 7190.0 | 30.0 | 28800.0 |

Table 1: Currents vs voltages for light of wavelength (λ=436nm) at different intensities

Table 1 describes the current change as the potential changes for each aperture size while keeping the intensity same. The data shows that the current increased exponentially with increasing potential and increasing aperture size resulted in even higher values of current. The stopping potential remained almost the same.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| Aperture size = 4 mm | | | | | |
| 365 nm | | 405 nm | | 546 nm | |
| V | I(10-13 A) | V | I(10-13 A) | V | I(10-13 A) |
| -1.923 | 0 | -1.462 | 0 | -0.785 | 0 |
| -2.0 | -12.5 | -2.0 | -9.0 | -2.0 | -6.9 |
| -1.5 | 161.0 | -1.5 | -2.1 | -1.5 | -6.7 |
| -1.0 | 512.0 | -1.0 | 70.6 | -1.0 | -6.0 |
| 0.0 | 1256.0 | 0.0 | 280.0 | 0.0 | 250.0 |
| 5.0 | 6500.0 | 5.0 | 1505.0 | 5.0 | 1410.0 |
| 10.0 | 11320.0 | 10.0 | 2590.0 | 10.0 | 2220.0 |
| 20.0 | 18430.0 | 20.0 | 4170.0 | 20.0 | 3200.0 |
| 30.0 | 23100.0 | 30.0 | 5220.0 | 30.0 | 3670.0 |

Table 2: Currents vs voltages in at constant intensity (aperture diameter 4mm) for different wavelengths

From Table 2 we can see the change in stopping potentials as the wavelength of the light changed. The higher frequency of light which means lower wavelength of light required more reverse potential to be applied to the tube. As the applied voltage increases the rate of increase of current gets smaller.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| λ [nm] | 365 | 405 | 436 | 546 |
| f [x1014 Hz] | 8.214 | 7.408 | 6.879 | 5.490 |
| V0 [V] | -1.923 | -1.462 | -1.324 | -0.785 |

Table 3: Stopping potentials of corresponding frequency of light

Table 3 brings together all the frequencies, as well as, wavelengths of light and the potential needed to stop the emitted electrons under that light. The table indicate that the stopping potential decreased with increasing wavelength.

*Plots:*

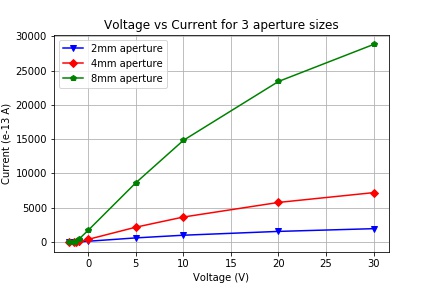


Figure 1. Voltage vs current plot under the same wavelength of light for different aperture sizes.

Figure 1 corresponds to the Table 1 in Data part. X interception corresponds to the stopping potential for the electrons which is almost the same for all 3 apertures.

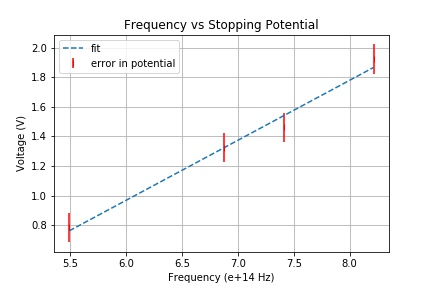


Figure 2. Corresponding stopping potentials for different frequencies of light with constant aperture size of 4mm.

Figure 2 corresponds to the Table 3 in data part. The slope of the plot(m) corresponds to h/e where h is the Planck’s constant and the e is the charge of the electron. The interception of the line with the horizontal axis correspond to the threshold frequency while the interception with horizontal axis is the work function.

*Calculations:*

From Figure 2, the slope ,

From Figure 2, the interception with the vertical axis ,

* Apparent value of Planck Constant: 6.496 ×10-34 J.s
* Accepted value of Planck Constant: 6.626× 10-34 J.s
* Work function: 1.467 eV
* Percentage error in Planck Constant: 1.90%

**Results and Discussion**

*Comments:*

Before the experiment we had two theories that predicted the results of the experiment. In the first part, we kept the frequency of the light constant while changing the intensity of light expecting increase in stopping potentials but from Table 1 and Figure 1 we saw that actually the stopping potential remained constant disproving Maxwell’s wave theory. But we did see exponential increase in the number of the electrons with increasing intensity as the potential increased which is the only part that classical theory could predict. Also, there was no observable time delay between the incident of light and the emission of the electrons.

In the second part, we measured the current rate for 3 different wavelengths of light and observed the decrease in stopping potentials and as well as in photocurrent with decreasing frequency which was predicted by Einstein. Looking at the Figure 1 we see that the interception with vertical axis occurs at a negative value which also proves the existence of the work function, therefore the existence of the threshold frequency. We didn’t see the levelling off the current to the same value for different apertures, but it can be explained with the fact that we needed higher potential difference to see the saturation of the current, but we were limited to 30 V. Even though the rate in increase of the current decreased with increasing potential they didn’t seem to get close to the same value of current at the end.

In conclusion, we could successfully finish the experiment as our result for Planck’s constant is within the scope of 1.9% error. Also, light is indeed quantized, and Einstein’s theory of light predicts the experiment result correctly, while the classical theory doesn’t go further than the explanation of increasing current with increasing intensity.

*Errors:*

In the first part, we ideally expected the I-V graph start from the stopping potential but for negative values of potential current was present. It’s explained by the photoemission from anode which is due to the fact that the anode acts as a photocathode when light strikes it as it deposited some of the evaporated cathode material[3]. Additionally, the absence of the saturation current can be understood since we use a Mercury lamp it has different intensities for different wavelengths as not all the colours are emitted at the same intensity. Additional error in intensity is introduced by the light filters since we don’t know their effect on the intensity of the incident light. Further errors can be explained by the fact that the current in the Apparatus was not exactly absent when we started the experiment and also the values for current kept fluctuating without getting exactly stabilized.

Overall, our result for Planck’s constant as shown in calculations part is consistent with the accepted value of it and is within the range of 1.9% error.

**Reference:**

[1] Nahin, P.J. (1992). *“Maxwell’s grand unification”.* IEEE Spectrum.

[2] Wikipedia: The Free Encyclopedia,*” Photoelectric effect”* (Accessed April 18, 2019)

[3] (2010).“The Photoelectric Effect” METU Department of Physics: Applied Modern Physics Laboratory Manual and Workbook. Ankara

1. https://ieeexplore.ieee.org/document/123329 [↑](#footnote-ref-1)
2. https://en.wikipedia.org/wiki/Photoelectric\_effect#cite\_note-1 [↑](#footnote-ref-2)