LAB REPORT OF LAB103

THE Quantization of Light

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Yubo Cai, Durmus Mehmet Emre

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1
INTRODUCTION

This lab assignment is about calculating the Planck constant (denoted by “h”). It is a fundamental physical constant that gives us the energy of light $E = h\omega$. E is the energy of light and ω is the frequency of the light. Planck’s constant is very fundamental to the study of quantum physics and to our understanding of the world.

In Measuring Planck’s constant with light-emitting diodes, Planck’s constant could be measured by simple electronic circuits with the property of LEDs. In the photoelectric effect, we use the principle of the photoelectric effect to determine Planck’s constant in a more theoretical way.

2
OBJECTIVES

We have a common objective for both experiments: calculating the best possible estimate for Planck’s constant. In the first experiment, we chose LEDs of different frequencies and measured the current and voltage in the circuit several times to measure Planck’s constant. In the second experiment, we will use the Photoelectric effect to measure Planck’s constant.

3
EXPERIMENT MEASURING PLANCK’S CONSTANT WITH LIGHT-EMITTING DIODES

In the first experiment, we use an LED to calculate Planck’s constant. To that end, you will initially measure the current-voltage (I-V) characteristic of one LED in order to determine its threshold voltage V_0 for light emission. In the threshold voltage, we can 0 calculate the energy of the emitted photon since the voltage corresponds to the electron energy and it gets expelled in form of light of the same energy. Also, we know the frequency of LED light, with those information we can definitely calculate the Plank’s constant.

3.1 The setting of the experiment

We connected the power source to the circuit we assembled like the graph below

We first turned the range selector of our multimeter to 200 mA. We then adjust the current in the circuit with the voltage roller until the multimeter showed a value around 25 mA. In our experiment was 25.1 mA

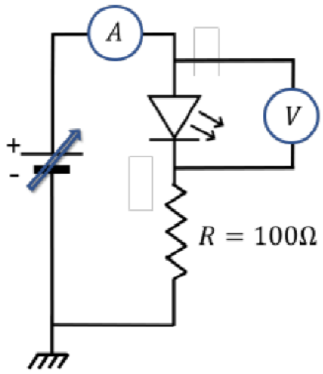


Figure 1: Electronic Circuit for Testing I-V across a LED (Cited from Lab Guideline)

3.2 Analysis of the experiment: $665nm$

We first analyzed the $665nm$ LED. Since we have all the data points and we can use **Scidavis** to draw the I-V Graph of the LED emitting light at $655nm$ which is shown below

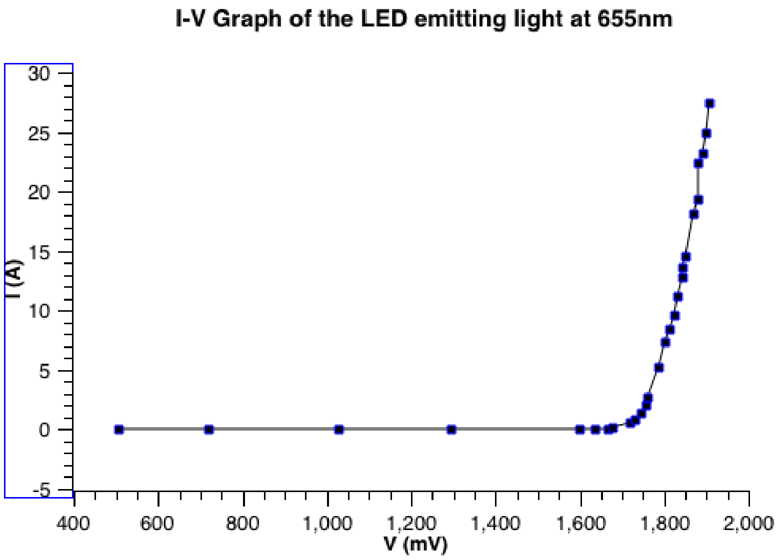


Figure 2: I-V Graph of the LED emitting light at $655nm$

From the graph, we can tell that the emitting voltage is around 1700 mV, and under this value, there is no current going through the diode. After that, the emitting voltage of the current through the circuit grows linearly with respect to the voltage.

Therefore, we use the linear fit tool in Scidavis in order to calculate the Plank's constant

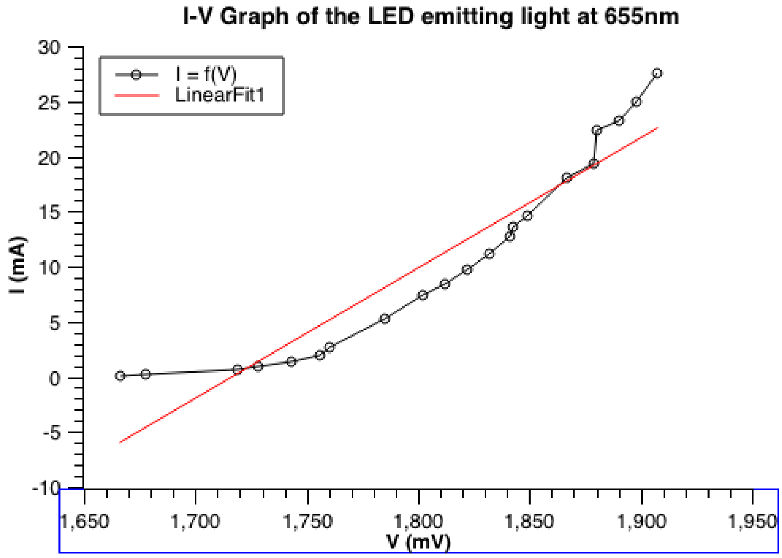


Figure 3: I-V Graph of the LED emitting light at $655nm$

3.2.1 • Calculation of Data: $655nm$

Using the formula $y = kx + b$ and **Scidavis** we have: $k = 0.118 + / - 0.009$, $b = -202.858 + / - 17.935$. We use the formula $V_0 \simeq -\frac{b}{k} = 1711mV$. Now we apply the formula for Plank's constant h that $E = h\omega$ $\omega = \frac{c}{\lambda}$ and $E_g = eV_0$

Then we have $h_1 = \frac{eV_0\lambda}{c}$ (c is the constant of the speed of light). By calculation, we got $h_1 = 5.99 \times 10^{-34}$ J $\cdot$ S

3.2.2 • Analysis for the second diode and the Third diode

We use Scidavis and apply the same analysis method for the second and third group data in order to find the Planck constant. We choose the LED light with $605nm$ and $470nm$

3.3 Analysis of the experiment: $605nm$

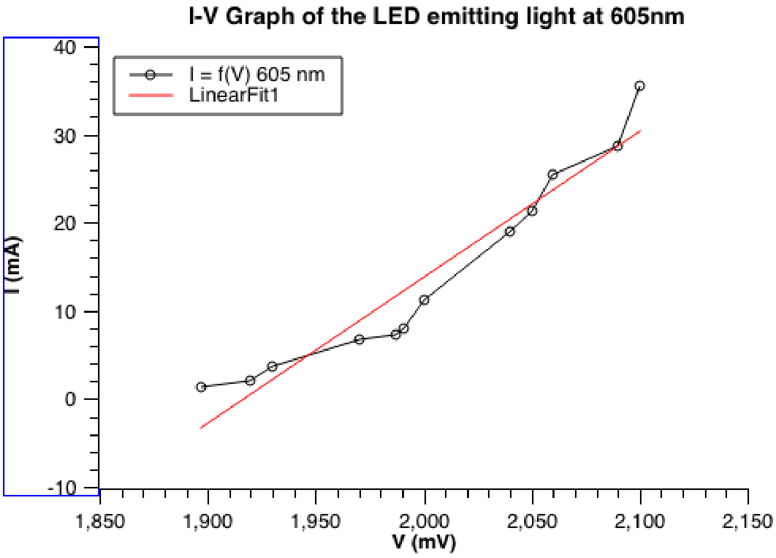


Figure 4: I-V Graph of the LED emitting light at $605nm$

3.3.1 • Calculation of Data: $605nm$

Using the formula $y = kx + b$ and **Scidavis** we have: $k = 0.165 + / - 0.019$, $b = -316.535 + / - 37.204$. We use the formula $V_0 \simeq -\frac{b}{k} = 1918mV$. Now we apply the formula for Plank's constant h that $E = h\omega$ $\omega = \frac{c}{\lambda}$ and $E_g = eV_0$

Then we have $h_2 = \frac{eV_0\lambda}{c}$ (c is the constant of the speed of light). By calculation, we got $h_1 = 6.20 \times 10^{-34}$ J $\cdot\, S$

3.4 Analysis of the experiment: $470nm$

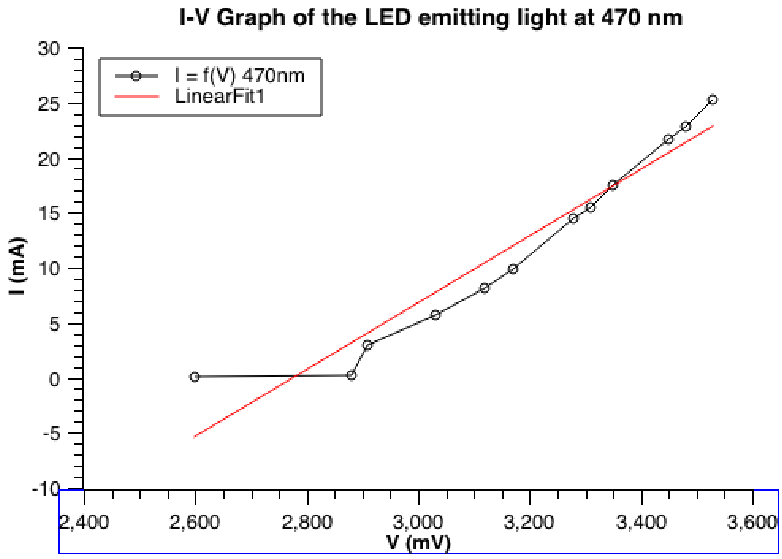


Figure 5: I-V Graph of the LED emitting light at $470nm$

3.4.1 • Calculation of Data: $470nm$

Using the formula $y = kx + b$ and **Scidavis** we have: $k = 0.030 + / - 0.0027$, $b = -84.305 + / - 8.509$. We use the formula $V_0 \simeq -\frac{b}{k} = 2810mV$. Now we apply the formula for Plank's constant h that $E = h\omega$ $\omega = \frac{c}{\lambda}$ and $E_g = eV_0$

Then we have $h_3 = \frac{eV_0\lambda}{c}$ (c is the constant of the speed of light). By calculation, we got $h_1 = 7.05 \times 10^{-34}$ J $\cdot$ S

3.5 Data Conclusion

We now take the average of our data points $\bar{h} = \frac{h_1+h_2+h_3}{3} = 6.41 \times 10^{-34}$
Relative deviation $= \frac{|\bar{h}-h|}{h} = 3.17\%$

3.6 Error Analysis

After discussion, we believe that the error mainly occurs in these places, the first in the experimental equipment, the wire and components are not ideal, so there are losses in current in the components.

The second point is our experimental error, we did not wait until the value in the multimeter is completely stable before recording, the value of the current and voltage in the multimeter has been fluctuating.

The third point is the problem of data processing tools. First of all, the I-V curve is not completely linear, but we are limited by our data processing tools to use a linear model for calculation. At the same time, the number of data points is not large enough, which leads to errors in the regression calculation.

4
THE PHOTOELECTRIC EFFECT

In this second experiment, the objective is to explore the phenomenon where electrons are emitted from a metallic plate when light is shone on it as a result of the energy transfer between the light wave and electron; in other words, the photoelectric effect. This is an important experiment as it challenges the classical views on the energy transfer between light and matter and introduces a new, more accurate, and discrete rather than continuous, ie. quantum, view on this phenomenon. The apparatus used, the phototube, is made up of an anode, which is a small metallic wire, surrounded by a large area of the metallic cathode, both of which are kept under a vacuum in a glass tube. Thanks to its large area, the cathode collects most of the incident photons on the phototube.The vacuum ensures that there are no other particles in the tube which could cause side reactions resulting in the emission of an electron and hence a current in the circuit. Since this device is also photosensitive due to the nature of its purpose, it is placed inside a darkened chamber to prevent ambient photons from affecting the measurement. The total energy of the electron leaving the cathode is given by $E = hv - W$, where $W$is the energy required to extract the electron from the cathode (called the work function for the cathode) and $hv$is the energy provided by the photon. This energy is purely kinetic at this moment as the electron has just left the metal. However, this energy is converted to potential energy as the electron travels towards the anode. This energy depends on the potential difference between the anode and cathode, ie. the Voltage, and is given by $-eV(x)$, where V is the voltage, x is its position, and e is the electrical charge of an electron. An electron will be able to reach the anode only if its potential energy at the anode is than its total energy, $E \geq eV$ will be able to reach the anode and flow into the circuit. Using this relation, Planck's constant and the work function can be determined by measuring the stopping voltage for multiple frequencies. According to the classical view, the kinetic energy of the electrons will increase with the intensity of the light, while for the quantum view, the kinetic energy of the electrons is independent of the intensity of the light and instead increases with the frequency. This experiment also aims to determine which view is correct.

The first part of the experiment is the determination of the stopping voltage, ie. the voltage at which the current in the circuit cancels out. Below can be found the tables for the current vs voltage of the circuit for light with wavelength 472 nm with intensities 100%, 50%, and 15% respectively.

Which give the following table and graphs:

At 100% the stopping voltage for this LED was measured to be $0.637V$; however, this voltage seemed to change with the intensity even if a little. In fact, the graphs for the different intensities indicate that the current is directly proportional to the intensity after the stopping voltage at a constant frequency. Nevertheless, some random and perhaps experimental errors are certainly at play here as there is an outlier for 15% light intensity. It seems as if the stopping voltage can be determined with the best precision at 100% intensity as the slope of the values

100%		50%		15%	
Current(nA)	Voltage(V)	Current(nA)	Voltage(V)	Current(nA)	Voltage(V)
0.276	0.719	0.226	0.719	0.152	0.719
0	0.637	-0.09	0.637	0.02	0.637
-0.161	0.596	-0.119	0.596	-0.74	0.596
0.71	1.965	0.492	1.965	0.284	1.965
-1.94	0.25	-1.763	0.25	-1.526	0.25
0.662	1.023	0.47	1.023	0.271	1.023
-1.605	0.308	-1.45	0.308	-1.211	0.308
0.693	1.342	0.484	1.342	0.273	1.342
0.699	1.501	0.485	1.501	0.278	1.501
-0.93	0.431	-0.814	0.431	-0.627	0.431
0.568	0.856	0.414	0.856	0.235	0.856
0.705	1.701	0.492	1.701	0.281	1.701
0.683	1.167	0.478	1.167	0.267	1.167

Table 1: The current vs voltage for different intensities of light

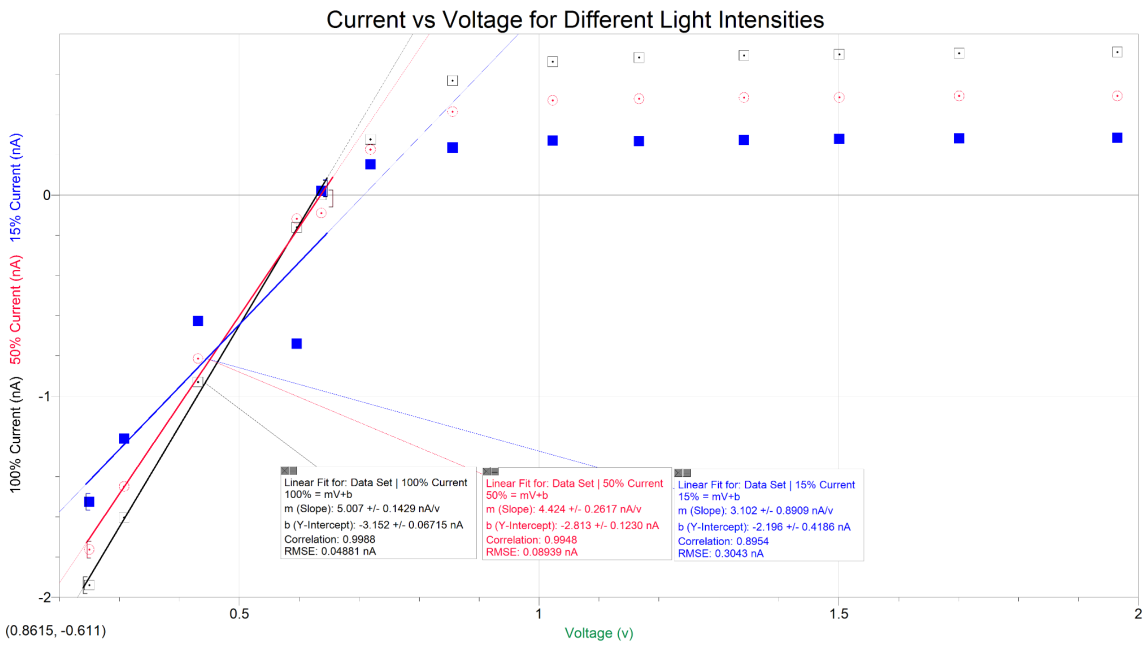


Figure 6: Current vs Voltage for Different Light intensities

is the steepest there indicating small uncertainty between the values. This is also intuitive as we can make better measurements with more photons. The difference between the currents for different intensities above the stopping voltage also makes sense as with higher intensity there are more photons that consequently extract more electrons which results in a higher current. From these results, the natural next step is to investigate the effect of light intensity on the stopping voltage, which is the second part of this experiment.

For this part light with wavelength $505nm$ was plugged into the phototube and the stopping voltage was measured for intensities with increments of 10% from 10% to 100%. The results are given below: For this LED, the stopping voltage and light intensity seem to be almost

intensity	stopping voltage(V)
10%	47%
20%	47%
30%	47%
40%	48%
50%	48%
60%	48%
70%	48%
80%	0.482
90%	0.483
100%	0.484

Table 2: The intensity of light vs the stopping voltage

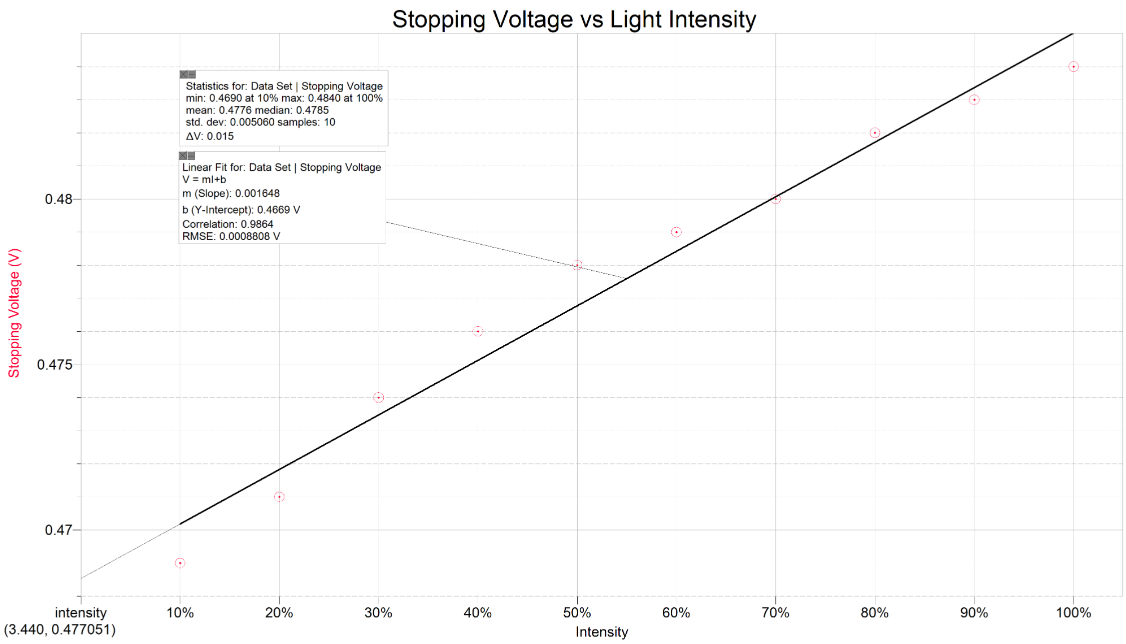


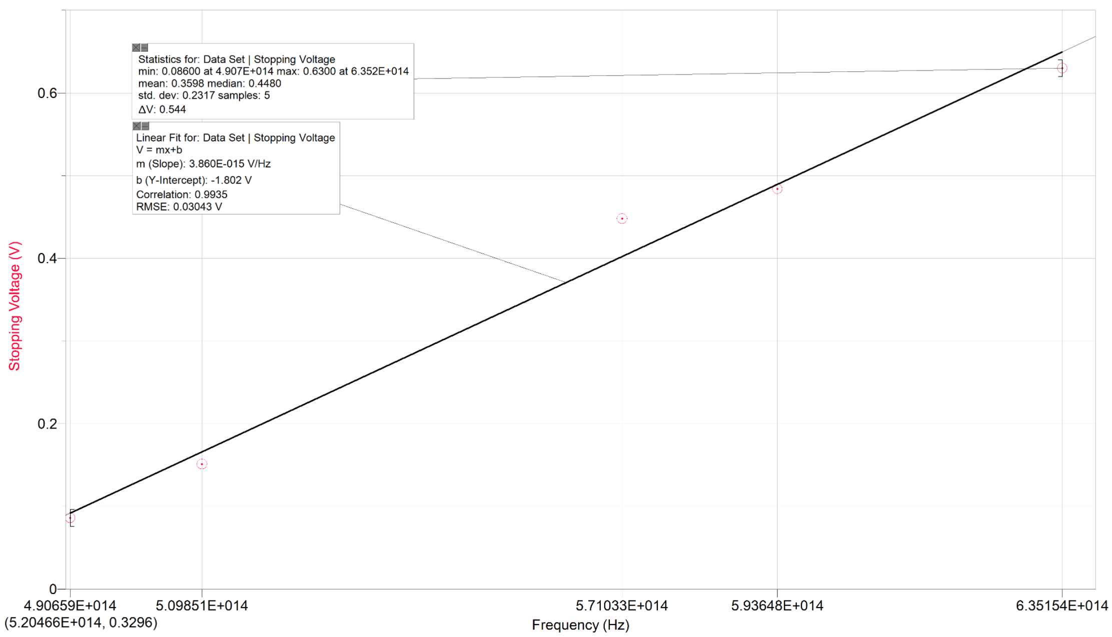
Figure 7: Stopping Voltage vs Light intensity

directly proportional, which agrees with what was observed in the first part of this experiment. However, the stopping voltage is lower for all intensities for this LED than the one used in the first part. This indicates that the frequency of light could affect the stopping voltage as well. The next step of the experiment is, thus, to investigate the effect of the light frequency on

Frequency(MHz)	Stopping Voltage(V)
635153512711864	0.630
593648431683168	0.484
571033253333333	0.448
509851119047619	0.151
490658687397709	0.086

Table 3: The stopping voltage vs the frequency of light

the stopping voltage. The results are given below: The graph indicates that there is a direct relationship between the frequency of light and stopping voltage. The theory suggests that this relationship is of the form: $V_{stop} = \frac{h}{e}v - \frac{W}{e}$, that is the slope should be approximately $4.136 * 10^{-15}$ V/Hz. The best fit line gives $3.860 * 10^{-15} \pm 2.551 * 10^{-16}$ V/Hz, which gives a 6.67% percentage error with the value derived from the literature values. As for the work function, the intercept is -1.802 ± 0.144 V, which gives $-2.887 * 10^{-19} \pm 2.307 * 10^{-17}$ when multiplied with the electrical charge of the electron, e. The value obtained for Planck's constant is $6.184 * 10^{-34} \pm 0.409 * 10^{-34} Js$. As mentioned before, the percentage error is 6.67%, which is higher than the value obtained in the first experiment, and hence the first experiment is more reliable in determining Planck's constant. This is to be expected as multiple measurements at constant frequency and intensity of light were made minimizing the errors in the overall measurement by keeping the uncertainty in the values constant. The phenomenon in the pho-



toelectric effect that is the most at odds with what we would expect relying solely on classical concepts for the behavior of light waves is 10 that the kinetic energy of the electrons depends on the frequency of the light rather than its intensity. Although our experiment seems to suggest that the current increases with the intensity, this only happens at higher voltages and doesn't necessarily indicate that the electrons are moving faster, instead of more electrons are moving. In other words, the counter-intuitive yet more accurate aspect of this phenomenon is that energy is carried by photons in packets and absorbed by electrons in packets, that is energy is quantized. A classical approach would suggest that the transfer of energy is continuous and hence it is the total energy that is carried is important. Nonetheless, this is not the case as only certain amounts of light and hence energy is absorbed and since these packets of energy are dependent on the frequency, the current created is as well, if it is at all. The intensity does still play a part in the value of the current, however, as it determines the number of photons incident on the phototube and hence the number of electrons being extracted per unit time, that is the current. The most surprising aspect of the photoelectric effect for me is the fact that the electrons can't be extracted from the material even if the intensity is really high if its frequency is too low. This experiment, however, merely scratches the surface of the weird and interesting world of quantum physics; regardless, it is still an essential experiment as it is at the core of quantum physics both historically and conceptually.