Manifestation of Light as a Particle Through the Emission of Photoelectrons

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March 14, 2019

Abstract

Theorizing light as quantized particles changed our perception of electromagnetic radiation, and has helped us understand and predict its behavior. We measured the stopping voltage of a current produced by photoelectrons, while varying the frequency of incident light. We then calculated the slope of stopping voltage vs inverse wavelength and obtained a value of $930 \pm 33 V \cdot nm$. This does not agree with the theory's predicted value of $1242 V \cdot nm$. We also observed the stopping potential stay constant within error bounds while varying the intensity of the electromagnetic radiation. This latter result does agree with Einstein's theory of photons.

1 Introduction

Considering electromagnetic waves to be quantized has been extremely important in modern day physics. The understanding of this discrete nature light has brought the development of lasers, atomic clocks and many other technological advances that we use on a day to day basis.[1, 2] It has also brought many questions as to what light is really made of. It behaves as a particle in some instances and as a wave in others. This is an open area of research as we try to further understand this wave-particle duality[3].

The concept of light being composed of particles was first introduced by Newton in 1704.[4] It was not until the early 1800's when Faraday unified electricity and magnetism and speculated light was a wave traveling through an electromagnetic field, yet he did not have the mathematical skills to prove this.[5] Later on J. C. Maxwell derived a set of equations unifying electricity and magnetism. Through these equations he was able to calculate the speed of electromagnetic radiation, which was equal to the measured speed of light through experiments, confirming that light was an electromagnetic wave.[7] This idea held for almost 100 years until 1887, when the photoelectric effect was observed for the first time by Hertz. This was at odds with Maxwell's theory of light which predicted that the light's energy should be proportional to its intensity. Hertz did not observe any correlation between these two factors in his experiment.[8] This behavior was not understood until Einstein theorized light to be comprised of energy packets, which he called "photons," and he called electrons emitted by photon absorption: "photoelectrons." Today, light is still modeled as a particle and as a wave depending on the experiment.[9]

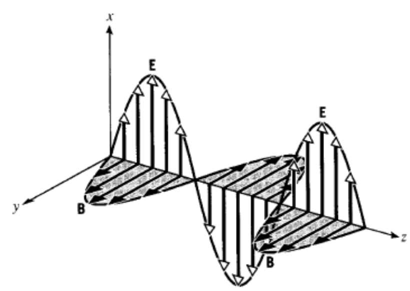

Figure 1: Visualization of J. Maxwell's Description of how an Electromagnetic Wave Propagates[6]

For this experiment, we aimed an electromagnetic radiation source at a cathode, in order to emit photoelectrons. These electrons would need to overcome a potential voltage difference to be able to reach an anode, and therefore create a current. We varied the wavelength and intensity of our radiation and plotted them in order to analyze their correlation with the stopping potential.

2 Theoretical Background

The energy of a photon is proportional to its wavelength, these two factors are related by Planck constant as follows

$$E_p = \frac{hc}{\lambda}. \tag{1}$$

Every material has a different "work function." The work function is the amount of energy by which an outermost electron is bound in the metal. Therefore, the photons colliding with the electrons on the surface need to have at least the same energy as the work function, and the rest of the energy will be converted to kinetic energy of the electron. This also means that the maximum kinetic energy an electron can have is related to the energy of the photon and the work function by the equation

$$E_k = E_p - \phi, \tag{2}$$

where ϕ is the work function. The kinetic energy of the photoelectrons can be measured in a simple manner by measuring the voltage difference that stops all the electrons, which is called the *stopping voltage*. This represents another potential well that the photoelectrons have to overcome in order to reach the anode. If we combine this with equation 1 and 2 we obtain:

$$eV_s = hc\frac{1}{\lambda} - \phi \tag{3}$$

Measuring stopping voltages for several different λ, and then plotting these stopping potentials against $\frac{1}{\lambda}$ will mean that the slope will represent $\frac{hc}{e}$. The accepted value for this slope is 1242 $V \cdot nm$ Opposed to the wave theory of light, the theory of photons predicts that if the energy of the incoming photons is not enough to overcome the work function energy then varying the intensity will not change any results in the current flow. This would mean that more photons are colliding with the metal, but all of them with the same amount of energy, therefore this should have no effect on the stopping potential.

Optical Density(OD) lenses filter the amount of photons that go through it, therefore reducing the intensity of a light source. The OD of a lens reduces intensity as follows

$$I = I_0 10^{-OD} \tag{4}$$

Where I is the intensity coming out of the lens, I_0 is the intensity of the light coming from the source and OD is dependent on the type of lens.

3 Experimental Procedure

Our experiment was setup inside a box in order to avoid any external photons interfering with our system, this setup is depicted in Figure 2. On the left we had a cathode connected to a Keithley 6485 picoammeter, which was connected

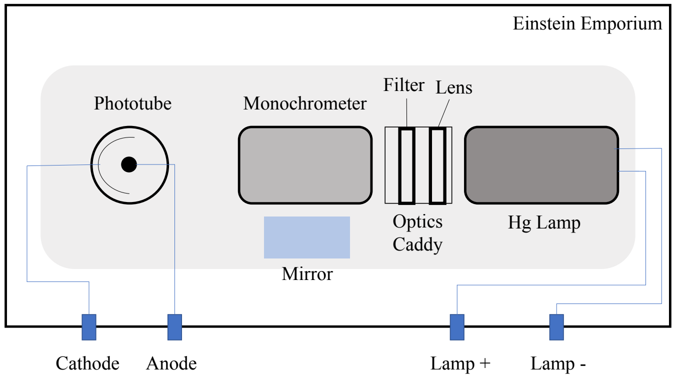

Figure 2: Einstein emporium observed from above. (Credit to my lab partner Sierra Casten for this figure)

as input in a DAQ (Data Acquisition device), this device sent the current data to LabVIEW software in the computer. LabVIEW was a computer software which read in the data from the devices and plotted the current in a graph for us. We connected the anode to the DAQ as output, which let us determine the voltage through the LabVIEW software.

On the other side of the box, we had the Hg lamp connected to a Tenma bench power supply at .25A and 18V. In front of the lamp, we had an Optics Caddy in which we mounted a focusing lens to aim the light at the monochrometer. We also included a mirror to be able to read off the value of the wavelength on the monochrometer and adjust it accordingly. We increased our voltage in a steady manner from -10V to 0V, it is important to note that we chose a sampling rate of 1/60 s to avoid error due to current being induced in our circuit by A/C current of the building which has a frequency of 60Hz. We then started recording measurements by only varying the wavelengths between trials. We recorded data for wavelenghts chosen by looking at the highest spectral emission lines of Hg. We then proceeded to vary the intensity of the light source by placing OD lenses in the optical caddy and recorded the currents as we increased the voltage again.

4 Data Analysis

4.1 Wavelength Dependency

4.1.1 Standard Deviation Method

First, we tried fitting a straight line from the beginning of the data. This would set our zero reference point for current, as the current should remain unchanged

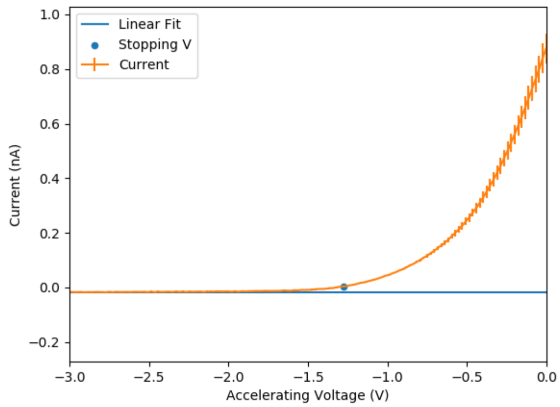

Figure 3: First method utilized to find stopping voltage by observing the first current point which is above the fitted line plus 3 standard deviations

until the photons reach the required energy. To find the stopping voltage we took the first point in our data that was above this line times three standard deviations.

We then plotted these stopping voltages against $\frac{1}{\lambda}$. We found a linear fit for this data and looked at equation 3, we would find that the slope represents $\frac{hc}{e}$, and the y-intercept represents $\frac{\phi}{e}$. These results are depicted in Figure 4.

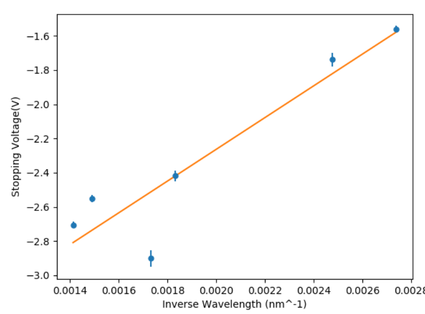

Figure 4: Plot equivalent to Equation 3 divided by e, failing to give a value for the slope and y-intercept anywhere close to the accepted values

As we can observe in Figure 4, we obtained values for the stopping potential, which do not show a linear correlation. The slope for the line obtained is $930 \pm 33 V \cdot nm$ which does not agree with the accepted value of 1242 $V \cdot nm$. Our uncertainty for the voltage comes from the sampling rate we chose. Having .02V increase between each voltage data point, and then taking the average of five trials we took for every wavelength. In addition to that, we calculated the span of voltage values that within 3 standard deviations would be considered stopping voltages and added that to our error.

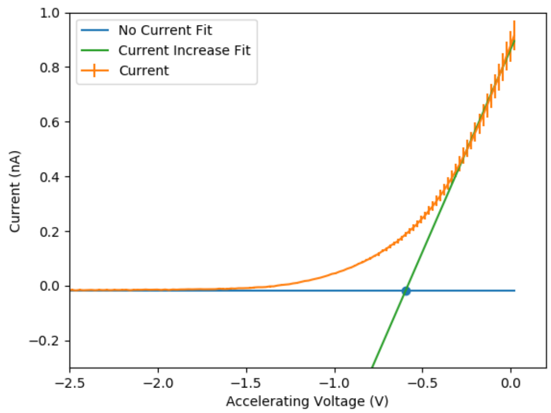

Figure 5: Second method utilized to find stopping voltage by finding the intersection of the tangent of the rising current and the zero current line

4.1.2 Two Linear Fit Intersection Method

Then, we proceeded to use another method, in which we fitted two lines. One is the same straight line as the previous method to have a zero level in our current. The second line is a fit of the data as it starts to rise. We then found the intersection of these to obtain the stopping potential as depicted in Figure 5. We can see the inverse wavelengths vs. stopping voltage plotted in Figure 6. These points show no correlation between them, therefore, making this straight line fit not appropriate at all. The slope in this case is -81.7 $\pm 43.3 V \cdot nm$, which again does not agree with the accepted value of $1242 V \cdot nm$. The uncertainty in this method was the .02V sampling rate, and the standard deviation of our fitted lines added.

4.1.3 Putting it All Together

These two methods brought very different results, so we tried analyzing the data visually. To do this, we normalized our data and plotted it together in one graph. As we can see from Figure 7 there is no clear trend of where the voltage is shifting. At first until 546nm it seems to be shifting to the right, which is what is expected, then it shifts to the left again.

Our results do not follow a straight linear trend, as they should,

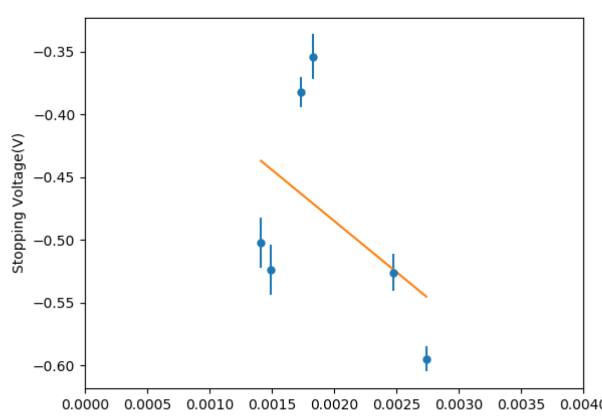

Figure 6: Plot equivalent to Equation 3 divided by e, with a linear fit that is not appropriate for this data

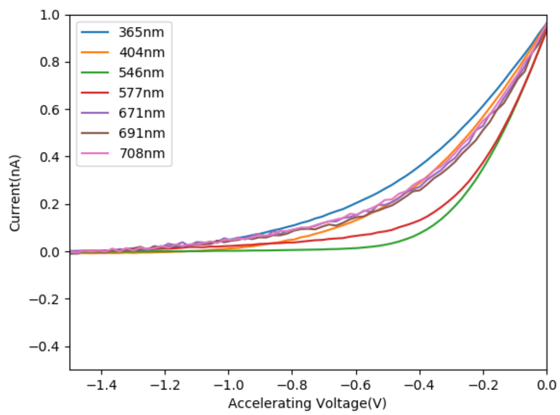

Figure 7: Plotting all data taken in one graph to analyze visually

in all 3 methods used. Without being able to fit them to a straight line we cannot find Planck's constant nor the work function of the metal. This is not the behavior we expected, as the stopping voltage seems to not have any correlation with the wavelength in our experiment. These results do not agree with Einstein's theory of photons.

One possible cause for this would be the timing of the trials for each wavelength. The higher the wavelength, the later the measurements were taken. As we can see in Figure 7 while the lower wavelengths have very smooth lines, the higher ones have a lot of noise. This experiment was conducted in a shared lab, and at the later times, there was more movement around our experiment. Any minimal movement by a person induces a current in our circuit, which is big enough to be very noticeable in our detector. In Figure 8 we can see a measurement of current that was only caused by human motion in close proximity to the circuit. This is a important source of error.

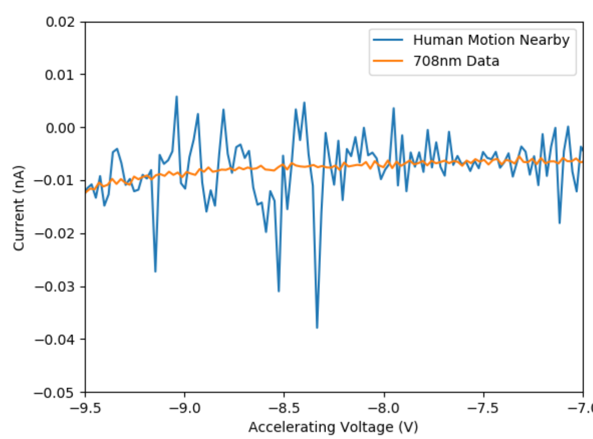

Figure 8: Current induced by a person moving in close proximity to our setup compared to one of our plots

Another thing to consider is that after the electrons have enough en-

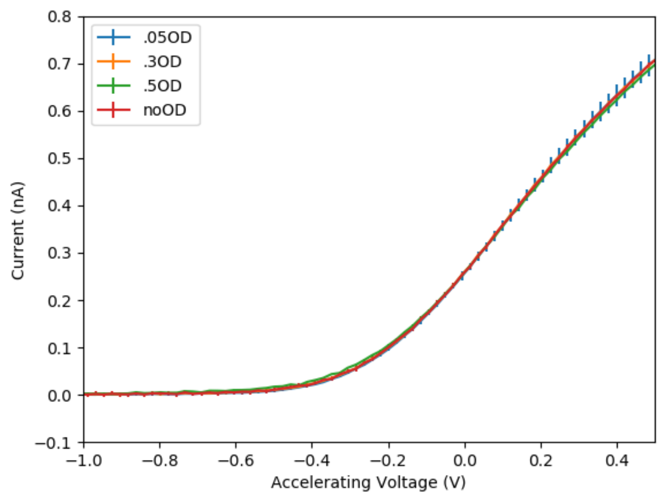

Figure 9: Normalized averages of several trials varying the intensity of the radiation

ergy to overcome the work function,
they are able to escape the metal but with little to no kinetic energy. Therefore, not being able to reach the anode, and ionizing the air inside the chamber as a consequence. Making it harder for subsequent electrons to reach the anode and thus, create current. Going from this hypothesis, this experiment might yield better results by starting with a high voltage and decreasing it with time, instead of starting with a low one and increasing it. This way instead of having no current until the stopping voltage is reached, you would have a steady current flow until reaching the stopping voltage. This should have a dramatic decrease in current, instead of having a slow rise in current as we did when reaching the stopping voltage.

4.2 Intensity Dependence

For this part of the experiment we varied the intensity of our radiation source to see if there was any correlation with the stopping potential. As we can observe in Figure 9 all of our data follow the same trend, there is no effect on the stopping potential. We then calculated the stopping potentials to be the following:

5 Conclusion

In this experiment we measured the current flow of photoelectrons against an electric potential. We were not successful in measuring the constant $\frac{hc}{e}$ which

OD Filter	Stopping Voltage(V)
.05	$-0.690 \pm .068$
.3	$-0.626 \pm .073$
.5	$-0.669 \pm .062$
none	$-0.636 \pm .069$

Table 1: Stopping Voltage of Different Wavelengths while Varying the Intensity

is accepted to be equal to $1242V \cdot nm$, instead we measured it to be $927 \pm 33V \cdot nm$. This does not agree with Einstein's theory of quantized light within error bounds. However, we were able to observe the lack of correlation between the stopping voltage and the intensity of the electromagnetic radiation, which does agree with Einstein's theory.

Acknowledgments: I would like to thank my lab partner Sierra Casten for assisting throughout the experimental procedure and the TAs Jason Brooks and Anish Zute for assisting us to understand these concepts better, providing the equipment for the experiment, and helping us utilize it.

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