Exploration of the Photoelectric Effect

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The photoelectric effect is a conceptually simple phenomena that demonstrates the necessity of understanding quantum effects and the limitations of classical electromagnetic theory. The non-intuitive realization that at certain energies (frequencies) light could not produce a photo current regardless of its intensity demands an explanation. In this analysis we establish the relationship between intensity of light and photo current, verify the nature of the photoelectric effect, and find a value for Planck's constant.

I. INTRODUCTION

The photoelectric effect encompasses the phenomena of electrons being 'dislodged' under the application of light. These dislodged electrons generate a photo current, absorbing the energy from the light and converting it into kinetic energy. Interestingly, however, there are a few non-intuitive phenomena related to the photoelectric effect which can not be explained without viewing light as a collection of quantum packets, photons.

One non-intuitive phenomenon occurs on the borders of the relationship between photo current and the intensity of light incident on the metal. Before the consideration of light as quanta, there was no explanation for "why low-frequency high-intensity light would not cause electrons to be emitted, while higher-frequency low-intensity light would" [1]. A second is "that the energy with which an electron is thrown out of a metal by ultra-violet light or X-rays is independent of the intensity of the light while it depends on its frequency" [5].

It is important to consider how counter intuitive Einstein's theory was at the time, postulating that light traveled in discrete packets of energy. The wave theory of light had, and has, immense success in describing the effects of interference, diffraction, and many other optical phenomena. In fact, upon his application to the Prussian academy of sciences in 1913, members including Planck still maintained that he had "missed the target... in his hypothesis of light quanta" [4].

Counter intuitive or not, the popular wave theory of classical physics was completely inadequate in describing the non-intuitive phenomena described above. Ultimately, it is this discretization, or quantization, of energy in electromagnetic radiation which prevailed to most accurately describe the photoelectric effect and its phenomena.

A. Theory and the Photoelectric Effect

In 1900 Planck had recognized that the minimum difference of energy between any two states of an electrically charged oscillator in a black box with radiation is equal to h, now known as Planck's constant [6]. In 1905 Einstein presented his theory that this constant was in fact the smallest increment of all electromagnetic radiation, not just for an oscillator in a black box as Planck had proven; he specifically applied it to the photoelectric effect [2].

In Einsteins theory, a light quanta, or photon, carries the energy hf where f is its frequency. Upon colliding with an electron, its entire energy is given to the electron. If this energy is greater than the energy required to 'dislodge' it, the electron will convert the remaining energy, K in equation 1, into kinetic energy and contribute to the photo current. At most intensities the contribution of an electron absorbing the energy of more than one photon (the multi-photon photoelectric effect) is minute [7], highly improbable, and thus if the energy of the photon is less than Φ the electron will simply release the photon back and no current will be generated.

After an electron is released, we can measure how much kinetic energy the electron was released with by applying a voltage to prevent the electron from leaving the metal. At lower voltages, only the less energetic electrons will be confined from leaving the plate, while the more energetic electrons will still contribute to the current. When the voltage applied results in the photo current, I, to be 0, we have found the stopping potential, V_s. Note, in this case we are only considering the amount of potential that is required to stop all of the electrons, i.e., the most energetic electrons; thus, the distinction of K_{max} in equation 2. Knowing V_s, we know K by the relation defined in equation 2. From equations 1 and 2 it is easy to see how Φ, the difference between the energy carried by each photon, hf, and the excess kinetic energy given to the electron after impact. This relationship is shown in equation 3.

$$hf = K + \Phi \tag{1}$$

$$K_{max} = eV_s \tag{2}$$

$$\Phi = hf - eV_s = hf_0 \tag{3}$$

This theory explains both non-intuitive phenomena listed above. The reason why high-intensity low-frequency light generates no current while low-intensity high-frequency light does. It also explains why the energy at which an electron is 'dislodged' depends on the frequency of light and not it's intensity.

II. EXPERIMENTS

Experimentation in this project involved analyzing the relationship between photo current and the intensity of light, analyzing the relationship between V_s and I, and analyzing the relationship between V_s and f.

A. Photo Current and Intensity

In this experiment, photo current was measured as a function of distance while the illumination source was held constant. We chose a particular light source and filter combination, the tungsten light source and the blue filter, and track the distance vs the photo current produced with the stopping voltage set to zero. The results of this experiment are plotted in figure 1.

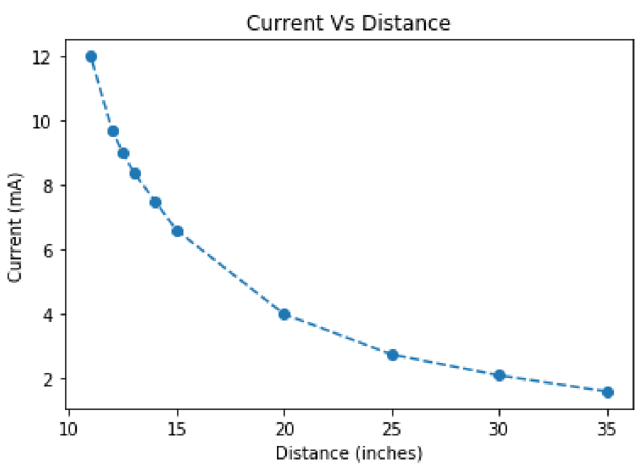

FIG. 1. Photocurrent measured against source distance

B. Photo Current and Stopping Potential

The relationship between the applied stopping potential and photocurrent was then explored. Several light sources were used; each respective distance between the photodetector and the light source was held constant, at a distance where 10mA of current was possible. The stopping potential was then varied and the resulting photocurrent was measured. The results from this experiment are shown in figure 2. The data measured for this experiment is displayed in table I. Note, our records contain values for both odd and even mA, 0mA - 10mA; for conciseness we display in the table only evens. The rest of the data is availible upon request.

Combination	0mA	2mA	4mA	6mA	8mA	10mA	distance
Hg-Blue	597	369	248.1	152.7	78.5	0.7	6
Hg-Green	536	292.8	201.7	127.8	70.0	0.7	0
Tung.-273	305	186.1	128.7	78.8	41.6	0.7	9
Tung.-Red	305.8	108.2	114.3	72.2	36.6	0.7	2.875
Laser-Red	340.9	162.5	107.8	65.3	40.7	0.7	29.5
	mV	mV	mV	mV	mV	mV	inches

TABLE I. Photo Current and Stopping Potential

Combination	1	2	3	4	5	6	Mean	Std Dev
Hg-Blue	1137	1014	1064	961	1047	949	1028.66	63.85
Hg-Green	381.5	389	364.4	344	407	394.4	380.05	20.65
	mV	mV	mV	mV	mV	mV	mV	mV

TABLE II. Statistical Assessment of Stopping Potential

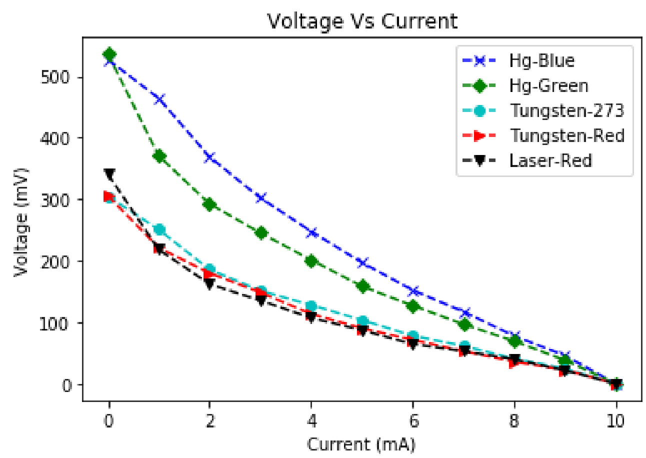

FIG. 2. Photo current measured while varying retarding voltage for various light sources

C. Statistical Assessment of Stopping Potential

In order to confirm the precision of our measurements we conducted a statistical assessment of stopping voltage for two different light source and filter combinations, Hg-Blue and Hg-Green. We measured the stopping voltage for each combination 6 times in order to generate a sample to calculate mean and variance upon. The distance between the light source and the photo detector was 2.5 inches. The results are listed in table II.

D. Stopping Potential and Intensity

The final experiment of this research was assessing the relationship between photo current and stopping poten-

Combination	5	7	10	15	20	N	Mean	Std Dev
Hg-Blue	1434	1218	1190	1230	906	30	1196	250.6
Tung-273	-	-	540	517	500	24	519.2	82.45
Tung-Red	454.0	574.0	554.0	-	-	30	527.3	88.80
	mV	mV	mV	mV	mV	samp.	mV	mV

TABLE III. Stopping Potential and Intensity

tial. We measured the stopping potential of 4 different light source and filter combinations at 5 different intensities, resulting in the measurements recorded in table III. The columns 5, 7, 10, 15, and 20 record the mean stopping potential recorded for each distance. The numbers correlate to the distance in inches between the light source and the photodetector. The columns N, Mean and Std Dev record the total sample size, total mean, and total variance across all different distances respectively.

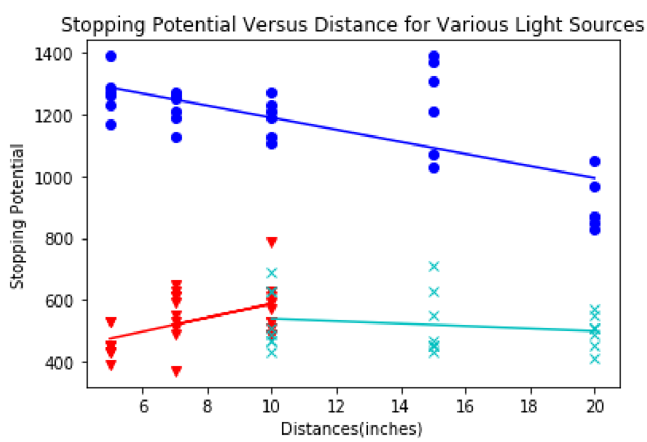

FIG. 3. Stopping potential statistics measured while varying intensity for various light sources

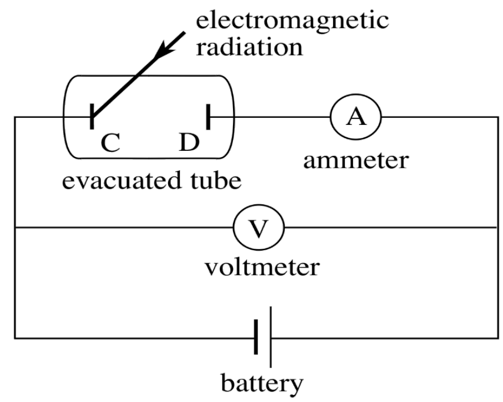

FIG. 4. Simple model for Experiment

III. DISCUSSION

Figure 4 sheds some light on our experimental model. As light bombards the surface of the emitter, electrons are subsequently emitted. The rate of electron emission in addition to the kinetic energy the electrons have upon emission can be measured as an electric current. The stopping potential, here shown as a battery, is found when the voltage is just enough to stop the movement the electrons. Electrons that usually would leave and contribute to the current would be stopped by the potential applied, as described in the section explaining equation 2.

A. Photo Current and Intensity

The results of this experiment are shown in figure 1. The current quite clearly does not vary linearly with a change in distance, taking on a parabolic form instead. This result is expected by the laws of classical optics and EM; the intensity of a light source upon an object is an inverse square law as a function of the distance between the two.

Given that the photons incident upon the photo detector carry enough energy to dislodge electrons, that is $hf > \Phi$, the amount of current produced does depend on the amount of photons incident on the metal at a time. In fact, in that case it is directly proportional, as more photons hit the metal more electrons can be released and contribute to the current. However, in the case that the incident photons do not carry enough energy to dislodge electrons, the intensity of light incident does not make any effect. This demonstrates a partial dependence of current upon the frequency of light.

B. Photo Current and Stopping Potential

As expected, the current produced by the photoelectric process can be regulated by applying a voltage on the circuit and converting the kinetic energy the electrons have upon dislodging into energy spent overcoming the electric field they feel due to the charge they carry. The higher the potential, the more energy is taken from the electron's kinetic motion and the lower the photo current.

The stopping potentials measured for each of the combinations of light source and filter are given in table I under the $0mA$ column.

C. Statistical Assessment of Stopping Potential

The results displayed in table II show that our measurements are relatively consistent. The standard deviation compared to the mean is quite small - meaning that the stopping potential we measure is consistent. A big question that arises from these measurements, however, is why the stopping potential measured at 2.5 inches away is largely different from the stopping voltages measured at 6 inches and 0 inches away for the blue and green filters respectively, as recorded in table I. One possible explanation is that there was some sort of human error causing the inconsistency in our measurements between the two experiments, most likely due to not fully appreciating the sensitivity of the microammeter when originally conducting experiment generating the results in table I. The cause of this error is further explained in the next section.

D. Stopping Potential and Intensity

The results demonstrated in figure 3 demonstrate a critical aspect underlying Einstein's explanation of the photoelectric effect. As clearly shown by the figure, the stopping potential, V_s, is completely unaffected by the intensity of light incident on the metal. While the current, given the frequency is large enough, is effected by the intensity of the light - the stopping potential is not. More precisely, the amount of extra energy each electron gains after absorbing a photons energy does not depend on the intensity of the light. This is a clear demonstration of the quantized nature of the photoelectric effect, the amount of energy carried by each photon, and the 1-to-1 ratio of photon absorption to electron under most intensities of light.

It is important to note that the scale was highly sensitive to voltage adjustments and that some distances (intensities) resulted in more consistent measurements than others. This is due to the imprecision of the equipment used in this experiment. To counteract this imprecision many measurements were taken in order to get a statistical average of the values and gain confidence in a measurement resulting from the data. It is this imprecision and variance of the measurements related to the equipment that results in slopes in figure 3 which differ from 0.

As can be seen when comparing the stopping potentials found for Hg-Blue in tables II and III we can see that - upon taking a statistical measure of the mean values, the values found in both experiments agree with eachother.

E. Plank's Constant

Upon rearranging equation 1 we discover a relationship between f and V_s similar to the familiar $y = mx + b$ relation. Intuitively we can then see that Plank's constant, h, can be interpreted as the slope relating the kinetic energy imparted upon electrons by photons with the frequency of said photon and the work function, Φ, can be interpreted as the y-intercept of the the same linear relationship.

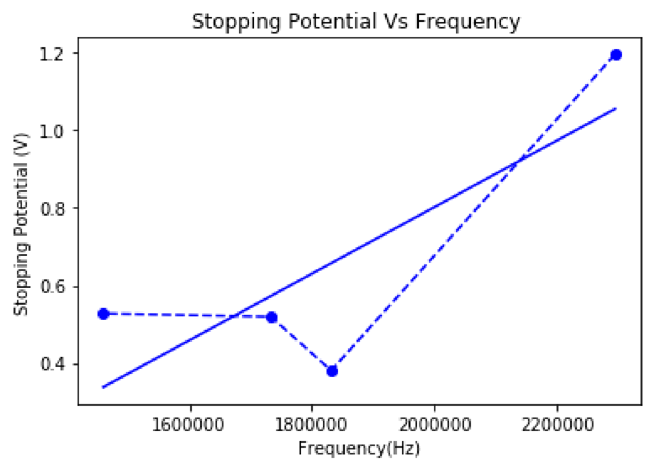

FIG. 5. Stopping potential as a function of frequency

We are able to use the stopping potentials found in both tables II and III, the most accurate of our stopping potential measurements, in order to derive both Φ and h. The line of best fit from 5, calculated by mean square error, results in measurements of $\Phi = 0.917eV$ and $h = 4.59 * 10^{-34} J * s$. The experiment value of h which was was found results in an error of 30%. This is relatively inaccurate for state of the art equipment but is within the correct order of magnitude of the true value and relatively close for the sensitivities on the equipment we have been working with. The experimentally determined value for the work function is reasonable. The true work function for the model of detector was unknown, however, the updated model, the EP-07, had a true work function value listed at $1.0323eV$ [3].

$$eV_s = hf - \Phi \tag{4}$$

$$V_s = \frac{h}{e}f - \frac{\Phi}{e} = mx + b \tag{5}$$

$$PercentError = \frac{|true - measured|}{true} * 100 \tag{6}$$

IV. CONCLUSION

The understanding and defining of the intricacies of photoelectric effect was a significant validation of quantum theory and a very non-intuitive challenge at that.

Previously well standing wave theory had to be reconsidered as observations turned to the microscopic. We have found that even with equipment lower than the state of the art it is possible to observe several distinct features of the quantum phenomena included in the photoelectric effect, such as the independence between the kinetic energy of photo electrons, the intensity of light and the partial dependence of current upon the frequency of light, and the value of Plank's constant.

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