PHYS307 - Applied Modern Physics

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Experiment 1 - Photoelectric Effect

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Section 1 - Introduction:

In this experiment, we will be exploring the duality in the nature of light which was backed with different theories through history. Mainly, we will be focused on Maxwell's and Einstein's theory and how their claims relate to the experimentally observed photoelectric effect. Our aim is to demonstrate the particle nature of light and calculate Planck's Constant[1]

In the late 1800s, inspired by the work of Michael Faraday, James Clerk Maxwell proposed a theory which suggests that light is an electromagnetic wave which propagates through space with the speed of light.[2] Not long after, his theory was experimentally supported by Heinrich Hertz who showed that radio waves travel at speed of light and exhibit light-like behaviour in terms of refraction, reflection, diffraction etc.[3] This observation tied the concepts of waves, light and electromagnetic waves hence strengthened claims of Maxwell's Theory.

Just one year before his experiment with radio waves, Hertz accidentally discovered the photoelectric effect. More importantly, he realized that this photoelectric effect can't be observed when experiment is conducted with visible light.[4] This very discovery along with the work of Philip Lenard in 1902 has challenged the wave theory of light. Later on, Albert Einstein was able to explain this characteristic of photoelectric effect using the "packets of light" theory whose foundations was laid by Max Planck. This approach successfully resolved the contradictions between wave theory of light and experimental observations of photoelectric effect by suggesting that light is made up of particles.

Just like their disagreement on the nature of light, each theory has a different interpretation for the property which determines energy carried in light. In Maxwell's Theory, determining factor was the light's intensity (i.e. what we perceive as brightness of visible light). Therefore his theory suggested that the energy of light is proportional to its intensity. On the contrary in Einstein's Theory, as suggested by Planck, the energy carried by light was dependent on its frequency, which we perceive as color in the visible range, rather than its brightness. This energy and frequency relation is given by the expression:

$$\boxed{E_{light} = h\nu} \tag{1}$$

where, h is the Planck's Constant ($\approx 6.62 * 10^{-34}\ \frac{m^2 * kg}{s}$) and ν is the frequency of light.

Experimental observations in photoelectric effects showed that light must deliver a certain amount of energy (E_{metal}) in order to break the bonds that bind electron to metal and eject it. These two theories disagree on the interpretation of this energy threshold.

Since light is a wave, according to Maxwell's Theory, it can be continuously absorbed by an electron, meaning that enough energy can be gathered over time by an electron even when using low intensity (i.e. low energy) light. Therefore this theory suggests that the photoelectric effect can occur at any intensity.[5] The only variation will be on time it takes to eject an electron. For the low-intensity light, it will take longer to gather up enough energy thus, leading to a longer waiting time and vice versa for high-intensity light but it will be ejected eventually.

On the contrary, since in Einstein's theory, light is a particle, it cannot be absorbed continuously (i.e. there are no "half particles" waiting to be absorbed). Therefore light particles must have the required energy to eject electron in the beginning. Since in this theory, energy is related to the frequency; light must be above a certain frequency threshold in order to eject an electron from a particular metal. Otherwise an electron will not be ejected no matter how long you wait and how bright is the light.

$$E_{light} \geq E_{metal} \implies h\nu \geq E_{metal} \tag{2}$$

Usually, energy delivered and previously stated E_{metal} will not be exactly equal. In this case if light delivers more than enough energy to eject an electron, that excess energy will take the form of kinetic energy for electrons. Obviously, kinetic energy implies motion, in this case motion of electrons moving from cathode to anode. From this knowledge, we should expect that kinetic energy of ejected electrons to increase if energy of light increases.

$$KE_e \sim E_{light} \tag{3}$$

Therefore if Einstein's Theory is valid, then we should observe an increase in kinetic energy of electrons as the frequency of light is increased. In order to measure kinetic energies of the electrons we apply a potential difference between cathode and anode. Theoretically, an electron should lose/gain 1 eV of kinetic energy while moving through 1 V of potential difference.[6] So we can measure their kinetic energies by using this definition which relates potential difference with kinetic energy. If we can find the potential difference that would cost the electron more kinetic energy than it already has, so that the electron can't overcome this potential and reach the anode, we can find its kinetic energy.

If we choose this potential such that, even the most energetic electrons can't reach the anode, that potential will be the stopping potential corresponding to that particular frequency of light (given an E_{metal} of course).In theory it should be defined by the following equations.

$$E_{light} = E_{metal} + KE_e \tag{4}$$

$$KE_e = E_{light} - E_{metal} \tag{5}$$

$$KE_e = h\nu - E_{metal} \tag{6}$$

and if potential difference between anode and cathode is set such that the electrons are no longer able to reach the anode equation becomes

$$KE_{max} = eV_s \tag{7}$$

thus

$$eV_s = h\nu - E_{metal} \tag{8}$$

since E_{metal} and e (elementary charge) is a constant

$$V_s \sim \nu \tag{9}$$

this implies that when we vary the frequency, if we also observe a change in stopping potential, then the energy carried by light is indeed dependent on its frequency. Therefore stopping potential is vital to this experiment and proving claims of Einstein's Theory. While conducting the experiment, stopping potential corresponds to the potential difference which the ammeter will show no current flow since electrons are not able to reach anode.

When we considered electron ejection criteria in Einstein's Theory, we've mentioned the word "certain frequency". The energy that this certain frequency refers is the work function for a particular metal. Below this limit light particles can't eject any electron. While performing the experiment, we will observe a difference between measured the kinetic energy of electrons and the energy of light which interacts with metal. Work function is the reason for this difference and it is used to break the bonds of electron and release it from metal. Now with all the definitions and explanations above we can define the formula for photoelectric effect with appropriate terms.

$$KE_e = h\nu - \phi \tag{10}$$

where:
KE_e is the kinetic energy, h is Planck's Constant, ν is frequency of light and ϕ is the work function.[7]

Essentially, this formula tells us that kinetic energy of electrons and frequency of light has a linear relation. Moreover, light must have a certain amount of energy in order to eject an electron (since kinetic energy can't be negative). If the light has more energy than required to release the electron, that excess energy will become kinetic energy for the electron.

Section 2 - Experiment Details:

Our experiment setup, consists of following devices/objects:

- Optical Filters
- Hg Arc Lamp
- Photoelectric Effect Apparatus
- Aperture

- Power Supply
- Phototube
- Cylindirical Tube

Hg lamp produces the light that will be shined on the phototube. An Hg lamp emits light at a wide spectrum.[5] However, in this experiment the frequency of the light is an independent variable so we should be able to isolate and use a single frequency. For practical purposes, instead of changing the light source in each step, we use optical light filters which allows only the desired frequency(at least a narrow range near it). We should note that, it is possible to use other light sources provided that they can produce light at desired frequencies and preferably in a discrete spectrum so that it is easier to isolate a single frequency. Chosen light source should be able to produce light with higher energy than the work function of the chosen metal, but it should be low enough so that it doesn't pose any safety issue and cause any undesired phenomena (possible chemical reactions due to high energy). Light produced by Hg lamp then passes through a cylindirical tube (which also houses aperture and filter) to get into the phototube. This cylindirical tube separates light from external sources from the light from Hg lamp so that only light with known properties is able enter into the phototube, which makes our measurements are less prone to error.

Light which has passed through the tube then arrives to the phototube. Phototube is a device which consists of an anode plate and a cathode plate, which are both metal, enclosed in a vacuum chamber. When the phototube is illuminated with the light from Hg lamp and if necessary conditions are met (i.e energy threshold) an electron-ideally only from the cathode- will be ejected by mechanisms of photoelectric effect. This ejected electron, if it reaches the anode, creates a current which can be measured using the highly sensitive ammeter in photoelectric effect apparatus. In order to produce this effect, we should use a phototube with a suitable cathode material. Suitable materials are metals with work functions that are below the energy levels of the light used in the experiment, otherwise we wouldn't be able to observe any photoelectrons. Preferably, this particular metal should have a good photoelectric efficiency so that the number of electrons ejected are high enough that the current they produce are measurable by our equipment without requiring very intense light. Moreover, for the experimental precision and accuracy it is better to use a surface with a higher uniformity of work function. In our setup, the material used satisfies first three criteria but its work function is said to be not highly uniform.[1]

Having said that both plates of the phototube are metals we can also expect anode to eject electrons in a non-ideal scenario. However, this is an undesired outcome since it can manipulate our measurements. In order to prevent this, we use an anode that is shaped as a ring so that it is not in the direct path of the light but still, it doesn't completely solve this issue.[1] However, in this particular setup anode plate is made up of nickel[8] which has work function about 5 eV[9] which is equivalent to the energy of light that has a wavelength of $\lambda \approx 248nm$. Since this value is outside of our experimental range we can assume that any electron ejection from the anode is negligible.

Along with a highly sensitive ammeter, the photoelectric effect apparatus also contains a voltage source (with its own voltmeter) that is used to apply potential difference between anode and cathode in adjustable steps. Voltage steps can be adjusted in intervals of 0.5 V in the range -2.0 and 0 Volts and 5V in the range 0.0 and 30 Volts.

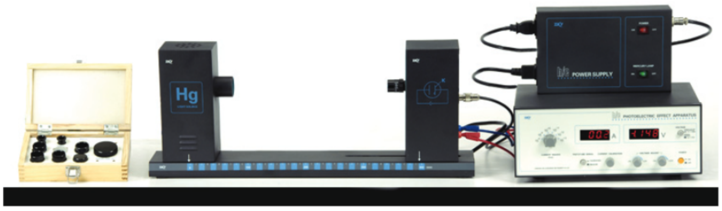

Figure 1: Overall appearance of the setup - Image Courtesy: Pasco

Section 3 - Measurement & Data Analysis:

Aperture = 4mm

365 nm		405 nm		436 nm		546 nm		577 nm	
V (V)	I (10^{-13}A)	V (V)	I (10^{-13}A)	V (V)	I (10^{-13}A)	V (V)	I (10^{-13}A)	V (V)	I (10^{-13}A)
-1.924	0.0	-1.463	0.0	-1.300	0.0	-0.791	0.0	-0.684	0.0
-2.0	-2.7	-2.0	-8.2	-2.0	-11.3	-2.0	-6.2	-2.0	-2.9
-1.5	123.5	-1.5	-2.3	-1.5	-8.4	-1.5	-6.3	-1.5	-2.7
-1.0	369	-1.0	60.1	-1.0	65.1	-1.0	-5.7	-1.0	-2.6
-0.5	638	-0.5	140.5	-0.5	188.8	-0.5	66.1	-0.5	16.4
0.0	953	0.0	235	0.0	335	0.0	229	0.0	86.8
5.0	5110	5.0	1324	5.0	1898	5.0	1286	5.0	480
10.0	8850	10.0	2250	10.0	3180	10.0	1975	10.0	747
15.0	11800	15.0	2980	15.0	4140	15.0	2500	15.0	909
20.0	14270	20.0	3580	20.0	5000	20.0	2850	20.0	1026
25.0	16200	25.0	4080	25.0	5690	25.0	3120	25.0	1110
30.0	17660	30.0	4450	30.0	6200	30.0	3300	30.0	1167

Table 1: Current Produced By the Phototube Given Potential Difference Between Plates and Different Wavelengths of Light With Constant Intensity.

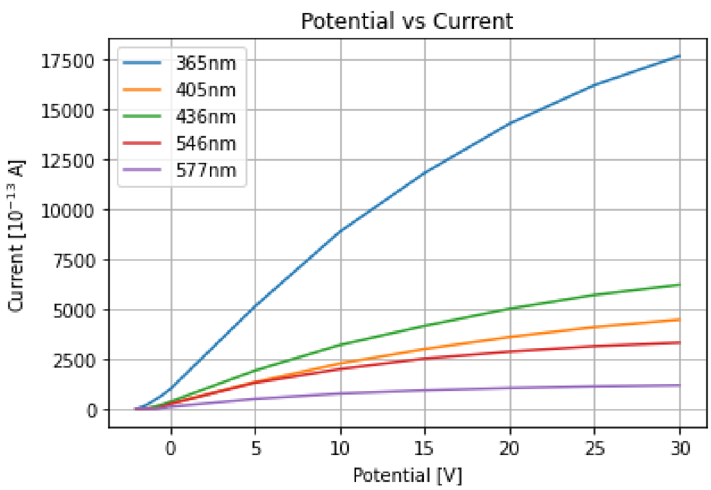

Figure 2: Plot for Table-1

By observing **Table-1** table we can see that the parameters changed are wavelength of light shined on the phototube and potential difference applied on the phototube plates, meanwhile light intensity is kept constant by using the same aperture value throughout the whole experiment. The variation in wavelength with a fixed intensity value indicates us that this experiment tests Einstein's Theory since in his theory energy carried with the light is related to its wavelength. On the top row of the table, we see values that are not in a sorted order like the rest of the table (i.e -1.918 before -2.0). Uppermost value for each wavelength column of the table shows a current value of 0. Recalling the definitions in the introduction section, we can see that these values correspond to stopping potentials. By looking at the table, for the interval -2.0V to 0V we can see that the current values increase exponentially. However, for the last three voltage values that are 20.0V to 30.0V we can observe that, even though current values continue to increase, their rates have started to slow down.

Wavelength (nm)	Frequency (10^{-14} Hz)	Stopping Potential (V)
365	8.21	1.924
405	7.4	1.463
436	6.88	1.300
546	5.59	0.791
577	5.20	0.684

Table 2: Wavelengths of Light and Their Respective Stopping Potentials.

In **Table-2** we can see that as wavelength of light increases, stopping potential that has to be applied decreases.

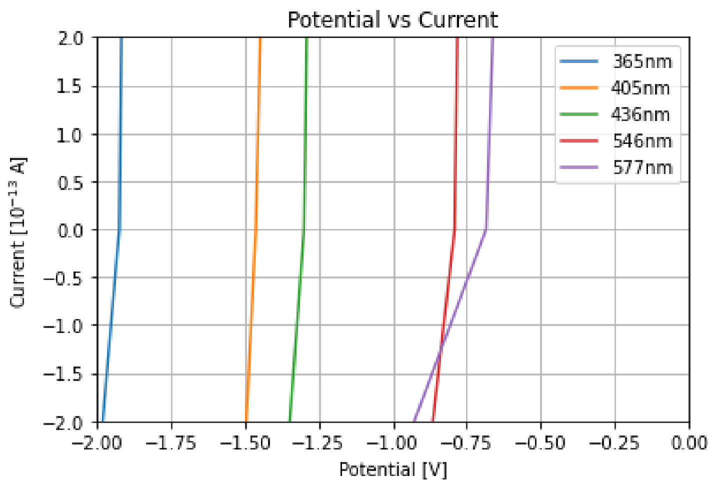

Figure 3: This plot is obtained by zooming Figure-2 about x:(-2,0) y:(-2,2)

On the figure above (**Figure-3**) we should note the existence of negative current values and the different potential values corresponding to zero current.

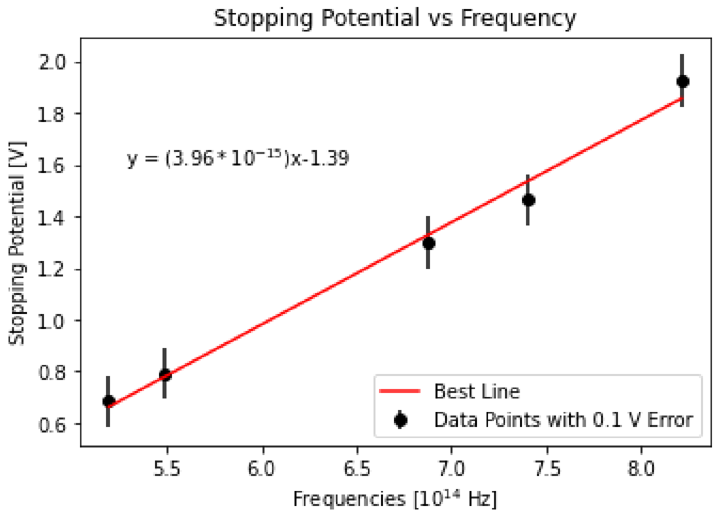

Figure 4: This Plot Shows the Relation Between the Frequency of Light and Stopping Potentials

Section 4 - Results and Discussion:

Looking at the values in **Table-2** with its visualisation in **Figure-4** and recalling that this experiment was conducted under constant intensity of light, we can claim that stopping potential is indeed correlated with the frequency of light. Furthermore, on **Figure-4** we can see that this correlation follows a linear trend. Since it was shown in **Equation-7**

$$KE_{max} = eV_s$$

that stopping potential is related with the kinetic energy. Therefore these findings are in favor of Einstein's Theory. In terms of actually "proving" the theory, I suppose it would have been better if we had tested the opposing theory as well, so that observing no variation in stopping potential by changing intensity can support Einstein's claim even further. Moreover, in Einstein's Theory it is also claimed that since light is delivered in discrete packets no photoelectrons can be observed below certain threshold, meanwhile in Maxwell's Theory an electron should be ejected eventually. Testing the non-existance of photoelectrons for light energies below work function could have been a supporting evidence as well. However, I suppose that by looking at the overall findings of this experiment it wouldn't be wrong to say that we were able to proove Einstein's Theory.

Even though we concluded that our results are in favor of Einstein's Theory there are a few highlights that we've encountered during the experiment that we should cover. First, since there are no flat region in **Figure-2** we can say that we weren't able to reach the saturation current. Saturation current is the current when all ejected electrons are able to reach the other plate. Apparently, highest potential used in this experiment is not sufficient to accelerate electrons with lowest energy enough such that they can reach the anode. Moreover, by looking in **Figure-2** we can also claim that even if we can achieve saturation current, that value will not be unique. This is an outcome of the characteristics of the light source we used.[1] Since the lamp has a different intensity output for different frequencies of light, different

frequencies of light will eject different amounts of electrons. So even if all of the ejected electrons can make it to the anode, difference in their numbers will lead to a difference in saturation currents.
Another point is the existance of negative currents as seen on **Figure-3**. This implies electron flow in reverse direction i.e. from anode to cathode. As discussed previously, anode is also made up of a metal which means it is also capable of emitting photoelectrons. Moreover, anode can be deposited with cathode material by the means of evaporation[1] which results with even higher rates of emission from anode due to the fact that cathode material is chosen for that purpose. This is the part where the choice of anode material and shape (a ring in this case) becomes important.

In previous section, using polynomial fitting we have obtained a relation between frequencies of light and stopping potentials as it can be seen on **Figure-4**.

$$y = 3.96 * 10^{-15}x - 1.39 \tag{11}$$

We know that this equation finds a potential difference value given a frequency. Since LHS and RHS of this equation must have matching units we can write

$$[V] = slope * [Hz] + intercept$$
$$[JC^{-1}] = slope * [s^{-1}] + intercept$$

Which implies that the units of slope and intercept in our equation are

$$slope \rightarrow 3.96 * 10^{-15} \left[\frac{Js}{C}\right]$$
$$intercept \rightarrow -1.39 \left[\frac{J}{C}\right]$$

Thus our equation takes the form

$$V_s = 3.96 * 10^{-15} \left[\frac{Js}{C}\right] * \nu - 1.39 \left[\frac{J}{C}\right] \tag{12}$$

when this equation is multiplied with the elementary charge (e = $1.60 * 10^{-19}$ C) so that it has units of energy, we obtain the following

$$eV_s = \left(1.60 * 10^{-19} [C]\right) \left(3.96 * 10^{-15} \left[\frac{Js}{C}\right] * \nu - 1.39 \left[\frac{J}{C}\right]\right) \tag{13}$$

$$eV_s = 6.34 * 10^{-34} [Js] * \nu - 2.22 * 10^{-19} [J] \tag{14}$$

We've already obtained the following relations

$$KE_{max} = eV_s$$
$$KE_e = h\nu - \phi$$

So we can write the following equation

$$6.34 * 10^{-34}\,[Js] * \nu - 2.22 * 10^{-19}\,[J] = h\nu - \phi \tag{15}$$

Since these are line equations of the variable ν we can simply equate respective coefficients to find

$$h_{exp} = 6.34 * 10^{-34}\,[Js] \tag{16}$$

$$\phi_{exp} = 2.22 * 10^{-19}\,[J] \tag{17}$$

Note that while mentioning kinetic energy, we alternated between KE_e and KE_{max}. In this case they were used interchangeably since the definition of the stopping potential lies with the electrons with maximum kinetic energies. This maximum kinetic energy actually corresponds to the energy that electrons should acquire when struck with light according to the theory, yet in reality due to a number of reasons energies of electrons might vary.
Now let's calculate our experimental error using following formula

$$\epsilon = \frac{|exp - true|}{true} 100\%$$

Planck's Constant to its third decimal is given as

$$h = 6.626 * 10^{-34} \left[\frac{kg * m^2}{s}\right]$$

Hence our error is

$$\epsilon = \frac{|6.34 * 10^{-34} - 6.63 * 10^{-34}|}{6.63 * 10^{-34}} * \%100 \approx \%4.37 \tag{18}$$

Every experiment is vulnerable to experimental errors due to their nature, now we shall be discussing possible sources of errors for this experiment. We may begin with the errors that might possibly be introduced by the light source and filters. As stated in previous sections, Hg lamp emits light at a frequency with various intensities and this light is passed through a color filter and an aperture. Due to these variations and less-than-perfect filtering of frequencies, light with different properties can reach to the cathode and alter our results. For example if we are experimenting with a certain wavelength (say 436 nm) but the filter also allows a portion of wavelengths in a small interval (say$\pm$3) about our desired wavelength, this will lead to a measurement of higher stopping potential since electrons that are struck with light of shorter wavelength is also ejected.

There are also the errors introduced by phototube itself, we've already discussed this issue while mentioning negative current values. Yet, we can add a few more reasons for errors aside from those caused by the emission from anode. Dark current of phototube is one of these reasons.[8] Dark current is the current that flows in phototube even when it is not illuminated.[10] Moreover, in the technical specification sheet of this experiment setup, it is stated that prolonged exposure of phototube to light could lead to reduced lifespan or damage.[8] Meaning if a certain phototube is particularly old or wasn't handled well, it might lead to faulty measurements.

Then, there are the most anticipated errors, which are the ones caused from and measurement devices. Since the current values we work with are very small, it is quite important to have accurate and precise measurements. For this reason, an uncalibrated or not well calibrated photoelectric effect apparatus might lead to inaccurate measurements. Yet still, at these orders of magnitudes, even for a nicely calibrated device, the internal electronics might introduce error depending on their temperature etc.
Finally, we have the errors that might be caused by the outside factors. Since this experiment is based on light, any external light source can introduce error to this experiment.

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