Photoelectric Effect

1 Introduction

In science, we reject or modify old ideas, to explain new observations. Sometimes we try to disprove an idea, but end up with supporting it never before. The historical development of the experiments and theory of the Photoelectric effect from its discovery by Heinrich Hertz in 1887 to the verification of Einstein's theory in 1914 by Robert Millikan is a nice example of this scientific approach. A comprehensive history of the subject can be read in (reference), here we give a brief description. History of photoelectric effect is important, illuminating and interesting.

Fresnel, Young and Hygen demonstrated and explained the observed phenomena of interference of light assuming that light is a kind of wave. In as early as 1847, based on some polarization effects, Michael Faraday proposed that light is a result of high frequency electromagnetic vibrations. Later, James Clerk Maxwell in 1862 demonstrated with systematic study of the equations of electricity and magnetisms, that in fact light is an electromagnetic wave. All the interference, diffraction and polarization phenomena that were known, could be explained. Moreover, Maxwell's theory predicted existence of electromagnetic waves at frequencies beyond the detection limit of human eye. We call these as radio, infrared, microwave, ultraviolet, x-ray or gamma rays today. They were all detected subsequently and are used in today's technology. In the year 1886 Heinrich Hertz successfully produced and detected the electromagnetic waves. Maxwell's theory of electromagnetic wave and light was very firmly established.

Ironically, Hertz did an interesting observation. He realized, some how the presence of light helps in the detection of the waves he produced. This observation, later supported by Wilhelm Hallwachs's work in 1888, was puzzling and could not be explained using Maxwell's theory. Later, after the discovery of electron by J. J. Thomson in 1897 and his work on the above effect, it was clear that electrons are being emitted from the metals by the icidence of light on them. The effect was called photoelectric effect.

Between 1900 and 1902 in a series of experiments, Philipp Lenard observed some peculiar properties of the photoelectric effect which could not be explained by Maxwell's theory. In 1905, it was Albert Einstein, who gave a radical explanation of the phenomena suggesting that the absorption of light by metal happens in definite discrete amounts. This is the famous light quantum hypothesis by Einstein which apparently suggested that sometimes light also behaves like particles. Since the wave theory of light by Maxwell was necessarily to explain the interference and other phenomena that are particular to waves, Einsteins hypothesis suggested that the light may behave like both, a wave and a particle, it has dual nature.

Einstein presented equations related to photoelectric effect. These equations can be used to precisely test his hypothesis. A theory, so radical was not accepted readily by the scientific community. In fact, in 1914, Robert Millikan performed a set of precise experiments designed to rule out Einstein's theory. It turned out though, the results came out exactly in accordance with Einstein's prediction. The discovery was so important that it was awarded two nobel prizes, in 1921 to Einstein and in 1923 to Millikan ! This was the pathway to the inception of quantum mechanics that explains (almost) every observed phenomena related to atomic and subatomic world.

The photoelectric effect is used now a days to make night vision goggles, to detect high energetic radiations etc. Some of you will work with those instruments later in your study. For now, we shall ponder upon the experiment that literally gave birth to the modern physics. The experiment itself is with almost the same setup by Lenard or Millikan. We shall first learn about the set up, the observation and Einstein's explanation of the effect with light quantum hypothesis. We would discuss a few related phenomena which we need to understand to perform the experiment wisely and outline the experimental procedure. It is strongly recommend to go through the theory of electromagnetic waves and why it can not explain the photoelectric effect before you start reading the next section.

2 Theoretical Understanding

Schematic diagram of the apparatus for performing the photoelectric effect experiment is shown in Figure (1-left). The light source shown here is an incandescent lamp which emits radiation across a wide range of frequencies around the visible region. A particular frequency[1] is selected using a filter (a colored glass) and focused using a lens onto a cylindrical metal plate called cathode. Under suitable condition electrons are ejected from the cathode with enough kinetic energy to reach the two strips of metals called anode. The anode and cathode are connected with a variable voltage source with the positive end of it joining the cathode. Here the voltage can be varied and can be measured using the voltmeter **V**. An ammeter **A** capable of measuring current in nano Ampere is added in the circuit as shown in the figure. Intensity of the radiation from the light source falling into the lens can be varied either changing the voltage across its filament or by changing the distance between the light source and the filter. The anode-cathode assembly is kept in a transparent vacuum tube usually called the photo tube. A set of filters with different colors (that is, it will only let light of a certain frequency to pass through) are usually used.

Here is what happens when we switch on the light. It passes through the filter that allows only light of a particular frequency to go through it. Inside the metallic anode there are electrons free from individual atoms of the material, but bound to the metal by their combined potential. As the light falls on the cathode, the electrons therein absorb the energy of the light. If they get enough energy to overcome the potential barrier, they will come out and some of them may also have enough energy to reach the anode. This will result in a current in the circuit and could be measured by the ammeter **A**. Note that with the polarity the voltage source is attached in the circuit, the potential difference will prevent the electrons to reach the anode. Since the anode is given a negative potential, it will repeal the electrons reaching them. As the applied potential here opposes the electrons to reach the anode, we shall call it retarding potential V_R. If we increase V_R, we would expect less and less electrons reaching the anode and the current is supposed to decrease.

It is observed that at a value of the retarded potential the current goes to zero. This means the electrons liberated from the cathode have a maximum kinetic energy. When the applied potential difference is the same or more than that, no electrons can reach the anode and hence no current. This value of the potential, at which the current becomes zero, is called the stopping potential and we shall denote it by V_0. More interestingly, if we change the intensity of the light, the stopping potential does not change. Surprisingly enough, if we change the color of the filter, the stopping potential changes.

[1] Actually a range of frequency, we shall discuss this later in detail.

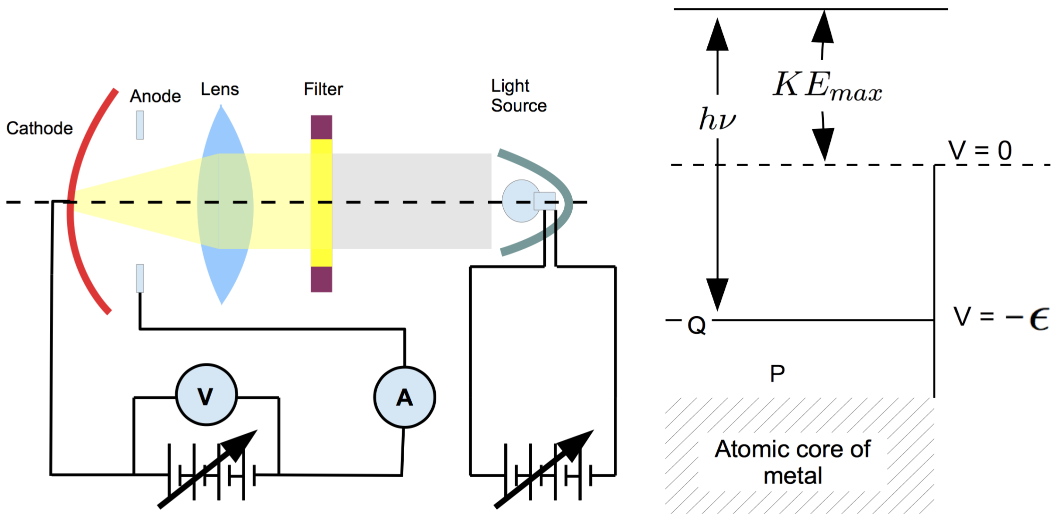

Figure 1: Schematic diagram of the apparatus for performing the photoelectric effect experiment (left) . The light source shown here is a incandescent lamp which emits radiation across a wide range of frequencies around the visible region. The cathode and the anode are kept in a vacuum tube to prevent ionization effects (you will fill it with gas when you will do the Frank-Hertz experiment). In the right side the energy diagram used to explain the photoelectric effect is shown.

Here is the explanation of these observations due to Einstein. Figure (1-right) shows the schematic diagram of the energy levels of metals. Electrons in the metals are not bound to individual atoms, but can move freely. At a finite temperature they can have various different energies up to a certain maximum energy which we call $-\epsilon$ here. This sea of electrons are often called the Fermi sea. All these electrons are subjected to combined potential of the atoms, we label this with a dot-dash line and set the zero of the energy at this level. Clearly, the electrons need to have at least an energy of 0 to get liberated from the atoms. Einstein hypothesized that when light of frequency ν is incident on the surface of the metal, it gives to the electron exactly $h\nu$ amount of energy, where h is the Plank's constant. Let us consider an electron say P in the Fermi sea which has an energy of $-E$. On the incident of a photon of energy $h\nu$, it will gain that much amount of energy and will have a total energy of $-E + h\nu$. If this energy is less than zero, then the electron will stay inside the metal. If it is more than zero, it will go out of the metal. Since it has to overcome the potential barrier, on ejection it will have an energy of $-E + h\nu$. In general this electron can go in any direction. Assuming this has the right direction of the velocity, this electron will eventually reach the anode and produce photocurrent. It is clear that the electron Q, which is having the energy $-\epsilon$ will have the maximum energy amongst the electrons liberated from the metal and is given by $-\epsilon + h\nu$. Clearly, if we apply a retarded potential to stop all the electrons from falling into the anode and make the photo current go to zero, we need to stop the electron with highest kinetic energy. Hence

$$KE_{max} = -\epsilon + h\nu = eV_0, \tag{1}$$

where e is the electronic charge. Now we can change the filter and perform the experiment and note down the values of V_0 with the filter transmission frequency ν. The graph of ν Vs V_0 would give a straight line with the slope same as h/e and the intercept will give the value of $-\epsilon$. Note that ϵ depends entirely on the characteristic of the metal and is known as the work function of the metal. The work function do depend on the temperature, we shall discuss this shortly. The quantity h/e is a universal constant.

3 Objectives

- **To estimate the Plank's constant and the work function of the metal giving the photoelectrons** by measuring the variation of stopping potential with the frequency of light.
- **To see the graph of current Vs voltage for different intensity and frequency of light**.

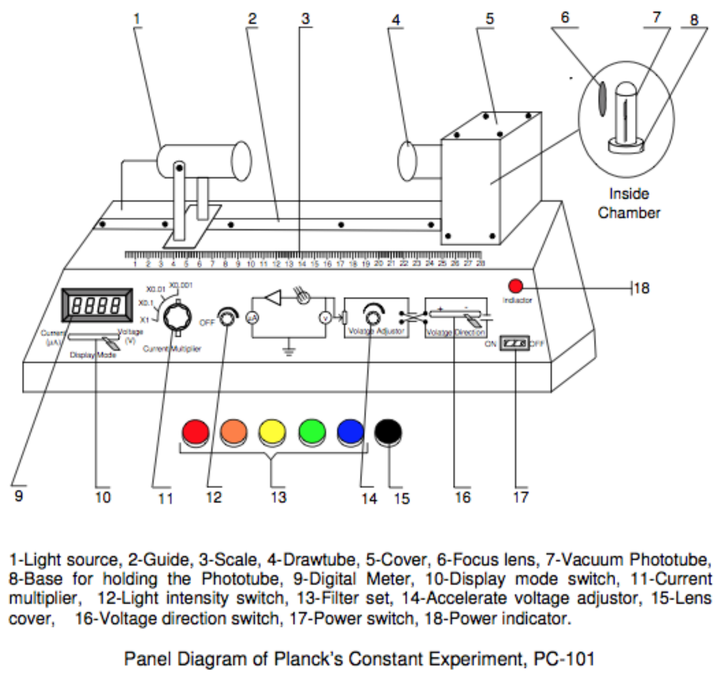

Figure 2: Schematic diagram of the SES instrument set up.

4 Experimental setup

The apparatus we will be using is from *SES Instruments Pvt. Ltd.*, a diagram from their manual booklet is shown in Figure (2). It essentially uses the same principle and circuit as in Figure (1). However, some electronic circuits are used to assist the precise change and measurements of the voltages and currents. We shall discuss the main components here.

- **Item 16** in the Figure is a voltage direction switch, which we shall keep in the **-** position such that we always use it to provide the retarding voltage.
- **Item 9 and 11** in the Figure (2) are related to the digital display of the current **A**. The current multiplier switch should be kept in $\times 0.001$ place, such that the readings we get in the display are in units of nA.
- **Item 10** in the Figure (2) is used to observe either V_R or the photo current in the display, we shall switch it back and forth as needed.
- **Item 14** in the Figure (2) is a knob used to change the values of V_R.
- Intensity of the light can be adjusted either by moving the source in the guide (**item 2**) or by changing the voltage to the bulb (**item 12**).

Rest of the apparatus is self explanatory. You will be given a filter bank along with this set up which will have filters of five different wavelengths. The filters can be placed at the entrance of **item 4** shown in the Figure (2). **There is a black opaque stop kept at the draw-tube when the apparatus is not in use. Make sure this happens. Also, do not keep the photo tube exposed to radiation (light) for long time. Either of these will degrade the photo tube and would cause the cathode coating to go and deposit on to the anode.**

5 Experimental Procedure

5.1 Some interesting effects that you need to care about

- The maximum energy of the electrons in a metal varies with temperature. In fact there is no sharp cut off energy $-\epsilon$. Effect of this effect may be observed if you keep the light on for long time causing the cathode temperature to rise. As a result the stopping potential and the incident light frequency do not follow the nice linear relationship if the temperature is somehow varied during the experiment. Try to figure out how much will be this effect for your lab set up. Interested students can have a look at this reference (reference). You would need to know statistical mechanics and its application to understand this effect.
- Often the cathode is coated with a particular material and the photoelectric effect happens from the coated surface. The work function that we see is of this coating, in your lab experiment it is of Cesium Antimony. Now, because of improper manufacturing process and also because of the vacuum in the photo tube some of this coating evaporates and settles down into the anode. The anode, otherwise is made of a metal with relatively higher work function and no photo electric effect is supposed to be seen when it is illuminated by the light of same frequencies used in the experiment. However, because of the above effect, if light falls on the anode, some of the electrons come out and produces a photo current in the opposite direction to that of the usual. In such cases, as you increase the potential difference between the cathode and the anode the current attains a minute negative value and do not

decrease further. This can be avoided by carefully choosing the light path and not letting the light fall on the anode. This is done with a stop at the light source in your apparatus and a lens in front of the vacuum tube thereby decreasing the chance of the light falling on the anode. Nevertheless, you may see this effect in your experiment. If you see, you would need to consider the value of the potential at which the photo current attains a steady (negative) value to mark the stopping potential.

- The photo current depends on both, the number of electrons produced and their energy. For a given retarded potential less than the stopping potential, it is not that only the electrons with maximum kinetic energy will reach the anode. Rather all the liberated electrons with energies on and above the applied retarded potential will reach the anode. All these electrons produce the photo current. When the retarded potential is zero, the electron liberated from the cathode are free to go towards the anode, they do not have to overcome any force field. Hence their motion from cathode to anode is like a free particle. When a non zero retarded potential is applied some of the electrons with rather lower energies would "feel" the force between the anode and cathode and would no more be free but decelerated. With small retarded potential (much less than the stopping potential), the number of effectively decelerated electrons are rather small and the current Vs voltage graph is still linear. However, when the retarded potential is very near to the stopping potential, much of the electrons are decelerated and the graph start to change from linear and get a curvature. Because of this it becomes very difficult to exactly measure the stopping potential. One way is to normalize the current values to the value at $V_R = 0$ and then find the point of maximum curvature of the graph. However, this is quite an involved method for the present class. You will find out the stopping potential by noting the value of V_R when the photo current start to become constant (zero or negative value).

- The filters used with the lab apparatus have very large bandwidth, that is they allow not only a particular frequency to pass through them, but also light of other nearby frequencies. This means if we are using a filter of say 435 nm, light with lower and higher wavelengths are also passing through it. This light will produce electrons with higher maximum kinetic energy than that of wavelength 435 nm. This is a limitation of the experimental set up we are using here.

5.2 To estimate the Plank constant and the work function of the material

5.2.1 Procedure and Precautions

- Attach the filter with the largest wavelength (**635 nm**). Set V_R to zero and **item 10** to measure the current. Set the intensity of the light such that you get a reading of the photo current in the digital display. If it goes off the display decrease the intensity.

- Attach in all the other filters one by one (one at a time) and repeat the above. Find the highest intensity for which for all the filters the photo current is measurable for $V_R = 0$ V.

- Now attach the filter with the highest wavelength (**635 nm**). Increase the values of V_R using **Item 14** in the Figure (2). Carefully note the value of V_R when the current attains a minimum constant value (zero or negative). This would give you the stopping potential V_0 for the corresponding filter.

- Repeat above with the other filters. Finally you would be able to fill up the Table (1) with your observations. You can convert the wavelength of λ to the frequencies ν by $\nu = c/\lambda$ where $c = 299792458$ m sec^{-1}, is the speed of light.

λ (nm)	ν (Hz) $\times 10^{14}$	V_0 (V)
635	4.72	-
570	5.26	-
540	5.56	-
500	6.00	-
460	6.52	-

Table 1: Measurement of stopping potential for different filters. Note that the stopping potentials are considered to have negative values.

5.2.2 Calculations and Result

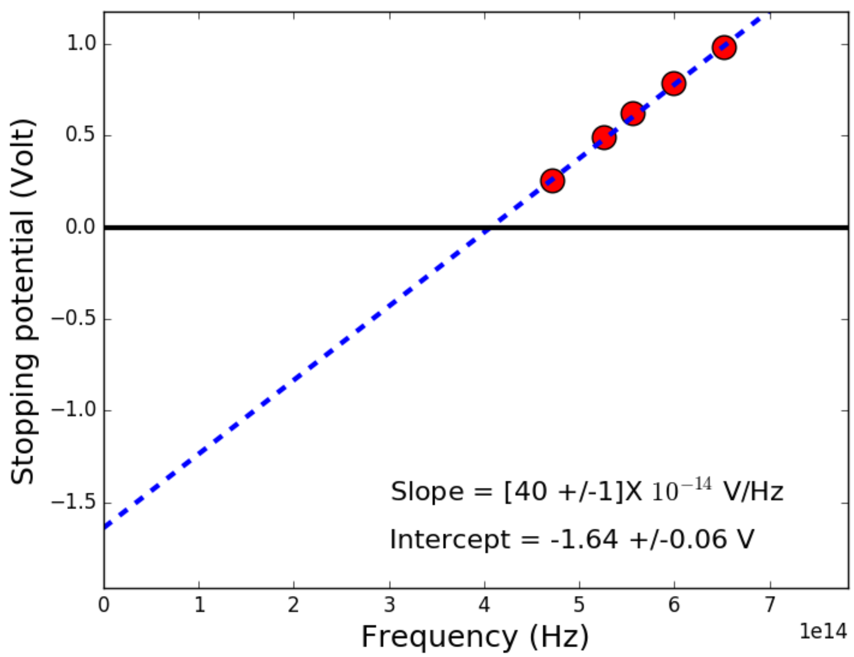

Figure 3: Sample graph of stopping potential Vs frequency.

- Plot a graph with frequency in the x-axis and stopping potential in the y-axis as points. The minimum value of the frequency should be 0 Hz. Find the best fit straight line to these points and extend it to the y axis to find the y-intercept. The way to find the best fit values to the data points and estimation of the errors in the fit is given in the general instructions. Figure (3) demonstrates such a plot. The blue dotted line is the best fit straight line to the data points in red circles. The best fit values of the slope and the intercepts are also mentioned.

- The y-intercept gives the work function of the material (at room temperature roughly). In this example it came out to be
$$\epsilon = -1.64 \pm 0.06 \quad \text{V}, \tag{2}$$
which is measured with three significant digits. See the general procedure to learn how to quote the result with significant digits.

- To determine the Plank's constant we recall that the slope is h/e, where $e = 1.602 \times 10^{-19}$ C is the electronic charge. Hence we get,
$$h = \ [6.4 \pm 0.2] \ \times 10^{-34} \text{ J sec}, \tag{3}$$
which is measured with two significant dgits.

5.3 Observation of current vs voltage characteristics for different frequencies and intensities.

5.3.1 Procedure and Precautions

- Attach the filter with the largest wavelength (635 nm). Set V_R to zero and **item 10** to measure the current. Put the light source 25 cm away from the photo tube. Set the intensity of the light such that you get a reading of the photo current in the digital display. If it goes off the display decrease the intensity using the **item 12**.
- Note down the value of the photo current I against $V_R = 0$ in the table. Gradually increase V_R and for each V_R note down the value of the photo current. You would need to use the display mode switch to select between current and voltage in the digital display. Keep on decreasing the voltage till the current comes down to a low constant value.
- Move the light source to 40 cm away from the photo tube and repeat the above. This will give you the change in the photo current with the retarding voltage for a given frequency but for two different intensities.
- Repeat the above steps with the filter of smallest wavelength (460 nm). You would be producing a table like the following:

5.3.2 Calculations

- Normalize the current values by dividing them to the values of the current at $V_R = 0$. We call this the normalized photo current I_N. Plot the graph of I_N with V_R for two different filters (430 nm and 635 nm) corresponding to the distance of 25 cm in a same paper. Do the same in another paper with the data of 40 cm distance. Figure (4) shows the sample curves.

$\lambda = 635$ nm						$\lambda = 460$ nm					
25 cm			40 cm			25 cm			40 cm		
V_R (V)	I (nA)	I_N	V_R (V)	I (nA)	I_N	V_R (V)	I (nA)	I_N	V_R (V)	I (nA)	I_N
0.	-	-	0.	-	-	0.	-	-	0.	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-

Table 2: Table to see the retarding voltage vs current graph for light of different frequencies and intensities.

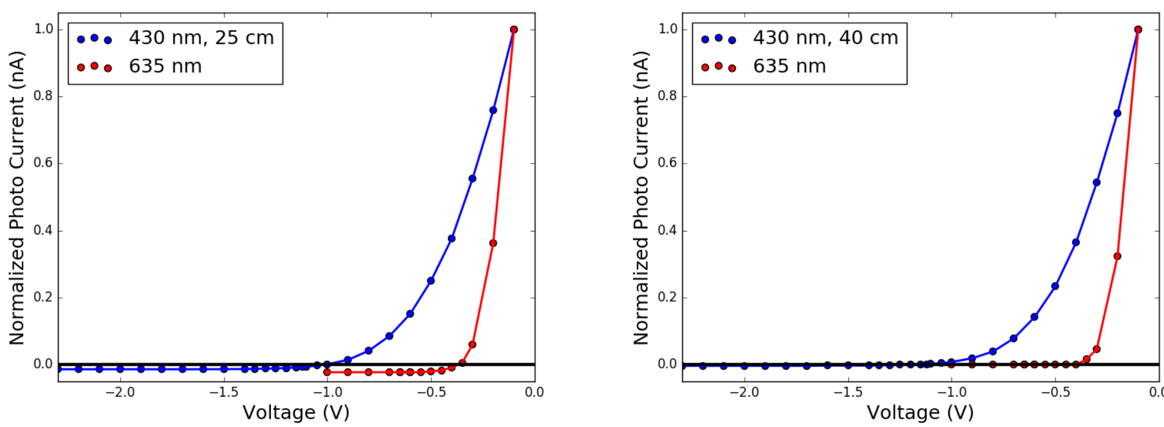

Figure 4: Variation of normalized photo current vs the retarding potential is shown for different filters and intensity.

6 Discussions and Thoughts

Here are the observations from the experiment.

- The value of the Plank constant we measure here ($h = \ [6.4 \pm 0.2] \ \times 10^{-34}$J sec) is in agreement with the standard measured value [$6.62607004 \times 10^{-34}$ J sec]. The large error bars here are due to several effects including the temperature variation, the broad wavelength width of the filters and the reverse photo current. Can you suggest some modification of the setup/experiment procedure that will reduce these errors and we can do more precise measurement ?

- The work function that we measure is also in agreement with the work function of the material that is used to coat the cathode (Cesium Antimony, 1.65 V). Learn about this material.

- We see from the Figure (4-left) and Figure (4-right) that the stopping potential for a particular filter is independent of the intensity, while depends on the filter color. This is one of the key observations that could not be explained by the Maxwells theory but could be explained by the light quantum hypothesis of Einstein.

- For the case when the distance between the source and the photo diode was 25 cm (lesser) we see a reverse photo current. This is an indication of the fact that for higher intensity, the light leaks to the anode and some photo electrons comes out of it. This is not seen when the intensity is lower as expected.