Photoelectric Effect

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September 7, 2020

CH-141-B
Group-6

Contents

Abstract

This experiment was based on the photoelectric effect which verifies the particle nature of light. The prime objective of the experiment was to calculate Plank's Constant (h) and the work-function (Φ) using different wavelengths of light produced by the photo-electrode (PbS). During the course of experiment, the produced maximum voltage by the photocell (PbS) was used to plot the graph against the frequency of spectral lines from which the planks constant and the work function were calculated. Our calculated value of Plank's constant was found to be $4.57 \pm 0.05 \cdot 10^{-34}$Js and the value of work-function was 1.286 ± 0.008 eV. The values were highly deviated from the standard value due to the malfunctioning of the equipment (probably amplifier) which was not improved until the end of the experiment. However, the experiment was conducted in a proper way.

1 Introduction and Theory

Before the approach of the quantum theory, light was considered as electromagnetic wave. Later, it was discovered that light shows both wave and particle nature. Quantum Theory describes light as a stream of discrete light quanta. Both the particle nature and the wave nature of light is described by the equation

$$E = h \cdot \nu \tag{1}$$

where h is the Plank's constant with the standard value $6.63 \cdot 10^{-34}$ kg$\cdot$ $m^2 \cdot s^{-1}$, ν is the frequency of electromagnetic radiation(light), and E is the energy associated to it.

The frequency of electromagnetic radiation is related to the wavelength as:

$$\lambda = \frac{c}{\nu} \tag{2}$$

where c is the velocity of light with value 299792458 m/s.

As the photon of light also acts as particle, it has certain momentum as well. The general formula that relates the momentum p of a particle with energy E is given by:

$$E^2 = c^2 p^2 + m_0^2 c^2 \tag{3}$$

where m_o is the rest mass of the photon.
As the rest mass of the photon is 0, the above equation becomes:

$$p = \frac{E}{c} = \frac{h \cdot \nu}{c} \tag{4}$$

The process of emission of electrons from a metal surface when striking with the light of suitable frequency is known as photoelectric effect. This property of light is not explained by wave nature. The particle nature of light posses certain characteristics that was analyzed in our experiment. The experiment showed that the emission of photo-electrons from the metal surface is independent on the intensity of the light used, rather it depends upon its frequency. During the course of experiment, we also analyzed that kinetic energy of emitted photo-electrons was also dependent upon the frequency of the light. The role of intensity of light was just to increase the number of emitted electrons if the light's frequency was high enough. One should not think that electrons is emitted due to the accumulated energy of light waves hitting the metal surface. It is the photon with sufficient energy that ejects electrons from the metal surface overcoming its nuclear attractive force within the atoms. This is the concept that verifies the particle nature of light.

The kinetic energy of the emitted electrons from metal surface when stroked with the light of suitable frequency is given by the Einstein's equation:

$$\frac{1}{2} \cdot m_e v^2 = h\nu - \Phi \tag{5}$$

where m_e is the mass of electron with value $9.12 \cdot 10^{-31}$kg and v is the velocity of the emitted electron.

Here, the work function Φ denotes the electron-binding force of a material. If a metal has high value of work function then it denotes that it's electron-binding force is strong enough and high energy is required to ionize such metal. Thus, it can also be concluded that photoelectric effect can also be used to quantify the ionization of metals. The value of Φ of materials are several eV. Einstein was the first person to discover this effect for which he was awarded with Nobel Prize, one of the most prestigious award in the field of science.

We used a photocell consisting PbS photo-cathode in the experiment. The literature value of the work function of the used photocell was 2 eV. The cathode of the photocell also consisted light-protected anode in order to collect the emitted photo-electrons. When the photons with sufficient energy hit the metal surface, electrons were ejected and were accumulated it the anode. The accumulated electrons started producing electric field due to the charge of the electron. As long as the kinetic energy of the emitted electron was strong enough to over come the electric field, they were able to reach the anode which further increased the electric field in the opposite direction. However, at some point, maximum electric field was produced by the accumulated electron at anode which repelled the electron and stopped them from reaching the anode. Thus, maximum potential U_{max} equal to the kinetic energy of the emitted electrons was established as:

$$e \cdot U_{max} = \frac{1}{2} m_e v^2 \tag{6}$$

where e is the charge of an electron with value $1.60 \cdot 10^{-19}$C.

From the above equation (5) and (6) we get:

$$e \cdot U_{max} = h\nu - \Phi \tag{7}$$

A linear relation between voltage U_{max} and the light frequency ν can drawn as:

$$U_{max} = \frac{h}{e} \cdot \nu - \frac{\Phi}{e} \tag{8}$$

where Φ is assumed to be independent of frequency.

In order to illuminate the photocell, a mercury high-pressure lamp as source of light was used in the experiment. The different wavelengths emitted by the light due to the electronic-transition in the mercury atom is shown below in the table.

Wavelength [nm]	Color
365.0	UV I
365.5	UV II
366.3	UV III
404.7	UV IV
435.8	Violet
546.1	Green
577.0	Yellow I
579.1	Yellow II

Table 1: Wavelengths of spectral lines obtained from Mercury lamp

Here, individual lines can be used for the investigation to analyze the dependence of photoelectric effect on the wavelength of light. Moreover, Plank's constant can be determined from the slope of the line constructed between U_{max} in Volt and the frequency ν in Hz.

In the experiment, diffraction grating was used to to separate the spectral lines of the mercury lamp. As a known fact, such diffraction grating diffracts the lights of shorter wavelengths at shorter angles whereas longer wavelengths at bigger angles. Although the diffraction grating separates the wavelengths of each color of light, it is very difficult to distinguish the individual wavelengths that are differed by smaller values such as UV lines I-III. Thus, only the line of the highest energy was used for our calculations i.e. UV I, and Yellow I.

2 Experimental Set-up and Procedure

As shown below in the figure, the experiment was set up.

Figure 1: Experimental Setup for determining Plank's constant using Photoelectric effect

Here, the mercury vapor lamp and the photocell were located at the ends of the optical bench. The lamp was connected to its power supply and the power was provided to it. The diffraction grating was slid into its holder and mounted in the middle of the optical bench. The slit was placed close to the lamp (about 1 cm) and the lens was located about 10 cm away from the lamp in such a way that the sharp image of the slit was focused on the entrance of the photocell. The slit width was selected about 1 cm. Also, a white paper was fix above the entrance of photocell for the better adjustment of the image.

The photocell was illuminated by different wavelengths of light coming from the lamp by turning the arm of the optical bench around the joint in the middle. In order to second order diffraction of the UV lines, the values for the green and yellow lines were falsified placing a color filters in front of the entrance of the aperture with the support of an attachable clamp holder (525 nm color glass for the green spectral line and 580 nm colored glass for the yellow spectral line).

Now, it was the turn of reading the output. Therefore, the output of the photocell was connected to the amplifier and the amplifier's output was connected to the Cassy sensor. To get the reliable reading, the measuring amplifier was turned on for 10 minuter before taking the initial reading. Prior to every single measurement, the capacitor at the entrance of the amplifier was discharged and the zero point was checked while the entrance of the photocell was closed. Then after, the photocell was illuminated with the light of certain wavelength and the reading of the maximum voltage was taken from the Cassy sensor. During the course of experiment, it was also observed the slight disturbance in the wire causes fluctuation in the voltage readings. The amplifier's setting was setup as:

Electrometer: R_e >10^{13} Ω
Amplification: 10^0
Time constant: 0
Cassy = ± 3 V
Data color filter: 525 nm, max transmittance at 525 nm
Band (nm): 480...570
Data color filter: 580 nm, max transmittance at 580 nm
Band (nm): 560...630.

3 Results and Data Analysis

As per the procedure of the experiment explained above, we conducted the experiment. However, we were not able to perform the experiment exactly as mentioned in the manual. We were not able to take 5 readings of each spectral lines as there was a technical issue with the apparatus and it was not giving the exact value as it should be. Thus, we took the reading of voltages for each spectral lines individually for three different attempts. As per the experiment conducted and the values we obtained, the type of spectral line, it's corresponding wavelength (λ), frequency (ν), including the maximum voltage U_{max} is shown below.

Spectral lines	Wavelength (λ) [nm]	Frequency (ν)[Hz]	U_{max} [V] (first attempt)	U_{max} [V] (second attempt)	U_{max} [V] (third attempt)
UV I	365.00	$8.22*10^{14}$	1.02	1.06	1.12
UV IV	404.70	$7.41*10^{14}$	0.74	0.79	0.86
Violet	435.8	$6.88*10^{14}$	0.67	0.70	0.77
Green	546.1	$5.49*10^{14}$	0.20	0.25	0.31
Yellow I	577.0	$5.20*10^{14}$	0.20	0.21	0.25

Table 2: Wavelength of spectral lines, its corresponding frequency, and maximum voltage produced

According to the results obtained in the table, a graph of maximum voltage produced as a function of frequency was drawn, which is shown below.

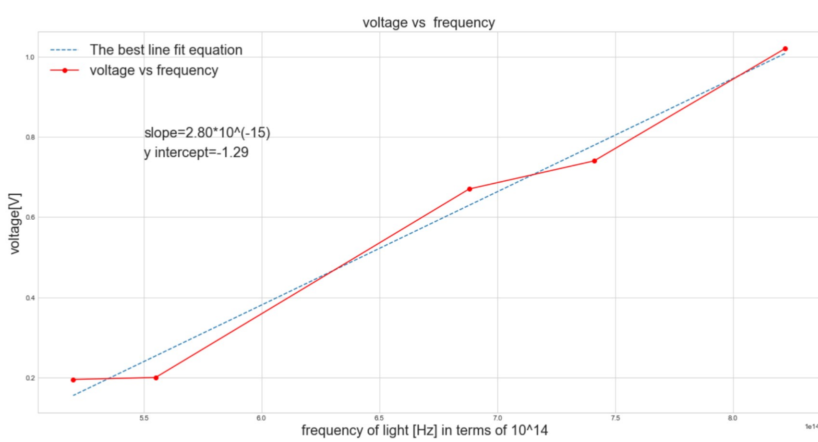

Figure 2: Graph of U_{max} as a function of frequency for the first attempt

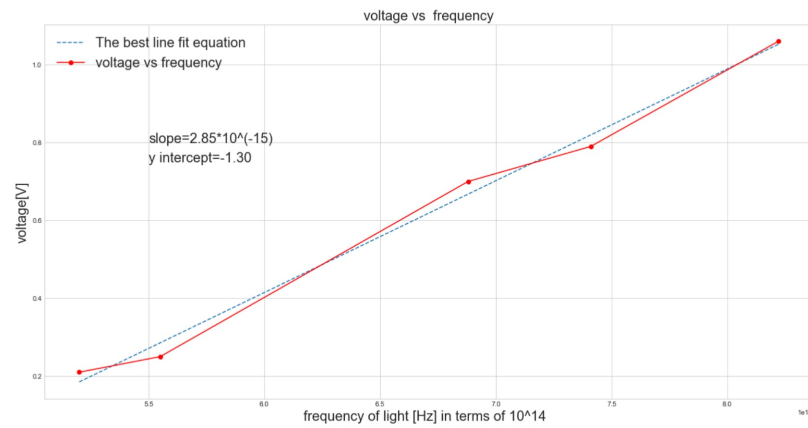

Figure 3: Graph of U_{max} as a function of frequency for the second attempt

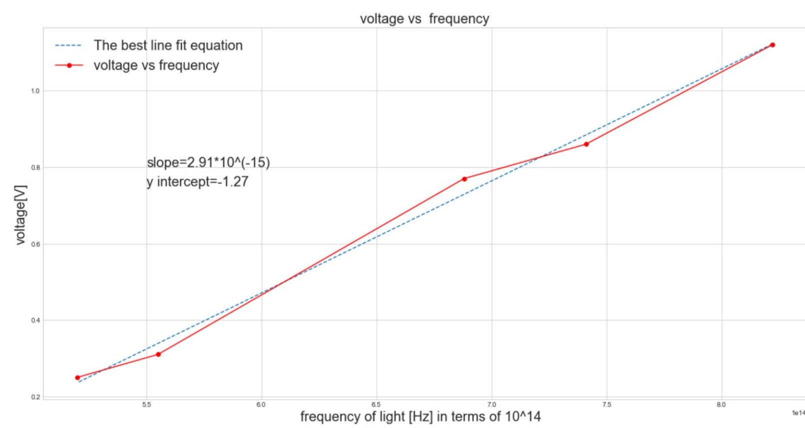

Figure 4: Graph of U_{max} as a function of frequency for the third attempt

The slope of the best line of fit found in the first experiment was $2.80 \cdot 10^{-15}$ V Hz^{-1}, in the second experiment was $2.85 \cdot 10^{-15}$ V Hz^{-1}, and in the third experiment was $2.91 \cdot 10^{-15}$ V Hz^{-1}.

In the first attempt of the experiment, the value of R_1 was found to be 0.99. So, error in slope:

$$\Delta m_1 = m \cdot \sqrt{\frac{1}{n-2} \cdot \frac{1-R_1^2}{R_1^2}} \tag{9}$$

where 'n' is the number of spectral lines.
Therefore,

$$\Delta m_1 = (2.8 \pm 0.126) \cdot 10^{-15} \; V \; Hz^{-1}$$

Using the above formula for calculating error in slope, we got:

$$\Delta m_2 = (2.85 \pm 0.34) \cdot 10^{-15}\ V\ Hz^{-1}$$

$$\Delta m_3 = (2.91 \pm 0.17) \cdot 10^{-15}\ V\ Hz^{-1}$$

The mean of the slope was calculated as 2.85$\cdot$ 10^{-15} and the standard deviation(S.D) for the slope was calculated to be 0.055.
Therefore,

$$Error\ in\ Slopes = \frac{S.D.}{\sqrt{n}} \tag{10}$$

$$= 0.031\ V\ Hz^{-1}$$

Therefore,

$$Slope\, with\, error\ = (2.85 \pm 0.031) \cdot 10^{-15}\ V\ Hz^{-1}$$

After proper calculation of the slope along with error analysis, we also came to evaluate the Y-intercepts of the three different graphs which was found to be 1.29 V, 1.30 V, 1.27 V for the first, second, and third graph respectively. The mean of the Y-intercepts was calculated to be -1.286 V.

Now, again using the formula as in equation (9), the margin of error for the Y-intercept was also found to be 0.008.
Therefore,

$$Y - intercept\, with\, error = (-1.286 \pm 0.008)\ V$$

Now, the equation of the best line of fit from our all of the calculation was found to be:

$$y = (2.85 \cdot 10^{-15} x - 1.286)\ V$$

Comparing it with equation:

$$U_{max} = \frac{h}{e} \cdot \nu - \frac{\Phi}{e}$$

we get,

$$\frac{h}{e} = (2.85 \cdot 10^{-15})\, V Hz^{-1}$$

Therefore,

$$h = 4.57 \cdot 10^{-34}\ kg\, m^2\ s^{-2}$$

For error in h,

$$\frac{\Delta h}{h} = \frac{\Delta e}{e} + \frac{\Delta m}{m}$$

As $\frac{\Delta e}{e} = 0$;

$$\Delta h = 0.05 \cdot 10^{-34} J\ s$$

Therefore,

$$h\,with\,error = (4.57 \pm 0.05) \cdot 10^{-34} J\,s$$

In the same way as we perform the calculation for h, we calculated everything for Φ.

$$\frac{\Phi}{e} = 1.286\,V$$

Therefore;

$$\Phi = 1.286\,eV$$

$$\Phi\,with\,error = (1.286 \pm 0.008)\,eV$$

Thus,
Planck's constant was found to be (4.57 ± 0.05) $\cdot 10^{-34}$ **J s**
Work function was found to be (1.286 ± 0.008) eV

4 Error Analysis

The mathematical error has been already discussed in the results and data analysis. Although, we used diffraction grating, we were not able to distinguish between individual UV- lines I,II and III as well as for yellow I and yellow II. So, the line with lowest wavelength (i.e highest energy)was used which is a possible source of error. Although the experiment was performed around 20 times, the experimental value of slope and y intercept of best line fit was way off from the literature value, which eventually altered the plank's constant and work function of PbS. Even the replacement of devices like photocell , amplifier, different cables, and Cassy did not work. It was assumed that there can be different sources of error such as ongoing experiment on the same building or near to our experimental room which might have created the electric field and altered the measurement of voltage in our Cassy, malfunctioning of the capacitor inside the amplifier, and so on. It was also difficult for us to note the stable maximum voltage as the Cassy was fluctuating randomly.

Although, we were not satisfied with the data from the readings, we used the best 3 readings to find the respective equation from the slope. The error in slope was found to be $0.126\cdot 10^{-15}$ V Hz^{-1}, $0.34\cdot 10^{-15}$ V Hz^{-1}, and $0.17\cdot 10^{-15}$ V Hz^{-1} in m_1,m_2, and m_3 respectively. The error was found to be $0.03\cdot 10^{-15}$ V and 0.008 V in mean slope and y intercept respectively. After all calculation, the error in plank's constant was found to be 0.05 J s and 0.008 eV for work function.

5 Discussion and Conclusion

The objective of this experiment was to measure the Plank's constant h and work function of photo cathode PbS from measurement of photoelectric voltage, which was found out to be $(4.57\pm 0.05) \cdot 10^{-34}$J s and 1.268 ± 0.008 eV respectively. The experimental value was way off from the literature value $6.62607004\cdot 10^{-34}$ J s for Plank's constant and few eVs for the work function Φ respectively. The experiment could have given proper result within the range of literature value if the experimental setup was performed with internal wiring system or use of advanced wiring system as movement of wire might have altered the readings in Cassy. Also, if the experiment was performed in a darker room with no external sources of light, the experimental value could be slightly better. If the equipment used was able to measure more stable value of maximum voltage, it would have improved the result.

From this experiment, it can be concluded that the exposure of light with enough energy which leads to collision with a material would eventually eject electrons from PbS surface. This was experimentally proved as stable potential difference was observed in the electrodes between anode and cathode. It equally suggests the particle nature of light. This phenomenon was used to determine the Plank's constant$h$ and the work function (Φ) of PbS surface.

6 References

- Modern Physics Lab Manual CH-141-B fall 2020 (Prof. Dr. Jürgen Fritz and Dr. Vladislav Jovanov).
- Error analysis booklet for physics teaching lab at Jacobs university
- University Physics by Young and Freedman