The Photoelectric Effect

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Abstract

The photoelectric effect is a phenomenon that illustrate particle property of light and can help determine a value of Planck's constant. As a metal plate located in a circuit is exposed to a monochromatic light for different wavelengths, a photoelectron in the metal plate is emitted. Then an electric potential can be applied to the recieving electrode in the circuit. According to Einstein's equation for the photoelectric effect, Plank's constant could be obtained as a slope by measuring kinetic energy which emitted electrons have for different frequencies of the incident light. Planck's constant could be experimentaly determined as $4.948 \cdot 10^{-34} Js$. The kinetic energy seemed dependent of intensity of the light, but it should not according to quantum mechanical theory.

Quantum Physics
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1 Introduction

In the 20^{th} century, Max Planck introduced that thermal radiation is quantitized in his explanation of blackbody radiation. This is absolutely nonsense to classical physics. A few years after, Einstein developed Planck's idea and explained that light is composed of packages of particles - photons. Einstein explained his idea of the photon with the photoelectric effect and equation $hf = E_{kinetic} + W$.

Actually, the photoelectric effect was observed for the first time in 1887 by Hertz. He observed that metal surface which were exposed to ultraviolet light emitted radiation. In 1888 Hallwachs observed that radiation which were emitted from a metal plate had negative charge and J.J. Thomson figured out in 1899 the emitted radiation were beams of electrons - photoelectrons. In 1902, Lenard found that electrons that are emitted from a metal plate irradiated by light have kinetic energy and that the maximum kinetic energy of the photoelectrons is independent of the intensity of the light. Lenard also found out that the maximum kinetic energy is instead determined by light frequency. [1]

How can it be explained that the kinetic energy of an emitted electron is dependent on frequency, not intensity? Einstein explained that the maximum kinetic energy is determined by light frequency by suggesting that light exist as 'light quanta' - packages of particles, photon, and that each photon carries a discrete energy. He suggested that the maximum energy of emitted electrons is linearly proportional to the frequency of the incident light and that the proportionality constants equals 'Plank's constant'. However, Millikan believed it was wrong because he thought light only exhibits wave properties. He devised an experiment to testify that Einstein's suggestion was wrong. However, his experiment confirmed Einstein's predictions in all points. In this experiment, we conduct a modified laboratory work of Millikan's to test and understand Einstein's explanation and also determine Planck's constant by measuring stopping voltages for different wavelengths.
In this practical experiment, the task is to reproduce a modified version of Millikans experiment in order to test and comprehend Einstein's explanation of the photoelectric effect and determine Planck's constant.

2 Theory

2.1 The Photoelectric Effect

The photoelectric effect is a phenomenon that can illustrate the particle property of light. When a light particle carrying a higher energy than the work function of a metal hits the metal surface, an electron in the metal can be emitted.
The kinetic energy the electron gets when emitted depends on the light that hits it can be described as

$$hf = E_k + W \tag{1}$$

where h is Planck's constant, E_k is the kinetic energy of the electron, f is the frequency of the light and W is the work function. The work function describes the energy necessary for the electron to leave the material. Here hf is the energy the photon has when it hits the electron. Either all of this energy is transmitted or nothing is. Each photon can only hit and transfer its energy to one electron, not to the metal plate as a whole.
The relationship between the wavelength of the light and its frequency is

$$f = \frac{c}{\lambda}, \tag{2}$$

where c is the speed of light in vacuum and λ is the wavelength.

According to the classical view of light as a wave, the energy of a photoelectron should be proportional to the intensity but show no frequency dependency.

3 Method

3.1 Conceptual Method

As seen in figure 1 below, a metal plate which is placed in electric circuit emits electrons when light particles - photons - reach the metal plate. The electrons that are emitted from the metal plate, the cathode, pass to the opposite electrode, the anode, through vacuum and electrons go through the circuit, creating a current.

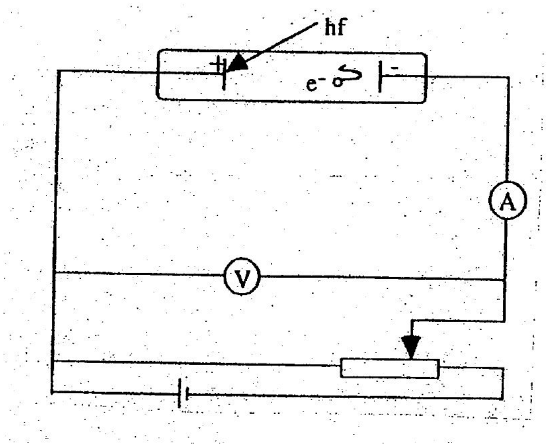

Figure 1 – A schematic circuit for experiment of the photoelectric effect. The emitted electrons produce electric current when photons in the light hit the cathode

The anode will repell the electrons since they both have a negative charge. By increasing the potential at the anode so that the electrons just barely stop before they reach the surface. The kinetic energy of the electron is

$$E_k = eU_{stop} \tag{3}$$

where e is the electron charge and U_{stop} is the stopping voltage. Using equation 1 and equation 3, the equation for U_{stop} becomes

$$eU_{stop} = hf - W. \tag{4}$$

h, e and W are considered to be constant, so if we compare equation 4 to the linear equation

$$y = kx - m. \tag{5}$$

where k is the slope and m is the intercept then equation 4 is seen to be linear as well. This means that Planck's constant, h, can be derived from the slope of the plotted data if, $k = h$. According to Einstein's theory eU is not depended of intensity, thus, if plotted, predicts a flat line with zero slope. The classical view suggest eU should be proportional to intensity and a plot of eU as a function of intensity should give rise to a straight line with some non-zero slope.

3.2 Equipment

With the use of a halogen lamp with maximum voltage of 12 V and maximum current of $4A$ the slit opening of a monochromator is irradiated. The light that enter the monochromator is reflected on a mirror to a continuous spectrum, since the grating can be rotated, only a narrow interval of wavelengths between $400 - 550$ nm is able to pass through the exit slit. A schematic view of the monocromator can be seen in figure 2.

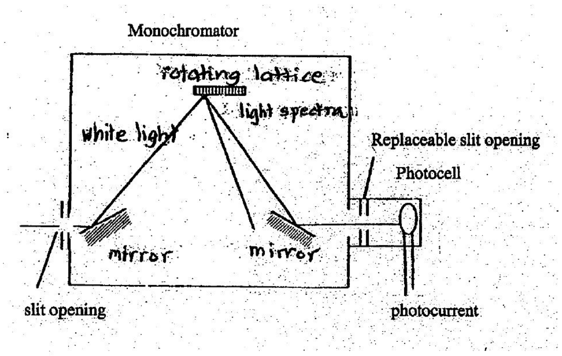

Figure 2 – A principal sketch of the monochromator.

After exiting the exit slit the monochromatic light hits the potassium cathode in the photocell, thus creating a photoelectric current, that is amplified by an amplifier. A battery connected to a potentiometer creates a retarding voltage, which is acting between the anode and the cathode, whose magnitude can be adjusted. The experimental set-up of the experiment, except the light source and the monochromator, can be seen in figure 3.

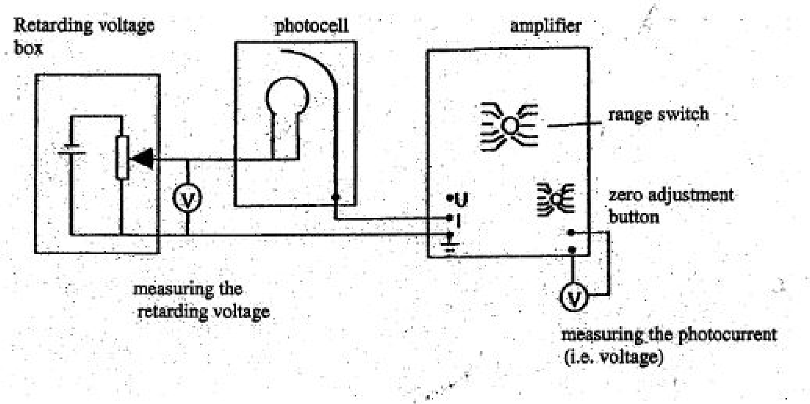

Figure 3 – A schematic figure of the setup for the experiment.

3.3 Procedure

3.3.1 Measuring Stopping Voltage

By changing the wavelength from 400 nm to 550 nm and keeping the intensity constant and then measure the voltage in the circuit, a retarding voltage, U_{stop}, could be applied to set the current in the curcuit zero. Thus changing the frequency from higher to lower. To ensure a stable measurement let the light source heat up and stabilize. Between each measurement the light were blocked so it wouldn't heat the photocell since the workfunction varies with temperature which would cause deviations from other measurements.

3.3.2 Measuring Light Intensity

In order to determine if the kinetic energy is dependent of the light intensity, the intensity of the light were changed. This was done by changing the current(3A, 3.5A 4A) supplied to the lamp and thus changing the intensity of the light it emitted. By plotting the results against the retarding voltage required to barely stop the electrons. This will give a relation between the two and it should not change with the intensity.

4 Results

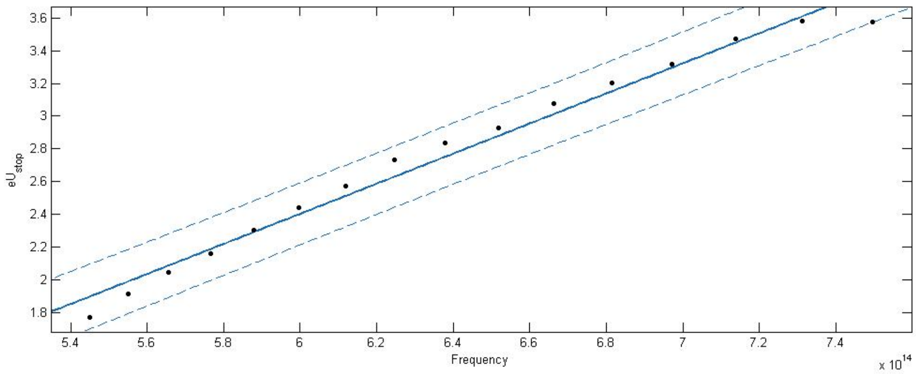

Figure 4 – The first measurement of eU_{stop} vs the corresponding frequency of the light. A linear fit of the data was created by using Matlab.

By observing figure, 4, we can see that it's approximatly linear with a slighty decreasling negative slope at higher frequency, and according to equation 4 we can obtain Planck's constant by looking at the slope of the plot.
This gives us the values for Planck's constant, $4.948[4.558, 5.338]10^{-34}$. This is not too far away from the Planck's constant is $6.626 \cdot 10^{-34}$ [2]. Possible reasons for not getting a closer value are mentioned in the discussion.

The data obtained from the experiments is attached in the appendix, table 1. Since there was no major deviation between the two measurements only the results of the first measurement were used.

Changing the intensity of the light caused U_{stop} and thereby the kinetic energy to change. According to Einstein this should not happen.

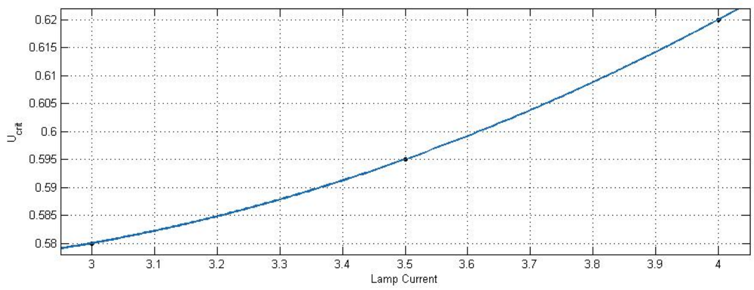

Figure 5 – A measurement of U_{stop} (called U_{crit} in the graph) depending on what current the light source has.

We believe the changes to E_K are caused by the monochromator not being precise enough to handle small changes in the intensity and changes the wavelengths enough to create a faulty measurement.

According to figure 4 and equation 3 we can clearly see that if the frequency changes so does the kinetic energy of the electron. This is in agreement with Einsteins theory.

5 Discussion

Possible reasons for not getting a closer value of Planck's constant might be that the light from the monochromator wasn't a single wavelength but many. Also the photocell were heated by the light and therefore making it easier for it to emit electrons. Thus introducing errors in the measured values. This is especially noticeable in fig.4 where the derivative seems to be decreasing instead of staying constant. When reading the circuit current, it was hard to see when it actually

were $0A$ because of oscillations between 0.0000 and 0.0001 on the display. The measurement tool were to precise so a better shielding of the circuit might remove small fluctuation that caused the oscillations.

Also, we assume that metal plate has regular and steady work function on its surface. However, that is the ideal case. In terms of real metal, the energy that is needed for electron outbounding is irregular by position or imperfection of the metal surface or structure. [3]

6 Reference

References

[1] Raymond Serway, Clement J. Moses, Curt A. Moyer, Modern Physics (Brooks/Cole, 2005)

[2] Carl Nordling, Jonny Österman, Physics Handbook

[3] Estimation of the absolute values of cohesion energies of pure metals, $http : //wwwold.kfki.hu/anyagokvilaga/tartalom/2001/jul/kaptay_csicsovszki_yaghmaee.htm$, Accessed 2014-03-29, G.Kaptay, G.Csicsovszki, M.S.Yaghmaee, University of Miskolc

7 Appendix

Wavelength $[nm]$	First measurement U_{crit} $[V]$	Second measurement U_{crit} $[V]$
400	1.200	1.211
410	1.202	1.225
420	1.166	1.152
430	1.114	1.114
440	1.076	1.076
450	1.033	1.034
460	0.983	0.984
470	0.952	0.955
480	0.917	0.917
490	0.863	0.872
500	0.819	0.826
510	0.774	0.784
520	0.725	0.727
530	0.687	0.688
540	0.642	0.646
550	0.595	0.596

Table 1 – The data obtained from the measurements

Lamp settings	U_{crit} $[V]$
$3A$, $8V$	0.580
$3.5A$, $8V$	0.595
$4A$, $8V$	0.620

Table 2 – Measurements of U_{crit} (called U_{crit} in the report) when light intensity is changed