Photoelectric Effect Experiment

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1 Introduction

In this experiment, the particle properties of light will be investigated and Einstein's theory of light will be compared with Maxwell's theory of Light.

2 Theory

Historically Coulomb suggested that there are charged particles and they apply force to each other which is inversely proportional to the distance between them. Fundamentally the main problem of the electromagnetic theory is solving the charge configuration according to the Coulomb's suggestion, what happens if the particles are in motion relative to each other? Experiments also suggested that there is also a field called the magnetic field. Lorenz, Faraday, and many others tried to figure out the relationship between these fields. The electric and magnetic fields turned out to be interdependent and these dependencies essentially boil down to four equations which are now called Maxwell's equations. The disturbance of the electromagnetic field travels at a finite speed according to Maxwell's equation and the wave itself carries momentum and energy. The energy of this electromagnetic wave is proportional to the electric field's amplitude.

Before attributing particle properties to light, it must be stated that Einstein's theory of special relativity pointed out the inter-dependency between space and time by removing the concept of the Galilean reference frame in which the Galilean transformations are being used while changing the reference frames. Doing such revealed the fact that electricity and magnetism are essentially the same phenomena manifesting themselves differently in different frames of reference.

The quantization idea was first proposed by Planck to explain the black-body radiation[2]. Classical electromagnetism's predictions on the black-body radiation stated that the emission in the ultra-violent region of the spectrum would increase. But in reality, after a peak, it decreases. To make a fit with the data Planck changed the formula of black-body slightly by assuming that the energy is transferred in discreet units instead of continuous.

Classical electromagnetism's explanation of the photoelectric effect is again predicted something that contradicts the experiment. In the experiment, a voltage difference between metal surfaces is applied and one of the metal surfaces is illuminated by a light source. Since light carries energy after the electrons on the metal surface absorb the energy, they become unbounded from the surface and go to the other metal plate thus completing the circuit and a current has been observed. Maxwell's electromagnetic theory states that for electrons to be unbounded, energy must be accumulated so there is a time lag between the light being turned on and the observation of a current. This process is frequency independent. In reality, however sometimes, depending on the frequency or color of the light, no current is observed. To overcome the problem, inspired by Planck's proposition of discreetness, Einstein proposed that light consists of photons each of which carries energy as follows

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

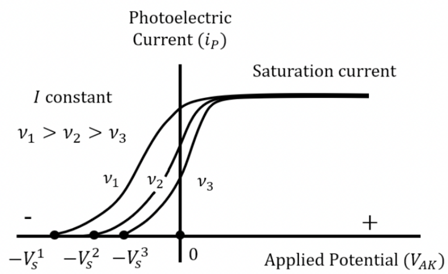


Figure 1: Current vs Voltage for different frequency, ν

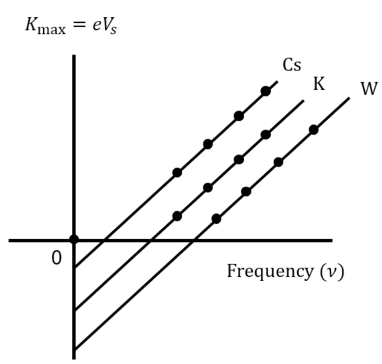
Where h is Planck's constant, ν is the frequency of light. To observe the emission, the frequency of the light source must be bigger than the cutoff frequency, which is the minimum frequency to observe current. At this moment a retreat must be made and the Schrödinger's equation must be remembered. An electron in an atom can only attain discreet energy values and those are the eigenvalues of the Hamiltonian operator, $\hat{H}$. So observing no current at some frequencies points out that the energy that has been sent is not enough for an electron on the metal surface to exhibit a transition.

Finally, in this experiment, the kinetic energy of the electrons will be determined by stopping potential V_s. It corresponds to the potential value where no current in the photoelectric circuit is observed (see fig.1). The relationship is as follows[2]

$$eV_s = \frac{1}{2}mv_{max}^2 = K_{max} \tag{2}$$

Finding the stopping potential for a metal surface, and applying light with different frequencies would yield a linear relationship. Calculating the slope of this graph would yield us the Planck's constant h, and the point where the line intersects the x-axis would give us the cutoff frequency, thus the work-function, the minimum required energy to eject electrons, ϕ is

$$\phi = \nu_0 h \tag{3}$$



So the emission of electrons from the metal surface is not possible if $\nu < \nu_0$. Thus the kinetic energy of an electron can be stated as

$$K_{max} = h\nu - \phi \tag{4}$$

3 Experimental Setup

As stated previously, the setup of this experiment consist of a metal plate inside photo-tube, a light source, voltage source and a current meter. The scheme can be seen below.

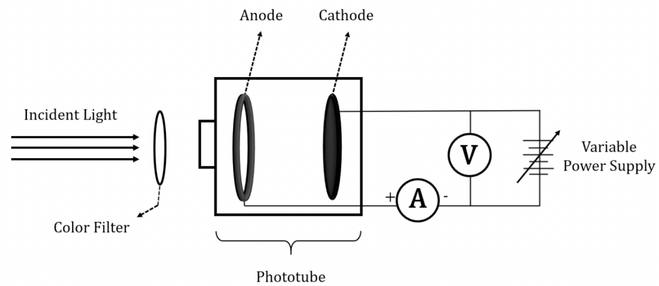
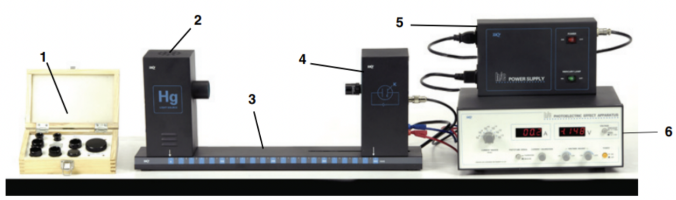


Photo-tube consists of anode and cathode plates which is a cesium antimonide photocathode surface with a low work function. But the metal surface has rather low uniformity so the work function that is being observed is not sharp. An error of 10 % is expected. Also, the ring shape of the anode provides the incident light's angle to the normal nearly zero, thus when electrons are scattered, most of them would reach the anode.

As a light source mercury lamp is used since it has a wide range of spectral emission range. Incident light is sent through a tube and a wavelength filter is attached to the end.

Actual setup of the experiment can be found below



1. Optical filters, apertures and caps for windows
2. Mercury arc lamp enclosure
3. Base
4. Photo-tube enclosure
5. Power supply
6. Photoelectric Effect apparatus

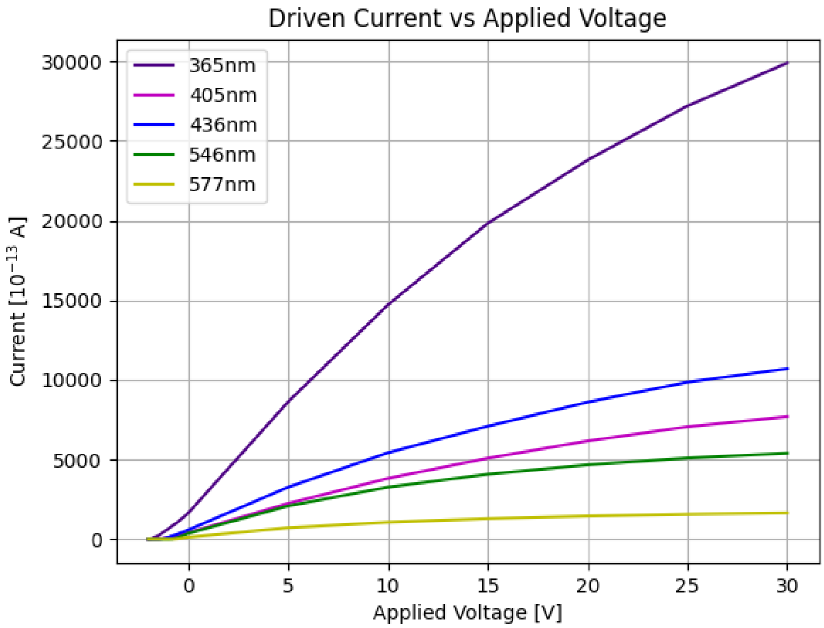
4 Measurements

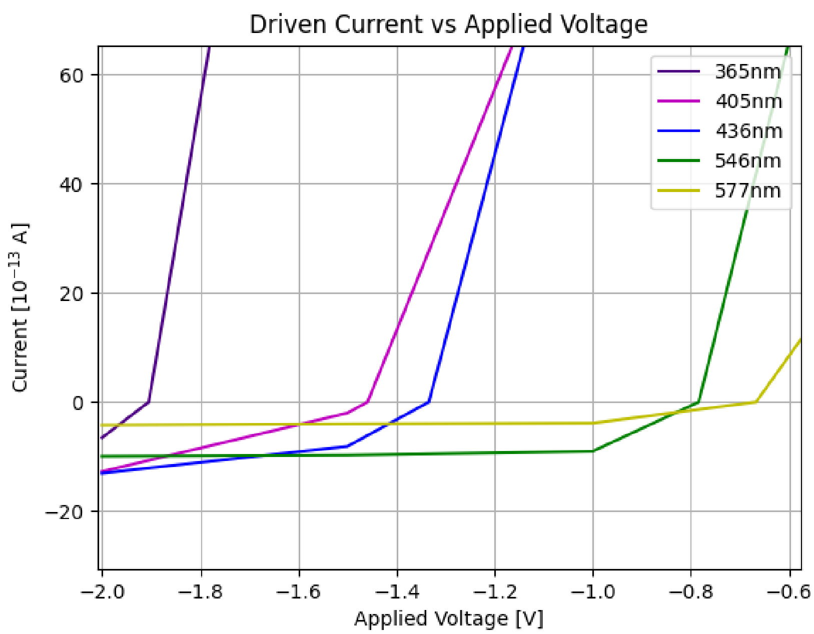
Aperature Size = 4mm									
365nm		405nm		436nm		546nm		577nm	
V	I ($10^{-13}A$)	V	I ($10^{-13}A$)	V	I ($10^{-13}A$)	V	I ($10^{-13}A$)	V	I ($10^{-13}A$)
-1.905	0.0	-1.459	0.0	-1.334	0.0	-0.784	0.0	-0.667	0.0
-2	-6.5	-2	-12.7	-2	-13	-2	-9.9	-2	-4.2
-1.5	213	-1.5	-2	-1.5	-8.1	-1.5	-9.7	-1.5	-4.0
-1	643	-1	101.5	-1	112.8	-1	-9.0	-1	-3.85
-0.5	1095	-0.5	240	-0.5	330	-0.5	101.6	-0.5	21
0	1630	0	395	0	574	0	359	0	120.3
5	8620	5	2240	5	3260	5	2080	5	710
10	14710	10	3810	10	5420	10	3260	10	1056
15	19830	15	5080	15	7085	15	4070	15	1282
20	23800	20	6160	20	8600	20	4660	20	1444
25	27200	25	7050	25	9850	25	5090	25	1560
30	29900	30	7690	30	10700	30	5390	30	1640

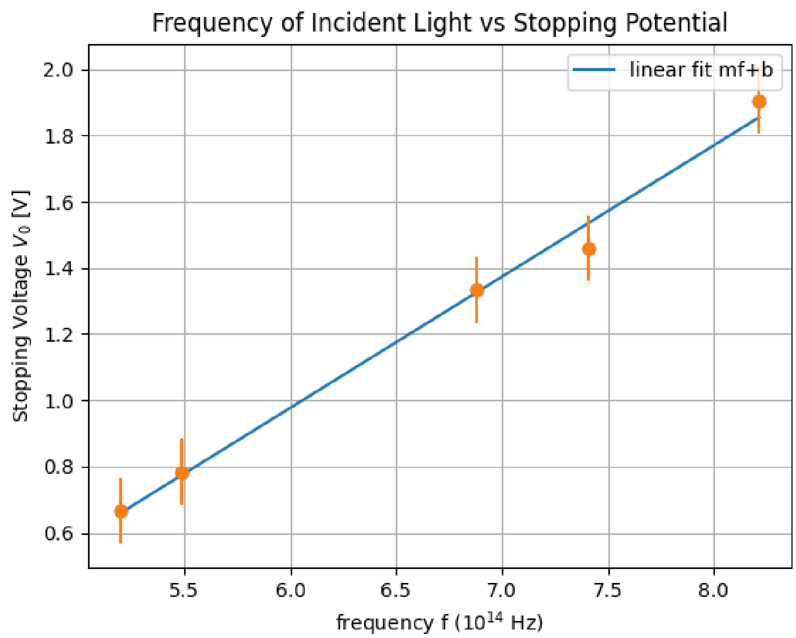
Table 1: Voltage vs Current data for constant optical apperature and three different wavelength filter

λ nm	365	405	436	546	577
f (10^{14} Hz)	8.214	7.408	6.879	5.490	5.196
V_0 (V)	1.905	1.459	1.334	0.784	0.667

Table 2: Stopping potential vs different frequencies of light


Driven Current vs Applied Voltage
365nm
405nm
436nm
546nm
577nm
Current [10^{-13} A]
Applied Voltage [V]
30000
25000
20000
15000
10000
5000
0
0
5
10
15
20
25
30


Driven Current vs Applied Voltage
365nm
405nm
436nm
546nm
577nm
Current [10^{-13} A]
Applied Voltage [V]
60
40
20
0
−20
−2.0
−1.8
−1.6
−1.4
−1.2
−1.0
−0.8
−0.6



5 Results and Discussion

The numerical values of the linear fit of the above graph are

$$V_s = mf + b = 0.3963622f - 1.4010147 \tag{5}$$

When these numerical values are calculated, the frequency data is multiplied by a factor of 10^{14} to be consistent with SI units. Multiplying this fit, the line equation for V_s, with the numerical value of e, would yield us the expression in the eq(4).

$$K_{max} = eV_s = hf + \phi = 6.35042 \times 10^{-34}f - 2.2467 \times 10^{-19} \tag{6}$$

Thus the work function ϕ and the Planck's constant h, can be stated as

$$h = 6.35042 \times 10^{-34}\frac{J}{Hz} \tag{7}$$

$$\phi = 2.2467 \times 10^{-19}J \tag{8}$$

Comparing the value of the Planck's constant obtained above with the accepted approximate value, the percentage error is

$$\left|\frac{h_{experimental} - h_{excepted}}{h_{excepted}}\right| \times 100 = 4.160\% \tag{9}$$

It must be stated that in the theory section, Einstein's prediction of saturation current has been stated (see 1). The data, however, in its interval, did not suggest that saturation current (see 4). The obvious explanation for this case is that the light source that has been used is a Mercury lamp and it emits discreet wavelengths of light probabilistic. In other words, the transition of the electron in the Mercury atom depends on the fine structure, i.e eigenvalues of the Hamiltonian operator $\hat{H}$. Since the probability amplitude of the discreet eigenstates is different, the amplitude that has been observed from the light source of different wavelengths was different, to begin with. In the same graph, a negative current has also been observed. The reason behind this is that in each measurement, there was applied voltage that was smaller than the stopping potential. This negative potential and the ring-shaped anode in a way interchanged the role of anode and cathode and the circuit is completed in opposite direction. The modest percentage error in Planck's constant h was caused by several reasons, the measurement devices had their own uncertainties and while measuring the stopping potential, there were small fluctuations in the current meter. So random human errors were also involved. Secondly, the surface of the anode and cathode were not exactly uniform, so the work function was also non-uniform.

Overall the theory of light of Einstein's is in agreement with this experiment since a linear relationship between the kinetic energy of electrons and the frequency of light is observed. Although intensities of the light of different wavelengths were different, it did not suggest a relationship between kinetic energies of the electrons and the amplitude of light, which was suggested as an extension of Maxwell's theory of light.

6 References

1-) Rybicki & Lightman 1979, p. 22
2-) Physics 307 Lab Manual