An Investigation of the Photoelectric Effect and a Determination of h/e and the Work Function of Silver Oxide

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Abstract

We investigate the behavior of electrons in a conductor when light is incident on it's surface, and compare it to the predictions of the particle model of light introduced by Albert Einstein. By calculating the energy of a light quantum of a certain frequency and comparing that to the work an electron emitted by the conductor must do to raise itself through a potential, the energy lost to the conductor's work function is determined using the law of conservation of energy. A value for the ratio of Planck's constant to the elementary charge is obtained from the relationship between the frequency of incident light and the stopping potential required to prevent photoelectrons from reaching the opposite electrode. The relationship between the intensity of light on the conductor and the current produced from the emitted electrons is predicted and investigated.

1 Introduction

At the end of the 19th century, Maxwell showed that light is an electromagnetic wave, however this model led to some incorrect predictions about the Photoelectric Effect, where light incident on a metal gives electrons enough energy to escape the material. It was expected that electrons would be emitted irrespective of the light's frequency and that their energies would be dependent on the light's intensity, but with faint light the emission of photoelectrons would be delayed whilst the electrons absorbed enough energy to escape. However, these were contradicted by the results of experiments, which showed that in actuality the intensity did not affect the energy distribution of the resulting photoelectrons, which were always emitted instantly, but only for light above a certain threshold, otherwise none would be emitted at all. This was all explained by Einstein, who extended an idea of Planck's by postulating that light consists of small packets of energy, called photons or light quanta. [1]

The first part of this experiment will aim to show the relation between the frequency of the incident light and the maximum energy of the produced photoelectrons, as well as to obtain values for the ratio of Planck's constant to the elementary charge and for the work function of Silver Oxide.

The second part of the experiment will aim to show the effect of light intensity on the production of photoelectrons, by changing the diameter of the aperture the light passes through in order to change the number of photons incident on the AgO electrode per second.

2 Theory

Each photon in a beam of light has an energy E proportional to the light's frequency ν,

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

When light is emitted or absorbed, it behaves as a particle, so when the light hits the metal in the Photoelectric Effect, a photon is absorbed by a single electron, which gains all the energy of that photon. That electron will then be emitted only if it has gained enough energy to overcome the work function ϕ of the metal, else it will re-emit its excess energy as another photon. As a consequence, photoelectrons are only emitted when the light's frequency is above the threshold frequency, where the energy of photons of that frequency exceeds the work function,

$$h\nu \geq \phi \tag{2}$$

The excess energy not used by the photoelectrons to overcome the work function will be kinetic energy, which will vary between photoelectrons up to a maximum of

$$K_{\text{max}} = h\nu - \phi \tag{3}$$

where only the minimum energy was needed to escape. Due to the one-on-one nature of the photon-electron interactions, the intensity of the light doesn't affect the energy gained by each electron, but rather affects the rate of photoelectron emission, with higher intensities corresponding to more photons incident on a given area in a given time interval. As the current I is the motion of charge Q from one region to another,

$$I = \frac{Q}{t} \tag{4}$$

the current produced by the Photoelectric Effect will be proportional to the rate of emission of photoelectrons, which is in turn proportional to the intensity S of the light. [1]

$$I \propto S \tag{5}$$

The light will be produced by a mercury lamp, which will produce light of certain frequencies corresponding to the differences between energy levels of the mercury atoms, with one specific frequency selected each time using a filter. With the light passing through an aperture of variable size, it will be incident on a Silver Oxide (AgO) electrode within a vacuum tube, where photoelectrons can be emitted towards the Nickel (Ni) electrode opposite, then pass through a circuit as current back to the AgO electrode. Then for each frequency of light, we will determine the stopping potential V_0, which is the potential difference between the AgO and Ni electrodes required to only just stop the highest energy photoelectrons, thus preventing the flow of current. The work done on an electron to raise it through a potential is

$$W = eV \tag{6}$$

where e is the elementary charge, so at the stopping potential,

$$eV_0 = K_{\mathrm{max}} = h\nu - \phi \tag{7}$$

Plotting a graph of V_0 against ν should give a straight line

$$V_0 = \frac{h}{e}\nu - \frac{\phi}{e} \tag{8}$$

with gradient $\frac{h}{e}$ and y-intercept $\frac{\phi}{e}$.

Varying the diameter d of the aperture that the light passes through will vary the power P of light incident on the area of the electrode,

$$P = S_0 \left(\pi \frac{d^2}{4} \right) \tag{9}$$

where S_0 is the intensity of the light before passing though the aperture, thus changing the intensity of the light incident on the electrode, as the area of the electrode does not change.

3 Experimental Details

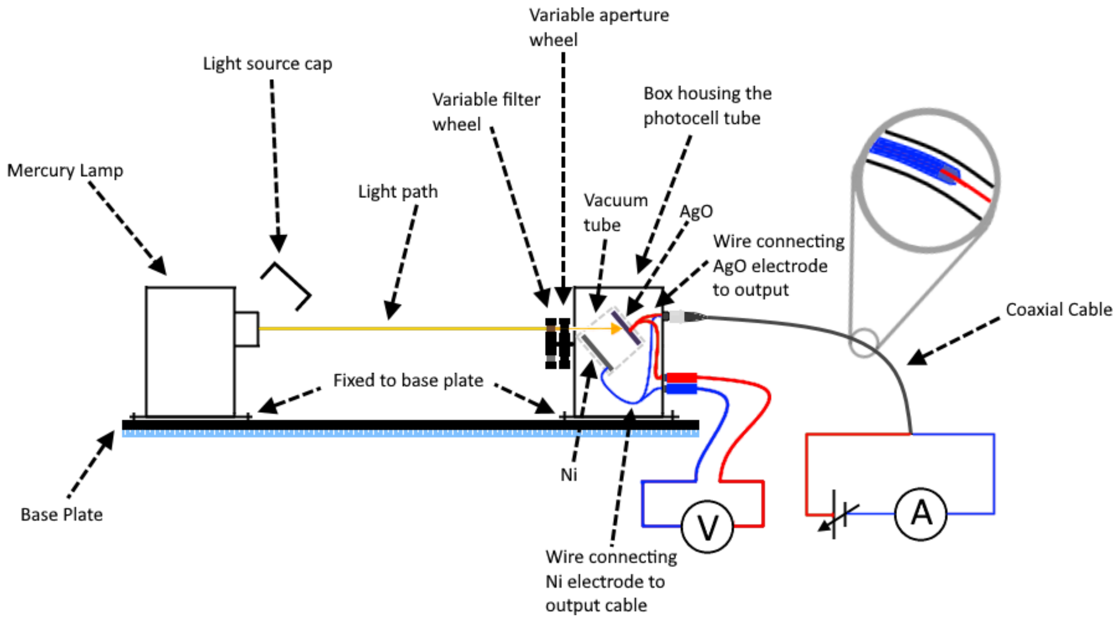

Figure 1: Schematic of experimental apparatus.

The experimental apparatus was set up as shown in Figure 1, with a mercury lamp emitting light towards the photocell's enclosure, passing through two wheels for selecting various wavelength filters and aperture sizes respectively. The enclosure provided ports internally wired to the electrodes for connecting a variable voltage power supply, voltmeter, and an ammeter. The lamp and photocell enclosures were on a track, and their position wasn't altered within each part of the experiment. The experiment was also performed in a darkened room, to minimise the light incident on the AgO electrode from other sources, and the other electrode in the photocell was made from Nickel as it has a high work function, so photoelectrons should only be generated by the mercury lamp light incident on the Silver Oxide. Finally, the lamp's cover was removed, then it was switched on and left to warm up for several minutes. Figure 2 shows the specific setup used.

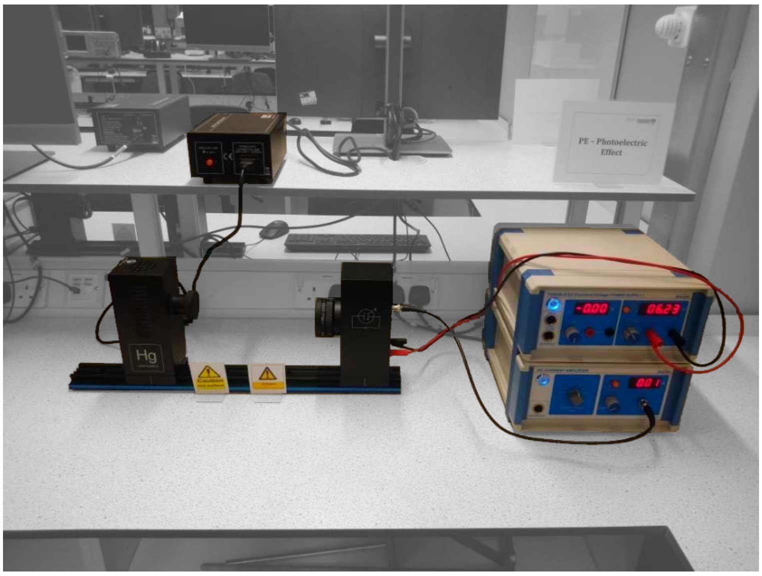

Figure 2: An edited photo of the setup, with the background desaturated.

For each of 5 different wavelengths of light emitted by the lamp, a filter was selected that encompassed that particular mercury emission line and excluded the others, allowing only that one wavelength to enter the photocell enclosure, with the 2mm diameter aperture selected. The potential across the electrodes was then varied until the current through the circuit was measured to be 0, to a precision of 10^{-13}A. Then the stopping potential was recorded as measured by the voltmeter, the wavelength filter then changed and the stopping potential measured for the next emission line. This was repeated until all 5 were done once, plus 4 additional repeats for the 365.4nm wavelength, in order to calculate an approximate uncertainty in the stopping potential from those 5 measurements that could then be used for V_0 at other wavelengths.

For the second part of the experiment, the 365.4nm wavelength filter and 2mm diameter aperture were selected, then the bias voltage of the power supply was varied until the current through the circuit was measured to be zero. The bias voltage and current readings were then both recorded. The bias voltage was then increased by between 1 and 1.5 volts, and the two readings recorded again; this was repeated until several results were obtained, at different bias voltages. Then, a set of similar measurements were taken for the 4mm diameter aperture, and then again for the 8mm setting.

4 Experimental Results and Discussion

The stopping potential V_0 obtained at each wavelength is given in Table 1, with uncertainty in stopping potential obtained from the repeats at the 365.4nm wavelength, and uncertainty in wavelength given by assuming the emission lines have a width of 0.1nm.

Table 1: Stopping Potential for each Wavelength of Light

Wavelength, λ (nm)	Stopping Potential, V_0 (V)
365.4 ± 0.05	-1.7754 ± 0.0007
404.7 ± 0.05	-1.508 ± 0.0007
435.8 ± 0.05	-1.164 ± 0.0007
546.1 ± 0.05	-0.609 ± 0.0007
577.0 ± 0.05	-0.471 ± 0.0007

Using the $\nu = c \div \lambda$ relation between the wavelength and frequency of light, the wavelengths were converted into their corresponding frequencies using the exact value of c, and the uncertainties were propagated in quadrature, which simplified to

$$\frac{\alpha_\nu}{\nu} = \frac{\alpha_\lambda}{\lambda} \quad \Rightarrow \quad \alpha_\nu = \frac{c}{\lambda^2}\alpha_\lambda \tag{10}$$

as there is no uncertainty in c. Then a graph of V_0 against ν was plotted (Figure 3) and a linear fit calculated, giving a linear correlation coefficient of $R^2 = 0.9994$ to 4sf, indicating that over 99.9% of the variance in stopping potential values is justified by the frequency values for a linear relationship, so this is a very good fit. The error bars are also very small, and hardly visible in the figure. The fit gives the value of the ratio $|\frac{h}{e}|$ as $(4.188 \pm 0.003) \times 10^{-15}$ Js C^{-1} from the gradient, and $\frac{\phi}{e} = -1.6773 \pm 0.0018$ V from the y-intercept. Using -1.60×10^{-19} as the value of e, the work function is $\phi = 1.60 \times 10^{-19} \cdot (1.6773 \pm 0.0018)$ Joules, or $\phi = 1.6773 \pm 0.0018$ eV.

$(4.188 \pm 0.003) \times 10^{-15}$ Js C^{-1} is very close to the accepted value of $|\frac{h}{e}| = 4.14 \times 10^{-15}$ Js C^{-1}, with a percentage error of 1.16% (3sf), however the difference is 16 times the uncertainty. Considering the nature of this experiment, it seems likely that there were other factors, such as external light entering the photocell enclosure, that did not remain constant, introducing extra uncertainty that was not accounted for, so the true uncertainty in this measurement is likely greater. Also, the reverse photocurrent effect, where applying a sufficiently negative potential across the electrodes can result in current flowing in the opposite direction, was not accounted for in this experiment, and would have to be investigated in order to determine what effect this may have had on the results. If this effect occurs at the stopping potentials from this experiment, then the ammeter would actually be reading zero when the reverse current balanced out the current from photoelectrons, not when the photoelectrons are all stopped by the potential, leading to the results in this experiment being greater (less negative) than the true stopping potentials.

The value of Silver Oxide's work function that was obtained, $\phi = 1.6773 \pm 0.0018$ eV, is within the uncertainty of the known value, $\phi = 1.55 \pm 0.15$ eV, so it seems to be an accurate result.

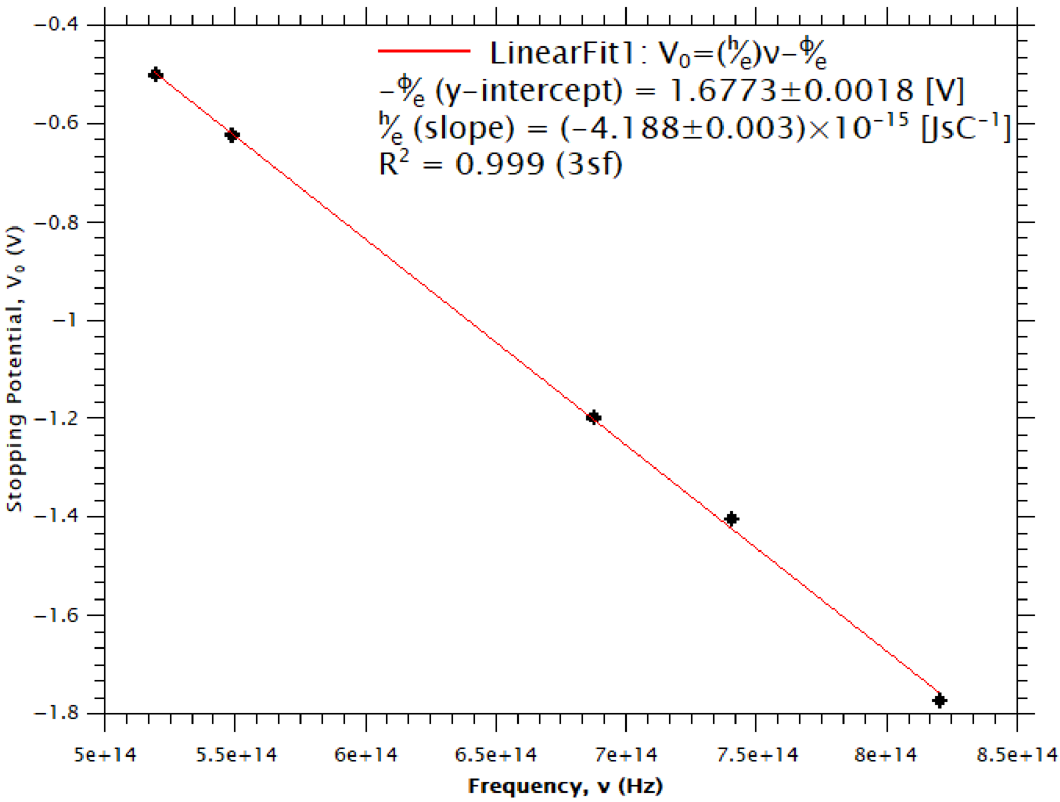

Figure 3: How stopping potential varies with frequency of incident light

For the second part, plotting I-V graphs for the different aperture diameters gave three graphs (Figures 4, 5 and 6, see Appendices) which each matched a linear fit very well ($R^2 > 0.98$ for all 3), but more closely resembled the inverse tangent function. Fitting to a custom equation of the form $y = a \arctan(bx - d) + c$ gave better R^2 values that were all in excess of 0.999, as shown in Table 2.

Table 2: Results of custom fit '$I = a \arctan(bV - d) + c$' for each I-V graph

Parameter	2mm Aperture	4mm Aperture	8mm Aperture
R^2 (4sf)	0.9991	0.9996	0.9999
a	$(9.2 \pm 0.9) \times 10^{-10}$	$(4.1 \pm 0.3) \times 10^{-9}$	$(1.35 \pm 0.08) \times 10^{-8}$
b	$(3.8 \pm 0.6) \times 10^{-1}$	$(2.8 \pm 0.3) \times 10^{-1}$	$(2.54 \pm 0.20) \times 10^{-1}$
c	$(9.0 \pm 0.4) \times 10^{-10}$	$(3.5 \pm 0.1) \times 10^{-9}$	$(1.16 \pm 0.03) \times 10^{-8}$
d	$(8.3 \pm 0.4) \times 10^{-1}$	$(7.3 \pm 0.8) \times 10^{-1}$	$(8.3 \pm 0.5) \times 10^{-1}$

As for the range of voltages used $bV - d \ll 1$, $\arctan(bV - d) \approx bV - d$, so the approximate gradient of the I-V graph is given by

$$\frac{dI}{dV} \approx ab \tag{11}$$

From Equation 11, the approximate gradients for the 2mm, 4mm and 8mm aperture I-V graphs are $(3.5 \pm 0.6) \times 10^{-10}$, $(1.15 \pm 0.15) \times 10^{-9}$ and $(3.4 \pm 0.3) \times 10^{-9}$ Amps per Volt respectively. This then gives values for the ratios between the gradients as 3.3 ± 0.7 between 2mm and 4mm; 3.0 ± 0.4 between 4mm and 8mm; and 9 ± 2 between 2mm and 8mm graph gradients.

As the current produced is expected to be proportional to the rate of photons incident on the photoelectrode, and therefore also on the power of the incident light, from Equation 9 it's expected that for a given bias voltage, the current will be proportional to the square of the aperture diameter, i.e.

$$I \propto d^2 \tag{12}$$

Therefore, the gradient of an I-V graph should also be proportional to d^2, so the expected ratios between the graph gradients would be 4 between 2mm and 4mm; 4 between 4mm and 8mm; and 16 between 2mm and 8mm. The ratios observed in this experiment were all lower, but they were all within a few multiples of their uncertainties of the expected values. Also, the ratios from 2mm to 4mm and from 4mm to 8mm were expected to be the same as each other, and the uncertainty of each obtained value was with the uncertainty of the other. Additionally, the 2mm to 8mm ratio was expected to be equal to the square of the smaller ratio, and as $3^2 = 9$ it is very close indeed. Therefore it does seem that the current produced is proportional to light intensity, as the predictions that resulted from that hypothesis seem to hold true. However, the cause of the inverse tangent relation between current and bias voltage is not clear.

5 Conclusions

From the measurements of the stopping potential for light of different wavelengths incident on a Silver Oxide electrode, a value for the ratio $|\frac{h}{e}|$ between Planck's constant h and the elemental charge e of $|\frac{h}{e}| = (4.188 \pm 0.003) \times 10^{-15}$ Js C^{-1} was obtained. Also from this, a value for the work function ϕ of Silver Oxide was determined as $\phi = 1.6773 \pm 0.0018$ eV. Then in the second part, it was shown that the current produced by a photocell is proportional to the intensity of the incident light.

Two interesting behaviours were observed, the reverse photo-current effect and a slight trigonometric relation between the bias voltage and the resulting current. Both of these are effects worth investigating further.

References

[1] Young H D, Freedman R A. *University Physics*. 14th ed. Harlow: Pearson; 2016.

A Appendices

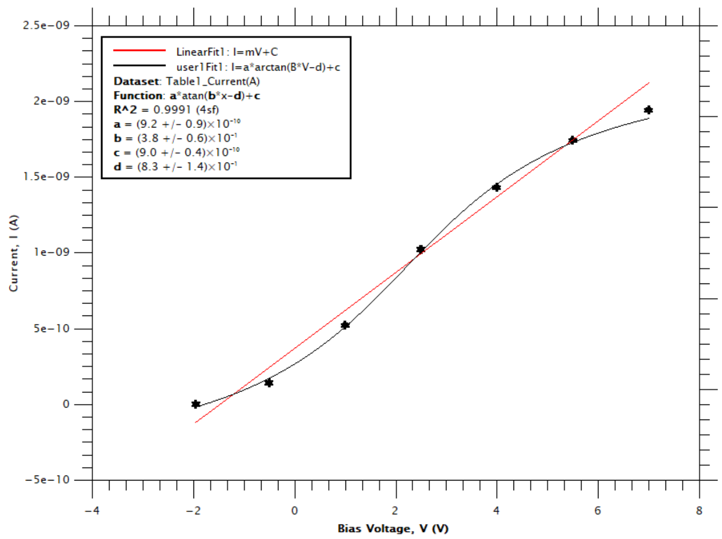

Figure 4: How Current varies with Bias Voltage for 2mm Diameter Aperture

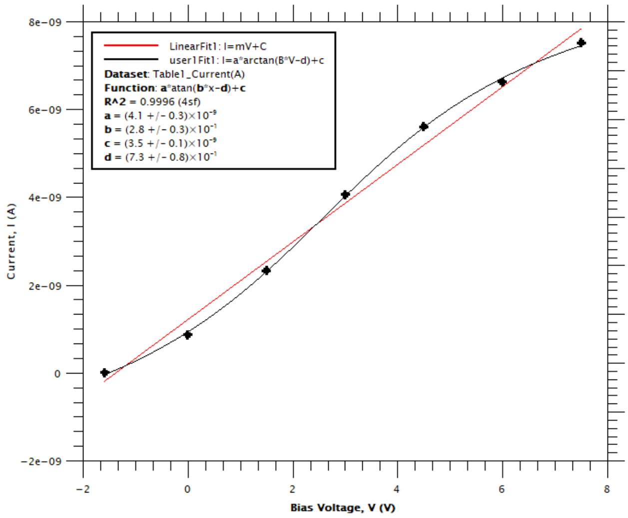

Figure 5: How Current varies with Bias Voltage for 4mm Diameter Aperture

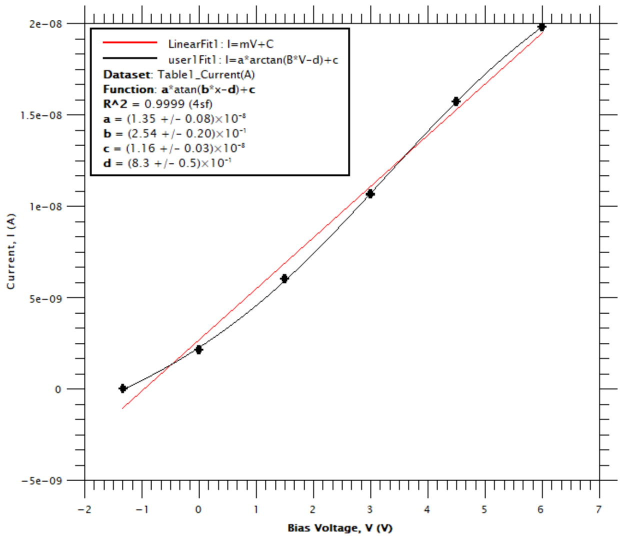

Figure 6: How Current varies with Bias Voltage for 8mm Diameter Aperture