

Overview of The Experiment of Photoelectric Effect and Determination of a Value for h , Planck's Constant

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ABSTRACT

When light is incident on certain metallic surfaces, electrons are emitted from the surface—This is called the photoelectric effect—The emitted electrons are called photoelectrons. The successful explanation which enabled the first convincing experimental verification of quantum theory had been provided by Einstein. In this article, light of a known frequency is assumed to shine upon the alkali metallic surface (potassium) acting as the photocathode in an evacuated tube. The photocathode is irradiated by light of approximately only one wavelength or colour (quasi-monochromatic light), and a voltage is applied between the anode (where the current is measured) and cathode so that it opposes the energy of the emitted photoelectrons. The potential energy gained (or kinetic energy lost) is eV where e is the charge of the electron and V is the potential difference or voltage between the anode and cathode. The voltage required to “just” stop the current flow V_s will thus be proportional to the maximum kinetic energy of the emitted. Indeed, the purpose of this article is to overview Einstein's theory of the photoelectric effect, and determine a value for h , Planck's constant by overview of the essential part of the experiment that served to establish the quantum theory of radiation.

Keywords: Photoelectric effect, experiment overview, Planck's constant

INTRODUCTION

During his experiments on em waves, Hertz noticed that sparks occurred more readily in the air gap of his transmitter when ultraviolet light was directed at one of the metal balls. He did not follow up this observation, but others did. They soon discovered that the cause was electrons emitted when the frequency of the light was sufficiently high. This phenomenon is known as the photoelectric effect and the emitted electrons are called photoelectrons [1],[2],[6]. It is one of the ironies of history that the same work to demonstrate that light consists of em waves also gave the first hint that this was not the whole story.

This important experiment, which provided the first convincing experimental verification of the quantum theory, was suggested by Einstein in 1905. He was later awarded the Nobel prize in 1921 for his theory. The actual phenomenon of photoemission of electrons from metals was observed by Hertz in 1887. Lenard in 1900 positively identified the liberated particles as electrons (discovered 3 years earlier by Thomson) and studied the energies and numbers (i.e. the current) of the photoelectrons as a function of the wavelength of the incident light and its intensity as best as he could with the equipment available. His results were impossible to explain using the wave theory of light (where the energy would be spread over space and time)[3],[4],[5].

Einstein postulated that not only is light emitted and absorbed in discrete but tiny bundles, as proposed by Planck, but it is propagated that way as well, flying through space like bullets. This conjecture nicely explained the photoelectric effect experiment. In this experiment, the maximum kinetic energy of the electrons leaving the surface of a metal when irradiated by quasi-monochromatic light is shown to depend upon the wavelength(or colour) of the light, and not upon the intensity of the light[7],[9]. When Einstein made his suggestion, there was not sufficient evidence to confirm or disprove his equations. Very precise measurements were subsequently made by Millikan, with the result that the theory was completely verified[6],[8].

Light contains energy. It is this energy that comes from the sun that

allows life to exist on this planet, causes weather, and drives ocean currents. Transfer of energy from light allows for photosynthesis in plants, eyesight, and photovoltaic cells. Hence, a correct description of how light interacts with matter is extremely important [3],[11]. Most importantly, the focus of this article is to verify Einstein's theory of the photoelectric effect, and determine a value for h , Planck's constant by overview of the essential part of the experiment that served to establish the quantum theory of radiation.

Overview of Photoelectric Effect

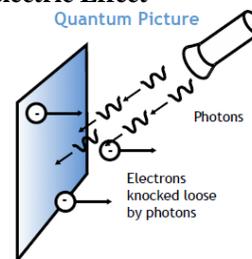


Figure 1: General Illustration Photoelectric Effect[10].

When light is incident on certain metallic surfaces, electrons are emitted from the surface—This is called the photoelectric effect—The emitted electrons are called photoelectrons. The effect was first discovered by Hertz. The successful explanation of the effect was given by Einstein in 1905—Received Nobel Prize in 1921 for paper on electromagnetic radiation, of which the photoelectric effect was a part[1],[2],[6].

I. Photoelectric Effect Schematic

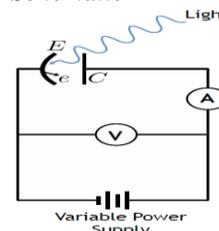


Figure 2: When light strikes E, photoelectrons are emitted.

Electrons that are collected at C and passing through the ammeter are a current in the circuit. C is maintained at a positive potential by the power supply[2].

II. Observation of the Photoelectric Effect

Figure 3 shows how the photoelectric effect was studied. An evacuated tube contains two electrodes connected to a source of variable voltage, with the metal plate whose surface is irradiated as the anode. Some of the photoelectrons that emerge from this surface have enough energy to reach the cathode despite its negative polarity, and they constitute the measured current. The slower photoelectrons are repelled before they get to the cathode[3],[6],[10]. When the voltage is increased to a certain value V_0 , of the order of several volts, no more photoelectrons arrive, as indicated by the current dropping to zero. This extinction voltage corresponds to the maximum photoelectron kinetic energy[3],[6],[11].

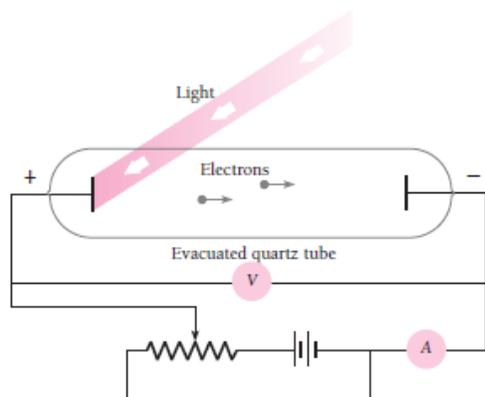


Figure 3: Experimental observation of the photoelectric effect[1].

The existence of the photoelectric effect is not surprising. After all, light waves carry energy, and some of the energy absorbed by the metal may somehow concentrate on individual electrons and reappear as their kinetic energy. The situation should be like water waves dislodging pebbles from a beach. But three experimental findings show that no such simple explanation is possible.

i) Within the limits of experimental accuracy (about 10^{-9} s), there is no time interval between the arrival of light at a metal surface and the emission of photoelectrons. However, because the energy in an em wave is supposed to be spread across the wavefronts, a period of time should elapse before an individual electron accumulates enough energy (several eV) to leave the metal. A detectable photoelectron current results when 10^{-6} W/m^2 of em energy is absorbed by a sodium surface. A layer of sodium 1 atom thick and 1 m^2 in area contains about 10^{19} atoms, so if the incident light is absorbed in the uppermost atomic layer, each atom receives energy at an average rate of 10^{-25} W . At this rate over a month would be needed for an atom to accumulate energy of the magnitude that photoelectrons from a sodium surface are observed to have[1],[2],[3].

ii) A bright light yields more photoelectrons than a dim one of the same frequency, but the electron energies remain the same. The em theory of light, on the contrary, predicts that the more intense the light, the greater the energies of the electrons[3],[11].

iii) The higher the frequency of the light, the more energy the photoelectrons have. Blue light results in faster electrons than red light. At frequencies below a certain critical frequency ν_0 , which is characteristic of each particular metal, no electrons are emitted. Above ν_0 the photoelectrons range in energy from 0 to a maximum value that increases linearly with increasing frequency. This observation, also, cannot be explained by the em theory of

light[3],[6].

III. Fundamental Theory

The three experimental observations listed above follow directly from Einstein's hypothesis. (1) Because em wave energy is concentrated in photons and not spread out, there should be no delay in the emission of photoelectrons. (2) All photons of frequency ν have the same energy, so changing the intensity of a monochromatic light beam will change the number of photoelectrons but not their energies. (3) The higher the frequency ν , the greater the photon energy $h\nu$ and so the more energy the photoelectrons have[1],[4].

What is the meaning of the critical frequency ν_0 below which no photoelectrons are emitted? There must be a minimum energy ϕ for an electron to escape from a particular metal surface or else electrons would pour out all the time. This energy is called the **work function** of the metal, and is related to ν_0 by the formula[2],[4]

$$\phi = h\nu_0 \quad (1)$$

where h is Planck's constant. The greater the work function of a metal, the more energy is needed for an electron to leave its surface, and the higher the critical frequency for photoelectric emission to occur.

To pull an electron from a metal surface generally takes about half as much energy as that needed to pull an electron from a free atom of that metal; for instance, the ionization energy of cesium is 3.9 eV compared with its work function of 1.9 eV. Since the visible spectrum extends from about 4.3 to about $7.5 \times 10^{14} \text{ Hz}$, which corresponds to quantum energies of 1.7 to 3.3 eV, it is clear from Table 1 that the photoelectric effect is a phenomenon of the visible and ultraviolet regions[3],[4].

Table1 Photoelectric Work Functions

Metal	Symbol	Work Function, eV
Cesium	Cs	1.9
potassium	K	2.2
Sodium	Na	2.3
Lithium	Li	2.5
Calcium	Ca	3.2
Copper	Cu	4.7
Silver	Ag	4.7
Platinum	Pt	6.4

According to Einstein, the photoelectric effect in a given metal should obey the equation[1],[4]

$$h\nu = KE_{max} + \phi \quad (2)$$

where $h\nu$ is the photon energy, KE_{max} is the maximum photoelectron energy (which is proportional to the stopping potential), and ϕ is the minimum energy needed for an electron to leave the metal.

In other words, the voltage required to "just" stop the current flow V_s will thus be proportional to the maximum kinetic energy of the emitted photoelectron (like a roller coaster just coming to a stop at the top of a hill; you are changing the height of the hill as you change the voltage)[1],[3],[4].

$$KE_{max} = eV_s \quad (3)$$

Making use of Planck's quantum ideas (from his description of

blackbody radiation), Einstein postulated that light consists of a stream of discrete bundles of energy, called photons. He suggested that each photon possesses an energy, E , given by[1],[2],[3]

$$E = h\nu = \frac{hc}{\lambda} \quad (4)$$

Following this assumption, the photoelectric effect is then the result of each photon transferring its entire energy to an electron in the metal. [It is possible for only part of the energy to be transferred (Compton effect) or for multiple photons to be transferred but not under these experimental conditions.] Some of the energy is used to tear the electron loose from the metal (known as the work function, ϕ), while any excess is used to give kinetic energy (motion) to the ejected electron. Using our previous results for the maximum kinetic energy and accounting for the energies[4]

$$eV_s = \frac{hc}{\lambda} - \phi \quad (5)$$

As it is already seen from table 1, the work function varies from material to material and is smallest for alkali metals (this apparatus uses potassium). We must have light such that $h\nu > \phi$ in order to see the photoelectric effect (known as the threshold frequency). The alkali metals have work functions such that the photoelectric effect is seen at the frequencies (or wavelengths) of visible light[2],[3]. For accurate results, the measurement of very small photocurrents is required. The electronics and ammeter to do this are all contained in the "Photoelectric Effect" apparatus by Daedelon Corp[3],[4].

IV. Theory of Operation

In this experiment, light of a known frequency is shone upon the alkali metallic surface (potassium) acting as the photocathode in an evacuated tube (keeps the surface clean and prevents collisions of photoelectrons with molecules in the air). Electrons are ejected from the cathode and some reach the collector producing a photoelectric current, I , as shown in Fig. 4 (with 3 "subfigures").

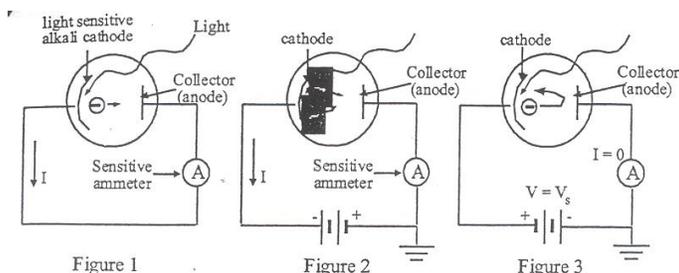


Figure 4: Showing Schematic in 3 parts[4]

The anode can be made negative (reverse bias) with respect to the cathode to repel the electrons. Only electrons leaving the emitter surface with initial kinetic energy greater than the potential energy between the cathode and collector will reach the anode and register a current. The potential difference can be increased until no electrons reach the collector and the current is stopped. This potential is called the stopping potential V_s .

Equation(5) can be tested experimentally by measuring the stopping voltage, V_s , for various frequencies of light, ν . The values of h and ϕ can then be found from the graph of stopping voltage vs. light frequency.

Determination of a value for h , Planck's constant (from Sample Data): Experiment Overview

Equation (5) can be verified by using the work function of the metal. We accessed sample data plotted to enable us find the stopping voltage(fig.5) and eventually used the plot of V_s vs. $1/\lambda$ (fig.6) to obtain a value for the Planck's constant. Moreover, the value for h , Planck's constant can be determined by applying max/min slopes of V_s vs. $1/\lambda$ graph and by using the known values for "c" and "e". Then, the average of the slopes is taken to be the estimated value

for h , Planck's constant and be compared with accepted value of h to back up the validity of data.

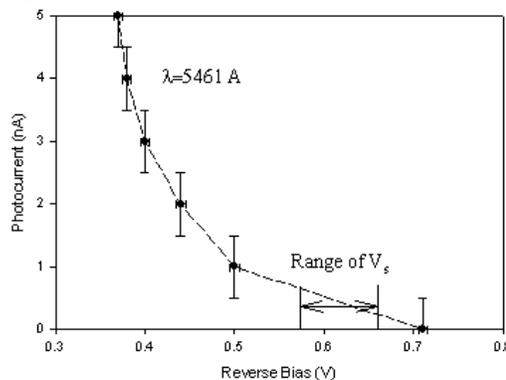


Figure 5: Sample data showing how to find stopping voltage and its uncertainty.

Table2: colors and their respective wavelength with some sources

Transmitted Colour	Wavelength (Angstrom= \AA) 1 Angstrom = 10^{-10} m	Source
Red	6328	red laser with red glass filter
Green	5435	green laser, green glass filter
Yellow	5777	
Green	5461	Hg lamp with multilayer filters
Bluish-violet	4358	
Violet	4050	

Then, the plot of V versus $1/\lambda$ has the following shape

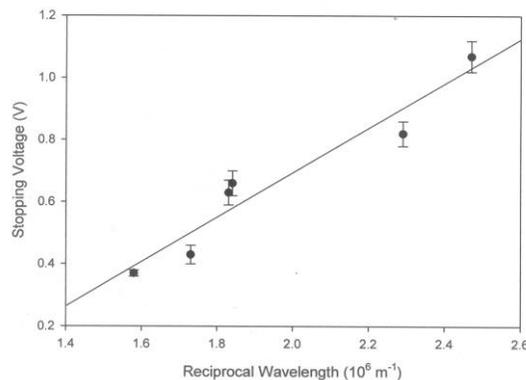


Figure 6: Example of how to find Planck's constant. Dashed lines in the above graph indicate estimated max and min slopes.

From a plot of V versus $1/\lambda$, the slope of the line can be determined. Since the slope equals hc/e , then

$$h = \frac{(\text{slope} \times e)}{c}$$

and the slope min and slope max from the plot of V versus $1/\lambda$ are respectively

$$(\text{slope})_{\min} = \frac{(0.8-0.6)V}{(2.3-1.81) \times 10^6 m^{-1}} = 0.41 \times$$

$10^{-6} Vm$, and

$$(\text{slope})_{\max} = \frac{(0.61 - 0.4)V}{(1.81 - 1.7) \times 10^6 m^{-1}} = 2 \times 10^{-6} Vm$$

using the known values of ($e = 1.602 \times 10^{-19}$ C and $c = 2.998 \times 10^8$ m/s), and applying equation ...to determine the value for h (for both values of slope), then

$$h_1 = \frac{(0.41 \times 10^{-6} Vm) \times (1.602 \times 10^{-19} C)}{2.998 \times 10^8 m/s} \approx 2.2 \times 10^{-34} Js \text{ [for } (\text{slope})_{\min}\text{].}$$

and similarly

$$h_2 = \frac{(2 \times 10^{-6} \text{ Vm}) \times (1.602 \times 10^{-19} \text{ C})}{2.998 \times 10^8 \text{ m/s}} \approx 11 \times 10^{-34} \text{ Js [for } (slope)_{max}\text{]}.$$

Hence, the value for h , Planck's constant can be obtained by taking the average of h_1 and h_2 :

$$h = \frac{h_1 + h_2}{2} = \frac{2.2 \times 10^{-34} \text{ Js} + 11 \times 10^{-34} \text{ Js}}{2} = \frac{13.2}{2} \times 10^{-34} \text{ Js} = 6.6 \times 10^{-34} \text{ Js}$$

[which is the average estimated value of h , Planck's constant].

To show the degree of the accuracy of estimated value for Planck's constant, it is reasonable to compare the estimated value ($h = 6.6 \times 10^{-34} \text{ Js}$) with accepted value of Planck's constant ($h = 6.626 \times 10^{-34} \text{ Js}$) through the definition percentage error.

i.e. % error = $\frac{|Approximate\ Value - Exact\ Value|}{|Exact\ Value|} \times 100\% = \frac{|6.6 \times 10^{-34} \text{ Js} - 6.626 \times 10^{-34} \text{ Js}|}{|6.626 \times 10^{-34} \text{ Js}|} \times 100\% = 0.39\%$ [which is even less than 1%].

CONCLUSION

Therefore, from the estimated value for Planck's constant, h and also from the calculated percentage error, it is successfully proven

that the result of experiment (the estimated value for Planck's constant, h) is in a very close agreement with its accepted (standard) value, $h = 6.626 \times 10^{-34} \text{ Js}$.

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